The Double-Edged Sword of Firm's Commitment to Net Zero on the Carbon Risk Premium

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Abstract

Achieving net zero is the only way to avoid the irreversible impact of global warming. More firms have recognized the importance of and have declared their commitment to net zero. By estimating the carbon risk premium in a cross-section of 1,100 listed firms that have declared a commitment to net zero as of December 2022 worldwide, we find that after firms declare a net zero commitment, the carbon risk premium may increase or decrease depending on firms' transition readiness. Institutional investors further divest from high-emitting firms that declare a net zero commitment, channeling carbon risk into stock markets.

Keywords: Carbon emissions; Climate change, Net zero commitment, Stock returns, Institutional investors
JEL: G12, G15, G23, G30, M14

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1. Introduction

Finance theory has long recognized the relationship between cross-sectional stock returns and various risk factors, such as market performance, size, book-to-market ratio, profitability, momentum, volatility, and other firm-specific characteristics. Since the Paris Agreement in December 2015, the emphasis on a new and significant risk factor --carbon risk-- has been growing. The Paris Agreement has set the goal of not only maintaining "the increase in the global average temperature to well below 2°C above pre industrial levels" but also pursuing efforts "to limit the temperature increase to 1.5°C above pre industrial levels" which has led governments to implement more stringent climate policies to curb greenhouse gas (GHG) emissions. The Agreement also raised the public's global awareness of the urgency of addressing climate change. In financial markets, more institutional investors and asset managers have started to include firms' GHG emissions in their investment decisions. Given the combined pressure from the government, the public and the financial market participants, firms' GHG emissions have become a new source of risk for investors.

Firms' GHG emissions could affect stock returns through various channels. First, governments may implement climate policies, such as carbon pricing, to penalize firms for having excessive GHG emissions. Second, increasing climate awareness could reduce consumers' demand for brown firms' products. Third, the evidence that firms with greater climate risk exposure are hardly to get low-cost funding from banks and investors is growing. Fourth, higher GHG emissions emitted by a firm imply that the potential abatement cost is also higher. These factors could negatively impact firms' cash flows, profitability, and valuations, especially for firms with disproportionately high GHG emissions. Building on Bolton and Kacperczyk (2021) who attempt to identify the association between firm's carbon emissions and its stock returns by a sample of listed companies in the US, the literature has framed this carbon risk issue as an important risk factor in explaining the variation in cross-sectional stock returns. When exposed to a higher carbon risk, forward-looking investors demand a positive carbon risk premium for holding the stocks of GHG emitters. In other words, higher GHG emissions should be associated with higher stock returns.

Meanwhile, recognizing that net zero is the only way to stop global warming (Intergovernmental Panel on Climate Change, 2018), more firms are committing to achieving net zero emissions in a certain foreseeable future. According to the net zero tracker,[1] more than half of the world's largest 2,000 publicly listed companies by revenue have committed to net zero and have declared that they are willing to contribute to the world achieving climate neutrality. Therefore, the amount of GHG released into the atmosphere is balanced by their removal from the atmosphere, which stops global warming. Intuitively, declarations of a commitment to net zero could alter the size and even the direction firms' carbon risk premiums after such declarations. On the one hand, a firm's declaration of a commitment to net zero could reduce its carbon risk premium if investors perceive that net zero is optimal for the firm in the long run. For instance, suppose that a firm has sufficient transition capacity to achieve a low-carbon transition in a cost-efficient manner. As such, firms enjoy greater net benefits during GHG abatement, and the carbon risk premium decreases with the declaration of a commitment to net zero. On the other hand, such a declaration could increase the carbon risk premium if investors perceive that net zero is suboptimal. For instance, some firms in countries with loose climate policies might face minimal urgency in low-carbon transitions. Achieving net zero might actually bring negligible benefits to these firms while they have to pay abatement costs.

[1] See https://zerotracker.net/

When the marginal benefits are smaller than the marginal costs, net zero is a suboptimal decision, and a declaration of a commitment to net zero could result in a larger carbon risk premium. As the carbon risk premium could be altered in either direction, the associated stock returns can also go in either direction.

A better understanding of the carbon risk premium is of high concern to policymakers. For example, the rise in carbon risk premium might lead to a sharp reduction in asset prices which pose volatility in the financial markets, it might also result in a sharp increase in the co-movement of asset prices which might challenge the effectiveness of market participants' ability to diversify their exposure to carbon risk. Building on the small but rapidly growing number of studies on carbon risk premiums, we attempt to advance the literature by systematically studying the impact of declarations of a commitment to net zero on carbon risk premium. By sampling over 1,100 largest listed firms by revenues worldwide in 49 countries from 2016 to 2022, we explore how the commitment to net zero declared by a firm could affect the size and even the direction of its carbon risk premium, and the determining factors that vary the impact of a commitment to net zero on the carbon risk premium. Following Bolton and Kacperczyk (2023), we utilize the granularity of firm-level observations with various fixed effects to overcome the challenges brought about by endogeneity and identification. To our knowledge, this study is the first on how the size of the carbon risk premium could be altered by firms' commitment to net zero.

The first contribution of our paper is to shed light on the impact of a firm's declaration of a commitment to net zero on carbon risk pricing. Existing studies mainly focus on the existence of carbon risk premiums and largely ignore the analysis of their determinants. Given the importance of net zero in mitigating climate change, it is natural to study whether and the channel through which the carbon risk premium is explained by a firm's declaration of a commitment to net zero and, in turn, allows policy-makers to identify the implications of financial instability originating from such a declaration. Thus, our paper, in which we utilize both theoretical modelling and empirical estimations, is the pioneer in exploring this topic.

The second contribution of our paper is that we have proposed an alternative explanation for how climate risk can be financially material. To explain the lower returns of green assets, existing studies mainly hypothesize that there exist investors' preferences for green assets, such that the risk premium for green assets is generally smaller than that for brown assets. This hypothesis based on preference, however, has limited predictive power. In contrast, we show that investors' behaviour can be rationalized through a cost benefit analysis. The prediction using cost benefit analysis is much richer, and our theoretical framework can explain a much more diverse green asset pricing phenomenon.

The final contribution of our paper is that we have uncovered institutional investors' investment strategies towards firms that have declared their commitments to net zero. Given the important role of institutional investors in shaping firms' behaviours, directing international capital flows, and facilitating price discovery, we provide crucial policy implications of how a firm's declaration of a commitment to net zero affects these investors' investment decisions, in turn affecting overall financial market development.

Three general striking results emerge from our analysis. First, the carbon risk premium is positively related to the level of GHG emission intensity, which is measured as the ratio of total GHG emissions to sales revenue, but not to the level of total GHG emissions, controlling for characteristics that predict stock returns. This result is statistically and economically significant in that a 1% increase in GHG emission intensity is associated with a 1.7% increase in annualized stock returns. Our result is different from that of Bolton and Kacperczyk (2021) and Bolton and Kacperczyk (2023) in that they show a positive association between stock returns and the level of total GHG emissions (but not to the level of GHG emission intensity). However, the sample used in our analysis is different, as we are analysing the largest firms based on revenues in the world, in contrast to all listed firms as in the US in Bolton and Kacperczyk (2021) and all listed firms globally as in Bolton and Kacperczyk (2023). Compared to other small to medium enterprises, investors might focus more on the carbon efficiency per unit of sales among the giants. In addition, Aswani, Raghunandan, and Rajgopal (2023) and Zhang (2024) suggested that emission intensity could be more informative for comparisons across firms. Hartzmark and Shue (2023) mentioned that investors almost exclusively focus on carbon intensity when discussing net zero investments. As such, not surprisingly, the relative importance of GHG emissions intensity in pricing carbon risk has increased.

Second, we find that, in general, a firm's carbon risk premium did not significantly change after its declaration of a commitment to net zero. However, we find that the impact of the commitment to net zero on the carbon risk premium varies substantially with the firm's transition readiness. Specifically, we find that after a firm declares its commitment to net zero, its carbon risk premium is likely to increase (decrease) if it is in a country with high (low) energy use per capita, low (high) renewable electricity output, high (low) trend in CO_2 per unit of gross domestic product (GDP) due to policy, low (high) share of CO_2 covered by a carbon price, or the firm has a low (high) environmental pillar score, and has (does not have) a golden parachutes rule. These findings indicate that the impact of the declaration of a commitment to net zero hinges on transition capacity, transition urgency, and discount rates given by investors of the firms. When the net zero transition plan is announced by a firm with high transition capacity, transition urgency, an investor base with a low discount rate, such as a country with lower demand for energy, higher renewable energy production, lower trend in CO_2 emissions per unit of GDP due to policy, higher environmental pillar score that could attract long-horizon investors or does not have a golden parachutes rule that encourage short-termism, reducing GHG emissions could bring long-term benefits to the firm and, thus, lower its carbon risk exposure. Therefore, investors are willing to accept a smaller premium. In contrast, firms operating in countries that rely heavily on energy, with undeveloped renewable energy sectors, having higher trend in CO_2 emissions per GDP due to policy, or having lower environmental pillars scores that deters long-horizon investors, are viewed as suboptimal to have net zero because the low-carbon transition could incur substantially high costs. As a result, the carbon risk premium for these firms tends to increase due to their declaration of a commitment to net zero. Given the potential increase in carbon risk premiums in financial markets, policymakers should pay particular attention to firms' declaration of a commitment to net zero. From the financial stability perspective, the accumulation of carbon risk premiums could lead to abrupt asset repricing when green policy shocks emerge.

Third, in line with the findings of Bolton and Kacperczyk (2021), we also find that institutional investors divest companies with high GHG emission intensity. Additionally, we find that the divestment behaviour of firms with high GHG emission intensity is more significant if they have declared a commitment to net zero. This result is statistically and economically significant: a 1% increase in GHG emission intensity is associated with a 1.71% decrease in institutional ownership if the company has declared its commitment to net zero, compared to a 1.36% reduction if the company has not declared such a commitment. Furthermore, we find that compared to firms with smaller institutional ownership, not only are the carbon risk premiums of firms with larger institutional ownership greater, but also the carbon risk premium will increase because of firms' declarations of a commitment to net zero. Overall, we find that institutional investors tend to divest more from high-emitting firms that have declared their commitment to net zero, implying that they focus more on concrete actions rather than merely verbal declarations.

One potential challenge is that similar to other studies on asset pricing, our cross-country analysis of the impact of a declaration of a commitment to net zero on carbon risk premiums is beset by endogeneity given that these variables are not perfectly randomly assigned. We could, to some extent, address these challenges in two ways. First, we exploit rich firm, industry and country-level variations in GHG emissions and other characteristics to identify how the declaration of a commitment to net zero affects the carbon risk premium. Combined with various fixed effects, this granularity of firm-level observations allows us to better understand the impact of a declaration of a commitment to net zero. Second, our sample is primarily selected from firms with the highest revenues instead of from the dependent variable, i.e., stock returns, given that the correlation between revenues and stock returns in our sample is not significant, the problem of an endogenous sample selection is absent from this study.

The remainder of this paper is organized as follows. Section 2 reviews the related literature, Section 3 describes and discusses the theoretical framework, Section 4 describes the data and provides summary statistics, Section 5 discusses the results, and Section 6 concludes.

2. Related Literature

Our work is related to the rapidly growing literature on the asset pricing implications of environment-related metrics. Early evidence revealed a negative association between a firm's environmental performance and the cost of capital. El Ghoul et al. (2011) document that firms with better corporate social responsibility (CSR) scores have a lower cost of equity. Chava (2014) reveals that firms deriving substantial revenues from the sale of fossil fuels are associated with higher costs of capital. More recently, studies have found a positive association between stock returns and firms' climate risk exposure. Oestreich and Tsiakas (2015) document the existence of a carbon risk factor that could explain part of the cross-sectional variation in stock returns in 65 German stocks. Bansal et al. (2019) show that long-run temperature fluctuations carry a positive risk premium in stock markets across 48 countries. Engle et al. (2020) document that portfolios of stocks constructed based on firms' environmental pillar scores could potentially be used to hedge against climate change news risk. Wen, Wu, and Gong (2020) find that the carbon premium in the Chinese stock market increased after China's carbon emissions trading market was established. Gorgen et al. (2020) show, among the sample of more than 26,000 firms worldwide, brown firms are associated with greater average returns than are green firms. Alessi, Ossola and Panzica (2021) reveal that investors in European markets accept lower returns to hold greener stocks. Rationalized by the preference for green assets, Pastor, Stambaugh, and Taylor (2021) show that green assets have low expected returns because investors enjoy holding them. Focusing on the US stock market, Bolton and Kacperczyk (2021) find evidence of a significant carbon risk premium for firms with higher total carbon dioxide emissions. Ilhan, Sautner, and Vilkov (2021) find that climate policy uncertainty is priced in the option market, in which the price of option protection against downside tail risks is greater for firms with more carbon-intense business models. Pastor, Stambaugh and Taylor (2022) show that although green stocks outperform brown stocks as climate concerns strengthen, the expected returns for green stocks are still lower than those for brown stocks. Using empirical estimation, Hsu, Li, and Tsou (2023) show that firms in the US with higher toxic emission intensities are associated with higher stock returns, as they are more exposed to the risk related to regulations. Furthermore, they also build a general equilibrium asset pricing model to rationalize how firm's exposure to environmental policy regime changes risks to its expected stock returns. Hong, Wang & Yang (2023) show that unexpected natural disasters associated with global warming led to a higher risk premium in the stock market. Faccini, Matin and Skiadopoulos (2023) find that climate policy factors are priced in the US stock market. Reshetnikova et al. (2023) find that a positive and statistically significant carbon premium exists in the Russian stock market. When covering more than 14,400 firms in 77 countries, Bolton and Kacperczyk (2023) find a widespread carbon premium in all sectors across Asia, Europe and North America following the announcement of the Paris Agreement. Cenedese, Han, and Kacperczyk (2023) document that firms with better alignment on net zero targets have lower expected returns. Wu and Wan (2023) show that the phenomenon of positive climate risk premium also exists in the country-level stock market indices, and such premium would increase the co-movement of stock market returns.[2]

A higher carbon risk premium means that asset prices become more vulnerable to carbon shocks. As such, when analysing a similar issue but from a different angle, the literature has also explored the price behaviour of different stocks due to unexpected climate shocks. Choi, Gao, and Jiang (2020) show that compared to stocks of firms with lower carbon emissions, stocks of carbon-intensive firms underperform in abnormally warm weather. Ramelli, Ossola, and Rancan (2021) show that carbon-intensive firms in Europe recorded substantially negative abnormal returns around the first global climate strike in 2019. Ardia et al. (2022) find that on days with an unexpected increase in climate change concerns, among the sample of S&P 500 companies, green firms' stock prices tend to increase, whereas brown firms' stock prices decrease.

A few studies also attempt to relate a firm's green commitment to its green performance and stock returns. At the regional scale, Peterson (2022) finds no statistically significant enhanced premium in stock valuation for a sample of large-cap, investor-owned utilities who made bold commitments to achieve carbon neutrality in the US. Liu et al. (2022) show that solid green commitment could reduce stock price crash risk in a sample of listed firms in China. In a sample of 166 listed UK and US firms, Xie et al. (2023) document that firms experience losses in market value from committing to being carbon neutral; however, better previous ESG performance could mitigate such adverse market reactions. These studies show that there exist association between firm's green commitment and its asset pricing in some selected markets. We contribute to this strand of literature by pushing forward the analysis towards a global scale and study how firm's commitment to net zero, which is regarded as the only way to rectify global warming, associated with its stock returns via the carbon risk premium channel.[3]

[2] The existing literature has also explored the relationship between climate risk and other financial assets classes, including corporate bonds (for example, Huynh and Xia (2020), Duan, Li, and Wen (2023)), municipal bonds (for example, Painter (2020), Goldsmith-Pinkham et al. (2023)), syndicated loans (for example, Ehlers, Packer, and De Greiff (2022), Ho and Wong (2023), Delis et al. (2024)) and real estate assets (for example, Bernstein, Gustafson, and Lewis (2019), Baldauf, Garlappi, and Yannelis (2020), Giglio et al. (2021), Wong, Ka, and Ng (2023)).

[3] In addition, Bolton and Kacperczyk (2024) document that firms committing to reduce their carbon emissions subsequently reduce their emissions; however, the aggregate impact has yet to be limited to tackling the climate problems. Chan, Cheung, and Shen (2024) show that a firm's net zero decision might not be optimal for firms with a sufficiently high stock of GHG emissions. These studies might also suggest that firm's green commitment could impact its asset price via other channels, including varying firm's green performance and long term profit optimality.

