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Green Bond Pricing and Greenwashing under Asymmetric Information

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ABSTRACT: We analyze the corporate green bond market under a rational framework without an innate green preference, using a simple adverse selection model. Firms can use green bonds to signal their green credentials to investors. Transition risk stems from uncertainty over the introduction of carbon pricing. We show that green bonds have a price premium over conventional bonds when there are information asymmetry, transition risk, and it is costly to engage in greenwashing, that is, false or exaggerated claims of being green. The extent of greenwashing in the market is a function of the green bond premium. A swift and gradual implementation of carbon pricing generates a small green bond premium and a low level of greenwashing, while delayed and large carbon pricing has an ambiguous effect on both. The model provides a rich set of policy implications, notably the need for swift action on carbon pricing and strong information disclosures and regulations to ensure the integrity of green bonds.

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WORKING PAPERS

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I. INTRODUCTION

The green bond market and green financial debt products more broadly have grown rapidly in recent years (Schmittmann and Chua, 2021). Many policymakers and practitioners view green bonds as an important instrument to raise funding for green purposes and help price climate risks. This paper proposes a model of the corporate green bond market under asymmetric information without a green preference. The model provides insights into the conditions that generate a green bond premium, the interaction between green bond pricing and greenwashing, and the role of carbon pricing.[1] The core idea of the model is that green bonds can provide a costly and partially credible signal of firms' green credentials, as proposed in Flammer's (2021) empirical investigation of green bonds. In our model, the signal is valuable to investors as it allows them to avoid firms at risk from the introduction of carbon pricing.

Academic research has mostly focused on empirical aspects of the green bond market, in particular the pricing of green bonds. Results are mixed – some studies find a price premium of green bonds relative to brown bonds ("greenium"), others do not (see next section). Theoretical work typically assumes green preferences for green bond issuers and investors to generate a premium for green bonds. The existence of a greenium in these cases also requires the assumption that the premium is not arbitraged away by investors without a green preference.

In contrast, we develop an adverse selection model in which information asymmetry exists between bond issuers (firms) and bond buyers (investors) and there is no green preference by market participants.[2] Firms have two types, green (no emissions) and brown (positive emissions), and firms' types are private information.[3] Every firm has one project and issues either green or brown bonds. Investors can buy either green or brown bonds without observing firms' types. The issuance of green bonds by green firms can be considered as a signal of their green credentials, but the signal is

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[1]We use carbon pricing and carbon taxation interchangeably. In practice, carbon pricing can be achieved by other means than carbon taxation, for example, through emission trading schemes.

[2]The focus of our paper is on corporate green bonds. The model intuition extends to financial institutions if production is thought of as lending or investment portfolios. Our model does not extend well to sovereigns for which the decision to impose carbon pricing is endogenous and the link between carbon pricing and sovereign default risk is not clear.

[3]Firms' types with respect to their climate profiles can be thought of in a forward-looking sense including not only firms' current emissions but also future plans to curb emissions.

imperfect because brown firms may also issue green bonds (in this case brown firms would engage in greenwashing) although at a higher cost. The optimal strategy of firms and investors is to choose the type of bonds that maximizes their expected profits. Transition risk in the model stems from the possibility of the government introducing a carbon tax after bonds are issued. Transition risk does not affect green firms which have zero carbon emissions, but it makes brown firms risky as they may face bankruptcy, if their emissions are large and/or the carbon tax rate is high. Investors are identical and do not have a non-financial preference for green assets. This implies that expected profits from investing in green and brown bonds must be equal for the bond market to clear. Under this no-arbitrage condition, we can derive the green bond price premium jointly with the level of greenwashing.

We find that, without an investor preference for green, a greenium exists when there are asymmetric information between bond issuers and buyers, transition risk, and costly greenwashing. Under perfect information, a greenium cannot exist because investors can directly identify green and brown firms. Without transition risk, a greenium cannot exist, because green firms and brown firms have the same default risk. Without greenwashing costs, a greenium cannot exist, because green bonds have no value in signaling. We further calculate the economy-wide level of greenwashing, which depends on the greenium, the additional issuing costs associated with green bond issuance relative to conventional bonds (e.g., certification, auditing, and consulting fees), and the cost of greenwashing.[4] With respect to carbon taxation, under perfect information, an arbitrarily small carbon tax can drive all brown firms out of the market. Under asymmetric information, a small carbon tax causes a small greenium and a low level of greenwashing, but the effects of a large carbon tax on greenium and greenwashing are uncertain.

The model makes simplifying assumptions for tractability, but the key insights on green bond pricing and greenwashing are unaffected by these assumptions. We assume that a firm has only one project, and we impose a strong identification of green firms, that is, green firms have zero

[4]The cost of greenwashing can be interpreted as the cost associated with being exposed as a brown firm that ex ante pretends to be green, which could entail legal liability and reputational damage. Such a cost has been empirically documented by Du (2015) who finds that firms' stock returns are abnormally low after they have been exposed for greenwashing. There is also anecdotal evidence for costly greenwashing. For example, Italy's Competition and Market Authority fined oil firm ENI Euro 5mn for claiming that its palm oil based diesel is "green". Several financial firms including Deutsche Bank and BNY Mellon have been fined by regulators for false environmental claims.

emissions. In reality, most firms operate green and brown business segments and are on a continuum between zero emissions and very large emissions. The assumption of zero emission for green firms can be relaxed by setting a non-zero threshold without changing the intuition of the model. Firms with both green and brown business lines can be thought of as a combination of green and brown firms in the model. The model does not attempt to describe the production side but focuses on the financial incentives of green bond issuance.[5] A limitation of our model is therefore the absence of any supply or price responses in the product market, for example related to underinvestment in brown production during the transition to net zero emissions. The only source of risk in the model stems from carbon pricing - we do not consider other sources of risk.

Several policy implications for green finance and climate policy follow from our model. First, to support the green bond market to work at scale, policymakers need to introduce a carbon pricing mechanism to generate transition risk which in turn provides an incentive for investors to buy green bonds. Second, swift implementation of carbon pricing is necessary to avoid the need for large carbon prices in the future. In the model, swift and gradual carbon pricing generates a small greenium and a low level of greenwashing, reducing uncertainty. Third, strong supervision and regulation are needed to reduce greenwashing. Government interventions, such as green bond subsidies currently in place in Japan and Singapore, can be helpful but have a potential risk of increasing greenwashing. Hence, rigorous screening procedures *ex ante* and strong information disclosure requirements *ex post* are necessary to increase greenwashing costs and ensure the integrity of green bonds.

The rest of the paper is structured as follows. Section 2 summarizes the related literature. Section 3 describes the model setting. Section 4 describes the benchmark case under perfect information. Section 5 solves the optimal decisions under asymmetric information, and discusses the pricing of green bonds and greenwashing. Sections 6 and 7 discuss model applications and related policy implications. Section 8 concludes.

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[5]For a production side view and the contribution of green firms to emission reduction see, for example, the environmental DSGE model in Ferrari and Landi (2021), and Niu, Yao, Shao, Li and Wang (2018).

II. RELATED LITERATURE

The literature on green bonds and green debt more broadly is mostly empirical. On the pricing of green bonds relative to brown bonds, the empirical literature has mixed results. IMF (2019), Flammer (2021), and Larcker and Watts (2020) show that there is no noticeable difference between the yields of green bonds and brown bonds. However, Sebastian and Karim (2020), Zerbib (2019), and Baker et al. (2018) find that green bonds tend to be priced at a premium, offering lower yields than traditional bonds. MacAskill et al. (2021) review the literature from 2007 to 2019, and find a somewhat greater number of studies in favor of the existence of a small greenium, especially for green bonds that are government issued, investment grade, and follow defined green bond governance and reporting procedures.

Empirical papers, especially those in favor of a greenium, tend to ascribe a green bond premium to investors' willingness to pay a higher price for green bonds out of concern for the environment. An exception is Flammer (2021) who argues that her empirical results – no green bond premium, a positive equity price response to green bond issuance, and better environmental performance by green bond issuers post issuance – are consistent with companies signaling their commitment toward the environment by issuing green bonds. Our model builds on Flammer's signaling argument, but with an important difference regarding the recipient of the signal. Flammer argues that the green bond signal makes a firm attractive to long-term and green investors including equity investors. In our simple one-period model with only debt financing, the signaling of green credentials is to bond investors and the value of the signal derives solely from bond default risk associated with the potential introduction of carbon pricing.

The theoretical literature on the pricing of green bonds mostly argues that there should be a price premium for green bonds. Using asset pricing frameworks with green investor preferences, Pedersen, Fitzgibbons and Pomorski (2021) and Pástor, Stambaugh and Taylor (2021) show that green assets have lower expected returns (higher prices) because investors enjoy holding these assets (green preference) and green assets provide a hedge against climate risks. Similar arguments are made by Baker et al. (2018), and Agliardi and Agliardi (2021). In contrast to these papers, our model can explain both a positive green bond premium and no premium, and is, therefore, more consistent with the mixed empirical evidence. In our model, a greenium exists when there are transition risks, green bond issuing costs, and greenwashing costs. In addition, our results do not require the assumption of a non-finanical green preference by investors to generate a premium for green bonds.

