Netspar

Network for Studies on Pensions, Aging and Retirement

NETSPAR ACADEMIC SERIES

The economics of green debt

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DP 06/2022-018

The economics of green debt*

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June 2, 2022

Abstract

We investigate the economics of green debt by modeling markets for green and regular bonds. Issuers use green bonds to cater to climate investors, thereby reducing funding costs but potentially also rationing volumes. Moreover, green bonds fragment debt issuances, which impairs liquidity and increases funding costs. Consequently, the possibility to issue green bonds can in- or decrease the volume of and the cost at which green and/or brown projects financed. Similarly, pressure on investors to become more sustainable may work or may backfire. We propose an alternative security design that preserves green earmarking but prevents fragmentation and rationing.

*We would like to thank Mathijs Cosemans, Mathijs van Dijk, Monique Donders, Joost Driessen, Darell Duffie, Peter Feldhutter, Joop Hessels, Frank de Jong, Andreas Rapp, Wolf Wagner, Olivier David Zerbib and participants to the RSM round table on Green Bonds for useful feedback and comments. There is a policy-friendly and -oriented version of the paper circulating under the name "The next step in green bond financing."

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1 Introduction

In recent years, environmental concerns have led to a widespread range of measures and initiatives to fight climate change and transition to environmentally friendly business models. One example is the Bloomberg Taskforce on Climate-Related Financial Disclosures, which requires investment funds to report on their environmental footprint.[1] Given the urgency expressed during, for example, the COP26 meeting, the scrutiny, regulation, and taxation of environmental footprints of sovereigns as well as corporates is expected to increase.

The aforementioned developments have given rise to a new asset class, namely green bonds. Green bonds can be issued by supra-nationals (e.g., multilateral development banks), (semi) governments, and corporates. Their cash flow and collateral rights are the same as those for regular bonds issued by the same party. The main difference between green bonds and regular bonds is that the funds raised by green bonds are earmarked for environmentally friendly (green) purposes. The market for green bonds has grown exponentially in recent years as evidenced by Figure 1.

In this paper, we set up a model to evaluate the role of green bonds as well as the recent societal and regulatory push for environmentally responsible investing in efforts to combat environmental problems. The model aims to capture, in an as simple way as possible, the three main motivations for issuing green bonds as reported by survey evidence from Maltais and Nykvist (2020): expanding the investor base, catering to investor preferences, and lowering capital costs.

To this end, we model a market for the demand and supply of debt capital in which an issuer raises financing from investors. The issuer has environmentally friendly and environmentally unfriendly projects and maximizes total profits. Investors are divided into two classes: regular investors and climate investors. Both are identical except for the fact that climate investors derive non-monetary utility from investing in green projects and non-monetary disutility from investing in other projects. We assume that the aggregate volume of available funding exactly matches aggregate demand, but that there could be a mismatch in the composition (e.g., there may be too many or too few green projects to satisfy the aggregate demand of climate investors).

Green bonds are a way of tying environmentally friendly projects to climate investors. Thereby, they allow, at least conceptually, for lower funding costs for such projects (since climate investors are willing to accept an interest rate reduction

[1] See `https://www.fsb-tcfd.org/`.

of at most their non-monetary utility). We call this the clientele effect. Yet, since bonds are uniformly priced across investors, the clientele effect only manifests itself if the green bond is only issued to climate investors. If there is a shortage of climate investors, the issuer faces a trade-off between reducing funding costs and rationing the volume of green projects.

The possibility to issue green bonds also has implications for bond liquidity. The literature has found issuance volumes of bonds to be important for their liquidity (e.g., Houweling et al. 2005). Green bonds fragment bond issues and thereby reduce issuance volumes. We confirm this empirically for issuers of both green and regular bonds. We also provide theoretical micro-foundations for such an effect on liquidity in a search and bargain market in the spirit of Duffie et al. (2005). As theoretically proposed in Acharya and Pedersen (2005) end empirically validated in Bongaerts et al. (2017), investors rationally incorporate expected transaction costs in their decision making process and hence, ask a liquidity premium equal to transaction costs times turnover. Hence, in her financing decisions, the issuer also trades off the economic benefits of the clientele effect of issuing green bonds against the associated increase in bond liquidity premia.

In this setting, we derive and characterize equilibria that materialize for different parameter ranges. Investors in these equilibria accept any offer that makes them at least break even in expected utility terms. Issuers maximize their profits and in doing so trade off clientele premia against liquidity premia and project volumes. There is a similar trade-off for brown projects with a shortage of regular investors.

In the model, funding costs are zero-sum transfers between investors and issuers. Similarly, transaction costs are zero-sum transfers between investors and market makers. Consequently, what matters for aggregate welfare is the number of projects as well as the economic surplus they create (project NPV net of non-monetary utility components of investors). Similarly, the environmental contribution of the issuer constitutes of the positive effects brought by green projects minus the negative ones by brown projects. These components scale linearly with the volumes of green and brown projects, respectively. Since funding costs affect equilibrium outcomes, but not aggregate welfare of the environmental contribution, the availability of the green bond design can positively, but also negatively affect the environment and aggregate welfare. Since the clientele premia result from the interaction of preferences and security design, also changes in preferences (e.g., a stronger preference for green and stronger aversion to non-green investments for climate investors) can affect the environment and aggregate welfare in a positive, but also in a negative way.

The aforementioned discussion shows limitations of the green bond security design. The trade-off of clientele premia against volumes arises because of the requirement of a uniform price on a debt instrument irrespective of investor type. The trade-off between fragmentation and clientele premia arises due to the binary nature of earmarking (either all money is spent green or it is not). We propose a different security design that reduces both frictions. Specifically, we recommend to separate the cash flow and earmarking part of green bonds, essentially unbundling it into separate features. This so called stripping is quite common for fixed income instruments. For example, a credit default swap (CDS) paired with a risk-free bond equals a credit risky bond, a fixed rate bond plus and interest rate swap equals a floating rate bond, and a risk-free bond paired with an inflation swap equals an inflation-linked bond.