Our work is also related to investors' climate investment strategies. Heinkel, Kraus & Zechner (2001) show that firms with higher emissions could generate higher stock returns due to divestments from investors. Hartzmark and Sussman (2019) find that both institutional and retail investors are more willing to hold stocks of socially responsible firms. More recent studies focus on institutional investors and generally find that these investors have incorporated carbon risk into their investment decisions. Dyck et al. (2019) show a positive relationship between institutional ownership and CSR. Nofsinger, Sulaeman, and Varma (2019) find that institutional investors underweight stocks with negative environmental and social indicators. Krueger et al. (2020) show that institutional investors believe that carbon emissions have become a material risk in the financial market and that a pricing of carbon risk exists in the market. Monasterolo and De Angelis (2020) find that the weight of low-carbon indices within an optimal portfolio tend to increase after the Paris Agreement in 2015. Bolton and Kacperczyk (2021) show that institutional investors tend to divest from firms with higher Scope 1 emission intensity, primarily in high-emitting sectors. Garel and Petit-Romec (2021) show that firms with responsible strategies for environmental issues experienced better stock returns during the COVID-19 crisis, and the association was stronger for firms with greater long-term institutional investor ownerships. Pedersen, Fitzgibbons, and Pomorski (2021) document that institutional investors have incorporated a firm's environmental performance during portfolio formation. In particular, institutional ownership is negatively associated with CO_2 intensity. Choi et al. (2021) find that financial institutions reduced their exposure to stocks of companies in high-emission industries after 2015, especially for those in high-climate-awareness countries. Avramov et al. (2022) reveal that a firm's ESG uncertainty could lead to a decrease in demand for the stocks held by institutional investors. Safiullah, Alam, and Islam (2022) document that institutional investors have promoted the abatement of corporate carbon emissions, and the result is more pronounced in firms with more independent, long-term, and monitoring institutional ownership. Kordsachia, Focke, and Valte (2022) show that sustainable institutional ownership is positively associated with a firm's environmental performance and its carbon disclosure. De Angelis, Tankov, and Zerbib (2022) show that green investors spur firms to reduce their carbon emissions by increasing the costs of capital of the most carbon-intensive companies. Cao et al. (2022) find that institutional investors are more willing to sell low-CSR stocks and more reluctant to sell high-CSR stocks. Kahn, Matsusaka, and Shu (2023) show that firms reduced their GHG emissions when stock ownership by green funds increases. Cohen, Kadach, and Ormazabal (2023) find that institutional investors are more likely to engage with and divest from top carbon emitters. These studies generally conclude that institutional investors tend to divest from firms with poorer green performance, we contribute to the literature to enhance our understanding on investment strategy of institutional investors by revealing how they respond to firm's commitment to net zero, and whether the response interact with firm's green performance.

In summary, the abovementioned studies show that stock market investors priced climate risk into stock returns. In particular, firms with greater exposure to climate risk have higher average stock returns, and the accumulation of climate risk premiums might also trigger abrupt asset price corrections during climate shocks. Existing studies generally rationalize the lower risk premium of green assets by the green preference hypothesis. However, the predictive power is limited in the sense that green assets always yields smaller expected returns according to the green preference hypothesis, unless investors are assumed to be irrational, yet this would be tautological. Motivated by Hsu, Li, and Tsou (2023) who adopted a general equilibrium model in explaining the pollution risk premium, our paper differs from green asset preference hypothesis by providing an alternative explanation of how climate risk can be financially material, and how rational investors price climate risk using cost benefit analysis. As such, the predictive power of our model is much stronger.

In addition, the literature also shows that institutional investors play a significant role in shaping the overall climate investment universe. Given the importance of a commitment to net zero, however, understanding of its interaction with climate risk premiums in a global set-up and the corresponding stock return are warranted but it has remained unexplored. To fill these research gaps, by using a sample of more than 1,100 listed firms from 49 countries that have declared their commitment to net zero as of December 2022, our study contributes to the literature by exploring how a firm's declaration of a commitment to net zero could alter its carbon risk premium, and whether and to what extent institutional investors channel such risk to stock returns.

3. Theoretical Framework

This section introduces a microeconomic model to analyse how a firm's declaration of its commitment to net zero affects investors' evaluation of its carbon risk and hence its enterprise value. Existing literature, such as Pastor, Stambaugh, and Taylor (2021) and Pastor, Stambaugh and Taylor (2022) predict that green assets have lower expected returns than brown due to investors' green taste and green assets is a better hedge against climate risk. Yet, their models fail to take financially material of climate risk into account. In contrast, our model, adopted from Chan et al. (2024) with modifications, rationalizes the change in carbon risk premium, as well as the enterprise value, by financially material of the carbon risk. As such, investors' behavior can be rationalized using cost benefit analysis without relying on the green preference. The prediction of our model in turn is much richer and the theory can explain more diverse pricing phenomenon.

The parameters measuring the firm's transition urgency β, transition capacity κ, and transition ambition ϕ are all from the (representative) investor's perspective to capture the idea that the carbon risk premium is driven by investor beliefs. Time is continuous and denoted by $t \geq 0$. Let $x(t)$ and $g(t)$ be the GHG emission intensity and gross profit (before accounting for the abatement costs and carbon risks pertaining to its emission intensity) of the firm at time t respectively. The initial emission intensity is $x(0) = x_0 > 0$. Apart from its GHG emission intensity, the firm's carbon risk is also proportional to the transition urgency perceived by the investor, which is measured as the parameter $\beta > 0$. The dollar value of the carbon risk borne by the firm at time t is then $\beta x(t)$. Nevertheless, the firm can choose to decarbonize its value chain.

$u(t) := -\dot{x}(t)$ denotes the decarbonization rate of the firm at time t. For simplicity, we impose the constraint $u(t) \geq 0$ to rule out recarbonization. For some parameter $\kappa > 0$, let $\frac{1}{2\kappa} u(t)^2$ be the abatement cost borne by the firm if its decarbonization rate is $u(t)$ at time t. The convexity of the cost function reflects the law of diminishing marginal returns of the abatement efforts. κ captures the firm's transition capacity perceived by the investor in the sense that a higher κ is associated with a lower marginal cost of abatement.

In line with the Paris Agreement net zero pledges, the firm in the model has a "deadline" to attain net zero at $t = 1$ such that it is endowed with only a unit of time to decarbonize. To render the deadline analytically meaningful, set $u(t) \equiv 0$ for $t > 1$. Since the model aims to capture the declaration of a commitment to net zero as a communication device for the firm's transition ambition, let $x(1) \equiv x_1 \in (0, x_0)$ be the emission intensity target perceived by the investor. Moreover, as the ambition of a target x_1 is relative to the initial emission intensity x_0, we define the transition ambition parameter $\phi \equiv 1 - x_1/x_0$. In the limit, $\phi = 0$ means that the firm maintains its status quo emission intensity $x_1 = x_0$, whereas $\phi = 1$ means that it attains net zero $x_1 = 0$.

Based on the above setting, the net profit of firm $\pi(t)$ at time t can be defined as follows, where $\mathbb{1}$ is the indicator function.

$$\pi(t) = g(t) - \beta x(t) - \frac{\mathbb{1}_{t\in[0,1]}}{2\kappa} u(t)^2$$

In this dynamic set-up, the investor has a discount rate of $r > 0$ and is concerned with the enterprise value of the firm, which is measured as the net present value of its net profit flows. However, the latter evidently hinges on the transition pathway $u(t)$ chosen by the firm. We assume that the investor evaluates the latter by considering the optimal transition pathway, allowing us to focus on the effects of the parameters. The optimized enterprise value can then be written as

$$\mathrm{V} = \max_{\{u(t)\geq 0\}_{t\in[0,1]}} \int_0^\infty e^{-rt} \left(g(t) - \beta x(t) - \frac{\mathbb{1}_{t\in[0,1]}}{2\kappa} u(t)^2 \right) dt \qquad \text{(P)}$$

This completes the description of the microeconomic model. Next, we proceed to analyse the firm's optimal transition pathway and its resulting enterprise value. To facilitate the analysis, define the function

$$F(z) \coloneqq 1 + z + W_0\left(-e^{-(1+z)}\right)$$

where W_0 is the principal branch of the Lambert W function.

Proposition 1: Let $\tau = \min\{1, \frac{1}{r} F\left(\frac{r^2\phi x_0}{\beta\kappa}\right)\}$. The optimal emissions pathway of the firm is

$$x^*(t) = \begin{cases} x_0 - \frac{\beta\kappa}{r} t - \left(\frac{e^{rt}-1}{e^{r\tau}-1}\right)\left(\phi x_0 - \frac{\beta\kappa}{r}\tau\right) & \text{if } t < \tau \\ x_1 & \text{if } t \geq \tau \end{cases}$$

Moreover, $\tau < 1$ if and only if $r + e^{-r} > 1 + \frac{r^2\phi x_0}{\beta\kappa}$.

Proof: See Appendix A1.

Proposition 1 shows that the firm may optimally exhibit two types of transition behavior: (a) attain its ambition at time $t = 1$ on the deadline, or (b) attain its ambition at time $t = \tau < 1$ ahead of the deadline. The transition pathway of case (b) is characterized by the condition $r + e^{-r} > 1 + \frac{r^2\phi x_0}{\beta\kappa}$. In other words, the firm's transition ambition ϕ is so low relative to its transition capacity κ and urgency β that it halts decarbonization ahead of the deadline ($u^*(t) = -\dot{x}^*(t) = 0$ for $t \in [\tau, 1]$). Whereas case (b) is theoretically possible, as our sample covers the largest 1,177 companies by revenues that have declared a commitment to net zero, the probability for these largest firms in the globe to cheap talks is slim. Therefore, we reckon that it is not representative of investors' expectations. Nevertheless, for completeness, we present the findings in both cases.

The present model aims to capture the declaration of a commitment to net zero as a communication device for the firm's transition ambition. Thus, the effect of the former is modelled as an upwards adjustment of the firm's transition ambition ϕ perceived by the investor. In the following, we capture the net zero commitment premium and the carbon risk premium of the firm as the decrease in its optimized enterprise value resulting from an increase in its perceived transition ambition ϕ and initial emission intensity x_0, respectively.

Proposition 2: Suppose that $r + e^{-r} < 1 + \frac{r^2\phi x_0}{\beta\kappa}$. The optimized enterprise value of the firm is

$$V_a \equiv \int_0^\infty e^{-rt} g(t)dt - \frac{\beta x_0}{r} - \frac{r^4\phi^2 x_0^2 - 2\beta\kappa r^3\phi x_0 + \beta^2\kappa^2(2 + r^2 - e^r - e^{-r})}{2\kappa r^3(e^r - 1)}$$

Moreover, the following statements hold for the firm.

(a) Its carbon risk premium is positive:

$$\frac{\partial V_a}{\partial x_0} < 0$$

(b) Declaring a commitment to net zero raises its optimized enterprise value if and only if its transition capacity and urgency are sufficiently high relative to its transition ambition:

$$\frac{\partial V_a}{\partial \phi} > 0 \quad \Leftrightarrow \quad \frac{r\phi x_0}{\beta\kappa} < 1$$

(c) Its declaration of a commitment to net zero raises its carbon risk premium if and only if its transition capacity and urgency are sufficiently low relative to its transition ambition:

$$\frac{\partial^2 V_a}{\partial\phi\partial x_0} < 0 \quad \Leftrightarrow \quad \frac{r\phi x_0}{\beta\kappa} > \frac{1}{2}$$

Proof: See Appendix A.2.

Proposition 2 captures how a firm's enterprise value varies with its initial GHG emission intensity and transition ambition if it belongs to the type that optimally decarbonizes until and only until the deadline. As expected, statement (a) suggests a carbon risk premium exists. However, as suggested by statement (b), declaring a commitment to net zero may reduce its enterprise value if investors believe that attaining net zero is not a priority or beyond the firm's capacity. As such, statement (c) shows that such a declaration may also raise the carbon risk premium of the firm.

Proposition 3: Suppose $r + e^{-r} > 1 + \frac{r^2\phi x_0}{\beta\kappa}$. With $\tau \equiv \frac{1}{r}F\left(\frac{r^2\phi x_0}{\beta\kappa}\right)$, the optimized enterprise value of the firm is

$$V_b \equiv \int_0^\infty e^{-rt} g(t)dt - \frac{\beta x_0}{r} - \frac{r^4\phi^2 x_0^2 - 2\beta\kappa r^3\tau\phi x_0 + \beta^2\kappa^2(2 + r^2\tau^2 - e^{r\tau} - e^{-r\tau})}{2\kappa r^3(e^{r\tau} - 1)}$$

Moreover, the following statements hold for the firm.

(a) Its carbon risk premium is positive:

$$\frac{\partial V_b}{\partial x_0} < 0$$

(b) Declaring a commitment to net zero raises the optimized enterprise value:

$$\frac{\partial V_b}{\partial \phi} > 0$$

(c) Declaring a commitment to net zero raises its carbon risk premium if and only if its transition capacity and urgency are sufficiently low relative to its transition ambition:

$$\frac{\partial^2 V_b}{\partial \phi \partial x_0} < 0 \quad \Leftrightarrow \frac{r^2 x_0 \phi}{\beta \kappa} > \ 1 + \frac{1}{2} W_0(-2e^{-2})$$

Proof: See Appendix A.3.

Proposition 3 is similar to Proposition 2, except that the former focuses on firms whose transition ambition is so low relative to their transition capacity κ and urgency β. Statement (a) suggests that the carbon risk premium is still positive. However, compared to type of firm in Proposition 2, for this type of firms, statement (b) shows that elevating the transition ambition perceived by investors via a declaration of a commitment to net zero can unambiguously increase their enterprise value as the declaration signal a strong increase in transition ambition. Nevertheless, similar to the type of firms in Proposition 2, statement (c) shows that declaring net zero commitment may elevate the carbon risk premium at the same time.

Propositions 2 and 3 of our theoretical model suggest that a declaration of a commitment to net zero could increase or decrease the carbon risk premium and the enterprise values, depending on firm's transition capacity and transition urgency. The higher the firm's transition capacity and urgency, the higher the likelihood for the carbon risk premium to decrease by firm's declaration of commitment to net zero, and the higher the likelihood for the enterprise value to increase by such declaration. To empirically test the prediction of our theoretical framework, in the next sections, we explore the impact of firm's net zero commitment declaration on its carbon risk premium, and its enterprise values, using a sample of a cross-section of more than 1,100 listed firms in 49 countries over the period ranging from 2016 to 2022.

4. Data and Sample

Our primary database covers the period ranging from 2016 to 2022 and includes three datasets: Trucost, which provides annual information on firm-level GHG emissions; S&P Capital IQ, which provides data on firms' financial statements, such as balance sheets, income statements, and annual reports; and environmental performance-related reports, such as ESG reports, sustainability reports, CDP questionnaires, and TCFD reports. These publicly disclosed reports allow us to extract information about when firms declare their commitment to net zero; and Bloomberg, which provides data on stock returns and institutional ownership. Since our sample covers the largest listed firms by sales revenue who have declared a commitment to net zero as of the end of December 2022 among the largest 2,000 listed companies in the world, we are able to perform matching using Ticker as a main identifier.[4] Overall, 1,177 out of the largest

[4] There are slight differences in the ticker structure between Bloomberg and S&P Capital IQ.

2,000 listed firms by sales revenue have been declared net zero as of the end of December 2022, and these 1,177 firms constitute our sample, which is about 52% of total market capitalizations of companies listed on stock exchanges worldwide as of the end of December 2022. We augment these data with data for country-level variables from the Our World in Data, which provides annual data on energy use per capita, renewable electricity output as a percentage of total electricity output by countries and coverage of carbon pricing, and data from the Yale Center for Environmental Law & Policy, which provides trends in country-level CO_2 emission intensity resulting solely from government policies rather than economic fluctuations.

(a) Data on firms' environmental performance and commitment to net zero

We sourced the firm's emissions data from Trucost. Trucost collects firms' environmental data from a variety of publicly disclosed sources, such as annual reports, 10-K reports, SEC filings, CSR reports, sustainability reports, and ESG reports. In the absence of public disclosures, Trucost provides data estimated using its environmentally extended input-output model.[5] Following the GHG Protocol,[6] Trucost provided all three scopes of GHG emissions data. Scope 1emissions are from directly emitting sources owned or controlled by a company, such as the internal combustion engines of a trucking company. Scope 2 emissions are from the consumption of energy generated upstream from a company's direct operation, such as purchased electricity and steam. Scope 3 emissions cover all other emissions associated with a company's operations that are not directly owned or controlled by the company, including emissions in the company's supply chain and downstream. All three scopes are reported in units of tons of GHG emitted in a year.