The idea of transition risks stemming from the transition to a low carbon economy is well established among policymakers and in the literature. Examples include, IMF (2019), Network for Greening the Financial System (2020), and Basel Committee on Banking Supervision (2021) which show that transition risk is an important concern for policymakers; Jondeau, Mojon and Monnet (2021) who show that transition risks could cause a run on brown assets; Bolton et al. (2020) who show that a rapid transition to low-carbon may have negative consequences for financial stability; Carattini, Heutel and Melkadze (2021) who show that ambitious climate policy can lead to financial instability but the risk can be alleviated through macroprudential policies. Our model also suggests that a delayed and large carbon tax can cause instability, which underscores the importance of quick action on carbon pricing to avoid the need for higher carbon pricing to achieve given climate goals in the future. In a dynamic extension of our model, a swift and gradual introduction of a carbon tax (as opposed to a delayed and large tax) supports the growth of green firms, and reduces greenwashing, aggregate carbon emissions, and financial stability risks from brown firm bankruptcies.

On government subsidies for green bonds, Ferrari and Landi (2021) use a DSGE framework with an environmental sector to show that central bank subsidies for green bonds have limited effects on reducing emissions. Our model implies similar results in the sense that a general subsidy for green bonds raises greenwashing and, therefore, undermines the effect of emission reduction. However, we show that subsidies combined with strong information disclosures, regulations, and enforcement can help alleviate the problem of greenwashing and reinforce green effects, consistent with Ferreira and Suntheim (2021).

Another related strand of literature is on adverse selection and imperfect costly signaling. In our model, brown firms incur a cost for pretending to be green firms (costly greenwashing), which makes green bonds an imperfect signal. The structure of costly state verification is originally from Townsend (1979) and later Bernanke, Gertler and Gilchrist (1999). Regarding the adverse selection model and signaling process, we refer to Dell'Ariccia and Marquez (2006), Ferrante (2018), and Gao and Ueda (2022).

III. THE MODEL SETUP

A. Setting

We adopt a simple one-period model, with bond issuers (firms) and bond buyers (investors). We assume that firms and investors are risk neutral and do not have a green preference. There are two types of bonds in the market, green bonds and brown bonds. The only shock in the model is a transition risk resulting from the possibility that the government introduces a carbon tax after bonds are issued.

Bond Issuers

There are N firms in the market. Green firms take up market share α, and brown firms take up the remainder $(1-\alpha)$. Firms are risk neutral and have limited liability. For simplicity, we make two assumptions: First, one firm has one project. Second, firms have no endowment, so they need to borrow to produce.

There are two types of firms: green firms and brown firms. For green firms, carbon emissions during production are zero. For brown firms, carbon emissions during production are strictly positive.[6] For simplicity, we assume that carbon emissions of brown firms are uniformly distributed: for a brown firm i, the emission intensity, that is, the emission level per unit of production, is denoted as e_i, where $e_i \sim U(0,1]$. Intuitively speaking, this assumption implies a sequential order of the emission intensities of brown firms. Furthermore, a firm's type (green or brown) is private information. Firms' types can be thought of as firms' future plans that impact their emissions profile. This interpretation goes beyond information asymmetry in current emissions which can be addressed with better disclosures.

For firms' production functions, we use a simple AK model.

$$y^j = A_d k^j \tag{1}$$

Type $j \in \{g, b\}$, where g denotes green firms, and b denotes brown firms. A green firm requires an

[6] We use zero emissions as the threshold for simplicity. Results still hold with a higher threshold.

amount of capital k^g for production and a brown firm requires k^b for production. We use the same productivity factor A_d for both green and brown firms, because we do not consider differences in real production of green and brown firms in our model.[7]

Bonds

Firms need to borrow to produce. In our model, bonds are the only available source of funding. We assume a firm can only issue one type of bond - either a green or a brown bond.

For simplicity, we normalize bond prices to one, and only consider the coupon rates. For brown bonds, the coupon rate is r^b, and for green bonds, the coupon rate is r^g. Brown bonds represent conventional bonds, while green bonds represent bonds associated with green projects or environmental commitments. In this model, we set brown bonds' coupon rate r^b as exogenously given, and let green bonds' coupon rate r^g be an endogenous variable, meaning the pricing of green bonds is endogenous in the model.

The green commitments associated with green bonds imply additional issuing cost, such as consulting fees, costs of internal compliance, project management and selection, reporting costs, and fees associated with external reviews and verification. For green firms, the additional issuing costs associated with green bonds are denoted as $\bar{C}$ per bond. Brown firms can also issue green bonds, but they incur a larger issuing cost. This additional cost can be thought of as the cost of greenwashing. Accordingly, brown firms issuing green bonds pay the green bond issuing cost $\bar{C}$ per bond, plus a greenwashing cost.

The cost of greenwashing for a brown firm depends on the carbon intensity of the brown firm. This is intuitive, because it is much harder (costlier) for a firm with high pollution to pretend to be green than for a firm that is a marginal polluter. In our model, the greenwashing cost of a brown firm i is denoted as $f(e_i)$. The function $f(e_i)$ needs to satisfy the following two requirements: (1) $f(e_i)$ is increasing, strictly convex, twice continuously differentiable; (2) $f(e_i = 0) = 0$. $f(e_i = 1) \to \infty$. Without loss of generality, we use the function below in our calculations. σ can be interpreted as the

[7] Carattini et al. (2021) discuss the impact of emissions on productivity A_d.

completeness of regulation, and a bigger σ means a higher cost for greenwashing.

$$f(e_i) = -\sigma ln(1 - e_i) \tag{2}$$

Bond Buyers

There are many investors in the market. Investors are risk neutral. Each investor has one unit of money. An investor can choose to buy either a brown or a green bond. When an investor buys a green bond, he will receive r^g if the bond is repaid; otherwise, he will receive a pro rata share of the bond issuer's output in the case of default. Similarly, when an investor buys a brown bond, he will receive r^b if the bond is repaid; otherwise, he will receive pro rata share of the bond issuer's output in the default case. Investors know whether bonds are green or brown, but they cannot observe whether bond issuers are green or brown firms. Since investors are identical, the expected return of a green bond and the expected return of a brown bond must be the same.

Transition Risk

The transition risk in our model refers to the possibility that the government will introduce a carbon tax after bonds have been issued.[8] To be more specific, the government will adopt a carbon tax τ per unit of emission with probability p and will not adopt any carbon tax with probability $(1 - p)$. Carbon tax rate τ and the probability p are exogenous in our model, and $\tau \in (0, 1)$, $p \in (0, 1)$. The transition risk could cause default of some brown firms through an inability to meet the tax payment.

B. Time Line

We use a simple one-period model, which can be divided into 4 steps: (1) green and brown firms choose to issue either green or brown bonds; (2) investors choose to buy either green or brown bonds; (3) transition risk (carbon tax magnitude) is realized; and (4) green and brown bonds are repaid or firms default, depending on firms' emissions and the realization of the transition risk.

[8]For simplicity, the only source of transition risk in our model is a carbon tax. Other sources of transition risks are possible including regulation, changing consumer preferences, and corporate liability, but would not change the intuition of our model.

In our model, the major friction is information asymmetry. At the beginning of the period, firms know their own types, while investors can observe bonds' types, but cannot observe firms' types. However, investors know the aggregate level of greenwashing in the green bond market. At the end of the period, if the carbon tax is implemented, firms' types will be automatically revealed by carbon tax payments; [9] if the carbon tax is not implemented, firms' types will stay private information. The model solves for the market price of green bonds.

IV. Model with Perfect Information

As a benchmark, we consider the case of perfect information in which both firms and investors observe firms' types before bond issuance. In this case, there is no signaling benefit associated with green bonds. Therefore, firms only issue conventional bonds under perfect information.

When there is no carbon tax, firms will not default. Firms' production follows the AK model discussed above. We assume that the number of firms N is large enough, so that it is a perfectly competitive market. Investors maximize their return on investments and require a bond coupon rate equal to the productivity rate A_d per unit of investment. Firms have zero profit because of the perfectly competitive market.

When there is a carbon tax (τ) before bond issuance, green firms will not pay the carbon tax because of their zero carbon emissions, but brown firms will pay the carbon tax on their carbon emissions. Since green firms do not pay the carbon tax, green firms are able to offer a coupon rate on their bonds at the productivity rate A_d per unit of capital. However, brown firms need to pay carbon tax first, thus, brown firms can only offer a coupon rate on their bonds at the productivity rate net of the carbon tax rate, that is, $(A_d - \tau)$ per unit of capital. From the perspective of investors, investors strictly prefer investing in green firms over brown firms, because of a higher coupon rate. Hence, for any substantial small carbon tax rate τ, brown firms cannot source funding and exit the market.

When there is a transition risk, a carbon tax τ will be implemented with probability p and no carbon tax will be implemented with probability $(1 - p)$. Since green firms do not pay carbon tax, green firms can still guarantee the coupon rate on their bonds at the productivity rate A_d per unit of

[9] We assume that firms are not able or willing to falsify their carbon emissions reporting to the regulator/tax authority.

capital. However, brown firms can only offer a coupon rate on their bonds at A_d per unit of capital with probability $(1-p)$, and $(A_d-\tau)$ per unit of capital with probability p. Hence, investors expected return from investing in brown firms is $(A_d-p\tau)$, which is strictly smaller than the expected return from investing in green firms, for any substantial small but positive τ. Investors will not invest in brown firms, thus, all brown firms exit the market.

V. Model with Asymmetric Information

Under asymmetric information, investors can only observe bonds' types, while firms' types are private information. In this setting, firms' optimal strategy is to issue the type of bond that maximizes their expected profits. Meanwhile, investors' profit maximizing behavior leads to price adjustments so that the expected returns on green bonds and brown bonds are equalized.