In this case, we propose to have all projects financed by a single large bond issue. This way, fragmentation is avoided. The proceeds of part of this issue can be earmarked for environmentally friendly projects by issuing so called green certificates. These are certificates solely certify that the notional amount stated in each certificate is used for environmentally friendly projects. This way, the issuer can still capitalize on the clientele effect. These green certificates can be issued and traded separately and carry the exclusive green reporting rights. We show that using green certificates leads to equilibria with (often strictly) higher welfare than green bonds. The environmental contribution with green certificates is in most cases also higher than with green bonds. Yet, in certain situations, green certificates may increase the number of environmentally unfriendly projects and thereby have a negative environmental contribution (relative to green bonds).

One may ask why the design that we suggest and claim to be superior has not gained more traction in practice. In our interactions with the investment community we often encountered the claim that green bonds do not require investors to sacrifice returns. Consistently, we met resistance to our idea because green certificates would make the yield discount for investors transparent, which would lower demand for green debt securities. To capture such effects, we extend our model with uncertainty for regular investors about the yield discount that green bonds command. We also provide theoretical micro-foundations for such uncertainty and calibrate this uncertainty to the same order of magnitude of the yield discount. This uncertainty, that is not present for green certificates, allows issuers to essentially miss-sell green bonds to investors that have no demand for them. Yet, for issuers, (and in particular large, creditworthy ones), such miss-selling is profitable. Therefore, the dominant parties in the green bond market are better off issuing intransparent green bonds. As a result, it is hard to reach critical mass for this alternative security design.

Our paper contributes to different strands of literature. First and foremost, we contribute to the literature on green finance and green bonds in particular. There is little theoretical work on green bonds. To the best of our knowledge, we are one of the first ones to investigate the implications of the green bond security design on economic outcomes and whether the design of green bonds serves the purposes of green debt securities. We are aware of one other, concurrent theory paper on green bond design by Daubanes et al. (2021), in which green bonds, in a setting with conflicts of interest between investors and managers, act as signalling devices for commitment to sustainable policies. Since the mechanisms at play in the different papers are very different in nature, these papers are complementary to one another.

Our analyses can also, at least in part, explain the empirically low yield discount (Baker et al. 2018, Zerbib 2019, Gianfrate and Peri 2019, Flammer 2021, Tang and Zhang 2020, Warmath 2021) by pointing out the fragmentation that green bonds give rise to. Our results are also consistent with the limited documented effectiveness of green bonds and policies and regulations aimed at making investors care more about the environmental contribution of their investments (Berensmann et al. 2018). In fact, we show that the environmental contribution resulting from the green bond security design and such measures can be even negative. In all, our paper paints a nuanced picture of the usefulness of green bonds and is consistent with a variety of empirical findings. While the small current yield discounts for green bonds suggest a limited willingness to pay for green earmarking, our paper also provides insights as to how various green debt securities affect economic and environmental outcomes when this willingness is much higher (e.g., due to regulation), at least for certain groups. Finally, our paper also discusses the welfare and environmental benefits and costs of (regulatory) interference with this willingness to pay in the presence of green debt securities.

Our study also relates to the literature on heterogeneous tastes for different asset types. Most models in this literature purely focus on the investor side and asset pricing implications (see e.g., Bhamra and Uppal 2013, Gandhi and Serrano-Padial 2014, Amihud and Mendelson 1986). Our paper, however, investigates the strategic behavior of a firm issuing securities when faced with a heterogeneous investor base. The heterogeneity in investor base and the potential mismatch in supply and demand of different security types gives rise to interesting results, such as a potential reduction in green projects when climate investors value these more.

We also contribute to the literature on the optimal structure and ownership of corporate debt. A large part of this literature focuses on the choice along the debt maturity spectrum, and thereby also incorporates fragmentation. Some of the theoretical studies in this field assume costs associated with fragmentation (e.g., Choi et al. 2018). We contribute by showing how such fragmentation-induced transaction costs arise in the context of an OTC market.

Our paper also contributes the literature on OTC markets with search frictions (e.g., Duffie et al. 2005) by showing that making market maker bargaining power inversely proportional in size generates the empirical observed pattern that larger bond issues are more liquid.

We also contribute to the literature on fragmentation in securities markets. Oehmke and Zawadowski (2017) show empirically that CDS spreads lead credit spreads due to standardization and reduced fragmentation, which result in higher liquidity. Our proposed security design of green certificates highlighting a different channel: the cost base. Speculative trades in decomposed features (such as green earmarking or credit risk) have a much lower cost base since the bond part has been removed. Moreover, the implications in the green debt market are different from any derivatives markets. Our results imply that green certificate financing should fully replace green bond financing. For the CDS market, however, full replacement is infeasible since CDS are zero net supply derivatives. Even if CDS were issued by the issuer itself, the positions would still be exposed to counterparty default risk, in which case risk mitigation would be largely artificial.

While not central in the paper, we micro-found the intransparency of green bonds. These micro-foundations show how security design in the context of earmarking matters for price-informativeness and thereby (indirectly) contributes to managerial governance. Thereby, they complement the literature on security design in the context of agency conflicts between management and investors (see e.g., Myers and Majluf 1984, Allen and Gale 1988, Fulghieri and Lukin 2001, DeMarzo and Sannikov 2006). These micro-foundations also provide a possible explanation for the apparent lack of market discipline in curbing greenwashing in green bonds (Flammer 2020, finds that green bonds are only effective if externally certified).

2 Setup

We set up a market for regular and green debt instruments. There are masses $\pi_c, \pi_r \in [0, 1]$ of climate and regular investors, respectively. We assume that total investor demand is normalized to one. Investors are atomistic and homogeneous within each group. Climate investors care about the environmental impact of their investments reflected by a convenience yield $\zeta \geq 0$ from investing in a green debt security. Moreover, climate investors suffer a utility loss of $\phi \geq 0$ when investing in a security that is not green. Regular investors experience a negligible but strictly positive convenience yield from investing in a green debt security.[2] We assume that investors anticipate to turn over bonds in the secondary market at turnover rate Q.