Apart from the level of GHG emissions, Trucost also provides the level of all three scopes of GHG emissions normalized by a company's annual consolidated revenues, which is also known as GHG emission intensity. GHG emission intensities are useful for comparing firms within and between different industries and assessing the carbon efficiency of a company. All three scopes are reported in units of tons of GHG emitted per millions of US dollars in a year. Since the three scopes of emissions capture different dimensions of emissions performance, we use the aggregate of all three scopes of emissions to measure firm's total emissions. A potential caveat is that Scope 3 emissions data are subject to a less comprehensive standardization and assessment (Ho and Wong (2023), Leung, Wan, and Wong (2023), Chan and Wan (2024)). However, since our sample covers only the largest listed firms globally, the probability of having fatal measurement errors is rare. Furthermore, as shown in the summary statistics, the relative importance of Scope 3 emissions is not lower than that of Scope 1 and Scope 2 emissions. Thus, including Scope 3 allows us to gain a more complete picture to gauge a firm's GHG performance.[7]

[5] One potential concern is that whether the estimated emissions data on a firm by Trucost can reasonably reflect the genuine emissions of the firm. For instance, Chan and Wan (2024) document that only about one-fourth of emissions data in Trucost are firm-disclosed data whereas three-fourth of them are estimated. Aswani, Raghunandan, and Rajgopal (2024) show that the Trucost estimates could be systematically different from firm-disclosed emissions. This concern, however, is insignificant in our study in the sense that we only select the largest companies worldwide. As such, most of the emissions data in our sample are firm-disclosed data. Specifically, more than 90% of Scope 1 and 2 emissions are firm-disclosed data whereas more than 60% for Scope 3.

[6] See https://ghgprotocol.org/

[7] Because downstream Scope 3 emissions recently just started assembling in Trucost, the gaps in the data are numerous. As such, throughout our study, Scope 3 refers to upstream Scope 3. The same treatment was also adopted in Bolton and Kacperczyk (2021), Bolton and Kacperczyk (2023), Dai et al. (2024).

In addition, Trucost also covers broader financially material environmental factors by providing firms' environmental pillar scores, as well as other indicators, including social pillar scores, and governance and economic pillar scores. All of the dimension scores range from 0 to 100. The higher the score is, the higher the corresponding dimension's association with the firm's performance.[8]

We sourced the firms' declaration of a commitment to net zero from S&P Capital IQ. S&P Capital IQ collects all publicly disclosed filings and reports of publicly listed firms, including annual reports, 10-K reports, CSR reports, sustainability reports, environmental reports, ESG reports, CDP questionnaires, and TCFD. We browse all of the publicly disclosed filings and reports and identify when a firm initially declared its commitment to net zero. Given that many entities use a range of interchangeable terms that are similar to net zero, such as "net zero", "zero emissions", "zero carbon", "climate neutral", "climate positive", "carbon neutrality", "carbon negative", "net negative", "1.5-degree target", "science-based target", etc., we use the first appearance of those terms in publicly disclosed reports to gauge when the firm started to declare its commitment to net zero. For the sake of quantitative analysis, we define a dummy variable $D_{i,t}^{NZ}$ which equals one if firm i has declared a commitment to net zero on or before time t and equals 0 otherwise.

Panel A of Table 1 reports the summary statistics of firms' environmental performance. The levels of both total emissions and emission intensity are normalized using the natural log scale. As such, the log of the sum of all three scopes of emissions (LOG GHG) of the average firm in our sample is 14.54, with a standard deviation of 1.97. We divide total emissions into three scopes and find that Scope 3 emissions are attributed to a firm's largest emissions footprint due to the broadest coverage of these emissions. For emissions intensity, the log of the sum of all three scopes of emissions (LOG GHG intensity) of the average firm in our sample is 5.16, with a standard deviation of 1.34. Similar to Scope 3 emissions, the intensity of these emissions is attributed to a larger footprint than that of the other two scopes of emission intensity. In addition, the average firm has an environmental pillar score of 57.1. Furthermore, 45% of our sample has declared their commitment to net zero.

Figure 1 depicts the cumulative density function of firms declaring their commitment to net zero. Among the 1,177 firms in our sample, most declared their commitment to net zero during 2020 and 2021. For instance, approximately 20% of the firms declared their commitment to net zero in 2019, and more than 80% declared in 2021. Figure 2 reports the breakdown of our sample into three regions, namely, North America, Europe and Others, based on a firm's location.[9] Firms in Europe are the leaders in declaring commitments to net zero, followed by those in North America and Others.

(b) Data on stock returns, institutional ownership, and other control variables

[8] The correlation between environmental pillar score and GHG emissions is not as high as one might have expected due to two reasons. First, apart from factors related to GHG emissions, environmental pillar score represents wide range of environmental factors, including biodiversity, climate strategy, waste and water management, etc. Second, environmental pillar score mainly captures the nonfinancial risks a firm is exposure to, which is different from a firm creating a positive or negative climate impact. For instance, a large GHG emitters could have higher environmental pillar score if it promises to decarbonize. In our sample, the correlation between environmental score and levels of total GHG emissions is 0.20 whereas the correlation between environmental pillar score and levels of GHG emissions intensity is 0.03.

[9] In case of multi-national corporations, we rely on the location of its primary business activities.

We sourced stock returns and institution ownership information from Bloomberg and other control variables from Bloomberg and S&P Capital IQ. Following Bolton and Kacperczyk (2021), Bolton and Kacperczyk (2023), and Aswani et al. (2024), our empirical analysis of stock returns employs a monthly measure of returns as a dependent variable. The dependent variable in our cross-sectional return regressions, $RET_{i,t}$, is the monthly return of individual stock i in month t. The monthly return in month t is computed as the log difference between the stock price in t versus stock price in $t-1$. Another dependent variable in our cross-sectional institutional ownership regressions is the monthly percentage of shares of individual stock i owned by institutional investors in month t, $IO_{i,t}$. Following Bolton and Kacperczyk (2023) and Aswani et al. (2024), we include the following control variables in our cross-sectional regressions: $LOGSIZE_{i,t}$, which is measured as the natural log scale of the market capitalization of firm i at the end of year t; $B/M_{i,t}$ which is measured as the book-to-market ratio of firm i at the end of year t; $LEVERAGE_{i,t}$, which is measured as the total debts divided by the total assets of firm i at the end of year t; $MOM_{i,t}$, which is measured as the average of the most recent 12 months' return of stock i leading up to and including month $t-1$; $INVEST/A_{i,t}$, which is measured as firm i's capital expenditures divided by total assets at the end of year t; $HHI_{i,t}$, which is measured as the Herfindahl concentration index of firm i with respect to its industry based on each industry's revenues at the end of year t; $LOGPPE_{i,t}$, which is measured as the natural log scale of property, plant, and equipment of firm i at the end of year t; $ROE_{i,t}$, which is measured as the net income divided by the total equity of firm i at the end of year t; and $VOLAT_{i,t}$, which is measured as the standard deviation of returns based on the past 12 months' return of stock i, leading up to and including month $t-1$. Unlike Bolton and Kacperczyk (2023) and Aswani et al. (2024), given that our sample consists of only the largest listed firms globally, outliers are not significance. Therefore, we did not winsorize our data. In addition, reflecting the short-termism of board members, we also include whether the firms have golden parachute rules.[10] Ultimately, our main sample contains 77,701 stock-month observations from January 2016 to December 2022 that cover 1,177 unique firms in 49 countries.

Panel B of Table 1 summarizes all of the relevant variables that we use in our cross-sectional analysis. The average firm's monthly stock return equals 0.77%, with a standard deviation of 9.06%. The average firm's shares are owned by 69.70% of institutional investors. The average firm has a market capitalization of 18.59 trillion in US dollars. The average book-to-market ratio and leverage are 0.71 and 0.28, respectively. The average capital expenditure-to-asset ratio is 0.03. The average firm has $7.13 trillion in property, plant, and equipment and having aa ROE of 0.11. Besides, slightly more than half of the sample have golden parachute.

Furthermore, we also include in our analysis country-level energy use per capita, renewable electricity output as a percentage of total electricity output, the trend in CO_2 emissions per unit of GDP due to policy, and the share of CO_2 emissions covered by a carbon price. The country-level energy use per capita and renewable electricity output as a percentage of total electricity output are sourced from Our World in Data, which is a proxy for energy consumption and the fraction of renewable energy production, respectively. The average firm is in a country with 4,753 kg of oil equivalent per capita and 20.4% of renewable electricity output as a percentage of total electricity output. The trend in CO_2 emissions per unit of GDP due to policy metrics is

[10] A golden parachute refers to a large financial compensation or substantial benefits guaranteed to company executives upon termination following a merger or takeover. Shive and Forster (2020) find that the presence of a golden parachute at the firm, which encourages short termism as it is more difficult for top decision-makers to be quickly replaced due to poor short-term financial performance, is positively associated to CO_2 emissions.

sourced from the Yale Center for Environmental Law & Policy and is calculated as the average of the recent 10 years of each country's emissions, with adjustments in variations in GHG emissions caused by changes in the economic business cycle. As such, the trend reflects only government policy rather than economic fluctuations (Wolf, et al., 2022). Finally, the country-level share of CO_2 emissions covered by a carbon price is sourced from Our World in Data, which indicates the size of the economic sector that has to pay a price for its GHG emissions. On average, a firm is in a country with 31% of the CO_2 covered by a carbon price.

Table 1
Summary statistics

This table reports summary statistics (averages, medians, and standard deviations) for the variables used in the regressions. The sample period is from 2016 to 2022. Panel A reports firms' environmental performance variables and declarations of a commitment to net zero. $D_{i,t}^{NZ}$ is a dummy variable equal one if firm i has declared a commitment to net zero at time t, and equals 0 otherwise. Panel B reports the summary statistics of the stock returns, institutional ownership, and other control variables. RET is the monthly stock return; IO is the percentage of shares owned by institutional investors; $LOGSIZE$ is the natural log scale of market capitalization; B/M is the book-to-market ratio; $LEVERAGE$ is the total debt to total asset ratio; MOM is the average previous 12-month stock return; $INVEST/A$ is the capital expenditure to total asset ratio; HHI is the Herfindahl index of a firm's industry with weights proportional to revenues; $LOGPPE$ is the natural log scale of property, plant and equipment; ROE is the ratio of net income to total equity; and $VOLAT$ is the standard deviation of the previous 12-month stock return. $GParachute$ is a dummy variable equal one if firm has golden parachute, and equals 0 otherwise; $ENUSEOC$ is a country's energy consumption per capita; $REOUTPUT(\%)$ is the percentage of renewable electricity output to total electricity output; CDA is the score of trend in CO_2 emissions per unit of GDP due to policy metrics of the country, and countries with lower trend in CO_2 per unit of GDP receive top scores; and $CPCOVERAGE(\%)$ is the share of CO_2 emissions covered by a carbon price.

Panel A: Firms' environmental performance and declaration of a commitment to net zero

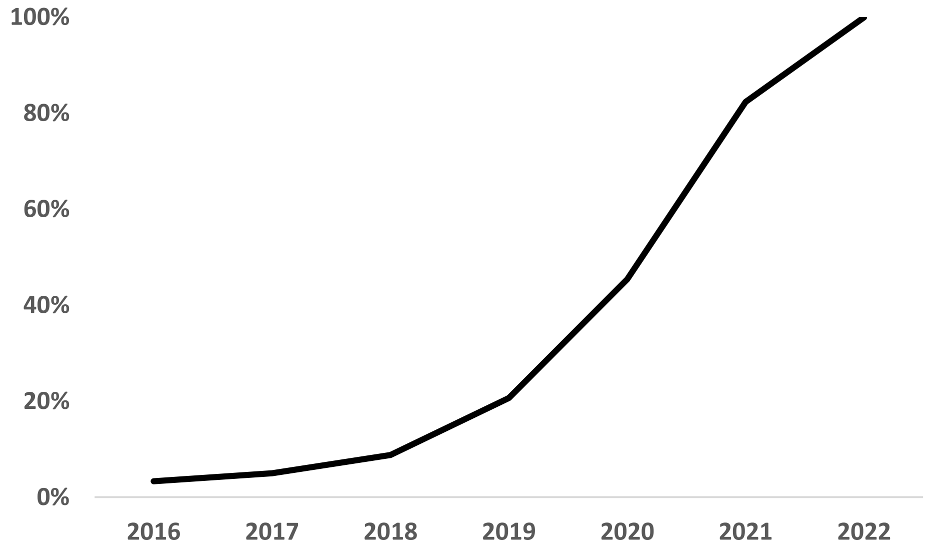
Variables	Mean	Median	Std Dev
LOG GHG	14.536	14.615	1.965
LOG Scope 1 emissions	11.864	11.656	3.019
LOG Scope 2 emissions	11.993	12.108	2.006
LOG Scope 3 emissions	13.956	14.111	1.800
LOG GHG intensity	5.159	5.077	1.358
LOG Scope 1 emission intensity	2.488	2.248	2.645
LOG Scope 2 emission intensity	2.619	2.647	1.577
LOG Scope 3 emission intensity	4.580	4.589	1.041
Environmental pillar score	57.069	57.000	22.400
$D_{i,t}^{NZ}$	0.448	0	0.497

Panel B: Stock returns, institutional ownership, and other control variables			
Variables	Mean	Median	Std Dev
RET (%)	0.768	0.657	9.055
IO (%)	69.700	70.270	26.300
$LOGSIZE$	23.646	23.603	1.185
B/M	0.711	0.636	2.538
$LEVERAGE$	0.279	0.258	0.199
MOM (%)	0.711	0.636	2.538
$INVEST/A$	0.033	0.025	0.033
HHI	2.721	1.954	3.294
$LOGPPE$	22.687	22.722	1.593
ROE	0.105	0.106	5.127
$VOLAT$	0.077	0.069	0.039
$GParachute$	0.521	1.000	0.500
$ENUSEPC$	4,753.470	4,325.524	2102.017
$REOUTPUT$ (%)	20.416	14.059	16.727
CDA	58.300	57.837	15.363
$CPCOVERAGE$ (%)	31.335	9.170	29.955

Figure 1

Cumulative density function of declaration of a commitment to net zero

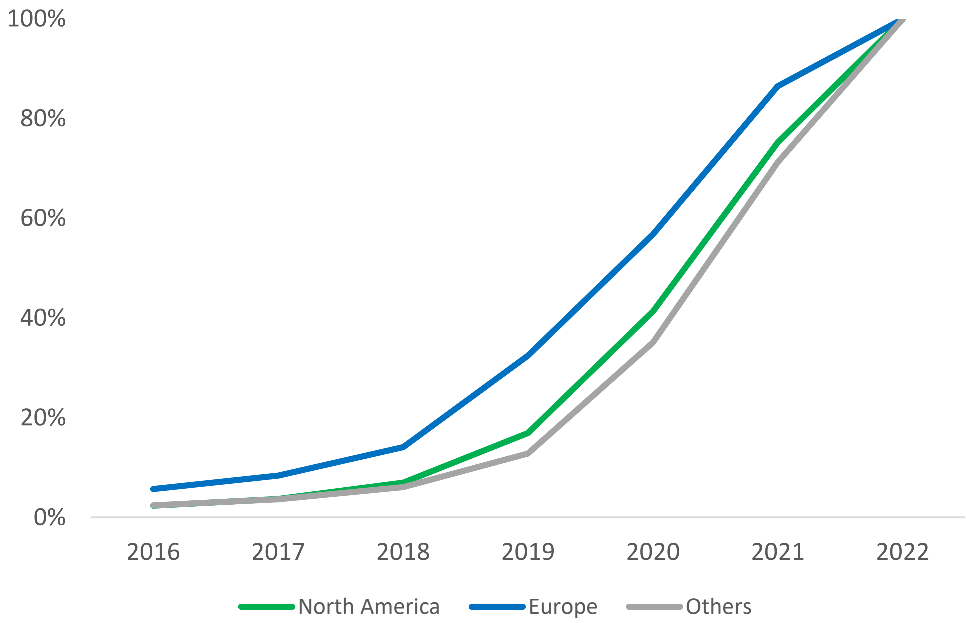
This figure presents the cumulative density function of firms in our sample declaring their commitment to net zero in the period from 2016 to 2022.