A. Green Firms

Green firms are not affected by transition risk, because they have zero carbon emission, thus, will not be taxed if the government introduces a carbon tax. Denote $E(\pi^{g\hat{g}})$ as green firms' expected profit issuing green bonds, and $E(\pi^{g\hat{b}})$ as green firms' expected profit issuing brown bonds.

$$E(\pi^{g\hat{g}}) = y^g - r^g k^g - \bar{C}k^g \tag{3}$$

$$E(\pi^{g\hat{b}}) = y^g - r^b k^g \tag{4}$$

A green firm's expected profit issuing a green bond is the firm's output y^g net of the green bond repayment of principal plus interest $r^g k^g$ and the green bond issuing cost $\bar{C}k^g$. A green firm's expected profit issuing a brown bond is the green firm's output y^g net of the brown bond repayment of principal plus interest $r^b k^g$.

$$y^g - r^g k^g - \bar{C}k^g \geq y^g - r^b k^g$$

$$r^g + \bar{C} \leq r^b \tag{5}$$

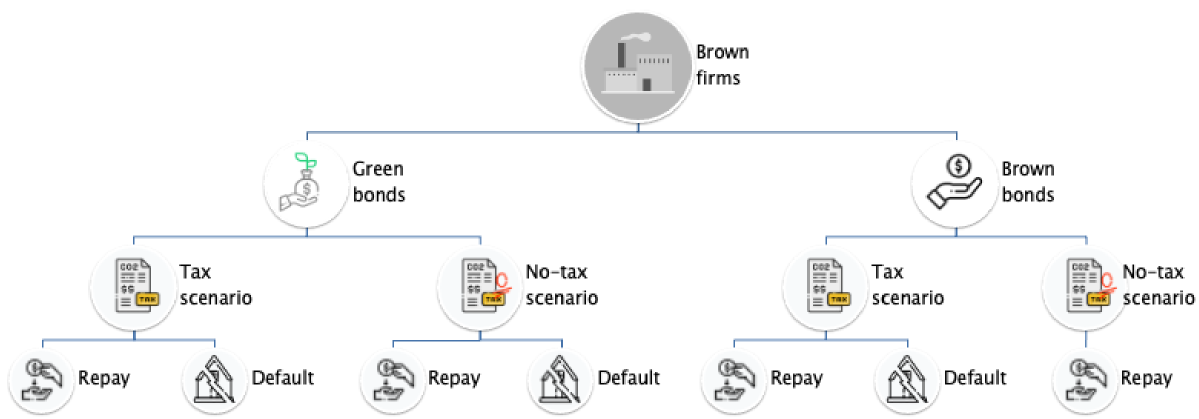
Since green firms choose the type of bond they issue by maximizing expected profit, green firms choose green bonds when (5) is satisfied. The left-hand side is the overall cost of issuing a green bond, including the coupon rate and additional green bond issuing costs. The right-hand side is the overall cost of issuing a brown bond, including the coupon rate only. We assume (5) is always satisfied, in other words, green firms always prefer green bonds. Otherwise, if green firms prefer brown bonds, we are left with the trivial case that a green bond market does not exist.

B. Brown Firms

The decision to issue green or brown bonds is more complex for brown firms. The optimal strategies of brown firms depend on government carbon tax policy and brown firms' carbon emissions.

Figure 1. Brown firm's bond issuing strategy profile

This figure shows all possible results of brown firm's repayment, given brown firm's bond issuing strategy and the realization of transition risk.



As shown in Figure 1, brown firms can choose to issue either green bonds or brown bonds. Since brown firms have positive carbon emissions during production, the introduction of a carbon tax affects the profits of brown firms. If the carbon tax rate is very high, and/or the level of the firm's carbon emissions is very high, the amount of carbon tax that the brown firm needs to pay will be high. This could lead to the bankruptcy of the brown firm and result in the firm defaulting on the bonds it issued.[10]

[10]The only source of default risk in the model is the carbon tax. There is no production or sales related default risk. Accordingly, if there is no carbon tax, brown firms will not default.

Next, we describe brown firms' expected profit under different cases. For a brown firm i, with emission intensity e_i, denote $E(\pi_i^{b\hat{g}})$ as brown firm i's expected profit issuing green bonds, and denote $E(\pi_i^{b\hat{b}})$ as brown firm i's expected profit issuing brown bonds. Under the carbon tax scenario, $\pi^{b\hat{g}t}(e_i)$ is brown firm i's profit issuing green bonds, and $\pi^{b\hat{b}t}(e_i)$ is brown firm i's profit issuing brown bonds.

$$\pi^{b\hat{g}t}(e_i) = \max\{y^b - r^g k^b - (\bar{C} + f(e_i))k^b - \tau e_i y^b, 0\} \tag{6}$$

$$\pi^{b\hat{b}t}(e_i) = \max\{y^b - r^b k^b - \tau e_i y^b, 0\} \tag{7}$$

Under the no carbon tax scenario, $\pi^{b\hat{g}0}(e_i)$ is brown firm i's profit issuing green bonds, and $\pi^{b\hat{b}0}(e_i)$ is brown firm i's profit issuing brown bonds.

$$\pi^{b\hat{g}0}(e_i) = \max\{y^b - r^g k^b - (\bar{C} + f(e_i))k^b, 0\} \tag{8}$$

$$\pi^{b\hat{b}0}(e_i) = y^b - r^b k^b \tag{9}$$

Because firms have limited liability, there are three turning points in brown firms' expected profits: e^g, e^{gt}, e^{bt} satisfy the following.

$$\pi^{b\hat{g}0}(e^g) = y^b - r^g k^b - (\bar{C} + f(e^g))k^b = 0 \tag{10}$$

$$\pi^{b\hat{g}t}(e^{gt}) = y^b - r^g k^b - (\bar{C} + f(e^{gt}))k^b - \tau e^{gt} y^b = 0 \tag{11}$$

$$\pi^{b\hat{b}t}(e^{bt}) = y^b - r^b k^b - \tau e^{bt} y^b = 0 \tag{12}$$

In our model, the government introduces a carbon tax with probability p, creating a transition risk. Brown firm i's overall expected profit can be calculated as below

$$E(\pi^{b\hat{g}}(e_i)) = (1-p)\pi^{b\hat{g}0}(e_i) + p\pi^{b\hat{g}t}(e_i) \tag{13}$$

$$E(\pi^{b\hat{b}}(e_i)) = (1-p)\pi^{b\hat{b}0}(e_i) + p\pi^{b\hat{b}t}(e_i) \tag{14}$$

Combining the three turning points, brown firm i's overall expected profit can be further specified:

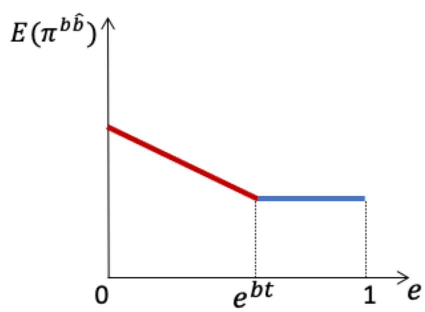
$$E(\pi^{b\hat{g}}(e_i)) = \begin{cases} y^b - r^g k^b - (\bar{C} + f(e_i))k^b - p\tau e_i y^b, & e_i < e^{gt} & (15) \\ (1-p)[y^b - r^g k^b - (\bar{C} + f(e_i))k^b], & e^{gt} \le e_i < e^g & (16) \\ 0, & e_i \ge e^g & (17) \end{cases}$$

$$E(\pi^{b\hat{b}}(e_i)) = \begin{cases} y^b - r^b k^b - p\tau e_i y^b, & e_i < e^{bt} & (18) \\ (1-p)(y^b - r^b k^b), & e_i \ge e^{bt} & (19) \end{cases}$$

When brown firm i issues green bonds, under the carbon tax scenario, firm i will repay if $e_i < e^{gt}$, and firm i will default if $e_i \ge e^{gt}$; under the no carbon tax scenario, brown firm i will default on green bonds if $e_i \ge e^g$, because of the high greenwashing cost. When brown firm i issues brown bonds, under the carbon tax scenario, firm i will repay if $e_i < e^{bt}$, and firm i will default if $e_i \ge e^{bt}$; under the no carbon tax scenario, brown firm i will not default on brown bonds.

Figure 2. Brown firm's expected profit.

$E(\pi^{b\hat{b}})$ and $E(\pi^{b\hat{g}})$ are brown firm's expected profits issuing brown bonds and green bonds. When a brown firm's emission intensity e is small, the brown firm does not default. With a high e, the brown firm defaults under carbon taxation. Without carbon taxation, brown firm with brown bonds never default, while with green bonds, default when $e \ge e^g$.



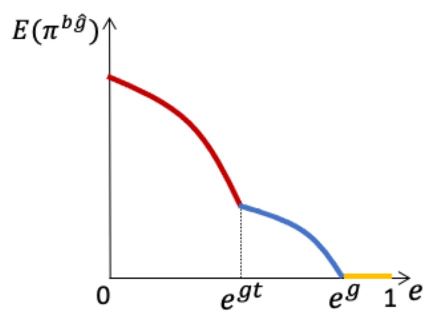


Figure 2 illustrates brown firms' expected profits. The horizontal axis is the brown firm's emission intensity and the vertical axis is the brown firm's expected profits. The LHS chart shows the brown firm's expected profits issuing brown bonds and the RHS chart shows the brown firm's expected profits issuing green bonds. In the charts, the red line (LHS) and the red curve (RHS) represent no default under the tax scenario, while the blue line (LHS) and the blue curve (RHS) represent default under the tax scenario and no default under the no tax scenario, (the yellow line (RHS) represents default under both tax and no tax scenarios). In the model, greenwashing is defined as brown firms issuing green bonds, the case shown in the RHS chart. Brown firms choose the types of bonds by maximizing their expected profit. The profit maximization can be visualized by comparing the two charts in Figure 2. When $e = 0$ (no emissions), it is easy to prove $E(\pi^{b\hat{g}}) > E(\pi^{b\hat{b}})$. We can also show that when the red line (LHS) and the red curve (RHS) intersect, the blue line (LHS) and the blue curve (RHS) also cross at the same point of emission intensity. The intersection is on the extension line/curve.