There is an issuer with respective supplies κ_G and κ_B of green and brown/regular projects that are in all other aspects identical. We again normalize the aggregate project size to one, such that aggregate demand and supply of capital are exactly matched. However, there can be a surplus or shortage of certain types of projects. Any such mismatch is measured by π_c/κ_G. When $\pi_c/\kappa_G > 1$ there is a shortage of green projects, when $\pi_c/\kappa_G < 1$ there is an excess, and when $\pi_c/\kappa_G = 1$ the market is exactly balanced.[3]

The profitability of green projects exceeds those of brown projects with a level of $\xi \in \mathbb{R}$ (a negative ξ means that green projects are less profitable). For tractability, we normalize net profitability of brown projects to $\beta > 0$. The issuer maximizes total profits.

For the financing part, the issuer makes a one-time take-it-or-leave-it offer to the market for regular, green and/or combined bonds with respective yields y_{RB}, y_{GB}, and y_{LB}. If the issuer decides not to issue a bond of type j, it sets $y_j = \emptyset$. A regular or combined bond can finance any project, but a green bond can only finance a green project. Investors optimize their expected utility. Expected utility for investors is linear and consists of expected returns, net of anticipated transaction costs and non-monetary benefits.

Regular investors lack sophistication for optimizing their investment decisions. In particular, regular investors will accept the claim that they do not sacrifice expected returns with green debt relative to regular debt if the discount in expected returns is small relative to the uncertainty about this discount σ_{GB}. Appendix B provides micro-foundations for the nature of such uncertainty and compares the transparency of green bonds to that of the alternative security design suggested in Section 5. In particular, they will assume a zero discount if $\frac{y_{RB}-y_{GB}}{\sigma_{GB}} \leq \alpha$, where α is a positive

[2]This makes them pick a green over regular debt if otherwise identical, but otherwise does not drive investment decisions.

[3]Matching aggregate supply and demand of assets allows to summarize any mismatch by π_c/κ_G, which significantly simplifies the exposition. In Section 6.1, we explore what happens when we relax this assumption.

constant that can be interpreted as a critical value for a t-test. As a result, regular investors pay up to $\sigma_{GB}\alpha$ extra on a green bond, without getting a non-monetary utility back for it.

Green and regular bonds trade in OTC markets that are intermediated by dealers as in Duffie et al. (2005) (the secondary market trading is not modelled explicitly). By assumption, any trade needs to go through a dealer (which largely conforms to market practice). Duffie et al. (2005), show that in such markets transaction costs depend on dealer bargaining power. We assume that all regular and green bonds are homogeneous in this market except for their size and the dealer bargaining power. In particular, we assume that dealer bargaining power z_j for bond j is inversely proportional to bond size S_j:

$$z_j = \frac{a}{S_j}, \tag{1}$$

where a is a constant. This way, dealer bargaining power and therefore bond liquidity only varies with bond size. Intuitively, one would indeed expect smaller markets to be more concentrated leading to higher market maker bargaining power.[4]

3 Equilibrium analysis

In this section, we define and derive equilibria, which we solve for backwards. We start by putting forward the equilibrium definition. Next, we derive expressions for expected transaction costs and liquidity premia. We then derive optimal responses of investors that are faced with quotes y_{GB}, y_{RB}, and/or y_{LB}. Finally, given these optimal responses of investors, we derive optimal quoting and issuance strategies of the issuer.

3.1 Equilibrium definition

Since all investors within a type are identical, we derive symmetric equilibria in which all investors of the same type act identically. We assume that investors play a trigger strategy for accepting investment offers.[5] That is, investors of type i accept any offer for security $j \in \{GB, RB, LB\}$ for which the yield quote y_j exceeds their

[4] This could be the result of fixed operating costs for market makers to be present in a market for a given security.

[5] We show in the proof of Lemma 3 that such trigger strategies are optimal.

trigger level $\theta_{i,j}$. All trigger levels for an investor i are collected in a vector θ_i. Investors set their thresholds $\theta_{i,j} = \theta^*_{i,j}$ to ensure positivity of their expected utility:

$$\theta^*_{i,j} = \inf\{\theta_{i,j} : U(y_j) \geq 0\} \ \forall i, j. \tag{2}$$

Given these optimal thresholds, issuers issue their bonds and set the yields $y_j \forall j$, collected in vector y so as to maximize expected profits Π:

$$y^* = \arg\max_y \Pi(y, \theta^*), \tag{3}$$

where

$$\Pi(y, \theta^*) = V_G(y, \theta^*)(\beta + \xi - y_{GB} I_{GB} - y_{LB} I_{LB}) + V_B(y, \theta^*)(\beta - y_{RB} I_{RB} - y_{LB} I_{LB}), \tag{4}$$

and V_G and V_R are the volumes of green and brown projects given the optimal investor thresholds (collected in vector θ^*) and the yields chosen by the issuer (collected in vector y), and $I_j \forall j$ are indicator functions that equal 1 if y_j is not set to empty. A (Nash) equilibrium is then defined as a tuple (θ^*, y^*).

3.2 Transaction costs and fragmentation

We can combine our assumption that dealer bargaining power is inversely proportional to bond size with the results from Duffie et al. (2005) to obtain closed-form expressions for round-trip transaction costs s in the secondary market.

Lemma 1 *The round-trip transaction costs s for a bond of size S are given by*

$$s = \frac{\mu}{d + S}, \tag{5}$$

where μ is a positive constant and d is a negative constant.

Proof. See Appendix. ■

As in Acharya and Pedersen (2005), investors need to be compensated for expected transaction costs in security j, and hence, the presence of transaction costs leads to a liquidity premium Qs_j in the bond yield. Now consider a brown project with size S_B and a green project with size S_G that could be financed by a large, single bond issue. These projects could also be financed by a regular bond and a green bond, for each respective project. The latter gives rise to fragmentation. As fragmentation reduces liquidity, doing so will increase the average liquidity premium for this issuer by a factor of around 2.