Source: Authors’ calculation based on information from S&P Capital IQ.

Figure 2
Cumulative density function of declaration of a commitment to net zero by region

This figure presents the cumulative density function of firms declaring their commitment to net zero in our sample by regional breakdown based on firm location in the period from 2016 to 2022.



Source: Authors’ calculation based on information from S&P Capital IQ.

We also describe how the data broke down in Table 2 into firms before and after their declaration of a commitment to net zero. We note that for the sample of observations after declaring a commitment to net zero, the average GHG emissions level (as well as all the three scopes) is slightly higher, whereas the average GHG emission intensity (as well the level of all three scopes) is slightly lower. In addition, after declaring a commitment to net zero, the sample of observations has a higher environmental pillar score and lower stock returns and returns on equity. However, other firms' characteristics are similar before and after they declare their commitment to net zero. In particular, their size, book-to-market ratio, leverage, capital expenditure, and fixed assets are very similar. Furthermore, the sample of observations after declaring a commitment to net zero are on average in countries with lower energy use per capita and have a higher share of renewable electricity output, lower trend in CO_2 emissions per unit of GDP due to policy, and higher carbon price coverage.

Table 2

Stock characteristics regarding declaration of a commitment to net zero

This table reports the sample means of the main variables during 2016-2022. All variables are defined in Table 1. Column (1) represents the sample of observations before their declaration of a commitment to net zero; Column (2) represents the sample of observations after the declaration of a commitment to net zero.

Dependent Variables: RET	(1) $D_{i,t}^{NZ} = 0$	(2) $D_{i,t}^{NZ} = 1$
LOG GHG	14.484	14.621
LOG Scope 1 emissions	11.828	11.923
LOG Scope 2 emissions	11.962	12.044
LOG Scope 3 emissions	13.905	14.039
LOG GHG intensity	5.193	5.104
LOG Scope 1 emission intensity	2.533	2.413
LOG Scope 2 emission intensity	2.672	2.531
LOG Scope 3 emission intensity	4.614	4.523
Environmental pillar score	54.211	60.543
RET (%)	0.935	0.720
IO (%)	70.276	68.742
$LOGSIZE$	23.548	23.766
B/M	0.774	0.796
$LEVERAGE$	0.270	0.289
MOM (%)	0.639	0.800
$INVEST/A$	-0.034	-0.032
HHI	2.629	2.834
$LOGPPE$	22.497	22.933
ROE	0.126	0.074
$VOLAT$	0.072	0.083
$GParachute$	0.544	0.494
$ENUSEPC$	4787.164	4697.580

$REOUTPUT$ (%)	19.606	21.761
CDA	57.394	59.805
$CPCOVERAGE$ (%)	30.149	33.368

Finally, we report summary statistics on the main determinants of firms' declarations of a commitment to net zero in Table 3. We regress the dummy variable of the commitment to net zero on a firm's emissions data and other firm-level characteristics. Year/month-fixed effects, country-fixed effects and industry-fixed effects (using SIC classification) are also included to capture the differences across countries and industries over time.[11] Columns (1) and (2) reflect the measurement of emissions as the natural log scale of the total emissions of all three scopes, and Columns (3) and (4) reflect this measurement by the natural log scale of emission intensity of all three scopes. Probit and Logit models are adopted as our dependent variable, commitment to net zero, is binary.[12]

We first note that the probability of a firm declaring its commitment to net zero generally decreases with both total GHG emissions and total GHG emission intensity, indicating that high-emitters and less carbon-efficient firms tend not to declare their commitment to net zero. Regarding firms' characteristics, we note that the probability of a firm declaring its commitment to net zero increases with its firm, book-to-market ratio, and tangible capital stock. These findings may suggest that firms declaring commitment to their net zero tend to have more solid fundamentals. The negative coefficient of leverage suggests that firms have a weaker incentive to exploit leverage and enhance profitability, given that the firm might face less carbon risk after its declaration of net zero commitment. Investment and ROE have a negative effect on the declarations of a commitment to net zero, suggesting that high-growth firms tend to focus more on growth than on carbon efficiency. Industry specialization has a negative effect on the declarations of a commitment to net zero, suggesting that firms declaring a commitment to net zero are generally less specialized. Institutional ownership has a positive effect on the declarations of a commitment to net zero, suggesting that institutional investors could be a driver of firms' environmental performance. Finally, the coefficients of firms' momentum and volatility are negative, indicating that firms declaring a commitment to net zero tend to be value stocks but not high growth stocks.

[11] As discussed from Aswani et al. (2023), the choice of industry classification system could yield significantly different results. However, the results are also robust to using other industry classification, including the Trucost industry classification, Bloomberg industry classification system and Global industry classification standard.

[12] For robustness check, we also performed fixed-effects estimations, and the results are similar. For brevity, we do not present here the estimation result of fixed-effects estimations. For interested readers, the results are available on request.

Table 3
Predictors of declarations of a commitment to net zero

The sample period is from 2016 to 2022. The dependent variable is the declaration of a commitment to net zero. All variables are defined in Table 1. Limited dependent variable models are adopted because the dependent variable is binary. Columns (1), (3), (5) and (7) reflect the adoption of Probit models, and Columns (2), (4), (6) and (8) reflect the adoption of Logit models. Standard errors are presented in parentheses. All regressions include year/month-fixed effects, country-fixed effects, and industry fixed-effects. *** 1% significance; ** 5% significance; * 10% significance.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Variables: D^{NZ}	Probit	Logit	Probit	Logit	Probit	Logit	Probit	Logit
LOG GHG	-0.06***	-0.11***			-0.01**	-0.02*		
	(0.01)	(0.02)			(0.01)	(0.01)		
LOG GHG intensity			-0.14***	-0.24***			0.01*	0.03**
			(0.02)	(0.03)			(0.01)	(0.01)
LOG SIZE	0.26***	0.49***	0.23***	0.45***	0.11***	0.19***	0.12***	0.20***
	(0.01)	(0.02)	(0.01)	(0.02)	(0.01)	(0.02)	(0.01)	(0.02)
B/M	0.08***	0.14***	0.08***	0.14***	-0.04***	-0.08***	-0.03**	-0.06***
	(0.01)	(0.02)	(0.01)	(0.02)	(0.01)	(0.02)	(0.01)	(0.02)
LEVERAGE	-0.13***	-0.17*	-0.13**	-0.16*	-0.07*	-0.10	-0.07*	-0.10
	(0.05)	(0.09)	(0.05)	(0.09)	(0.04)	(0.07)	(0.04)	(0.07)
INVEST/A	0.04***	0.07***	0.03***	0.07***	0.01***	0.03***	0.01***	0.03***
	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)
HHI	-0.01***	-0.03**	-0.01***	-0.02**	0.01*	0.01	0.00	0.00
	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.00)
LOG PPE	0.06***	0.10***	0.04***	0.05**	0.11***	0.21***	0.09***	0.17***

	(0.01)	(0.03)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
ROE	-0.00**	-0.01**	-0.00***	-0.01**	-0.00	-0.00	-0.00	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
IO	0.00***	0.00***	0.00***	0.00***	0.00*	0.00**	0.00*	0.00**
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
MOM	-0.01***	-0.02***	-0.01***	-0.02***	-0.01***	-0.02***	-0.01***	-0.02***
	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)
VOLAT	-0.01***	-0.02***	-0.01***	-0.02***	-0.01***	-0.01***	-0.01***	-0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Year/month-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry-fixed effects	Yes	Yes	Yes	Yes	No	No	No	No
Observations	69897	69897	69897	69897	69897	69897	69897	69897

We then run the regression once without including the industry fixed-effects in Columns (5), (6), (7) and (8). We notice that in Columns (5) and (6), high-emitters, among the entire sample, are still less likely to declare their commitment to net zero. However, Columns (7) and (8) reflect that less carbon-efficient firms, without limiting to within-industry comparison, are likely to declare their commitment to net zero. The latter results suggest that when compared to the entire sample, less-carbon efficient firms are more likely to declare their commitment to net zero whereas within each industry, the less-carbon efficient firms are less likely to declare such commitment. In additional, when compared to the entire sample, we notice that firms with smaller book-to-market ratio are more likely to declare a commitment to net zero, where leverage, industry specialization and ROE turns out to be not as significant as within industry comparison in explaining firm's declaration to commitment to net zero.

5. Results

We organize our discussion into three subsections. The first subsection replicates Bolton and Kacperczyk (2023) by evaluating the carbon risk premium among the 1,177 firms in our sample. The second subsection explores the impact of the declaration of a commitment to net zero on the size (and direction) of the carbon risk premium. The third subsection investigates the role of institutional investors in channelling the impact of a declaration of a commitment to net zero on the carbon risk premium.

A. Carbon Risk Premium

In this section, we present our findings on the carbon risk premium. We begin by describing the specification of estimation model. We then report the findings for the full sample of firms. Finally, we show how the carbon risk premium is distributed across different geographical regions.

A.1. Empirical Specification

Following Bolton and Kacperczyk (2023), we evaluate the carbon risk premium by estimating the following cross-sectional characteristic-based regression which is found to be more appropriate for adoption than is the risk factor-based approach in the sample with rich cross-sectional variation in firm characteristics:

$$RET_{i,t} = \alpha_0 + \alpha_1 Emissions_{i,t-1} + \alpha_2 Controls_{i,t-1} + \mu_{country} + \delta_{industry} + \gamma_t + \varepsilon_{i,t}. \quad (1)$$

The dependent variable $RET_{i,t}$ measures the stock return of firm i in month t. The independent variable $Emissions$ is the generic term representing for $LOG\ CO2$ and $LOG\ CO2\ intensity$. The vector of firm-level controls includes the firm-level variables $LOGSIZE$, B/M, $LEVERAGE$, MOM, $INVEST/A$, HHI, $LOGPPE$, ROE, and $VOLAT$. Both $Emissions$ and the control variables are lagged by 1 month. $\mu_{country}$, $\delta_{industry}$ and γ_t are country-fixed effects, industry-fixed effects, and year/month-fixed effects, respectively. α_1, our coefficient of interest, is the carbon risk premium, as it represents the marginal impact of $Emissions$ on stock returns.[13]

[13] A potential caveat is that $Emissions$ might not be the perfect measure of the transition risk, a firm with a better technological reserve or carbon management plan, despite its current high emissions, is not necessarily associated

A.2. Full Sample

We first analyse the carbon risk premium by estimating Equation (1) using our full sample of 1,177 firms in 49 countries from 2016 to 2022. Table 4 reports the estimation results. Columns (1) and (2) correspond to the natural log scale of the sum of all three scopes of total emissions and the natural log scale of the sum of all three scopes of emission intensity. In Column (1), we find a negative relation between the level of total emissions and stock returns, whereas in Column (2), we find a positive relation between the level of emission intensity and stock returns. These results suggest that among the largest firms in the world, there is a positive carbon risk premium for the level of emission intensity but not for the level of total emissions.

The coefficient is both statistically and economically significant. Specifically, a 1% increase in the level of emission intensity corresponds to a 14-bps increase in monthly stock returns, or a 1.7% increase in annualized returns. The existence of a carbon risk premium for the emission intensity level instead of the total emissions level is different from the findings in Bolton and Kacperczyk (2023), who show a carbon risk premium for the total emissions level instead of the emission intensity level. However, given that their sample covers almost all of the listed firms worldwide and up to 2018, our results complement their findings and suggest that, in recent years, investors might have a more comprehensive consideration and might focus more on firms' carbon efficiency among the largest firms. In addition, Aswani, Raghunandan, and Rajgopal (2023) and Zhang (2024) suggest that emission intensity could be more informative for comparisons across firms. Hartzmark and Shue (2023) also mention that investors almost exclusively focus on carbon intensity when discussing net zero investments. As such, not surprisingly, the relative importance of GHG emission intensity in pricing carbon risk has increased.

Table 4
Carbon emissions and stock returns

The sample period is from 2016 to 2022. The dependent variable is RET. The main independent variables are GHG emissions levels (Column (1)) and GHG intensity levels (Column (2)). All variables are defined in Table 1. Standard errors are presented in parentheses. All regressions include year/month-fixed effects, country-fixed effects, and industry fixed-effects. *** 1% significance; ** 5% significance; * 10% significance.

Dependent Variables: RET	(1)	(2)
	Emissions = GHG emissions	*Emissions = GHG intensity*
Emissions	-0.22***	0.14**
	(0.05)	(0.07)
LOG SIZE	0.93***	0.88***
	(0.06)	(0.05)
B/M	-0.15***	-0.17***
	(0.05)	(0.05)

with a higher transition risk. We attempt to tackle this problem by incorporating a battery of control variables and fixed-effects which might be helpful in capturing these unobservable.

LEVERAGE	-0.09	-0.04
	(0.20)	(0.20)
MOM	-0.18***	-0.18***
	(0.01)	(0.01)
INVEST/A	-0.02	-0.03*
	(0.01)	(0.01)
HHI	0.01	0.01
	(0.02)	(0.02)
LOG PPE	-0.47***	-0.61***
	(0.06)	(0.05)
ROE	0.01**	0.01**
	(0.01)	(0.01)
VOLAT	0.20***	0.20***
	(0.01)	(0.01)
Year/month-fixed effects	Yes	Yes
Country-fixed effects	Yes	Yes
Industry-fixed effects	Yes	Yes
Observations	72276	72276
R-squared	0.258	0.258

A.3. Regional Breakdown

Next, we compare the results for our regression models in three regions: North America, Europe, and Others. Since we have found that the carbon risk premium exists only for the emission intensity levels in our sample, we tabulate the results using only these levels going forward. Given that North America and Europe are relatively more well-developed, the expectation is that firms in these two regions will take more responsibility. For example, in the climate context, investors might expect firms in these two regions to bear a certain amount of abatement cost and reduce their GHG emissions. As such, the carbon risk premiums in these two regions should differ for those of firms in Others. We classify firm's regions based on the location of firm's parent.

Table 5 reports the estimation results. As expected, the carbon risk premium is significantly positive for firms in North America and Europe, whereas the carbon risk premium is statistically insignificant for firms in all other regions. The results suggest that compared to firms in other regions, investors perceive that firms in North America and Europe face greater carbon risk, which demands for a positive carbon risk premium. Although the numerical results are different from those of Aswani, Raghunandan, and Rajgopal (2024) in that the carbon risk premiums are mostly insignificant in the US and sometimes insignificant in Europe, given that these premiums are larger in Europe than in the US, our findings are still in line with them as they show investors of European firms may care more about emissions than do those of US firms. In addition, given that Aswani, Raghunandan, and Rajgopal (2024) cover the period before 2020, our results complement their findings and suggest that investors might focus more on the largest firms' carbon efficiency in recent years.

Table 5

Carbon emissions and stock returns by region

The sample period is from 2016 to 2022. The dependent variable is RET. The main independent variables are carbon intensity levels. Firms are classified by their locations. Column (1) corresponds to firms in North America; Column (2) corresponds to firms in Europe; and Column (3) corresponds to firms in all other regions. All variables are defined in Table 1. Standard errors are presented in parentheses. All regressions include year/month-fixed effects, country-fixed effects, and industry fixed-effects. *** 1% significance; ** 5% significance; * 10% significance.

Dependent Variables: *RET*	(1)	(2)	(3)
	North America	Europe	Others
LOG GHG intensity	0.20*	0.28*	-0.03
	(0.12)	(0.17)	(0.15)
LOG SIZE	1.01***	0.79***	0.86***
	(0.10)	(0.11)	(0.13)
B/M	-0.92***	-0.54***	-0.04
	(0.17)	(0.11)	(0.07)
LEVERAGE	-0.39	-1.03*	-0.34
	(0.26)	(0.59)	(0.73)
MOM	-0.22***	-0.24***	-0.12***
	(0.02)	(0.03)	(0.03)
INVEST/A	-0.01	0.01	0.04
	(0.02)	(0.03)	(0.03)
HHI	-0.10	0.00	0.02
	(0.17)	(0.02)	(0.14)
LOG PPE	-0.80***	-0.39***	-0.60***
	(0.08)	(0.09)	(0.11)
ROE	0.01	0.27***	0.30***
	(0.01)	(0.07)	(0.06)

VOLAT	0.24***	0.26***	0.06***
	(0.02)	(0.02)	(0.02)
Year/month-fixed effects	Yes	Yes	Yes
Country-fixed effects	Yes	Yes	Yes
Industry-fixed effects	Yes	Yes	Yes
Observations	31179	22573	18522
R-squared	0.319	0.312	0.192

Having identified the existence of a carbon risk premium, especially among firms in North America and Europe, in the next subsection, we explore the impact of firms' declarations of a commitment to net zero on the size of such a premium.