Lemma 1. *When $e_i \in (0, \hat{e})$, brown firm i prefers green bonds, that is, greenwashing. The threshold for greenwashing, $\hat{e}$, satisfies*

$$r^g + \bar{C} + f(\hat{e}) = r^b \tag{20}$$

Proof. Using brown firms' expected profit functions (15)∼ (19), we can calculate: Under the no default condition, by (15) and (18), brown firms are indifferent between green and brown bonds when (21) is satisfied. Accordingly, we can solve the greenwashing threshold $\hat{e}_1$ that satisfies $r^g + \bar{C} + f(\hat{e}_1) = r^b$. Under the default condition, by (16) and (19), brown firms are indifferent between green and brown bonds when (22) is satisfied. Accordingly, we can solve the greenwashing threshold $\hat{e}_2$ that satisfies $r^g + \bar{C} + f(\hat{e}_2) = r^b$. Hence, $\hat{e}_1 = \hat{e}_2 \equiv \hat{e}$.

$$y^b - r^b k^b - p\tau e_i y^b = y^b - r^g k^b - (\bar{C} + f(e_i))k^b - p\tau e_i y^b \tag{21}$$

$$(1-p)(y^b - r^b k^b) = (1-p)[y^b - r^g k^b - (\bar{C} + f(e_i))k^b] \tag{22}$$

Graphically, the threshold of greenwashing is the intersection point of LHS and RHS charts in Figure 2. By (21) and (22), when the red line (LHS) and the red curve (RHS) intersect, the blue line (LHS) and the blue curve (RHS) also cross at the same point of emission intensity. Because the intersection of red line and red curve and the intersection of blue line and blue curve are at the same emission intensity, a case such that at $\hat{e}$ a red line/curve crosses a blue line/curve cannot happen. The reason is that the carbon tax is on brown firms, not on brown bonds.

Q.E.D.

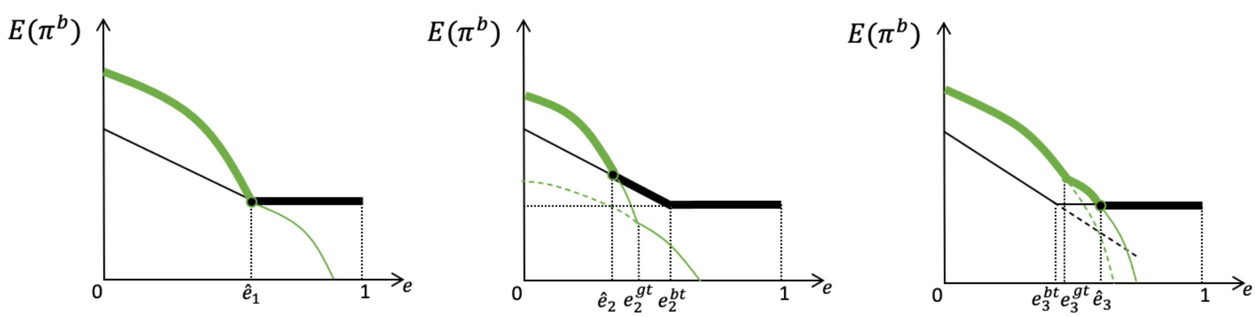
The interpretation of the greenwashing threshold $\hat{e}$ is that when a brown firm's carbon intensity is smaller than $\hat{e}$, it will choose to issue green bonds, that is, greenwashing; when a brown firm's carbon intensity is bigger than $\hat{e}$, it will choose brown bonds for financing; when a brown firm's carbon intensity is equal to $\hat{e}$, it is indifferent between green bonds and brown bonds.

The intuition behind (20) is as follows. The LHS $(r^g + \bar{C} + f(\hat{e}))$ implies the cost of a brown firm issuing green bonds, which includes green bond coupon rate plus green bonds' additional issuing cost and greenwashing cost. The RHS r^b implies the cost of a brown firm issuing brown bonds, which includes only brown bond coupon rate. Firms choose bonds by maximizing expected profit, in other words, minimizing the funding cost, that is, the overall bond issuing cost in the model.

To illustrate the choices facing brown firms, we combine the two charts in Figure 2 into one chart, and describe brown firms' optimal bond issuance strategies following Lemma 1. Brown firms' expected profits differ with different carbon tax rates [11] and carbon emission intensities. Brown firms will choose the type of bonds which offer the higher expected profit. Brown firms' expected profits can be categorized into 3 cases, as shown in Figure 3.

Figure 3. Brown firm's bond issuance strategy

Brown firms issue the type of bonds that generate the highest expected profit. $E(\pi^b) = \max\{E(\pi^{b\hat{g}}), E(\pi^{b\hat{b}})\}$. Brown firm's bond issuance strategy depends on two factors: emission intensity and transition risk.



(1) $\tau = \hat{\tau}$ (2) $\tau < \hat{\tau}$ (3) $\tau > \hat{\tau}$

In Figure 3, the horizontal axes show the emission intensities and the vertical axes show brown firms' expected profits. Green curves represent the expected profits of brown firms that issue green

[11]For simplicity, the transition risk is characterized by the carbon tax rate τ and we assume the probability of tax implementation p is constant.

bonds. Black lines represent the expected profits of brown firms that issue brown bonds. The dotted lines/curves are the extensions of the solid lines/curves of expected profits. Bold lines/curves are brown firms' optimal strategies of bond issuance. The intersections of green bold curves and black bold lines are the thresholds of greenwashing. Each chart represents a case for a range of carbon tax rates. Based on different tax rates, the relations among $\hat{e}, e^{bt}, e^{gt}$ can be different, which can be calculated using (11), (12), and (20). Recall that e^{gt} is the default threshold of brown firms issuing green bonds under the carbon tax scenario, and e^{bt} is the default threshold of brown firms issuing brown bonds under carbon tax scenario.

Figure 3 case 1 represents the baseline case where transition risk satisfies $\tau = \hat{\tau}$. Under $\tau = \hat{\tau}$, three turning points overlap: $\hat{e}_1 = e_1^{gt} = e_1^{bt}$. When $e_i \in (0, \hat{e}_1)$, brown firm i prefers green bonds, that is, greenwashing, and there is no default on green bonds. When $e_i \in [\hat{e}_1, 1]$, brown firm i prefers brown bonds, and all brown bonds default under carbon tax scenario.

Figure 3 case 2 describes the case of a carbon tax that is lower than the carbon tax in case (1), that is, $\tau < \hat{\tau}$, and hence, $\hat{e}_2 < e_2^{bt}$. At a lower level of carbon tax, the default threshold of brown bonds e_2^{bt} is bigger than the baseline e_1^{bt}, because the financial burden from the carbon tax is lower given emissions, and brown firms with emissions slightly higher than e_1^{bt} can survive in case 2 relative to case 1. By (12) and (20), we find $\hat{e}_2 < e_2^{bt}$. When $e_i \in (0, \hat{e}_2)$, brown firm i prefers green bonds, and there is no default. When $e_i \in [\hat{e}_2, 1]$, brown firm i prefers brown bonds, and for $e_i \in [\hat{e}_2, e_2^{bt}]$, there is no default; for $e_i \in (e_2^{bt}, 1]$, brown bonds default under the carbon tax scenario.

Figure 3 case 3 describes the case that the carbon tax is higher than the carbon tax in case (1), that is, $\tau < \hat{\tau}$, and hence, $e_3^{gt} < \hat{e}_3$. At a higher level of carbon tax, the default threshold of green bonds e_3^{gt} is lower than the baseline e_1^{gt}. By (11) and (20), we find $e_3^{gt} < \hat{e}_3$. When $e_i \in (0, e_3^{gt}]$, brown firm i prefers green bonds, and there is no default. When $e_i \in (e_3^{gt}, \hat{e}_3)$, brown firm i prefers green bonds, and green bonds default under the carbon tax scenario. When $e_i \in [\hat{e}_3, 1]$, brown firm i prefers brown bond and all brown bonds default under the carbon tax scenario.

C. Green Bond Pricing and Greenwashing

Based on green firms' strategies, brown firms' strategies, and their expected profits, we can calculate the market pricing of green bonds and the level of greenwashing under various carbon tax.

Case 1 – Baseline Carbon Tax Rate $\tau = \hat{\tau}$

In the baseline case, $\hat{e}_1 = e_1^{bt}$. We replace e_1^{bt} with $\hat{e}_1$ in (12), and get $y^b - r^b k^b - \tau \hat{e}_1 y^b = 0$. The carbon tax rate in the baseline case can be expressed as a function of $\hat{e}_1$.

$$\tau = \frac{y^b - r^b k^b}{\hat{e}_1 y^b} \tag{23}$$

Recall that brown firms with emission intensities smaller than $\hat{e}_1$ issue green bonds and there is no default under the carbon tax scenario; for brown firms with emission intensities bigger than or equal to $\hat{e}_1$, they issue brown bonds and all default under the carbon tax scenario. For green firms, they issue green bonds and do not default, regardless of carbon taxation.