Lemma 2 *Issuing a green bond that fragments bond issues but leaves total issued volume unaffected increases the average liquidity premium by a factor of around 2 (compared to the combined issue). This result is independent of the relative size of the green and brown project.*

Proof. See Appendix. ■

The effect of fragmentation from Lemma 2 is economically large. In Appendix C, we verify empirically that liquidity is indeed increasing with issue size for both green and regular bonds in a sample of issuers that issue both. Of course, if issuing a green bond were to increase the total bond volume issued, the increase in average liquidity premium will be smaller and if issuing a green bond would decrease total bond volume (e.g., through rationing) the increase in average liquidity premium will be larger.

3.3 Optimal strategies of investors

Investors accept bond offers if the expected utility resulting from doing so is positive given their beliefs. Their expected utility consists of monetary and non-monetary components. The monetary components are the (perceived) expected returns and the anticipated transaction costs. The non-monetary components are the convenience yield or disutility of climate investors from holding green and regular investments, respectively. This yields a relatively simple optimal strategy for investors.

Lemma 3 *The optimal trigger level $\theta^*_{i,j}$ for investor of type i to invest in bond of type j is given by*

$$\theta^*_{i,j} = Qs_j - \zeta I_{c,GB} + \phi(I_{c,RB} + I_{c,LB}) - \sigma_{GB}\alpha I_{r,GB}. \quad (6)$$

where $I_{i,j}$ are indicator functions that equal one if an investor of type i invests in security of type j and zero otherwise.

Proof. See Appendix. ■

3.4 Optimal strategies of issuers and equilibria

In this section, we take the optimal investor strategies from Lemma 3 as given and derive optimal issuer strategies and thereby equilibria. As we will see, these equilibria differ depending on liquidity, preferences of climate investors, and the degree to which demand and supply of capital are matched.

3.4.1 No consolidation

In this section, we analyze equilibria when combined bonds are ruled out. These equilibria are useful as they give a benchmark as to what would happen in perfectly liquid markets ($\mu = 0$), or in markets in which investors only buy-and-hold ($Q = 0$), as the only benefit of a large bond is to avoid fragmentation. In this setting, the only reason for matching climate investors to brown projects or regular investors to green projects would be to increase the volume of projects undertaken. To induce climate investors to invest in brown projects, larger yields should be offered, which also benefit regular investors. Similarly, to induce regular investors to invest in green projects, larger yields should be offered, which also benefit climate investors. Hence, in the presence of a misalignment in supply and demand for capital ($\frac{\pi_c}{\kappa_G} \neq 1$), issuers trade off the cost of invested capital against the amount of capital that can be invested (Eqns.(12) and (13)). Naturally, issuers only undertake projects when it is profitable to do so.

Proposition 1 *Assume $\mu = 0$. In equilibrium, investors act according to lemma 3 and issuers optimally set $y = y^*$, where*

$$y^* = \begin{cases} (\emptyset, \emptyset, \emptyset), & \textit{if (10) and (11) are violated} \\ (\theta_{c,GB}, \emptyset, \emptyset), & \textit{if (11) and [(9) or (13)] are satisfied and (10) is violated} \\ (\emptyset, \theta_{r,RB}, \emptyset), & \textit{if (10) and [(8) or (12)] are satisfied and (11) is violated} \\ (\theta_{c,GB}, \theta_{r,RB}, \emptyset), & \textit{if (10), (11) and [(8) or (12)] and [(9) or (13)] are satisfied} \\ (\theta_{r,GB}, \emptyset, \emptyset), & \textit{if (10), (9), (13) are violated and (11) satisfied} \\ (\theta_{r,GB}, \theta_{r,RB}, \emptyset), & \textit{if (9), (13) are violated and (11), (10) satisfied} \\ (\emptyset, \theta_{c,RB}, \emptyset), & \textit{if (11), (8), (12) are violated and (10) satisfied} \\ (\theta_{c,GB}, \theta_{c,RB}, \emptyset), & \textit{otherwise.} \end{cases} \tag{7}$$

with conditions

$$\pi_r \geq \kappa_B \qquad \text{[Capacity brown]} \tag{8}$$

$$\pi_c \geq \kappa_G \qquad \text{[Capacity green]} \tag{9}$$

$$\beta - \theta_{r,RB} \geq 0, \qquad \text{[Profitability brown]} \tag{10}$$

$$\beta + \xi - \theta_{c,GB} \geq 0, \qquad \text{[Profitability green]} \tag{11}$$

$$\pi_r(\beta - \theta_{r,RB}) \geq \kappa_B(\beta - \theta_{c,RB}), \qquad \text{[Size/ROI brown]} \tag{12}$$

$$\pi_c(\beta + \xi - \theta_{c,GB}) \geq \kappa_G(\beta + \xi - \theta_{r,GB}). \qquad \text{[Size/ROI green]} \tag{13}$$

Proof. See Appendix. ■

Proposition 1 shows that, in a very liquid market, issuers find it profitable to issue green bonds to cater to investors with green preferences (scenarios 2, 4, 5, 6, and 8), and on top of that to expand their investor base (scenarios 5 and 6), potentially by miss-selling to investors that have no fundamental interest in them. Climate investors will only finance brown projects when sufficiently compensated for this. Issuers will provide such a compensation if there is a (severe) shortage of regular investors and brown projects are very profitable.

3.4.2 With scope for consolidation

Now assume that liquidity premia are substantial and can, at the margin, influence issuance and investment decisions. In this case, issuers may optimally decide not to cater to preferences of climate investors w.r.t. bond types as fragmentation is prohibitively costly. Rather, the issuer may pool green projects with brown projects and issue a combined bond to finance both. Interestingly, this may allow green projects to be undertaken even when these are optimally not undertaken when financed with a green bond.