B. *Commitment to Net Zero*

A firm's declaration of a commitment to net zero implies that it has pledged to act to curb its GHG emissions at certain levels before certain deadlines. Having shown in Propositions (2) and (3) in the theoretical framework that firms' declaration of a commitment to net zero could alter the size of the carbon risk premium in both ways, in this subsection, we systematically evaluate the impact of this declaration by a firm on its carbon risk premium and the determinants of this impact.

B.1 Empirical Specification

Defining the dummy variable $D_{i,t}^{NZ}$ equals 1 when firm i has declared its commitment to net zero since time t and equals 0 otherwise. We can evaluate the impact of the declaration of a commitment to net zero on the carbon risk premium by augmenting the cross-sectional characteristics-based regression Equation (1) as follows:

$$RET_{i,t} = \alpha_0 + \alpha_1 Emissions_{i,t-1} + \alpha_2 D_{i,t-1}^{NZ} + \alpha_3 Emissions_{i,t-1} \times D_{i,t-1}^{NZ} + \alpha_4 Controls_{i,t-1} + \mu_{country} + \delta_{industry} + \gamma_t + \varepsilon_{i,t}. \quad (2)$$

Under the specification in Equation (2), the marginal impact of $Emissions$ equals $\alpha_1 + \alpha_3 D_{i,t-1}^{NZ}$. As such, the additional impact on the carbon risk premium from a firm's declaration of a commitment to net zero can be attributed to α_3. If α_3 is positive (negative), then a declaration of a commitment to net zero results in a larger (smaller) carbon risk premium. Meanwhile, under the specification in Equation (2), the marginal impact of a declaration of a commitment to net zero on stock returns equals $\alpha_2 + \alpha_3 Emissions_{i,t-1}$.

B.2. Full Sample

We begin the analysis of the impact of a firm's declaration of a commitment to net zero on its carbon risk premium by estimating Equation (2) using our full sample. Table 6 reports the estimation results. We find that, on average, a firm's commitment to net zero has no impact on its carbon risk premium, as the coefficient of *LOG GHG intensity* $\times$ D^{NZ} is statistically insignificant, indicating that the declaration of a commitment to net zero has no additional marginal impact on the firm's emission intensity level on stock returns. In addition, the declaration of a commitment to net zero commitment has no additional impact on stock returns.

Table 6

Carbon emissions, net zero commitment and stock returns

The sample period is from 2016 to 2022. The dependent variable is RET. The main independent variables are carbon intensity levels and D^{NZ}, a dummy variable equal to one if a firm has declared a commitment to net zero and 0 otherwise. All variables are defined in Table 1. Standard errors are presented in parentheses. All regressions include year/month-fixed effects, country-fixed effects, and industry fixed-effects. *** 1% significance; ** 5% significance; * 10% significance.

Dependent Variables: RET	(1)
LOG GHG intensity	0.13*
	(0.07)
D^{NZ}	-0.07
	(0.27)
LOG GHG intensity × D^{NZ}	0.02
	(0.05)
LOG SIZE	0.88***
	(0.05)
B/M	-0.17***
	(0.05)
LEVERAGE	-0.03
	(0.20)
MOM	-0.18***
	(0.01)
INVEST/A	-0.03*
	(0.01)
HHI	0.01
	(0.02)
LOG PPE	-0.61***
	(0.05)
ROE	0.01**
	(0.01)

VOLAT	0.20***
	(0.01)
Year/month-fixed effects	Yes
Country-fixed effects	Yes
Industry-fixed effects	Yes
Observations	72276
R-squared	0.258

However, the statistically insignificant impact of a firm's declaration of a commitment to net zero on the carbon risk premium and the associated stock returns is unsurprising in the sense that such a declaration could alter the size of the carbon risk premium in both directions.[14] As suggested in Section 2, the size of the carbon risk premium depends on the carbon risk exposure to investors. Whether the carbon risk premium increases due to a firm's declaration of a commitment to net zero thus depends on investors' perceptions of whether net zero is optimal to the firm. If investors believe that a firm declaring a commitment to net zero has sufficiently high transition readiness and can decarbonize smoothly, net zero is optimal as it brings a positive net-benefit on long-run profit maximization. Investors are willing to accept a lower return; thus, the carbon risk premium would decrease. In contrast, if investors perceive that the declaration of a commitment to net zero is indeed difficult to attain, for example, if firms without sufficient technology know how to complete a low-carbon transition, the reduction in GHG emissions might not be sufficiently smooth and they might have to bear insurmountable abatement costs. Firms might then face an even higher operational risk bourn by existing GHG emission intensity in turn increase the carbon risk premium. Therefore, we segment the sample data to investigate the determinants of the sign of α_3 and the total impact on the stock returns.

B.3. Transition Capacity

Transition capacity refers to the likelihood that a firm achieves the targeted emissions level. When firms have lower transition capacity, such as those with insufficient technology for a low-carbon transition, abating GHG emissions might not be optimal, as it would incur prohibitively high costs for their operations. Once those firms declare their commitment to net zero, their carbon risk premium is expected to increase, as they would face an even greater uncertainty during their low-carbon transition. In contrast, for firms with higher transition capacity, achieving net zero allows them to eliminate potential risks that adhere to their stocks of GHG emissions in the long run. Once those firms declare their commitment to net zero, their carbon risk premium is expected to decrease.

As such, we first divide the sample into two groups. The first group consists of firms from the full sample that are in countries with a lower-than-median energy use per capita. The second group consists of firms from the full sample that are in countries with a higher-than-median

[14] For robustness check, we also performed the regression estimations based on LOG Scope 1 emission intensity, LOG Scope 2 emission intensity, and LOG Scope 3 emission intensity individually. The results remain largely unchanged. For brevity, we do not present the estimation result of fixed-effects estimations here. For interested readers, the results are available on request.

energy use per capita. Energy use per capita is not only a proxy for firms' reliance on fossil fuel energy but also is a proxy for firms' transition capacity, as firms with higher energy consumption per capita imply that their current decarbonization technology is insufficient and prohibits them from reducing energy consumption to decrease their stocks of GHG emissions. In other words, the greater is the energy use per capita of the country in which firms are in, the lower is firms' transition capacity, and the greater is the cost of the firms in a net zero transition.[15] Therefore, we expect that compared to firms in countries with lower-than-median energy use per capita, the change in the carbon risk premium of firms in countries with higher-than-median energy use per capita, which have a lower transition capacity, is more positive after their declarations of a commitment to net zero.

We estimate Equation (2) for the two subsamples. Table 7 reports the estimation results. Column (1) corresponds to firms in countries with a lower-than-median energy use per capita in the full sample; Column (2) corresponds to firms in countries with a higher-than-median energy use per capita in the full sample. We note that in both Column (1) and Column (2), there are no significant carbon risk premiums before the firm declared its commitment to net zero. Furthermore, Column (1) indicates no significant evidence shows that the carbon risk premium decreases after firms in countries with lower-than-median energy use per capita declare a commitment to net zero. However, in Column (2), the carbon risk premium increased by 13-bps after the declaration of a commitment to net zero, indicating a higher carbon risk premium once the firms in countries with a high-than-median energy use per capita declare their commitment to net zero.

Table 7

Carbon emissions, net zero commitment and stock returns: Transition capacity

The sample period is from 2016 to 2022. The dependent variable is RET. The main independent variables are carbon intensity levels and D^{NZ}, a dummy variable equal to one if a firm has declared a commitment to net zero and 0 otherwise. Column (1) corresponds to firms in countries with a lower-than-median energy use per capita in the full sample; Column (2) corresponds to firms in countries with a higher-than-median energy use per capita in the full sample. Column (3) corresponds to firms in countries with a lower-than-median share of renewable electricity output in the full sample; Column (4) corresponds to firms in countries with a higher-than-median share of renewable electricity output in the full sample. All variables are defined in Table 1. Standard errors are presented in parentheses. All regressions include year/month-fixed effects, country-fixed effects, and industry fixed-effects. *** 1% significance; ** 5% significance; * 10% significance.

Dependent Variables: RET	(1)	(2)	(3)	(4)
	Energy use per capita < Median	Energy use per capita > Median	Share of renewable electricity output > Median	Share of renewable electricity output < Median
LOG GHG intensity	0.15	0.13	0.04	0.23**
	(0.12)	(0.10)	(0.12)	(0.11)
D^{NZ}	0.63	-0.59	0.65	-0.78**
	(0.43)	(0.38)	(0.43)	(0.39)
LOG GHG intensity × D^{NZ}	-0.12	0.13**	-0.13*	0.17**

[15] Ideally, a firm's transition capacity should be measured by firm-level's reliance on energy. However, such information is yet to be available. As such, we adopt the country-level's energy consumption per capita as the proxy, this proxy is also adopted by Bolton and Kacperczyk (2023) to measure firms' technological level in energy mix.

	(0.08)	(0.07)	(0.08)	(0.07)
LOG SIZE	1.04***	0.88***	1.04***	0.86***
	(0.09)	(0.08)	(0.09)	(0.09)
B/M	-0.04	-0.70***	-0.03	-0.65***
	(0.06)	(0.13)	(0.06)	(0.12)
LEVERAGE	-0.35	-0.21	-0.72	-0.20
	(0.49)	(0.24)	(0.49)	(0.24)
MOM	-0.19***	-0.22***	-0.20***	-0.21***
	(0.02)	(0.02)	(0.02)	(0.02)
INVEST/A	0.07**	-0.04**	-0.02	-0.01
	(0.03)	(0.02)	(0.03)	(0.02)
HHI	0.05	0.01	0.01	-0.08
	(0.11)	(0.02)	(0.02)	(0.16)
LOG PPE	-0.60***	-0.69***	-0.56***	-0.70***
	(0.08)	(0.07)	(0.08)	(0.08)
ROE	0.19***	0.01*	0.01**	-0.00
	(0.05)	(0.01)	(0.01)	(0.01)
VOLAT	0.18***	0.22***	0.20***	0.22***
	(0.02)	(0.01)	(0.02)	(0.01)
Year/month-fixed effects	Yes	Yes	Yes	Yes
Country-fixed effects	Yes	Yes	Yes	Yes
Industry-fixed effects	Yes	Yes	Yes	Yes
Observations	30707	39288	30784	36907
R-squared	0.240	0.297	0.228	0.308

The analysis above shows that, using the consumption side measure of transition capacity, investors' perceived declarations of a commitment to net zero increase the carbon risk for firms in countries with higher energy use per capita. Next, we empirically explore how the production side measure of transition capacity impacts the size of the declaration of a net zero on the carbon risk premium.

Similarly, the sample is divided into two groups, with the first group consisting of firms in countries with a higher-than-median share of renewable electricity output in the full sample and the second group consisting of firms in countries with a lower-than-median share of renewable electricity output in the full sample. Given that renewable electricity sources emit much less GHG than do traditional fossil fuel electricity sources, the share of renewable electricity output is a proxy for the transition capacity in the sense that countries with a higher share of renewable electricity output indicate that they have relatively higher technological knowledge in achieving a low-carbon transition. In other words, a lower share of renewable electricity output of the country in which firms are located is associated with firms' lower transition capacity, and more-costly net zero transitions for firms. Therefore, we expect that compared to firms in countries with a higher-than-median share of renewable electricity output, the change in the carbon risk premium of firms in countries with a lower-than-median share of renewable electricity output, which have a lower transition capacity, is more positive after their declaration of a commitment to net zero.

We estimate Equation (2) for the two subsamples. Table 7 reports the estimation results. Column (3) corresponds to firms in countries with a higher-than-median share of renewable electricity output in the full sample; Column (4) corresponds to firms in countries with a lower-than-median share of renewable electricity output in the full sample. We note that Column (3) reflects no significant carbon risk premiums before the firm declared its commitment to net zero. Furthermore, Column (3) indicates that the carbon risk premium decreases by 13-bps after firms in countries with a greater-than-median share of renewable electricity output declare a commitment to net zero. In contrast, Column (4) reflects significant carbon risk premiums before the firm declared its commitment to net zero, and the carbon risk premium further increased by 17-bps after such a declaration, indicating a higher carbon risk premium once the firms in countries with a lower-than-median share of renewable electricity output declared their commitment to net zero.

The analysis above shows that using the production side measure of transition capacity, investors' perceived declarations of a commitment to net zero increase (decrease) the carbon risk for firms in countries with lower (higher) shares of renewable electricity output. These results, combined with the consumption side measure, seem to verify that investor perceived net zero is suboptimal (optimal) for firms with lower (higher) transition capacity.

Regarding the impact of a commitment to net zero on stock returns, Column (3) shows that a commitment to net zero reduces stock returns via a reduction in the carbon risk premium. Specifically, the marginal impact of a commitment to net zero on stock returns equals $-0.13 \times LOG\ GHG\ intensity$. In other words, the decrease in the stock returns is more significant for firms with higher GHG emission intensity after their declaration of a commitment to net zero. In contrast, Column (4) shows that the impact of declarations of a commitment to net zero on stock returns equals $-0.78 + 0.17 \times LOG\ GHG\ intensity$. In other words, stock returns decrease when $LOG\ GHG\ intensity$ is less than 4.579 but increases when $LOG\ GHG\ intensity$ is greater than 4.579.[16]

The latter result suggests that even if firms have low transition capacity, it is still possible that the low-emitters could obtain a higher enterprise value after their declaration of a commitment to net zero. It may be due to the total abatement cost born by its low GHG emission intensity stock is sufficiently low, or the demand for stocks of such firms increased after their net zero commitment declaration. However, a declaration of a commitment to net zero eventually hurts the total enterprise value once the stock of GHG emission intensity exceeds a certain threshold.[17] We then proceed to explore how transition urgency shapes the size and direction of carbon risk premiums in the next subsection.

[16] In this subsample, 66% of the observations have a $LOG\ GHG\ intensity$ value larger than 4.579.

[17] For robustness check, we also performed the regression estimations based on LOG Scope 1 emissions intensity, LOG Scope 2 emissions intensity, and LOG Scope 3 emissions intensity individually. The results remain largely unchanged. For brevity, we do not present the estimation result of fixed-effects estimations here. For interested readers, the results are available upon request.

B.4. Transition Urgency

Transition urgency refers to the degree to which a firm must act immediately in a low-carbon transition. Different firms face different degrees of transition urgency. Firms in countries with loose climate policies could have weak transition urgency because their marginal cost of emitting GHG emissions is negligible. In this scenario, achieving net zero might not be optimal because firms have to pay unnecessary abatement costs. In contrast, some countries, such as those with high carbon prices and carbon neutrality in their policy documents, might be more ambitious in setting up and implementing climate policies. In turn, firms in these countries face stronger transition urgency. In this scenario, achieving net zero is optimal because it could eliminate the potential policy risk borne by their stock of GHG emissions.

As such, we divide the sample into two groups, with the first group consisting of firms in countries with a lower-than-median trend in CO_2 emissions per unit of GDP due to policy metrics in the full sample, whereas the second group consists of firms in countries with a higher-than-median trend in CO_2 emissions per unit of GDP due to policy metrics in the full sample. The trend in CO_2 emissions per unit of GDP due to policy metrics, sourced from the Environmental Performance Index constructed by the Yale Center for Environmental Law & Policy (Wolf et al., 2022), captures whether countries' government climate policy is stringent to reach zero emissions. The trend in CO_2 emissions per unit of GDP due to policy metrics are computed by averaging the most recent 10 years of data adjusted by the economic trend. Thus, the trend reflects the CO_2 emissions per unit of GDP growth due to government policy rather than economic fluctuations. A score is generated that represents the country's performance. Countries with lower growth in CO_2 emissions per unit of GDP due to policy metrics receive the highest scores. A higher score indicates that the country has implemented a stringent climate policy to curb CO_2 emissions per unit of GDP from increasing rapidly.