In the green bond market, there are αN green firms, and $(1-\alpha)N\hat{e}_1$ brown firms. There is no default on green bonds, regardless of carbon taxation. Hence, the expected return for investors in green bonds, denoted as $E(R_1^g)$, is simply equal to the coupon rate of green bonds. r_1^g is the endogenous coupon rate of green bonds in case 1.

$$E(R_1^g) = r_1^g \tag{24}$$

In the brown bond market, there are $(1-\alpha)N(1-\hat{e}_1)$ brown firms. There is no default on brown bonds under the no carbon tax scenario, but all brown bond issuers default under the carbon tax scenario. Hence, the expected return for investors in brown bonds is denoted as $E(R_1^b)$ as follows.

$$\begin{aligned}
E(R_1^b) &= \frac{1}{(1-\alpha)N(1-\hat{e}_1)} \sum_{\hat{e}_1}^{1} \left[(1-p)r^b + p(1-\tau e_i)\frac{y^b}{k^b} \right] \\
&= (1-p)r^b + p\left(1 - \tau \frac{\hat{e}_1 + 1}{2}\right)\frac{y^b}{k^b} \\
&= r^b - p\left[r^b - \left(1 - \tau \frac{\hat{e}_1 + 1}{2}\right)\frac{y^b}{k^b} \right] \\
&= r^b - \frac{1}{2}p\left(\frac{y^b}{k^b} - r^b\right)\left(\frac{1}{\hat{e}_1} - 1\right)
\end{aligned} \tag{25}$$

Because $\hat{e}_1$ is smaller than 1, the second term is negative, implying a loss from possible defaults. $E(R_1^b) < r^b$, implies brown bonds' expected return for bond buyers is lower than the bond coupon rate.

Since bond buyers can freely choose between green and brown bonds, there must be no arbitrage in the expected returns of green and brown bonds.

$$E(R_1^g) = E(R_1^b) \tag{26}$$

We define F_1, and solve for the green bond coupon rate r_1^{g*}, which satisfies $F_1(r_1^{g*}) = 0$.

$$\begin{aligned} F_1 \equiv E(R_1^g) - E(R_1^b) &= r_1^g - r^b + p\left[r^b - \left(1 - \tau\frac{\hat{e}_1 + 1}{2}\right)\frac{y^b}{k^b}\right] \\ &= r_1^g - r^b + \frac{1}{2}p\left(\frac{y^b}{k^b} - r^b\right)\left(\frac{1}{\hat{e}_1} - 1\right) \end{aligned} \tag{27}$$

Recall Lemma 1, $\hat{e}_1$ satisfies $r_1^g + \bar{C} + f(\hat{e}_1) = r^b$. By the function of greenwashing cost, $f(e_i) = -\sigma ln(1 - e_i)$, we have $\hat{e}_1 = 1 - e^{-\frac{1}{\sigma}(r^b - r_1^g - \bar{C})}$. By the first order condition, F_1 is an increasing function of r_1^g. When $r_1^g = 0$, F_1 is negative; when $r_1^g = r^b$, F_1 is non-negative. $r_1^{g*} \in (0, r^b]$. The solution of case 1, r_1^{g*} satisfies (28), together with greenwashing level $\hat{e}_1^*$ in (29) and carbon tax rate $\hat{\tau}$ in (30).

$$r_1^{g*} - r^b + \frac{1}{2}p\left(\frac{y^b}{k^b} - r^b\right)\left(\frac{1}{\hat{e}_1} - 1\right) = 0 \tag{28}$$

$$\hat{e}_1^* = 1 - e^{-\frac{1}{\sigma}(r^b - r_1^{g*} - \bar{C})} \tag{29}$$

$$\hat{\tau} = \frac{y^b - r^b k^b}{\hat{e}_1^* y^b} \tag{30}$$

Case 2 – A Lower Carbon Tax Rate $\tau < \hat{\tau}$

Consider the market state in case 1, $(r_1^{g*}, \hat{e}_1^*, \hat{\tau}, r^b, k^g, k^b, p, \bar{C}, A_d)$, a smaller carbon tax has an immediate and a subsequent effect. When the carbon tax rate decreases, assuming all other state variables do not change immediately, the expected return of green bonds for bond buyers still equals the green bond coupon rate, while the expected return of brown bonds for bond buyers increases, because the probability of brown bond default decreases and the average loss of one defaulted bond decreases. This implies a short-term violation of the no-arbitrage condition. To correct this violation and reach a new pricing equilibrium in the bond market, the green bond interest rate will increase, as investors will prefer brown bonds until the expected returns of green bonds and brown bonds are equal again. Next, we will calculate the market price of green bonds when the carbon tax is lower than the baseline.

When $\tau < \hat{\tau}$, brown firms with emission intensities smaller than $\hat{e}_2$ issue green bonds, with no default under the carbon tax scenario; brown firms with emission intensities within range $[\hat{e}_2, e_2^{bt}]$ issue brown bonds, with no default under the carbon tax scenario; brown firms with emission intensities within range $(e_2^{bt}, 1]$ issue brown bonds, with default under the carbon tax scenario. For green firms, they issue green bonds and do not default, regardless of carbon taxation.

In the green bond market, there are αN green firms, and $(1-\alpha)N\hat{e}_2$ brown firms. No bonds in the green bond market default, regardless of carbon taxation. Hence, green bonds' expected return for bond buyers is denoted as $E(R_2^g)$ below. r_2^g is the endogenous coupon rate of green bonds for case 2.

$$E(R_2^g) = r_2^g \tag{31}$$

In the brown bond market, there are $(1-\alpha)N(1-\hat{e}_2)$ brown firms. Under the no carbon tax scenario, brown bonds do not default. Under the carbon tax scenario, brown firm i with emission intensity $e_i \in [\hat{e}_2, e_2^{bt}]$ will not default; brown firm i with emission intensity $e_i \in (e_2^{bt}, 1]$ will default. Hence, brown bonds' expected return for bond buyers is denoted as $E(R_2^b)$ below.

$$\begin{aligned}
E(R_2^b) &= (1-p)r^b + p\left[\frac{e_2^{bt}-\hat{e}_2}{1-\hat{e}_2}r^b + \frac{1-e_2^{bt}}{1-\hat{e}_2}\left(1-\tau\frac{e_2^{bt}+1}{2}\right)\frac{y^b}{k^b}\right] \\
&= r^b - p\frac{1-e_2^{bt}}{1-\hat{e}_2}\left[r^b - \left(1-\tau\frac{e_2^{bt}+1}{2}\right)\frac{y^b}{k^b}\right] \\
&= r^b - \frac{1}{2}p\left(\frac{y^b}{k^b} - r^b\right)\frac{(1-e_2^{bt})^2}{e^{bt}(1-\hat{e}_2)}
\end{aligned} \tag{32}$$

We can also see that $E(R_2^b) < r^b$, meaning brown bonds' expected return for bond buyers is lower than the coupon rate . By the no arbitrage condition, we have $E(R_2^g) = E(R_2^b)$. Hence we define F_2

as below,

$$F_2 \equiv E(R_2^g) - E(R_2^b) = r_2^g - r^b + p\frac{1-e_2^{bt}}{1-\hat{e}_2}\left[r^b - \left(1 - \tau\frac{e_2^{bt}+1}{2}\right)\frac{y^b}{k^b}\right]$$
$$= r_2^g - r^b + \frac{1}{2}p\left(\frac{y^b}{k^b} - r^b\right)\frac{(1-e_2^{bt})^2}{e^{bt}(1-\hat{e}_2)} \tag{33}$$

where τ is substituted using the definition of e_2^{bt}. We solve r_2^{g*} satisfying $F_2(r_2^{g*}) = 0$. The greenwashing threshold $\hat{e}_2^*$ can also be calculated. When $\tau < \hat{\tau}$, the market coupon rate of green bonds satisfies (34), the greenwashing level satisfies (35).

$$r_2^{g*} - r^b + \frac{1}{2}p\left(\frac{y^b}{k^b} - r^b\right)\frac{(1-e_2^{bt})^2}{e^{bt}(1-\hat{e}_2)} = 0 \tag{34}$$
$$\hat{e}_2^* = 1 - e^{-\frac{1}{\sigma}(r^b - r_2^{g*} - \bar{C})} \tag{35}$$

Next, we compare case 2, a low carbon tax case, to case 1, the baseline carbon tax case, and we can show that $r_1^{g*} < r_2^{g*}$.

Lemma 2. *When the carbon tax rate is lower than the baseline level, $\tau < \hat{\tau}$, keeping the brown bond coupon rate constant, the green bond coupon rate is higher than the baseline level, and the level of greenwashing is lower than in the baseline level.*

Proof. Comparing (28) and (34), the only difference is the third term.

$$\frac{(1-e_2^{bt})^2}{e_2^{bt}(1-\hat{e}_2)} < \frac{(1-e_2^{bt})^2}{e_2^{bt}(1-e_2^{bt})} < \frac{1-e_2^{bt}}{e_2^{bt}} < \frac{1}{\hat{e}_1} - 1$$

where $\hat{e}_2 < e_2^{bt}$, $e_2^{bt} > e_1^{bt} = \hat{e}_1$. Keeping the brown bond coupon rate r^b constant, $r_1^{g*} < r_2^{g*}$, by (28) and (34). Using (29) and (35), we have $\hat{e}_1^* > \hat{e}_2^*$. *Q.E.D.*

The intuition behind Lemma 2 is straightforward. When the carbon tax is lower, brown bonds offer a higher expected return to bond buyers, although still below the brown bond coupon rate; green bonds offer an expected return equal to their coupon rate (no defaults). With a fixed brown bond coupon rate and a higher brown bond expected return, a higher green bond expected return is needed to restore the no arbitrage condition. This implies a higher green bond coupon rate and in turn a higher cost of issuing green bonds. With a smaller pricing differential between green and brown bonds, the benefit of greenwashing is lower and there is less incentive for brown firms to engage in greenwashing.