Proposition 2 *With the opportunity to issue a combined bond, investors' and issuers' equilibrium behavior is as in Proposition 1, except that issuers now set*

$$\begin{pmatrix} y_{GB}, \\ y_{RB}, \\ y_{LB} \end{pmatrix}' = \begin{cases} (\emptyset, \emptyset, \theta_{r,LB}), & \text{if (15) is satisfied and (17) violated,} \\ (\emptyset, \emptyset, \theta_{c,LB}), & \text{if (16) and (17) are satisfied,} \end{cases} \tag{14}$$

with conditions

$$\pi_r(\beta - \theta^*_{r,LB}) + \xi(\kappa_G I_{\xi\geq 0} + \min(\kappa_G, \pi_r - \kappa_B)(1 - I_{\xi\geq 0})) \geq \max_{y|y_{LB}=\emptyset} \Pi(y, \theta^*), \quad (15)$$

$$\beta + \kappa_G\xi - \theta^*_{c,LB} \geq \max_{y|y_{LB}=\emptyset} \Pi(y, \theta^*), \quad (16)$$

$$\beta + \kappa_G\xi - \theta^*_{c,LB} \geq \min(\kappa_G + \kappa_B, \pi_r)(\beta - \theta r, LB) + \xi(\kappa_G I_{\xi\geq 0} + \min(\kappa_G, \pi_r - \kappa_B)(1 - I_{\xi\geq 0}). \quad (17)$$

Proof. See Appendix. ■

The scenarios in Equation (14) conform to how green projects were financed before green bonds were invented. All projects are financed with a large regular bond and climate investors only participate when they are compensated sufficiently for their aversion to invest in non-green bonds. Such a compensation is a bonus for regular investors. In case there are sufficiently many regular investors for a combined bond, climate investors are squeezed out of the market as they are too expensive to cater for. Conditions (15) and (16) essentially require the size of green preference ζ (to prevent rationing and segmentation) and brown aversion ϕ to be sufficiently small to do combined bonds.

3.5 Equilibrium regions

The equilibrium strategies outlined above give rise to a multitude of parameter regions with different equilibria. To get a better overview on the implications of green preferences and security design, we analyze the resulting equilibria across different ranges of non-monetary preference offsets and supply-demand imbalances in terms of environmental preferences regarding investment projects. We do this first for scenarios in which both, either, or neither type of projects are profitable and green bonds are perfectly transparent. Next, we take the scenario with high profitability for all projects and assess the effect of green bond intransparency and the associated scope for miss-selling.

We present the equilibrium regions for the different scenarios graphically in Figures 2 to 6. For the sake of exposition and tractability, we restrict the distaste of climate investors for non-green investments to be equally large as their preference for green investments (i.e., $\zeta = \phi$).

3.5.1 Low profitability on all projects

If profitability on both types of projects is low (low β), there are two ways to get investment in equilibrium. Either low revenues are compensated by low funding costs due to large non-monetary benefits ζ from climate investors (they essentially subsidize operational losses). In that case, only green bonds are financed by climate investors (rather dark blue area in Figure 2). Alternatively, funding costs are reduced by pooling funding needs and issuing large combined bonds. If the climate investors' distaste for combined bonds is not too large (small ϕ), all investors invest in them and all projects are funded (yellow area in Figure 2). Bond fragmentation and the associated liquidity is minimized this way. There is an interest rate premium to compensate climate investors for their disutility from co-investing in brown projects. If this disutility (measured by ϕ) is sufficiently large and there is a shortage of climate investors, it may be more profitable for issuers to only let regular investors invest in a combined bond that finances both types of projects (orange area in Figure 2). This way, the distaste premium is avoided and fragmentation is mitigated. However, not all projects are funded and the issuer misses out on the clientele effect of climate investors.

3.5.2 Low profitability of brown projects only

If only brown projects exhibit low profitability (low β but positive ξ), the picture looks similar to the case in which all projects have low profitability (Figure 3), but with one difference. The orange region in Figure 3 is larger than that in Figure 2. The reason is that the combined bond now ensures that all green projects are undertaken (albeit by regular investors). If only climate investors invest in green projects, such projects are rationed when there is a shortage of climate investors and there are more unrealized utility gains. Therefore, issuers will in equilibrium be more inclined to issue a large combined bond that is only appealing to regular investors, thereby (counterintuitively) excluding investors from the market with the strongest taste for the most profitable projects.

3.5.3 Low profitability of green projects only

Now consider the case in which green projects have very low profitability, but brown projects are profitable (high β and negative ξ). If there is a shortage of regular investors and non-monetary offsets are small, only regular investors invest in regular bonds (middle blue area in Figure 4), there is a large bond financing all projects in which all investors invest (yellow are in Figure 4), or climate investors invest in regular bonds at a premium to compensate their disutility ϕ (green are in Figure 4). The latter two are more profitable for an issuer if ϕ is smaller and the preference mismatch is larger (since the associated volume increase and transaction cost decrease are larger). If non-monetary offsets ζ are large, these compensate for the low profitability ξ of green projects and climate investors invest in green bonds. If the shortage of regular investors is large enough (but not extremely large), climate investors also invest in regular bonds at a premium to compensate their disutility (brown area in Figure 4). If the shortage of regular investors becomes extremely large, regular bond issues become too small to be profitable and only climate investors invest in green bonds (dark blue area in Figure 4). If there is a shortage of climate investors, it may be optimal to issue a combined bond in which only regular investors invest (as before; orange area in Figure 4). This is more profitable than letting regular investors also invest in green bonds as both green bonds and regular bonds would then have relatively small issues sizes. In all other scenarios, there is a perfect segmentation of security types across investor types (light blue area in Figure 4).