Under this set-up, firms in countries with a higher score are considered to have a stronger transition urgency because these countries have more stringent climate policies such that CO_2 emissions per unit of GDP growth could be kept at a low level. Governments in these countries are likely to impose more stringent climate policies, and the general public in these countries is also likely to be more climate conscious. In contrast, firms in countries with lower scores are considered to have weaker transition urgency because they have a looser climate policy. As such, we expect that the change in the carbon risk premium of firms in countries with a higher-than-median score of trend in CO_2 emissions per unit of GDP will tend to be more negative than that of firms in countries with a lower-than-median score of trend in CO_2 emissions per unit of GDP through their declaration of a commitment to net zero.

We estimate Equation (2) for the two subsamples. Table 8 reports the estimation results. Column (1) corresponds to firms in countries with a higher-than-median score of trend in CO_2 emissions per unit of GDP in the full sample; Column (2) corresponds to firms in countries with a lower-than-median score of trend in CO_2 emissions per unit of GDP in the full sample. We note that in Column (1), there were significantly positive carbon risk premiums before the firm declared its commitment to net zero. However, the carbon risk premium decreased by 18-bps after firms in countries with a higher-than-median score of trend in CO_2 emissions per unit of GDP declare a commitment to net zero, suggesting a reduction in carbon transition risk after this declaration. In contrast, in Column (2), although there were insignificant carbon risk premiums before firms in countries with lower-than-median score of trend in CO_2 emissions per unit of GDP declared their commitment to net zero, the carbon risk premium increased by

12-bps after such declaration, indicating a higher carbon risk premium once firms declared their commitment to net zero.

Regarding the impact of commitment to net zero on stock returns, Column (1) shows that such a commitment impacts stock returns by $0.98 - 0.18 \times LOG\ GHG\ intensity$. In other words, a commitment to net zero is associated with higher stock returns for observations with $LOG\ GHG\ intensity$ below 5.444, while a commitment to net zero is associated with lower stock returns for observations with $LOG\ GHG\ intensity$ above 5.444.[18] This result shows that even if firms face a strong transition urgency, the marginal benefit from abating GHG emissions for low-emitters is too small compared to the additional cost incurred in declaring a commitment to net zero. In contrast, Column (2) indicates that the marginal impact of a commitment to net zero on stock returns equals to $0.12 \times LOG\ GHG\ intensity$, showing that higher stock returns are associated with greater GHG emission intensity after firms have declared their commitment to net zero.

Table 8

Carbon emissions, net zero commitment and stock returns: Transition urgency

The sample period is from 2016 to 2022. The dependent variable is RET. The main independent variables are carbon intensity levels and D^{NZ}, a dummy variable equal to one if a firm has declared a commitment to net zero and equal to 0 otherwise. Column (1) corresponds to firms in countries with a higher-than-median score of trend in CO_2 emissions per unit of GDP due to policy metrics in the full sample; Column (2) corresponds to firms in countries with a lower-than-median score of trend in CO_2 emissions per unit of GDP due to policy metrics in the full sample; Column (3) corresponds to firms in countries with a higher-than-median share of GHG emissions covered by a carbon price in the full sample; Column (4) corresponds to firms in countries with a lower-than-median share of GHG emissions covered by a carbon price in the full sample. All variables are defined in Table 1. Standard errors are presented in parentheses. All regressions include year/month-fixed effects, country-fixed effects, and industry fixed-effects. *** 1% significance; ** 5% significance; * 10% significance.

Dependent Variables: RET	(1)	(2)	(3)	(4)
	Score of CO2 per GDP trend > Median	Score of CO2 per GDP trend < Median	Share of GHG emissions covered by a carbon price > Median	Share of GHG emissions covered by a carbon price < Median
LOG GHG intensity	0.24**	0.13	0.05	0.23**
	(0.12)	(0.10)	(0.13)	(0.10)
D^{NZ}	0.98**	-0.54	0.62	-0.75**
	(0.43)	(0.37)	(0.42)	(0.37)
LOG GHG intensity × D^{NZ}	-0.18***	0.12*	-0.11	0.15**
	(0.08)	(0.07)	(0.08)	(0.06)
LOG SIZE	0.66***	1.04***	1.04***	0.81***
	(0.09)	(0.08)	(0.09)	(0.08)
B/M	-0.64***	-0.10*	-0.04	-0.94***
	(0.12)	(0.08)	(0.06)	(0.12)

[18] In this subsample, 38% of the observations have a $LOG\ GHG\ intensity$ value larger than 5.444.

LEVERAGE	-0.39	-0.47*	-0.21	-0.46*
	(0.30)	(0.28)	(0.49)	(0.24)
MOM	-0.29***	-0.17***	-0.22***	-0.14***
	(0.02)	(0.02)	(0.02)	(0.02)
INVEST/A	-0.04**	-0.02	-0.05**	0.01
	(0.02)	(0.02)	(0.02)	(0.02)
HHI	-0.00	0.07	0.01	-0.02
	(0.02)	(0.14)	(0.02)	(0.11)
LOG PPE	-0.43***	-0.76***	-0.65***	-0.59***
	(0.07)	(0.07)	(0.07)	(0.07)
ROE	0.00	0.01	0.02**	-0.00
	(0.01)	(0.01)	(0.01)	(0.01)
VOLAT	0.22***	0.20***	0.23***	0.20***
	(0.02)	(0.01)	(0.02)	(0.01)
Year/month-fixed effects	Yes	Yes	Yes	Yes
Country-fixed effects	Yes	Yes	Yes	Yes
Industry-fixed effects	Yes	Yes	Yes	Yes
Observations	29183	42924	31190	40056
R-squared	0.257	0.277	0.244	0.285

The analysis above shows that investors perceived that declarations of a commitment to net zero increase (decrease) the carbon risk for firms in countries with greater (lower) growth in CO_2 emissions per unit of GDP due to policy. As mentioned earlier, the government might introduce carbon pricing during the transition to carbon neutrality. By pricing carbon, firms face a higher cost in emitting GHG emissions. As such, firms in countries with a positive carbon price are subject to stronger transition urgency than are those without a carbon price. However, carbon prices were not imposed on all economic sectors in the country. Intuitively, a government with a more ambitious carbon neutrality goal includes a wider range of economic sectors to be covered by the carbon price. As such, we proxy for firms' transition capacity using the share of CO_2 emissions covered by a country's carbon price.[19] By dividing the sample into two groups, with the first group consisting of firms in countries with a higher-than-median share of CO_2 emissions covered by a carbon price in the full sample and the second group consists of firms located at countries with a lower-than-median share of CO_2 emissions covered by a carbon price in the full sample, we proxy for firms in the first group that face a stronger transition urgency, whereas the second group faces weaker transition urgency.

[19] Carbon price mainly takes two forms: carbon taxes, where a price is set for each unit of CO_2 emitted, and cap-and-trade, which limits the total amount of CO_2 that can be emitted by firms by forcing firms to purchase emissions rights if they exceed a given emissions allowance.

We estimate Equation (2) for the two subsamples. Table 8 reports the estimation results. Column (3) corresponds to firms in countries with higher-than-median shares of GHG emissions covered by a carbon price in the full sample; Column (4) corresponds to firms in countries with lower-than-median shares of GHG emissions covered by a carbon price in the full sample. Column (3) suggests that commitment to net zero only brings statistically insignificant reduction in carbon risk premium for firms locate in countries with a greater carbon pricing policy coverage. In contrast, Column (4) shows that in countries with a lower carbon pricing policy coverage, the carbon risk premium increased by 15-bps after the declaration of a commitment to net zero, indicating a greater carbon risk premium once firms declared their commitment to net zero.

Regarding the impact of a commitment to net zero on stock returns, Column (3) shows that such a commitment has a negligible impact on the stock returns of firms in countries with greater carbon pricing policy coverage. However, in countries with lower carbon pricing policy coverage, Column (4) indicates that the marginal impact of a commitment to net zero on stock returns equals $-0.75 + 0.15 \times LOG\ GHG\ intensity$. In other words, a firm's declaration of a commitment to net zero is associated with lower stock returns if $LOG\ GHG\ intensity$ is below 5 whereas a firm's declaration of a commitment to net zero is associated with higher stock returns if $LOG\ GHG\ intensity$ is above 5.[20] The latter result indicates that for high-emitting firms with weak transition urgency, declaring a commitment to net zero could lower their total enterprise values.

The analysis above shows that investors' perceived declarations of a commitment to net zero increase the carbon risk for firms in countries with lower carbon pricing policy coverage. Combined with the finding of the growth of CO_2 emissions per unit of GDP due to policy, these results seem to indicate that investors' perceived net zero is suboptimal (optimal) for firms with weaker (stronger) transition urgency.[21] Next, we empirically explore the impact of the investor discount rate on the impact of a declaration of a commitment to net zero on the carbon risk premium.

B.5. Investors' Discount Rate

The literature shows that investors investing in stocks with better environmental performance do so for the longer term (for example, Starks, Venkat, and Zhu, 2017; Pastor, and Vorsatz, 2020; Garel, and Petit-Romec, 2021). Although the environmental pillar scores mainly capture the nonfinancial risks from environmental dimension a firm is exposed to which could be different from a firm creating a positive or negative climate impact, many investment managers still implementing ESG investment strategies by using ESG scores and sub-scores (Elmalt, Igan, and Kirti, 2021). These longer-term investors place a higher value than do short-term investors on the long-term benefits from achieving net zero. In other words, the discount rate placed by investors on firms with higher environmental pillar score is lower than that placed on firms with lower environmental pillar score. As such, we divide the sample into two groups, with the first group consisting of firms with a higher-than-median environmental pillar score in the full sample, and the second group consists of firms with a lower-than-median environmental pillar score in the full sample. Under this specification, the likelihood of

[20] In this subsample, 49% of the observations have a value $LOG\ GHG\ intensity$ smaller than 5.

[21] For robustness check, we also performed the regression estimations based on LOG Scope 1 emissions intensity, LOG Scope 2 emissions intensity, and LOG Scope 3 emissions intensity individually. The results remain largely unchanged. For brevity, we do not present the estimation result of fixed-effects estimations here. For interested readers, the results are available upon request.

attracting long-term investors for the first group is greater, and the discount rate placed by investors is lower. In contrast, the likelihood of attracting short-term investors for the second group is higher, and the discount rate is higher. Against this backdrop, we should expect net zero to be relatively optimal in the first group but suboptimal in the second group.

We estimate Equation (2) for the two subsamples. Table 9 reports the estimation results. Column (1) corresponds to observations with an above-the-median environmental pillar score in the full sample; Column (2) corresponds to observations with a below-the-median environmental pillar score in the full sample. We note that in Column (1), there is a significant positive carbon risk premium of 45-bps before the firm declared its commitment to net zero, and the carbon risk premium decreased by 14-bps after the declaration of a commitment to net zero, suggesting a reduction in carbon transition risk. In contrast, in Column (2), we found no significant carbon risk premium before the firms declared their commitment to net zero, which might imply that investors investing in firms with lower environmental pillar scores might not consider the carbon risk factor important. However, the carbon risk premium increased by 15-bps after the declaration of a commitment to net zero, suggesting that investors do not regard such a declaration by firms with low environmental pillar score could yield positive outcomes, they also regard such commitment as increasing firms' operational risk. For example, firms have to place prohibitively high costs on abating GHG emissions. As a result, investors place greater carbon transition risk on those firms.

Regarding the impact of a commitment to net zero on stock returns, Column (1) shows that the change in stock returns due to the declaration of a commitment to net zero equals $0.75 - 0.14 \times LOG\ GHG\ intensity$. In other words, such a declaration by a firm is associated with lower stock returns if $LOG\ GHG\ intensity$ is above 5.357 but is associated with higher stock returns if $LOG\ GHG\ intensity$ is below 5.357.[22] In contrast, Column (2) shows that the change in stock returns due to a declaration of a commitment to net zero equals $-0.75 + 0.15 \times LOG\ GHG\ intensity$. In other words, a firm's declaration of a commitment to net zero is associated with lower stock returns if $LOG\ GHG\ intensity$ is below 5, whereas such a declaration is associated with higher stock returns if $LOG\ GHG\ intensity$ is above 5.[23]

Table 9

Carbon emissions, net zero commitment and stock returns: Discount rates

The sample period is from 2016 to 2022. The dependent variable is RET. The main independent variables are carbon intensity levels and D^{NZ}, a dummy variable equals one if firm has declared a commitment to net zero and 0 otherwise. Column (1) corresponds to observations with environmental pillar scores above the median in the full sample; Column (2) corresponds to observations with environmental pillar scores below the median in the full sample. All variables are defined in Table 1. Standard errors are presented in parentheses. All regressions include year/month-fixed effects, country-fixed effects, and industry fixed-effects. *** 1% significance; ** 5% significance; * 10% significance.

Dependent Variables: RET	(1)	(2)	(3)	(4)
	E score > Median	E score < Median	Without golden parachute	With golden parachute
LOG GHG intensity	0.45***	-0.10	-0.06	0.18
	(0.12)	(0.10)	(0.14)	(0.12)

[22] In this subsample, 45% of observations have a $LOG\ GHG\ intensity$ value larger than 5.357.

[23] In this subsample, 33% of observations have a $LOG\ GHG\ intensity$ value larger than 5.

D^{NZ}	0.75*	-0.75*	0.47	-0.76*
	(0.39)	(0.43)	(0.46)	(0.45)
$LOG\ GHG\ intensity \times D^{NZ}$	-0.14*	0.15**	-0.09	0.16**
	(0.07)	(0.07)	(0.08)	(0.08)
LOG SIZE	0.95***	0.86***	1.19***	0.81***
	(0.08)	(0.09)	(0.11)	(0.11)
B/M	-0.04	-0.49***	-0.23**	-1.75***
	(0.06)	(0.11)	(0.11)	(0.21)
LEVERAGE	0.08	-0.20	0.11	-1.02***
	(0.36)	(0.26)	(0.28)	(0.38)
MOM	-0.27***	-0.17***	-0.25***	-0.25***
	(0.02)	(0.02)	(0.02)	(0.02)
INVEST/A	-0.01	-0.03*	0.06*	-0.03
	(0.02)	(0.02)	(0.03)	(0.02)
HHI	0.01	0.00	0.01	-0.09
	(0.09)	(0.02)	(0.09)	(0.17)
LOG PPE	-0.64***	-0.63***	-0.77***	-0.70***
	(0.08)	(0.07)	(0.09)	(0.09)
ROE	0.01	0.01*	0.00	0.01*
	(0.01)	(0.01)	(0.04)	(0.01)
VOLAT	0.20***	0.20***	0.23***	0.25***
	(0.02)	(0.01)	(0.02)	(0.02)
Year/month-fixed effects	Yes	Yes	Yes	Yes
Country-fixed effects	Yes	Yes	Yes	Yes
Industry-fixed effects	Yes	Yes	Yes	Yes
Observations	34292	35921	24798	30064
R-squared	0.271	0.265	0.276	0.319

The above finding suggests that long-term investors tend to reaffirm declarations of a commitment to net zero by firms with higher environmental pillar scores, which could yield positive outcomes, and reducing GHG emissions could ultimately reduce their exposure to carbon transition risk. In contrast, short-term investors tend to perceive declarations of a commitment to net zero of firms with lower environmental pillar scores as an unprofitable project. Investors were not convinced that they could curb GHG emissions in a cost-effective manner. Therefore, given an expected increase in carbon risk over time, investors would demand a larger carbon risk premium on the firms in the second group.[24]

To further investigate the impact of short-termism, we divide the sample into two groups, with the first group consisting of firms without golden parachute in the full sample, and the second group consists of firms with golden parachute in the full sample. Under this specification, the second group consists of firms with additional job security for executives which encourages them to take short term performance which deter longer-term investors (Shive and Forster, 2020). As such, compared to the first group, the likelihood of attracting short-term investors for the second group is higher, and the discount rate is higher.

We estimate Equation (2) for the two subsamples. Table 9 reports the estimation results. Column (3) corresponds to observations without golden parachute in the full sample; Column (4) corresponds to observations with golden parachute in the full sample. We note that in Column (3), there is no significant carbon risk premium before the firm declared its commitment to net zero. Furthermore, the carbon risk premium insignificantly decreased after the declaration of a commitment to net zero. In contrast, in Column (4), we found no significant carbon risk premium before the firms declared their commitment to net zero, yet, the carbon risk premium increased by 16-bps after the declaration of a commitment to net zero. These findings again suggest that as the commitment to net zero is not in line with the short-termism of the board, investors regard such commitment as increasing firms' operational risk. This finding verifies that shorter-term investors regard net zero as suboptimal to firm's profit maximization objective, thus demanding a larger carbon risk premium.