Case 3 – A Higher Carbon Tax Rate $\tau > \hat{\tau}$

Relative to case 1, an increase in the carbon tax rate causes uncertainty in green bond pricing. In the short term, assuming state variables $(r_1^{g*}, \hat{e}_1^*, \hat{\tau}, r^b, k^g, k^b, p, \bar{C}, A_d)$ remain unchanged, when the carbon tax rate increases, the expected return on green bonds for bond investors decreases, because brown firms with emission intensities slightly below $\hat{e}_1^*$ default on their green bonds because of a higher carbon tax. The expected return on brown bonds for bond investors also decreases. As the carbon tax rate increases, the probability of brown bond default is one, same as in the baseline, but the average loss of a defaulted bond increases. Accordingly, the changes to the no-arbitrage condition between green and brown bonds in case 3 are a priori uncertain. We calculate the market price of green bonds in case 3.

When $\tau > \hat{\tau}$, brown firms with emission intensities smaller than $\hat{e}_3$ issue green bonds, among which brown firms with emission intensities within the range $(0, e_3^{gt}]$ do not default under the carbon tax scenario; brown firms with emission intensities within the range $(e_3^{gt}, \hat{e}_3)$ default under the carbon tax scenario. Brown firms with emission intensities within the range $[\hat{e}_3, 1]$ issue brown bonds and all default under the carbon tax scenario. Green firms issue green bonds and do not default, regardless of carbon taxation.

In the green bond market, there are αN green firms, and $(1-\alpha)N\hat{e}_3$ brown firms. There is no default among green firms and brown firms with emission intensities smaller than e_3^{gt}. Brown firms with emission intensities within $(e_3^{gt}, \hat{e}_3)$ default under the carbon tax scenario. Hence, green bonds' expected return for bond investors is denoted as $E(R_3^g)$ below. r_3^g is the endogenous coupon rate of green bonds in case 3. $E(f(e))$ is denoted as the average of greenwashing cost $f(e_i)$ for firms with

$e_i \in (e_3^{gt}, \hat{e}_3)$.

$$\begin{aligned} E(R_3^g) = \quad & (1-p)r_3^g + p\left\{\frac{\alpha}{\alpha+(1-\alpha)\hat{e}_3}r_3^g + \frac{(1-\alpha)e_3^{gt}}{\alpha+(1-\alpha)\hat{e}_3}r_3^g + \frac{(1-\alpha)(\hat{e}_3-e_3^{gt})}{\alpha+(1-\alpha)\hat{e}_3}\right. \\ & \left.\left[\left(1-\tau\frac{e_3^{gt}+\hat{e}_3}{2}\right)\frac{y^b}{k^b} - \bar{C} - E(f(e))\right]\right\} \\ = \quad & r_3^g - p\frac{(1-\alpha)(\hat{e}_3-e_3^{gt})}{\alpha+(1-\alpha)\hat{e}_3}\left\{r_3^g - \left[\left(1-\tau\frac{e_3^{gt}+\hat{e}_3}{2}\right)\frac{y^b}{k^b} - \bar{C} - E(f(e))\right]\right\} \end{aligned} \tag{36}$$

For subsequent calculation, denote $A \equiv \frac{(1-\alpha)(\hat{e}_3-e_3^{gt})}{\alpha+(1-\alpha)\hat{e}_3}$.

In the brown bond market, there are $(1-\alpha)N(1-\hat{e}_3)$ brown firms. Under the no carbon tax scenario, brown bonds do not default. Under the carbon tax scenario, all brown bonds default. Hence, the expected return for bonds investors on brown bonds is denoted as $E(R_3^b)$ below.

$$\begin{aligned} E(R_3^b) &= (1-p)r^b + p\left(1-\tau\frac{\hat{e}_3+1}{2}\right)\frac{y^b}{k^b} \\ &= r^b - p\left[r^b - \left(1-\tau\frac{\hat{e}_3+1}{2}\right)\frac{y^b}{k^b}\right] \end{aligned} \tag{37}$$

By (36), $E(R_3^g) < r_3^g$, because some green bonds issued by brown firms engaging in greenwashing default under the carbon tax scenario. By (37), $E(R_3^b) < r_3^b$. By no arbitrage, we have $E(R_3^g) = E(R_3^b)$. Hence, we define F_3 as below.

$$\begin{aligned} F_3 =& r_3^g - r^b - pA\left\{r_3^g - \left[\left(1-\tau\frac{e_3^{gt}+\hat{e}_3}{2}\right)\frac{y^b}{k^b} - \bar{C} - E(f(e))\right]\right\} + p\left[r^b - \left(1-\tau\frac{\hat{e}_3+1}{2}\right)\frac{y^b}{k^b}\right] \\ =& r_3^g - r^b + pA\left[\frac{y^b}{k^b} - r_3^g - \bar{C} - E(f(e))\right] - p\left(\frac{y^b}{k^b} - r^b\right) + p\tau\left[-A\frac{e_3^{gt}+\hat{e}_3}{2} + \frac{\hat{e}_3+1}{2}\right]\frac{y^b}{k^b} \\ =& r_3^g - r^b + pA\left(\frac{y^b}{k^b} - r_3^g - \bar{C} - E(f(e))\right) - p\left(\frac{y^b}{k^b} - r^b\right) + \frac{1}{2}p\left[\frac{y^b}{k^b} - r_3^g - \bar{C} - f(e_3^{gt})\right] \\ & \left(\frac{1}{e_3^{gt}} - A + (1-A)\frac{\hat{e}_3}{e_3^{bt}}\right) \end{aligned} \tag{38}$$

By the definition of e_3^{gt}, τ can be substituted as

$$\tau = \frac{y^b - r_3^g k^b - (\bar{C} + f(e_3^{gt}))k^b}{e_3^{gt} y^b}$$

The calculation of the last term of F_3 is as following.

$$\begin{aligned}
&p\tau\left[-A\frac{e_3^{gt}+\hat{e}_3}{2}+\frac{\hat{e}_3+1}{2}\right]\frac{y^b}{k^b}\\
=&\frac{1}{2}p\left[\frac{y^b}{k^b}-r_3^g-\bar{C}-f(e_3^{gt})\right]\left(-A\frac{e_3^{gt}+\hat{e}_3}{\hat{e}_3}+\frac{1+\hat{e}_3}{\hat{e}_3}\right)\\
=&\frac{1}{2}p\left[\frac{y^b}{k^b}-r_3^g-\bar{C}-f(e_3^{gt})\right]\left(\frac{1}{e_3^{gt}}-A+(1-A)\frac{\hat{e}_3}{e_3^{bt}}\right)
\end{aligned}$$

We solve r_3^{g*} satisfying $F_3(r_3^{g*})=0$. The greenwashing threshold $\hat{e}_3^*$ can also be calculated. When $\tau>\hat{\tau}$, the market coupon rate of green bonds satisfies (39) and the greenwashing level satisfies (40).

$$r_3^{g*}-r^b+pA\left(\frac{y^b}{k^b}-r_3^{g*}-\bar{C}-E(f(e))\right)-p\left(\frac{y^b}{k^b}-r^b\right)+\frac{1}{2}p\left[\frac{y^b}{k^b}-r_3^{g*}-\bar{C}-f(e_3^{gt})\right]$$
$$\left(\frac{1}{e_3^{gt}}-A+(1-A)\frac{\hat{e}_3}{e_3^{bt}}\right)=0 \tag{39}$$
$$\hat{e}_3^*=1-e^{-\frac{1}{\sigma}(r^b-r_3^{g*}-\bar{C})} \tag{40}$$

Next we compare case 3, a high carbon tax, to case 1, the baseline carbon tax, and show that the relation between green bond coupon rates in case 3 (r_3^{g*}) and case 1 (r_1^{g*}) is uncertain.

Lemma 3. *When the carbon tax rate is higher than the baseline level, $\tau>\hat{\tau}$, keeping the brown bond coupon rate r^b constant, the adjustment of the green bond coupon rate r^g and the degree of greenwashing are uncertain compared to the baseline level.*

Proof. We compare the last term of equation (39) to the last term of equation (28). Since $e_3^{gt}<e_1^{gt}=\hat{e}_1$, $A<1$, and $r_3^g+\bar{C}+f(e_3^{gt})<r^b$, we can show the last term of equation (39) is bigger than the last term of equation (28) as below.

$$\frac{1}{2}p\left[\frac{y^b}{k^b}-r_3^{g*}-\bar{C}-f(e_3^{gt})\right]\left(\frac{1}{e_3^{gt}}-A+(1-A)\frac{\hat{e}_3}{e_3^{bt}}\right)>\frac{1}{2}p\left(\frac{y^b}{k^b}-r^b\right)\frac{(1-e_2^{bt})^2}{e^{bt}(1-\hat{e}_2)}$$

However, in equation (39), the relation between $A\left(\frac{y^b}{k^b}-r_3^g-\bar{C}-E(f(e))\right)$ and $\left(\frac{y^b}{k^b}-r^b\right)$ is uncertain, depending on parameters. Thus, the relation between r_1^{g*}, r_3^{g*} depends on economic state variables, given equations (28) and (39). Since the relation between r_1^{g*}, r_3^{g*} is uncertain, the relation between $\hat{e}_1, \hat{e}_3$ is also uncertain, by (29) and (40). *Q.E.D.*

The uncertainty in Lemma 3 has the following intuition: With a higher carbon tax than the baseline level, green bonds issued by brown firms start to default. Recall that green bonds are risk free assets in the baseline case, in the sense that green bonds do not default regardless of the carbon taxation. On the other hand, brown bonds default both in the baseline and the high carbon tax case, while the average loss given default is bigger in the high carbon tax case compared to the baseline case. Accordingly, both green bonds and brown bonds offer lower expected returns to bonds investors in the high carbon tax case relative to the baseline case.