3.5.4 High profitability of all projects

If all projects exhibit high profitability (high β), these are likely to be all undertaken. The only exceptions are when there is an extreme preference mismatch in demand and supply of projects. If there is a severe shortage of regular investors and ϕ is large enough, only green bonds are issued and brown projects are not undertaken because the very small volume of regular bonds leads to excessively high liquidity premia (dark blue area in Figure 5). If there is a severe shortage of climate investors and ϕ is large enough, a large bond is issued only to regular investors and some green projects may not be undertaken (orange area in Figure 5). Otherwise, if ϕ is small enough, a combined bond is issued to all investors and all projects are funded (yellow area in Figure 5). If ϕ is too large, a combined bond becomes excessively expensive as climate investors need to be compensated for their disutility. With a shortage of climate investors, regular investors also invest in green bonds, but only when the resulting increase in volume more than offsets the effect of the resulting interest increase due to missing out on the clientele effect of climate investors (green area in Figure 5). Similarly, with a shortage of regular investors climate investors also invest in regular bonds, but only when the resulting increase in volume more than offsets the effect of the resulting interest increase due to compensating climate investors for their disutility (brown area in Figure 5). In all other scenarios, there is a perfect segmentation of security types across investor types (light blue area in Figure 5).

3.5.5 Miss-selling

So far we looked at situation in which green bonds are perfectly transparent so that there is no scope for miss-selling. When $\alpha, \sigma_{GB} > 0$, there is scope for miss-selling. In particular, such a setting is similar to one with a non-monetary benefit $\sigma_{GB}\alpha$ to investing in green bonds for regular investors. The setting with miss-selling is perfectly nested in the equilibria developed in the earlier sections. The only thing that miss-selling does is that it makes it less costly for issuers to have regular investors invest in green bonds to increase the volume of green projects funded (i.e., it relaxes Condition (13)). This is reflected in Figure 6, which is the equivalent of Figure 6, but with miss-selling (because of which the green area is larger). Naturally, there is no miss-selling when $\pi_c \geq \kappa_G$.

4 Welfare, trends, and policies

In this section, we evaluate the welfare and climate effects resulting from the availability of green bonds and those resulting from changes in regulations and investor preferences. We start by defining welfare (within the context of the model) and climate effects. Next, we analyze how equilibrium outcomes in terms of welfare and environmental impact are affected by the availability of green bonds and by recent trends and regulations (which would be reflected by changes in model parameters).

4.1 Welfare and environmental impact definitions

We measure aggregate welfare as the sum of issuer, dealer, and investor utility. In the context of the model, financing costs are zero sum transfers from investors to issuers (or the other way around if negative). Similarly, transaction costs are zero sum transfers from investors to dealers. Since transaction costs are purely the result of dealer bargaining power, it is sufficient for welfare calculations to only consider the volume and operational profitability of projects and the non-monetary offsets for investors. Hence, aggregate welfare is given by

$$WF = V_{c,G}(\beta + \xi + \zeta) + V_{r,G}(\beta + \xi) + V_{c,B}(\beta - \phi) + V_{r,B}\beta. \qquad (18)$$

The second term in Eq. (18) shows that miss-selling, if any, comes at a welfare cost if green projects are loss-making (i.e., $\beta + \xi < 0$; negative NPV projects are undertaken). If $\beta + \xi > 0$, which is more likely for illiquid green bonds, miss-selling still constitutes a welfare loss for investors, but is a welfare gain for issuers and/or dealers and is hence welfare neutral.

Similarly, we can measure the environmental contribution as

$$EC = (V_{c,G} + V_{r,G}) - \tau(V_{c,B} + V_{r,B}), \qquad (19)$$

where the environmental benefit of a green project of unit size is normalized to one and the environmental damage of a brown project of unit size denoted by τ.

4.2 Implications of the possibility to issue green bonds

We start by analyzing welfare implications of the opportunity to issue green bonds. We can obtain a benchmark for the situation without green bonds by setting intransparency σ_{GB} to zero and removing any benefit for climate investors to buy green bonds relative to regular or combined bonds. In that situation there is no scope for clientele effects and hence, fragmentation is optimally minimized because it is costly.

Corollary 1 *The equilibrium materializing without green bonds is equivalent to that with green bonds, but with* $\sigma_{GB} = 0$ *and* $\zeta = -\phi < 0$.

Proof. See Appendix. ■

The first thing to notice is that the possibility to issue green bonds allows (financially) unprofitable green projects to be financed, because climate investors are willing to pay a premium when financed by a green bond. This is good for welfare, as any negative value creation is at least compensated by non-financial value creation. It is also has a positive environmental contribution as green projects are financed this way where before they were not.

Second, one notices that when green and brown projects are sufficiently profitable, these will be undertaken irrespective of security design available. Hence, the environmental contribution in this case is zero. Since green bonds create additional (non-monetary) utility for climate investors, aggregate welfare is positively affected.

Third, when green projects are profitable, but there is a shortage of climate investors, the opportunity to issue green bonds can lead to a supply-side rationing of green projects. The reason is that the clientele effect needs to be given up for the additional green projects to be financed, which for the issuer is prohibitively expensive. Hence, it is possible that the availability of green bonds reduces the number of profitable green projects undertaken. Interestingly, this effect is stronger when climate investors care more about the environment. This effect is detrimental for aggrate welfare and environmental payoffs.

Proposition 3 *The number of green and brown projects undertaken in equilibrium can increase, decrease, or remain unaffected by the possibility to issue green bonds. Consequently, welfare and environmental payoff can also improve, deteriorate or remain unaffected by the possibility to issue green bonds.*

Proof. See Appendix. ■

4.3 Implications of regulations and preference changes

We can also analyze the effect of trends and regulations in society to promote environmentally friendly investments in a setting in which green bonds are available. To start with, one can analyze what happens when the size of non-monetary offsets ζ and ϕ increases. An increase in ζ leads to a higher likelihood for green projects with low profitability to be undertaken. At the same time, an increase in ζ makes it less likely that profitable green projects are undertaken if there is a shortage of climate investors, simply because the issuer would need to give up a larger part of the welfare gains resulting from a high ζ. The former effect improves welfare and the environmental payoff, whereas the latter effect reduces those.