Regarding the impact of a commitment to net zero on stock returns, Column (3) shows that the change in stock returns due to the declaration of a commitment to net zero is negligible. In contrast, Column (4) shows that the change in stock returns due to a declaration of a commitment to net zero equals $-0.76 + 0.16 \times LOG\ GHG\ intensity$. In other words, a firm's declaration of a commitment to net zero is associated with lower stock returns if $LOG\ GHG\ intensity$ is below 4.75, whereas such a declaration associated with higher stock returns if $LOG\ GHG\ intensity$ is above 4.75.[25]

These findings suggest that a declaration of commitment to net zero is a double-edged sword to firms, it could increase or decrease a firm's carbon risk premium, hinging on the transition readiness which increase with its transition capacity and transition urgency, and decrease with discount rates placed by investors on the firm. As such, although declarations of a commitment to net zero has no significant impact on the size of the carbon risk premium of average firms, it could lower the carbon risk premium and increase the enterprise value of firms with a greater transition readiness, as investors might perceive that the declaration of a commitment to net zero in this case is optimal. In line with the prediction of Proposition (3) in our theoretical framework, the increase in enterprise value is driven by financial materiality due to transition readiness, rather than a green preference which is frequently hypothesized in the literature.

In contrast, a commitment to net zero could also increase the carbon risk premium of firms with lower transition readiness, as investors might perceive that such a declaration in this case

[24] For robustness check, we also performed the regression estimations based on LOG Scope 1 emission intensity, LOG Scope 2 emission intensity, and LOG Scope 3 emission intensity individually. The results remain largely unchanged. For brevity, we do not present the estimation result of fixed-effects estimations here. For interested readers, the results are available upon request.

[25] In this subsample, 62% of observations have a $LOG\ GHG\ intensity$ value larger than 4.75.

would incur greater risk to the firms. In fact, this finding is in line with the literature that firms might not necessarily improve their environmental performance even after they make certain environmental commitments. For example, Brandon et al. (2022) find that some investment companies do not necessarily invest responsibly after signing up as a UNPRI signatory and committing to implementing responsible investing.[26] Bolton and Kacperczyk (2024) find that long-term emissions reductions are insignificant after firms make an emissions reduction commitment to a carbon disclosure project (CDP) and a science-based target initiative (SBTi). These finding yields crucial financial stability implications in the sense that policymakers should ensure that firms declaring their commitment to net zero have a sufficient degree of transition readiness; otherwise, the carbon risk premium in the financial market might accumulate rapidly from such a declaration, which might lead to the abrupt repricing, as well as sharp increase in co-movement, of asset prices in financial markets when any climate shocks emerge. In contrast, to facilitate a smooth low-carbon transition while maintaining a stable financial market development, policymakers should implement relevant policies to increase firm's transition readiness. These may include international cooperation on developing low-carbon transition technology knowhow which could boost the transition capacity, as well as capacity building on the general public which could raise the transition urgency.

C. *Divestment from Institutional Investors*

As shown in Bolton and Kacperczyk (2021), the existence of a carbon risk premium could result from institutional investors' divestment of stocks of companies with high emissions. In this subsection, we also explore whether the change in the carbon risk premium could be attributable to the divestment behaviour of institutional investors. We first explore whether institutional investors further reduce holdings on firms with higher emissions and explore whether institutional investors act as a factor in the carbon risk premium.

C.1. Empirical Specification

To test whether institutional investors divest more from high carbon emitting firms after their declarations of a commitment to net zero, we estimate the following regression model:

$$IO_{i,t} = d_0 + d_1 Emissions_{i,t-1} + d_2 D^{NZ}_{i,t-1} + d_3 Emissions_{i,t-1} \times D^{NZ}_{i,t-1} + d_4 Controls_{i,t-1} + \mu_{country} + \delta_{industry} + \gamma_t + \varepsilon_{i,t}. \quad (3)$$

Under this specification, the dependent variable $IO_{i,t}$ measures the percentage of the shares of firm i owned by institutional investors in month t. Under this specification, the marginal impact of $Emissions$ on institutional holding equals $d_1 + d_3 D^{NZ}_{i,t-1}$. Therefore, whether institutional investors divest more from a firm's declaration of a commitment to net zero based on its emissions can be attributed to d_3.

C.2. Institutional Investor Holdings

[26] Anecdotal evidence is plentiful regarding instances of greenwashing associated with well-known, publicly listed firms, thus often prompting government investigations. For instance, BNY Mellon was fined $1.5 million by the SEC for allegedly misstating and omitting information about ESG investment considerations for mutual funds that it managed (*Financial Times, May 2022,* https://www.ft.com/content/ff0097c4-3f1c-49d8-8189-153fc56aeeb3). Deutsche Bank-controlled investment firm DWS, who marketed itself as a leader in ESG investing, was charged $25 million by the SEC to settle over misstatements regarding its ESG investment process (*Reuters, September 2023,* https://www.reuters.com/legal/dws-pay-25-mln-over-us-charges-over-esg-misstatements-other-violations-2023-09-25/).

We report the estimation results in Table 10. Column (1) shows that the association between institutional ownership and GHG emissions is insignificantly negative while Column (3) shows that a 1% increase in GHG emission intensity significantly lowers institutional ownership by 1.51 percentage points. These findings are in line with Bolton and Kacperczyk (2021) that institutional investors do hold a smaller fraction of companies with emission intensity, but they are not underweight companies with high levels of emissions.

We analyze the impact of the commitment to net zero on institutional ownership in Column (2) and (4). Column (2) shows that after the firm declares its commitment to net zero, the marginal reduction in institutional ownership due to a 1% increase in GHG emissions equals to 0.42 percentage point, suggesting that institutional investors start reducing holding of firms with high levels of GHG emissions after their commitment to net zero. In addition, Column (4) shows that the marginal reduction in GHG emission intensity on institutional ownership increases by 0.35 percentage point after the firm declares its commitment to net zero. suggesting that institutional investors not only tend to reduce the holdings of firms with high emission intensity but also divest more after the firm's declaration of a commitment to net zero.[27]

Alternatively, we could interpret the results as firms' declarations of a commitment to net zero not necessarily resulting in greater institutional ownership. Specifically, Column (2) shows that the marginal impact of a declaration of a commitment to net zero on institutional ownership equals $7.20 - 0.42 LOG\ GHG$ while Column (4) shows that the marginal impact of a declaration of a commitment to net zero on institutional ownership equals $2.76 - 0.35 LOG\ GHG\ Intensity$. In other words, a declaration of a commitment to net zero for firms with $LOG\ GHG$ above 17.14 (in Column (2)) and $LOG\ CO2\ Intensity$ above 7.89 (in Column (4)) results in less institutional ownership. These results further verify that declarations of a commitment to net zero declaration by high-emitters could result in divestment by institutional investors, as they regard the increase in transition risk due to such a declaration by high-emitters as materialized.

Table 10

Carbon emissions, net zero commitment, and institutional ownership

The sample period is from 2016 to 2022. The dependent variable is IO. The main independent variables are GHG emissions, GHG emission intensity and D^{NZ}, a dummy variable equal to one if a firm has declared a commitment to net zero and 0 otherwise. All variables are defined in Table 1. Standard errors are presented in parentheses. All regressions include year/month-fixed effects, country-fixed effects, and industry fixed-effects. *** 1% significance; ** 5% significance; * 10% significance.

Dependent Variables: IO	(1)	(2)	(3)	(4)
	Emissions = GHG emissions	*Emissions = GHG emissions*	*Emissions = GHG intensity*	*Emissions = GHG intensity*
Emissions	-0.05	0.12	-1.51***	-1.36***
	(0.10)	(0.10)	(0.14)	(0.14)

[27] For robustness check, we also performed the regression estimations based on LOG Scope 1 emission intensity, LOG Scope 2 emission intensity, and LOG Scope 3 emission intensity individually. The results remain largely unchanged. For brevity, we do not present the estimation result of fixed-effects estimations here. For interested readers, the results are available upon request.

D^{NZ}		7.20***		2.76***
		(1.04)		(0.54)
$Emissions \times D^{NZ}$		-0.42***		-0.35***
		(0.07)		(0.10)
LOG SIZE	-0.44***	-0.50***	-0.54***	-0.59***
	(0.11)	(0.11)	(0.11)	(0.11)
B/M	1.00***	0.98***	1.01***	0.99***
	(0.10)	(0.10)	(0.10)	(0.10)
LEVERAGE	-1.25***	-1.25***	-1.31***	-1.32***
	(0.39)	(0.39)	(0.39)	(0.39)
MOM	0.11***	0.12***	0.12***	0.12***
	(0.03)	(0.03)	(0.03)	(0.03)
INVEST/A	-0.17***	-0.17***	-0.17***	-0.17***
	(0.03)	(0.03)	(0.03)	(0.02)
HHI	0.02	0.02	0.02	0.02
	(0.04)	(0.04)	(0.04)	(0.04)
LOG PPE	-3.12***	-3.13***	-3.00***	-3.00***
	(0.11)	(0.11)	(0.09)	(0.09)
ROE	-0.03***	-0.03***	-0.03***	-0.03***
	(0.03)	(0.01)	(0.01)	(0.01)
VOLAT	-0.31***	-0.30***	-0.31***	-0.30***
	(0.02)	(0.02)	(0.02)	(0.02)
Year/month-fixed effects	Yes	Yes	Yes	Yes
Country-fixed effects	Yes	Yes	Yes	Yes
Industry-fixed effects	Yes	Yes	Yes	Yes
Observations	68946	68946	68946	68946
R-squared	0.663	0.663	0.663	0.663

As shown in Bolton and Kacperczyk (2021), institutional investors implement exclusionary screening only in a few salient industries in the sample of US. In other words, only the salient high-CO_2 industries are excluded in the portfolio of institutional investors. As such, following Bolton and Kacperczyk (2021), we re-estimate equation (3) again with the exclusion of high-emitting industries, namely, Energy, Transportation and Utilities, in order to investigate whether the divestment behavior still exist among institutional investors in the sample of the largest firms in the globe.

We report the estimation results in Table 11. Column (1) and (3) show that after excluding the salient high-emitting industries, institutional investors would hold less high-emitting companies in the sample of the largest companies in the World, indicating that the exclusionary screening among the largest companies was not just implemented among the selected salient high-emitting industries. Interestingly, the coefficient of $Emissions$ in Column (1) turns out to be significantly negative, indicating that institutional investors tend to divest from high-emitting firms among the sample after the exclusion of high-emitting industries.

Moreover, the impact of the commitment to net zero on institutional ownership remains unchanged. Column (2) and (4) indicate that institutional investors divest even more from high-emitting firms after the firms' declaration of a commitment to net zero. As such, declarations of a commitment to net zero declaration by high-emitters could result in divestment by institutional investors.

Table 11
Carbon emissions, net zero commitment, and institutional ownership: excluding salient high-emitting industries

The sample excludes companies in the Energy, Transportation, and Utilities. The sample period is from 2016 to 2022. The dependent variable is IO. The main independent variables are GHG emissions, GHG emission intensity and D^{NZ}, a dummy variable equal to one if a firm has declared a commitment to net zero and 0 otherwise. All variables are defined in Table 1. Standard errors are presented in parentheses. All regressions include year/month-fixed effects, country-fixed effects, and industry fixed-effects. *** 1% significance; ** 5% significance; * 10% significance.

Dependent Variables: IO	(1)	(2)	(3)	(4)
	Emissions = GHG emissions	*Emissions = GHG emissions*	*Emissions = GHG intensity*	*Emissions = GHG intensity*
Emissions	-0.80***	-0.59***	-1.51***	-1.35***
	(0.13)	(0.13)	(0.19)	(0.19)
D^{NZ}		8.27***		2.39***
		(1.16)		(0.62)
Emissions × D^{NZ}		-0.52***		-0.34***
		(0.08)		(0.12)
LOG SIZE	0.37***	0.32**	0.05	0.01
	(0.13)	(0.13)	(0.12)	(0.12)
B/M	1.89***	1.80***	1.68***	1.67***
	(0.15)	(0.15)	(0.15)	(0.15)
LEVERAGE	-1.41***	-1.41***	-1.37***	-1.38***
	(0.40)	(0.40)	(0.40)	(0.40)

MOM	0.09***	0.10***	0.11***	-0.11***
	(0.03)	(0.03)	(0.03)	(0.03)
INVEST/A	-0.24***	-0.26***	-0.27***	-0.28***
	(0.04)	(0.04)	(0.04)	(0.04)
HHI	0.01	0.01	0.02	0.02
	(0.04)	(0.04)	(0.04)	(0.04)
LOG PPE	-3.07***	-3.09***	-3.43***	-3.43***
	(0.13)	(0.13)	(0.10)	(0.10)
ROE	-0.03	-0.03	-0.03	-0.03
	(0.02)	(0.02)	(0.02)	(0.02)
VOLAT	-0.34***	-0.34***	-0.34***	-0.34***
	(0.02)	(0.02)	(0.02)	(0.02)
Year/month-fixed effects	Yes	Yes	Yes	Yes
Country-fixed effects	Yes	Yes	Yes	Yes
Industry-fixed effects	Yes	Yes	Yes	Yes
Observations	57170	57170	57170	57170
R-squared	0.679	0.679	0.679	0.679

C.3. Impact on Carbon Risk Premium

We then explore whether a reduction in institutional holdings could impact the size of the carbon risk premium. Similar to the preceding analysis, we divide the sample by observations into four groups, with the first, second, third, and fourth groups consisting of observations with first, second, third and fourth quartiles of institutional ownership, respectively. As such, the relative importance of institutional investors is the lowest for observations in the first group, whereas the relative importance of institutional investors is the highest for observations in the fourth group. We then estimate Equation (2) using these four subsamples.

Table 12 presents the estimation results. Columns (1), (2), (3) and (4) correspond to observations with first, second, third and fourth quartiles of institutional ownership, respectively. We note that in Columns (1) and (2), for observations with a smaller relative importance of institutional investors, there were insignificant carbon risk premiums both before and after the firm declared its commitment to net zero. However, when the participation of institutional investors increases, the carbon risk premium starts to emerge. Column (3) shows that compared to the observations in Columns (1) and (2), a firms' declaration of a commitment to net zero increases its carbon risk premium. Specifically, the carbon risk premium increased by 18-bps after the firms declared their commitment to net zero. The impact becomes even more significant in Column (4), which represents the subsample with the highest institutional ownership. Before the firms declared their commitment to net zero, there was a 33-bps carbon risk premium. The carbon risk premium further increased by 23-bps after firms' declarations of a commitment to net zero.

Regarding the impact of a commitment to net zero on stock returns, Columns (1) and (2) show that a declaration of a commitment to net zero has no impact on stock returns when institutional investors' participation is small. Column (3) indicates that declarations of a commitment to net zero are associated with higher stock returns when $LOG\ GHG\ intensity$ is above 5.333,[28] whereas Column (4) indicates that such declarations are associated with higher stock returns when $LOG\ GHG\ intensity$ is above 4.913.[29]

Table 12

Carbon emissions, net zero commitment and stock return

The sample period is from 2016 to 2022. The dependent variable is RET. The main independent variables are carbon intensity levels and D^{NZ}, a dummy variable equal one if a firm has declared a commitment to net zero and 0 otherwise. Column (1) corresponds to observations with first quartile institutional ownership; Column (2) corresponds to observations with second quartile institutional ownership; Column (3) corresponds to observations with third quartile institutional ownership; Column (4) corresponds to observations with fourth quartile institutional ownership. All variables are defined in Table 1. Standard errors are presented in parentheses. All regressions include year/month-fixed effects, country-fixed effects, and industry fixed-effects. *** 1% significance; ** 5% significance; * 10% significance.

Dependent Variables: RET	(1)	(2)	(3)	(4)
	IO:1st quartile	IO:2nd quartile	IO:3rd quartile	IO:4th quartile
LOG GHG intensity	0.12	0.12	0.20	0.33*
	(0.19)	(0.20)	(0.14)	(0.18)
D^{NZ}	0.60	0.37	-0.96*	-1.13**
	(0.64)	(0.63)	(0.57)	(0.57)
LOG GHG intensity × D^{NZ}	-0.13	-0.02	0.18*	0.23**
	(0.11)	(0.11)	(0.10)	(0.11)
LOG SIZE	1.26***	0.90***	0.92***	1.05***
	(0.14)	(0.14)	(0.15)	(0.13)
B/M	0.06	-0.38***	-0.79***	-1.53***
	(0.07)	(0.14)	(0.19)	(0.25)
LEVERAGE	-0.73	0.03	-0.44	-0.46
	(0.89)	(0.70)	(0.45)	(0.29)
MOM	-0.26***	-0.11***	-0.22***	-0.24***
	(0.03)	(0.03)	(0.03)	(0.03)
INVEST/A	-0.03	0.01	0.01	0.00
	(0.04)	(0.04)	(0.03)	(0.03)

[28] In this subsample, 48% of observations have a $LOG\ GHG\ intensity$ value larger than 5.333.
[29] In this subsample, 50% of observations have a $LOG\ GHG\ intensity$ value larger than 4.913.