To sum up, we find that for different levels of carbon taxation, the market prices of green bonds (coupon rates) vary, as in (28), (34), and (39). In addition, the level of greenwashing also varies, as in (29), (35), and (40). To interpret the results, we show two model applications in the next section.

VI. MODEL APPLICATIONS

A. The Existence of a Green Bond Premium

In this section, we calculate the pricing of green and brown bonds under various carbon tax scenarios. We discuss under what conditions a greenium emerges and how our results can explain the empirically observed pricing of green bonds.[12] We reorganize (28), (34), and (39) to get (41), (42), and (43), respectively.

$$r^b - r_1^{g*} = p\left[r^b - \left(1 - \tau\frac{\hat{e}_1 + 1}{2}\right)\frac{y^b}{k^b}\right] \tag{41}$$

$$r^b - r_2^{g*} = p\frac{1 - e_2^{bt}}{1 - \hat{e}_2}\left[r^b - \left(1 - \tau\frac{e_2^{bt} + 1}{2}\right)\frac{y^b}{k^b}\right] \tag{42}$$

$$r^b - r_3^{g*} = p\left[r^b - \left(1 - \tau\frac{\hat{e}_3 + 1}{2}\right)\frac{y^b}{k^b}\right] - pA\left\{r_3^g - \left[\left(1 - \tau\frac{e_3^{gt} + \hat{e}_3}{2}\right)\frac{y^b}{k^b} - \bar{C} - E(f(e))\right]\right\} \tag{43}$$

In (41), (42), and (43), LHS parts represent brown bond spreads over green bonds (i.e., the greenium), and RHS parts represent risk premiums of brown bonds over green bonds. Recall that in our model, the only risk is the transition risk stemming from uncertainty over the government's

[12]Our model assumes firms issue either green or brown bonds. It cannot explain pricing differences between identical green and brown bonds issued by the same firm. Such differences would suggest the presence of investors with green preferences and limits to arbitrage.

introduction of a carbon tax after bond issuance. The transition risk leads to default risk for some brown firms with high emission intensities. The default risk premium is a function of the magnitude of the carbon tax rate and firms' emissions. In our model, investors demand that bond yields reflect the default risk premium, given that bonds are the only available financing tool. Hence, the default risk premium, defined as the difference between default losses of green and brown bonds, is equal to the spread, defined as difference between the yields on green and brown bonds.

Next, we decompose the default risk premium into two components – the probability of default and the average loss given default. Using (11), (12), (24), (25), (31), (32), (36), (37), we can calculate the probability of default and the average loss given default for the three cases of carbon tax levels discussed in the previous section (Table 1).

Table 1. Default risk premium decomposition.

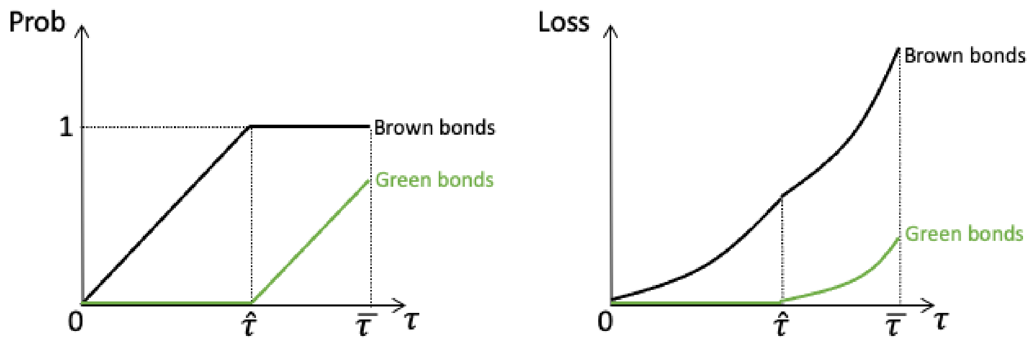
The table shows the probability of default and loss given default for green and brown bonds under three carbon tax scenarios.

	Green bonds		
	Case 1 ($\tau = \hat{\tau}$)	Case 2 ($\tau < \hat{\tau}$)	Case 3 ($\tau > \hat{\tau}$)
Probability of default	0	0	$\frac{\hat{e}_3 - e_3^{gt}}{\hat{e}_3}$
Loss given default	0	0	$r_3^g - \left(1 - \tau \frac{e_3^{gt} + \hat{e}_3}{2}\right) \frac{y^b}{k^b} + \bar{C} + E(f(e))$
	Brown bonds		
	Case 1 ($\tau = \hat{\tau}$)	Case 2 ($\tau < \hat{\tau}$)	Case 3 ($\tau > \hat{\tau}$)
Probability of default	1	$\frac{1 - e_2^{bt}}{1 - \hat{e}_2}$	1
Loss given default	$r^b - \left(1 - \tau \frac{\hat{e}_1 + 1}{2}\right) \frac{y^b}{k^b}$	$r^b - \left(1 - \tau \frac{e_2^{bt} + 1}{2}\right) \frac{y^b}{k^b}$	$r^b - \left(1 - \tau \frac{\hat{e}_3 + 1}{2}\right) \frac{y^b}{k^b}$

We can also show the results of Table 1 graphically as in Figure 4.

Figure 4. Default risk premium decomposition.

Graphical expressions of Table 1. The horizontal axis is the level of carbon tax. LHS shows the average probability of default, and RHS shows the average loss given default.



When brown bonds have a higher default probability or a higher average loss given default than green bonds, the default risk premium is positive, hence, a greenium exists. Intuitively, the brown bond market is a lemon market in which heavily-polluting firms are concentrated. Recall that the green bond market is comprised of all green firms and of brown firms with low emission intensities. The brown bond market consists of brown firms with high emission intensities. Issuing green bonds is unattractive for high emission brown firms, because greenwashing cost is an increasing function of emission intensity.

There are some special cases in which the prices of green and brown bonds are equal. We will discuss three cases: (1) no transition risk, that is, $p = 0$ or $p = 1$; (2) no greenwashing cost, i.e., $f(e_i) = 0$; (3) no information asymmetry.[13]

For the first case, when $p = 0$, firms and investors believe that there will be no carbon taxation before bond maturity. By (41), (42), and (43), we can show that $r^b = r^{g*}$, i.e., a greenium does not exist. Investors are indifferent between green and brown bonds, because both have the same default risk and pricing. Firms will not issue green bonds given a typically positive cost of issuing green bonds, that is, $\bar{C} > 0$. Even if $\bar{C}$ is zero, firms are indifferent between issuing green and brown bonds. The bottom line is that without transition risk there is no green bond market.

When $p = 1$, bond issuers and bond buyers firmly believe that a carbon tax will be implemented in this period. We can prove that $r^b = r^{g*}$, i.e., a greenium does not exist. When brown firms choose

[13]For the third case, the proof is in Section IV.

which type of bonds to issue, they will take the carbon tax payment into consideration *ex ante*. Heavily-polluting brown firms anticipate that they will default after paying carbon tax, and thus they will not enter the market. As a result, there are no defaults in either the green bond market or brown bond market. For investors, by the no arbitrage condition, yields on green and brown bonds must be the same.

For the second case, when there are no greenwashing costs, that is, $\forall e_i \in (0, 1]$, $f(e_i) = 0$, which implies the greenwashing threshold $\hat{e} = 1$, we can prove that there is no pricing difference between green and brown bonds, $r^b = r^{g*}$. According to (18), (19), (15), (16) and (17), let $f(e_i) = 0$, it is easy to show the new greenwashing threshold which is consistent with Lemma 1. When $r^g + \bar{C} < r^b$, both brown and green firms issue green bonds, and there is no brown bond market. When $r^g + \bar{C} > r^b$, both brown and green firms issue brown bonds, and there is no green bond market. When $r^g + \bar{C} = r^b$, both green firms and brown firms are indifferent between green bonds and brown bonds. Coupon rates must be equal and $\bar{C}$ must be zero. The intuition of $f(\cdot) = 0$ is that green bonds have no signaling value when greenwashing is not costly (a free signal has no value).

Our model can explain both the existence of a greenium and the absence of it. The model provides insights to the conditions required for a greenium. We acknowledge that other factors outside the scope of our model can cause a positive greenium. One possible factor is a green (or ESG) preference of investors.[14] In this case, investors are willing to sacrifice return to support green businesses. Another explanation for a greenium could be the value of green bond signaling beyond the bond market. Flammer (2021) and Tang and Zhang (2020) show that the issuance of green bonds has a positive effect on firms' performance in the equity market. In addition, there could also be a value of signaling green credentials to other stakeholders including customers, policymakers, regulators, employees, and suppliers.