Corollary 2 *The number of green and brown projects undertaken in equilibrium can increase, decrease, or remain the same by an increase in ζ. Consequently, welfare and environmental payoff can also improve, deteriorate or remain unaffected by an increase in ζ.*

Proof. See Appendix. ■

One can also look at the effect of increasing ϕ. The effect here is more straightforward. Climate investors are less likely to invest in bond issues that (also) finance brown projects. This reduces scope for combined bonds and climate investors investing in regular bonds. As a result, fewer projects are undertaken which reduces welfare. Yet, typically, it is the brown projects that now become constrained in their funding, which is an improvement for the environment. The only exception is the reduced likelihood of combined bonds. If green projects are not very profitable, this can lead to a reduction of green projects as well.

Corollary 3 *The number of green and brown projects undertaken in equilibrium decreases with an increase in ϕ. Consequently, welfare decreases with an increase in ϕ. The environmental contribution can in- or decrease.*

Proof. See Appendix. ■

Finally, one can look at the fraction of climate investors relative to the number of green projects, π_c/κ_G. The effect here is more subtle. On the one hand, the issuer will be less willing to give up a low interest rate in favor of more projects financed if π_c/κ_G is close to 1. On the other hand, in case of such unwillingness, the welfare loss is larger when the mismatch is more severe (π_c/κ_G is further away from 1). These effects are more important when ζ and ϕ are large as in that case the interest increase due to mismatch of investor preferences to project types is largest. For the environment, regular investors financing green projects is good and climate investors financing brown projects is bad. Hence, if ϕ is small, π_c/κ_G close to 1 is optimal for the environment, whereas when ϕ is larger, a large over-supply of climate investors is optimal for the environment (as this implies more severe rationing of brown projects).

Corollary 4 *The number of green and brown projects undertaken in equilibrium can increase, decrease, or remain unaffected by an increase in π_c/κ_G. Consequently, welfare and environmental contribution can also improve, deteriorate or remain unaffected by an increase in π_c/κ_G.*

Proof. See Appendix. ■

5 Alternative forms of green debt

In this section, we introduce a different version of green debt to act as an alternative for green bonds. In essence we decompose, or strip, a green bond into a regular bond and a certificate that solely arranges green earmarking (we call this a green certificate). Moreover, since the certificate solely arranges green earmarking and is issued (and potentially traded) separately, there is no intransparency w.r.t. expected returns. We first show that such a bundle in perfectly liquid market, without any intransparency of expected green bond returns ($\sigma_{GB} = 0$), is equivalent to a green bond.

Lemma 4 *The combination of a regular bond and a green certificate in a perfectly transparent market is equivalent to a green bond with the same liquidity as the regular bond.*

Proof. See Appendix. ■

With this structure, the regular bond can be issued in a large combined issue without misaligning with the preferences of climate investors.

Lemma 5 *The optimal threshold $\theta^*_{c,j}$ for climate investors to accept a quote y_j on a bond of type $j \in \{RB, LB\}$ is given by*

$$\theta^*_{c,j} = \frac{Q\mu}{d + S_j} + \phi(1 - I_{c,GC}), \tag{20}$$

where $I_{c,GC}$ is an indicator function that equals one if a climate investor also purchases a green certificate along with the bond. Green certificates are bought by climate investors if the quoted equivalent yield component y_{GC} resulting from it does not fall below

$$\theta^*_{c,GC} = -\zeta. \tag{21}$$

The other optimal trigger thresholds are as in Lemma 3.

Proof. See Appendix. ■

Lemma 5 shows that the green certificates have the potential to lower the funding costs for green projects by reducing fragmentation while preserving the clientele effect. We next investigate what the impact of this security design is on equilibria and market outcomes.

Proposition 4 *With the opportunity to issue a combined bond with green certificates, investors' and issuers' equilibrium behavior is as in Proposition 1, except that* *issuers now set*

$$\begin{pmatrix} y_{GB}, \\ y_{RB}, \\ y_{LB} \end{pmatrix}' = \begin{cases} (\emptyset, \emptyset, \frac{Q\mu}{d+1} + \phi I_{\pi_c > \kappa_G}), & \text{if (23) is satisfied} \\ (\emptyset, \emptyset, \frac{Q\mu}{d+\kappa_G+\pi_r}), & \text{if (24) is satisfied,} \\ (\emptyset, \emptyset, \frac{Q\mu}{d+\kappa_B+\pi_c}), & \text{if (25) is satisfied,} \end{cases} \tag{22}$$

with conditions

$$\beta - \phi I_{\pi_c > \kappa_G} + \kappa_G \xi + \min(\pi_c, \kappa_G)\zeta - \frac{Q\mu}{d+1} = \Pi_1^{GC} \geq \max\left(\max_{y|y_{LB}=\emptyset} \Pi(y, \theta^*), \Pi_2^{GC}, \Pi_3^{GC} \right), \tag{23}$$

$$(\kappa_G + \pi_r)(\beta - \frac{Q\mu}{d + \kappa_G + \pi_r}) + \kappa_G(\xi + \zeta) = \Pi_2^{GC} \geq \max\left(\max_{y|y_{LB}=\emptyset} \Pi(y, \theta^*), \Pi_1^{GC}, \Pi_3^{GC} \right), \tag{24}$$

$$(\kappa_B + \pi_c)(\beta - \frac{Q\mu}{d + \kappa_B + \pi_c}) + \pi_c(\xi + \zeta) = \Pi_3^{GC} \geq \max\left(\max_{y|y_{LB}=\emptyset} \Pi(y, \theta^*), \Pi_1^{GC}, \Pi_2^{GC} \right). \tag{25}$$

In any of these situations, the issuer sells a mass $\min(\pi_c, \kappa_G)$ *of green certificates to climate investors for a price that corresponds to a yield discount* $y_{GC} = \theta^*_{c,GC} = -\zeta$.