HHI	-0.01	0.00	0.08	0.14
	(0.02)	(0.21)	(0.14)	(0.15)
LOG PPE	-1.04***	-0.45***	-0.62***	-0.73***
	(0.14)	(0.12)	(0.13)	(0.12)
ROE	0.01**	0.04	-0.01	-0.00
	(0.01)	(0.08)	(0.02)	(0.02)
VOLAT	0.17***	0.16***	0.18***	0.28***
	(0.02)	(0.02)	(0.02)	(0.02)
Year/month-fixed effects	Yes	Yes	Yes	Yes
Country-fixed effects	Yes	Yes	Yes	Yes
Industry-fixed effects	Yes	Yes	Yes	Yes
Observations	14687	15220	18508	20526
R-squared	0.214	0.262	0.264	0.342

The combined results indicate the importance of institutional investors in channelling carbon risk into stock returns. Institutional investors not only tend to divest from stocks with high emission intensity but also price a larger premium to high emitters. The latter impact tends to be more significant after a firm's declaration of a commitment to net zero and for firms with more concentrated institutional holdings. In other words, institutional investors play a crucial role in penalizing such declaration by high emitters.[30] The findings are also highly-relevant firms' decisions in declaring their commitment to net-zero, given that funds from institutional investors might put their money sideline if the firm has relatively high levels of emission intensity, which might eventually introduce additional volatility toward the wealth of shareholders.

6. Conclusion

Achieving net zero is the only way to avoid any irreversible impact of global warming. Coordinated actions around the globe must be taken. More climate policies will be rolled out from policymakers, and the general public is expected to place greater demand on firms to take climate actions. In addition, more firms have declared their commitment to net zero, and have pledged to take part in the net zero transition campaign. However, it is uncertain whether firms could undergo a smooth, low-carbon transition after their declarations of a commitment to net zero. Given such uncertainty, it is natural to ask whether and to what extent this uncertainty affects the size of the carbon risk premium in stock returns and the channel through which such risk is reflected in stock returns.

[30] For robustness check, we also performed the regression estimations based on LOG Scope 1 emission intensity, LOG Scope 2 emission intensity, and LOG Scope 3 emission intensity individually. The results remain largely unchanged. For brevity, we do not present the estimation result of fixed-effects estimations here. For interested readers, the results are available upon request.

We have addressed these questions by utilizing both theoretical framework and empirical estimation. Theoretically, we show that the change in carbon risk premium, as well as the enterprise value, depend on the financial materiality of the carbon risk. Investors' behavior can be rationalized using cost-benefit analysis. Compared to existing studies that rationalize the lower expected returns of green assets, our model provides an alternative explanation, and our prediction is much richer, and the theory can explain more diverse pricing phenomenon. Empirically, we undertake a cross-sectional returns analysis with more than 1,100 large, listed firms in 49 countries based on revenues. We have found that among large firms worldwide, there is a positive carbon risk premium in a firm's emission intensity, i.e., stock returns increase with firm's emission intensity. Although this carbon risk premium, on average, is not affected by a firm's declaration of a commitment to net zero, we have found that the relationship between the carbon risk premium and such a declaration is related to the firm's transition capacity, transition urgency and investor discount rate. These findings are important to policies, as policymakers should monitor the behavior of firms that declare a commitment to net zero, as the accelerated accumulation of carbon risk premiums in the equity market could result in substantial equity market volatility.

Regarding the channel through which carbon transition risk is connected to stock returns, we have also identified the importance of institutional investors in channelling carbon risk into stock returns. Institutional investors tend to divest from stocks with high emission intensity and price in a larger premium for high emitters, as found in the literature. The latter impact tends to be more significant after a firm's declaration of a commitment to net zero and for firms with more concentrated institutional holdings. Policymakers should also monitor declaration of a commitment to net zero, especially in markets with which the government wants to expand its institutional investors base.

Finally, to better understand the impact of declarations of a commitment to net zero on financial markets, we highlight three directions for future research. First, additional proxies of firms' transition readiness could be considered given that the concept of readiness is relatively intrinsic and abstract. Additional proxies, including firms' social and governance scores, could be good candidates. Second, we treat different firms' declarations of a commitment to net zero as homogenous. However, the degree of ambitiousness of the declaration of a commitment to net zero of different firms could be different. This might also affect transition readiness and, consequently, the carbon risk premium. Third, as different types of institutional investors might have different investment horizons and environmental consciousness, a more granular breakdown of the type of institutional investor could increase our understanding of the variation in importance in channelling carbon risk among different institutional investors. We leave them for future research.

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Appendix A1

We deploy optimal control theory to solve the maximization problem (P) in Section 3. For each $t \in [0,1]$, the Hamiltonian equation is defined by

$$H\big(t, x(t), u(t), \lambda(t)\big) = e^{-rt}\left(g(t) - \beta x(t) - \frac{u(t)^2}{2\kappa}\right) - \lambda(t)u(t),$$

where $\lambda(t)$ is a continuous function adjoint of constraint $\dot{x}(t) = -u(t)$. Note that the Hamiltonian is concave at $\big(x(t), u(t)\big)$. By Theorems 9.10.2 and 9.10.3 in Sydsaeter et al. (2008), a pair of functions $\big(x^*(t), u^*(t)\big)$ are a solution to (P) if and only if they satisfy the relevant constraints in the problem and the following conditions: for all $t \in [0,1]$,

(1) $u(t) = u^*(t)$ maximizes $H\big(t, x^*(t), u(t), \lambda(t)\big)$ for $u(t) \geq 0$;
(2) $\dot{\lambda}(t) = -\,\partial H\big(t, x^*(t), u^*(t), \lambda(t)\big)/\partial x(t)$ whenever $u^*(t)$ is continuous.

Now, we examine the implications of each of the two conditions. For condition (1), note that

$$\frac{\partial H\big(t, x^*(t), u(t), \lambda(t)\big)}{\partial u(t)} = -e^{-rt}\frac{u(t)}{\kappa} - \lambda(t)$$

If $\lambda(t) \geq 0$, then $H\big(t, x^*(t), u(t), \lambda(t)\big)$ is decreasing in $u(t)$; thus, $u^*(t) = 0$. If $\lambda(t) < 0$, however, then strict concavity of $H\big(t, x^*(t), u(t), \lambda(t)\big)$ in $u(t)$ implies that $u^*(t)$ is pinned down by the first-order condition. Together, these imply

$$u^*(t) = \begin{cases} 0 & \text{if } \lambda(t) \geq 0 \\ -\kappa e^{rt}\lambda(t) & \text{if } \lambda(t) < 0 \end{cases} \qquad \text{(E1)}$$

Second, we study condition (2). Note that

$$\frac{\partial H\big(t, x^*(t), u^*(t), \lambda(t)\big)}{\partial x(t)} = -\beta e^{-rt}$$

This means $\dot{\lambda}(t) = \beta e^{-rt}$. Simple integration implies that, for some constant A_1,

$$\lambda(t) = -\frac{\beta}{r}e^{-rt} + A_1. \qquad \text{(E2)}$$

From (E2), note that $\dot{\lambda}(t) > 0$. Applying this to (E1), we can divide the analysis into 3 cases: (a) $\lambda(1) \leq 0$; (b) $\lambda(0) < 0 < \lambda(1)$; and (c) $\lambda(0) \geq 0$. Case (c) can be ruled out directly, as this would imply $u^*(t) = 0$ for all $t \in [0,1]$ and thus $x^*(1) = x_0$, a contradiction. Next, we study cases (a) and (b).

Case (a): From (E1) and (E2), $u^*(t) = \frac{\beta\kappa}{r} - \kappa e^{rt}A_1$ for all $t \in [0,1]$. Applying this to the constraint $u^*(t) = -\dot{x}^*(t)$ yields $x^*(t) = -\frac{\beta\kappa}{r}t + \frac{\kappa}{r}e^{rt}A_1 + A_2$ for some constant A_2. However, the initial and terminal conditions pin down two simultaneous equations:

$$\begin{cases} x^*(0) = \frac{\kappa}{r}A_1 + A_2 = x_0 \\ x^*(1) = -\frac{\beta\kappa}{r} + \frac{\kappa}{r}e^r A_1 + A_2 = x_1 \end{cases}$$

Solving the above system yields $A_1 = \frac{\beta\kappa + r(x_1 - x_0)}{\kappa(e^r - 1)}$ and $A_2 = -\frac{\beta\kappa + r(x_1 - x_0 e^r)}{r(e^r - 1)}$. Plugging the constants back into $x^*(t)$ expression above yields

$$x^*(t) = \begin{cases} x_0 - \frac{\beta\kappa}{r}t - \left(\frac{e^{rt} - 1}{e^r - 1}\right)\left(\phi x_0 - \frac{\beta\kappa}{r}\right) & \text{if } t < 1 \\ x_1 & \text{if } t \geq 1 \end{cases}$$
$$u^*(t) = \begin{cases} \frac{\beta\kappa}{r} + \frac{r\phi x_0 - \beta\kappa}{e^r - 1}e^{rt} & \text{if } t < 1 \\ 0 & \text{if } t \geq 1 \end{cases} \tag{E3}$$

(E2) implies $\lambda(t) = \frac{\beta}{r}\frac{e^{-r}}{1-e^{-r}}(r + e^{-rt} - e^{r(1-t)} - \frac{r^2\phi\gamma}{\beta\kappa})$. However, the solution is consistent with $\lambda(1) \leq 0$ if and only if $r + e^{-r} \leq 1 + \frac{r^2\phi x_0}{\beta\kappa}$, as desired.

Case (b): According to the intermediate value theorem, there exists a unique $\tau \in (0,1)$ such that $\lambda(\tau) = 0$. Fixing that τ. By (E1), $u^*(t) = 0$ and $x^*(\tau) = x_1$ for $t \in [\tau, 1]$. Below, we derive the solution for the range $t \in [0, \tau)$. From (E1) and (E2), we have $u^*(t) = \frac{\beta\kappa}{r} - \kappa e^{rt}A_1$. Applying this to the constraint $u^*(t) = -\dot{x}^*(t)$ yields $x^*(t) = -\frac{\beta\kappa}{r}t + \frac{\kappa}{r}e^{rt}A_1 + A_2$ for some constant A_2. The initial and terminal conditions pin down two simultaneous equations:

$$\begin{cases} x^*(0) = \frac{\kappa}{r}A_1 + A_2 = x_0 \\ x^*(\tau) = -\frac{\beta\kappa}{r}\tau + \frac{\kappa}{r}e^{r\tau} A_1 + A_2 = x_1 \end{cases}$$

Solving the above system yields $A_1 = \frac{\beta\kappa\tau + r(x_1 - x_0)}{\kappa(e^{r\tau} - 1)}$ and $A_2 = -\frac{\beta\kappa\tau + r(x_1 - x_0 e^{r\tau})}{r(e^{r\tau} - 1)}$. Plugging the constants back into the $x^*(t)$ expression above yields

$$x^*(t) = \begin{cases} x_0 - \frac{\beta\kappa}{r}t - \left(\frac{e^{rt} - 1}{e^r - 1}\right)\left(\phi x_0 - \frac{\beta\kappa}{r}\tau\right) & \text{if } t < \tau \\ x_1 & \text{if } t \geq \tau \end{cases}$$
$$u^*(t) = \begin{cases} \frac{\beta\kappa}{r} + \frac{r\phi x_0 - \beta\kappa\tau}{e^{r\tau} - 1}e^{rt} & \text{if } t < \tau \\ 0 & \text{if } t \geq \tau \end{cases} \tag{E4}$$

(E2) implies $\lambda(t) = -\frac{\beta}{r}e^{-rt} + \frac{\beta\kappa\tau + r(x_1 - x_0)}{\kappa(e^{r\tau} - 1)}$. Yet the condition $\lambda(\tau) = 0$ is equivalent to

$$r\tau + e^{-r\tau} = 1 + \frac{r^2\phi x_0}{\beta\kappa} \tag{E5}$$

As $r\tau + e^{-r\tau}$ increases in τ, the solution is consistent with the constraint $\tau < 1$ if and only if $r + e^{-r} > 1 + \frac{r^2\phi x_0}{\beta\kappa}$, as desired. Finally, note that (E5) is equivalent to $\tau = \frac{1}{r}F\left(\frac{r^2\phi x_0}{\beta\kappa}\right)$. ■

Appendix A2

The V_a expression in the proposition can be derived by plugging the solutions in (E3) into (P):

$$\int_0^\infty e^{-rt}\left(g(t) - \beta x^*(t) - \frac{1}{2\kappa}u^*(t)^2\right)dt = V_a$$

Statement (1):

$$\frac{\partial V_a}{\partial x_0} = \frac{\beta}{r}\left(\phi\frac{r - \frac{r^2\phi x_0}{\beta\kappa}}{e^r - 1} - 1\right) < \frac{\beta}{r}\left(\phi\frac{1 - e^{-r}}{e^r - 1} - 1\right) < 0$$

The first inequality holds by rearranging the precondition $r + e^{-r} < 1 + \frac{r^2\phi x_0}{\beta\kappa}$, and the second inequality holds because $\phi \in (0,1)$ and $e^r + e^{-r} > 2$ for $r > 0$.

Statement (2):

$$\frac{\partial V_a}{\partial \phi} = \frac{\beta x_0}{e^r - 1}\left(1 - \frac{r\phi x_0}{\beta\kappa}\right)$$

The characterization is self-evident.

Statement (3):

$$\frac{\partial^2 V_a}{\partial \phi \partial x_0} = \frac{2\beta x_0}{e^r - 1}\left(\frac{1}{2} - \frac{r\phi x_0}{\beta\kappa}\right)$$

The characterization is self-evident. ■

Appendix A3

With $\tau = \frac{1}{r}F\left(\frac{r^2\phi x_0}{\beta\kappa}\right)$, the V_b expression in the proposition can be derived by plugging the solutions in (E4) into (P):

$$\int_0^\infty e^{-rt}\left(g(t) - \beta x^*(t) - \frac{1}{2\kappa}u^*(t)^2\right)dt = V_b$$

For simplicity, let $\theta \equiv \frac{r^2\phi x_0}{\beta\kappa}$. As the variable τ involves the principal branch of the Lambert W function W_0, we first point out that $W_0\left(-e^{-1-\theta}\right) \in (-1,0)$. The following partial derivatives stem from applying (E5) and some key properties of W_0; a detailed derivation is omitted.

Statement (1):

$$\frac{\partial V_b}{\partial x_0} = -\frac{\beta}{r}\left(1 + \phi W_0\left(-e^{-1-\theta}\right)\right) < 0$$

This inequality holds because $\phi \in (0,1)$.

Statement (2):

$$\frac{\partial V_b}{\partial \phi} = -\frac{\beta}{r} x_0 W_0\left(-e^{-1-\theta}\right) > 0$$

The characterization is self-evident.

Statement (3):

$$\frac{\partial^2 V_b}{\partial \phi \partial x_0} = \frac{\beta}{r} \frac{-W_0\left(-e^{-1-\theta}\right)}{1 + W_0(-e^{-1-\theta})}\left(1 + W_0\left(-e^{-1-\theta}\right) - \theta\right)$$

Hence, the sign of the cross partial derivative is that of $G(\theta) \coloneqq 1 + W_0\left(-e^{-1-\theta}\right) - \theta$. Note that $\lim_{\theta \to 0^+} G(\theta) = 0$ and $G''(\theta) = \frac{W_0\left(-e^{-1-\theta}\right)}{\left(1+W_0\left(-e^{-1-\theta}\right)\right)^3} < 0$. Therefore, if there exists $\theta^* > 0$ such that $G(\theta^*) = 0$, then the solution is also unique. It can be derived that $\theta^* = 1 + \frac{1}{2} W_0(-2e^{-2})$. However, the concavity of G implies that $G(\theta) < 0$ if and only if $\theta > \theta^*$. ■