B. The Impact of Transition Risk on Green Bond Pricing and Greenwashing

In the previous section, we show that transition risk stemming from the potential introduction of carbon pricing is a necessary condition for the existence of a greenium. Next, we discuss how the

[14]Related papers include Sebastian and Karim (2020), Ehler and Packer (2017), Karpf and Mandel (2017), Baker et al. (2018), Zerbib (2019), Fatica et al. (2021), Pastor et al. (2021), van der Beck (2021), Kapraun et al. (2021), and Pietsch and Salakhova (2022).

level of carbon taxation affects the greenium.

Lemma 4. *Given the state variables* $(r^b, k^g, k^b, p, \bar{C}, A_d)$*, the green bond coupon rate varies as the carbon tax rate changes. The baseline solutions are denoted as* $(r_1^{g*}, \hat{e}_1^*)$ *with the baseline carbon tax rate* $\hat{\tau}$*. When the carbon tax is lower than baseline* $\hat{\tau}$*, the green bond coupon rate is higher than the baseline level, and greenwashing is lower than the baseline level. When the carbon tax is higher than baseline* $\hat{\tau}$*, the green bond coupon rate and greenwashing level are uncertain compared to the baseline level.*

Proof. By (41), (42), and (43), it is easy to show that $r_1^{g*} < r_2^{g*}$. The relation between r_1^{g*} and r_3^{g*} is uncertain. The greenwashing level can be calculated by (29), (35), and (40). *Q.E.D.*

Given the brown bond coupon rate r^b, the greenium $(r^b - r^g)$ can be interpreted as the default risk premium. The default risk premium equals the difference between the probabilities of default multiplied with the loss given default for green and brown bonds. In Figure 4, at $\hat{\tau}$, the difference of probabilities of default is 1, and the difference in the loss given default is shown in the RHS chart. When the carbon tax rate is smaller than the baseline level $\hat{\tau}$, the difference of probabilities of default is smaller than 1, and the difference in the loss given default is smaller than the baseline level. Hence, the default risk premium is smaller than the baseline level. Thus, the spread between green and brown bonds is smaller, and the green bond coupon rate is higher than the baseline level.

When the carbon tax rate is higher than the baseline level $\hat{\tau}$, the difference in the probabilities of default is smaller than 1, but the difference in losses given default is bigger than the baseline level. It is unclear which effect dominates – default risk or loss given default. Accordingly, the change in the default risk premium and in the green bond coupon rate are uncertain when the carbon tax rate is higher than in the baseline.

Apart from the effects on green bond pricing, carbon taxation also affects the extent of greenwashing. By Lemma 1, we find that the greenwashing threshold is determined by three parts: the spread $(r^b - r^g)$, the green bond additional issuance cost $\bar{C}$, and the greenwashing cost $f(\cdot)$. The spread $(r^b - r^g)$ depends on the carbon tax and other state variables. When the carbon tax is lower than the baseline level, greenwashing is lower than the baseline level, because the spread is smaller than the baseline level. When the carbon tax is higher than the baseline level, greenwashing is uncertain compared to the baseline level.

VII. Policy Implications

A. The Need for Carbon Pricing and Climate Financial Regulations

As discussed in the previous section, without transition risk, the green bond market is unlikely to work at scale. If the government does not intend to implement a carbon tax, investors have no monetary incentive to invest in green bonds. As suggested by Pedersen et al. (2021) and Pástor et al. (2021), investors could be driven by other motives such as a general green preference, but we believe that without financial self-interest at stake, green finance will not scale.

Our model also shows that green finance requires greenwashing to be costly. This is intuitive: if firms that are not green can pretend to be green without incurring costs, green financial products have no signaling value to investors. In practice, making greenwashing costly requires guidelines, disclosures, fines for false information about green credentials and emissions[15], and effective validation and screening processes both before and after issuance. Progress is being made on these issues, but there is room for improvement. Guidelines for green financial products such as green bond standards are mostly non-binding. Firm level environmental disclosures at the overall entity level (e.g., emissions) and related to the issuance of green financial products (e.g., on the environmental additionality of the proposed projects and *ex post* monitoring of the use of proceeds) need to improve. Increasingly, regulators recommend and investors demand that issuers of green financial products including green bonds provide detailed reporting and that external reviewers provide assurances. There are also conceptual difficulties as to what constitutes activities that should be considered green or helping with the transition to low carbon. Efforts by regulators to provide guidance on this including through taxonomies of green and brown activities are important to reduce greenwashing.

[15]Regulators are increasingly imposing fines on firms engaged in greenwashing. See footnote 4.

B. The Need for Swift Action on Carbon Pricing

If policymakers delay actions on carbon pricing, a very high carbon price is needed eventually to achieve climate targets that limit global warming to non-catastrophic levels (IMF Fiscal Monitor October 2019). The risk of delayed and therefore large adjustments has been recognized as a potential "climate Minsky moment" by Carney (2015). The swift and gradual introduction of carbon pricing reduces the risk of disorderly adjustments that could cause financial instability.

In our simple one-period model setting, by Lemma 2, comparing case 2 to case 1 under a small carbon tax, the greenium is small, and the level of greenwashing is low. By Lemma 3, comparing case 3 to case 1, under a high carbon tax, the levels of greenium and greenwashing are uncertain, adding a new source of uncertainty to the market.

As an extension, a multi-period model can be expressed as repetitions of the one-period model. For simplicity, we assume firms' types (green and brown) do not change across periods, and we also assume that firms' types become public information after production at the end of each period. In period 1, green firms take up market share α, and brown firms' market share is $(1-\alpha)$. At the end of period 1, green firms (α) remain in the market, brown firms $(1-\alpha)$ exit, and an equal number of new firms $(1-\alpha)$ with unknown types enter. In period 2, α portion of the market has perfect information, while $(1-\alpha)$ portion of the market faces the same information asymmetry problem as in period 1. We assume again the market share for green firms is α among new entrants. Hence, at the end of period 2, $[\alpha(1+1-\alpha)]$ green firms remain in the market. Green firm's market share increases after each iteration. This can be considered as a gradual transition of the economy to carbon neutral production incentivized by carbon taxation. In contrast, when there is no carbon taxation until the very last period, the market shares of green and brown firms remain constant. The economy does not adapt to carbon neutrality. When a large carbon tax is finally introduced in the very last period, brown firms face bankruptcy, leading to financial instability and a sudden drop in production.

C. The Need for Strong Disclosure Requirements Attached to Subsidy Programs

The issuance of green bonds is more costly than conventional bonds due to additional costs related to reporting, consultancy fees, and external verification of green credentials. To support green bond issuance, several governments including Japan and Singapore are providing subsidies to defray the higher costs of green bond issuance for issuers. These programs typically include reporting and external verification requirements. Our model underscores the need for these requirements and strong screening safeguards to avoid greenwashing. In the following, we discuss this point more formally.

By Lemma 1, we show that the cost of green bond financing includes three parts: green bond coupon rate r^g, green bond issuance cost $\bar{C}$, and greenwashing cost $f(e_i)$. Both green firms and brown firms incur the green bond issuance cost. Brown firms incur greenwashing costs, for example, related to public relations and intentional overstatements of green credentials.

Government subsidies decrease the green bond issuance cost $\bar{C}$, for example, by reimbursing issuers for external review costs and consultant fees. Without strong safeguards, brown firms can take advantage of subsidies. Lowering $\bar{C}$ encourages more brown firms to issue green bonds and therefore raises overall greenwashing.

Strong information disclosure requirements and government regulations on green bond issuance and green bond subsidy eligibility steepen the greenwashing cost function which reduces overall greenwashing and the issuance of green bonds by brown firms.

To conclude, government subsidy and support programs can support the development of green financial markets and the issuance of green financial products, but such subsidies need to be accompanied by strong disclosure requirements, regulations, and screening, to avoid greenwashing.

VIII. CONCLUSION

We use an adverse selection model to solve for the equilibirum prices in the green bond market and the extent of greenwashing. The model can explain empirically observed attributes of the green bond market and provides rich policy insights. We find that a greenium exists when there is asymmetric information between bond issuers and bond buyers with respect to issuers' type, transition risks stemming from carbon pricing, and costly greenwashing. The impact of carbon pricing on the greenium and greenwashing depends on the speed with which carbon pricing is introduced – a swift but gradual implementation generates a small greenium and a low level of greenwashing, while a delayed and therefore large carbon pricing has an ambiguous effect on the greenium and grenwashing.

Our model does not rely on an exogeneous green preference by investors, but instead can explain higher prices for green bonds as the result of a valuable signal of green credentials associated with green bond issuance. Our model formalizes the idea of green bonds as a signal proposed in Flammer (2021). In practice, there might be a role for a signaling and risk-based explanation of green bond pricing as in our paper alongside a role for green preferences. Further empirical work to quantify the respective importance of these channels would be useful. A potential approach to isolating a green preference effect could be to look at firms that issue green and brown bonds simultaneously. In this case, any pricing difference should be due to green preferences.

Several policy implications for green finance and climate policy follow from our model. First, in a rational framework without an innate green preference among investors, transition risk stemming from the introduction of carbon pricing is essential. Transition risk is the source of higher default risk for brown firms which is needed for the signal from green bonds to be valuable and to generate a greenium. Second, swift action on carbon pricing is preferable to a delayed introduction which would imply larger carbon pricing steps to achieve climate goals. Third, strong supervision and regulation are needed to make green bonds work. This includes disclosure and reporting requirements that increase greenwashing costs and therefore reduce greenwashing. Fourth, government intervention such as green bond subsidies, as currently in place in Japan and Singapore, can be helpful to develop the market but should be associated with strong information disclosure requirements and measures to ensure compliance with standards.

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