Proof. See Appendix. ■

Proposition 4 shows that with green certificates in general more projects are undertaken, and those that are undertaken generally come with a lower funding costs than when green bonds are available instead of green certificates. In most situations, all projects are financed with a combined bond and fragmentation is minimized while the issuer still capitalizes on the clientele effect (corresponding to Condition (23)). If there is an excess of climate investors and ϕ is large, brown projects are rationed (corresponding to Condition (24)). If there is a shortage of climate investors and ξ is negative, but offset by ζ, green projects are rationed because ζ only materializes for climate investors (corresponding to Condition (25)).

Since green certificates allow to reduce fragmentation of bond issues, generally, more (or the same number of) projects will be undertaken, allocation is improved, and welfare will be higher than with green bonds. The associated increase in green projects is an improvement for the environment. The associated increase in brown projects yields a negative environmental contribution, which can outweigh the positive environmental contribution of the increased number of green projects if τ is sufficiently large. Moreover, the improved transparency will prevent any miss-selling to investors. This is good for investor welfare (as miss-selling is inefficient), but may hurt the environment (as fewer green projects are undertaken). Yet, in general, one would consider green certificates to be an improvement over green bonds.

Proposition 5 *When markets are not too illiquid (d is close to 0), green certificates improve welfare, but can increase, decrease or leave the environmental contribution constant compared to a system with green bonds.*

Proof. See Appendix. ■

Using regular bonds paired with green certificates is typically optimal for issuers, except for situations in which liquidity is high and there is miss-selling. With high liquidity, the benefits of preventing fragmentation are small, while there are costs of not being able to miss-sell. Hence, even when green certificate financing maximizes welfare and the environmental contribution, issuers may not be incentivized to issue green certificates and may stick to green bonds instead.

Corollary 5 *Issuers will resist green certificates if σ_{GB} and α are high and transaction costs, turnover, ζ, and π_c/κ_G are low.*

Proof. See Appendix. ■

Corollary 5 shows that private issuers may have private incentives to resist superior security design at the expense of aggregate welfare and environmental contributions. This creates a potential scope for legislative and regulatory bodies to provide an institutional framework to counter such behavior.

6 Robustness

This section discusses robustness results and extensions for the main results presented in the previous sections.

6.1 Mismatches between aggregate demand and supply

Throughout the paper we assumed that the aggregate demand for projects equals the aggregate supply. In reality, there may be an excess or a shortage of aggregate demand relative to the aggregate supply of projects. In case of a shortage of projects, the results are qualitatively unaffected (the size of the area in which climate investors solely invest in green bonds and regular investors solely in regular bonds is expanded). If there is a shortage of investors, results are qualitatively the same again, but the likelihood of having regular investors invest in green bonds or climate investors in regular bonds is lower. Hence, issues like miss-selling are less likely to occur.

6.2 Other issuer benefits of green bonds

In this study, we explore the several possible motivations for issuers to issue green bonds, based on the recent survey evidence from Maltais and Nykvist (2020). Yet, it is possible, that issuers have other motivations for doing so than the ones referred to in this and their study. For example, issuers could try to signal their commitment to greening business models by issuing green bonds as suggested by Flammer (2021) and Daubanes et al. (2021). Any additional benefits of issuing green bonds for the issuer can be incorporated by adding a constant ν to the issuer utility when issuing a green bond, or equivalently by increasing $\sigma_{GB}\alpha$ and ζ both by ν. Naturally, this will make an issuer more likely to issue a green bond, but will leave all other trade-offs qualitatively unaffected.

7 Conclusion

In this paper we have shown how green bonds can on the one hand lower yields on debt used to finance green projects, but on the other hand may fragment debt issues. This gives rise to trade-offs for issuers related to clientele, liquidity fragmentation, and market power effects on interest rates. As a consequence, we show that the availability of green bonds as a security type can increase or reduce the volumes of green and brown projects undertaken in equilibrium and thereby increase or reduce equilibrium welfare and climate outcomes. We also show that an alternative security design that decouples earmarking from cash flow rights is in most situations superior to green bonds in terms of equilibrium welfare and climate outcomes because it reduces frictions related to fragmentation. We also show that in the presence of miss-selling of green bonds to regular investors, such security design need not arise by itself and regulatory intervention may be required.

While relevant, the insights developed in this paper rely on assumptions. One of those assumptions is homogeneity across projects within a project type. One could allow for heterogeneity and thereby allow for richer conclusions. We leave such analysis for future research.

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Figures

Figure 1: The figure shows the global annual issuance volumes of green bonds.
Source: Climate Bonds Initiative

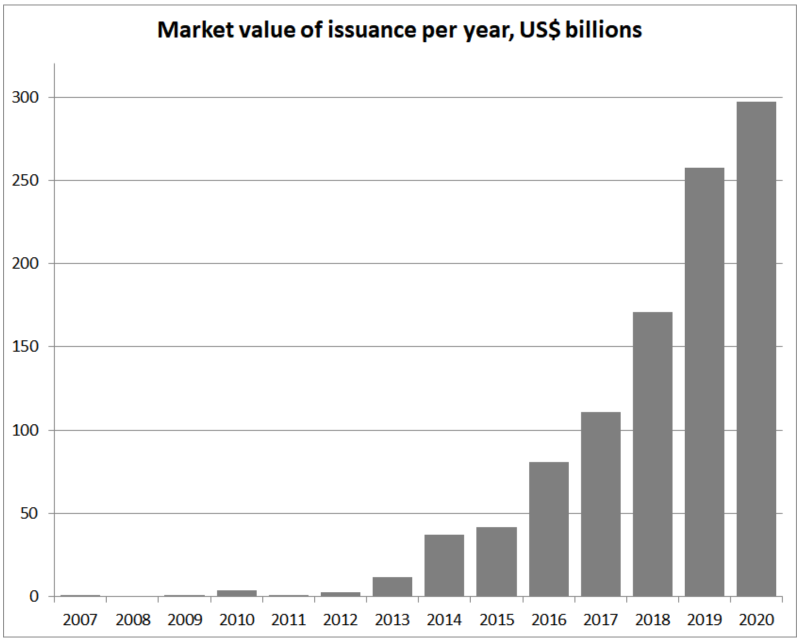
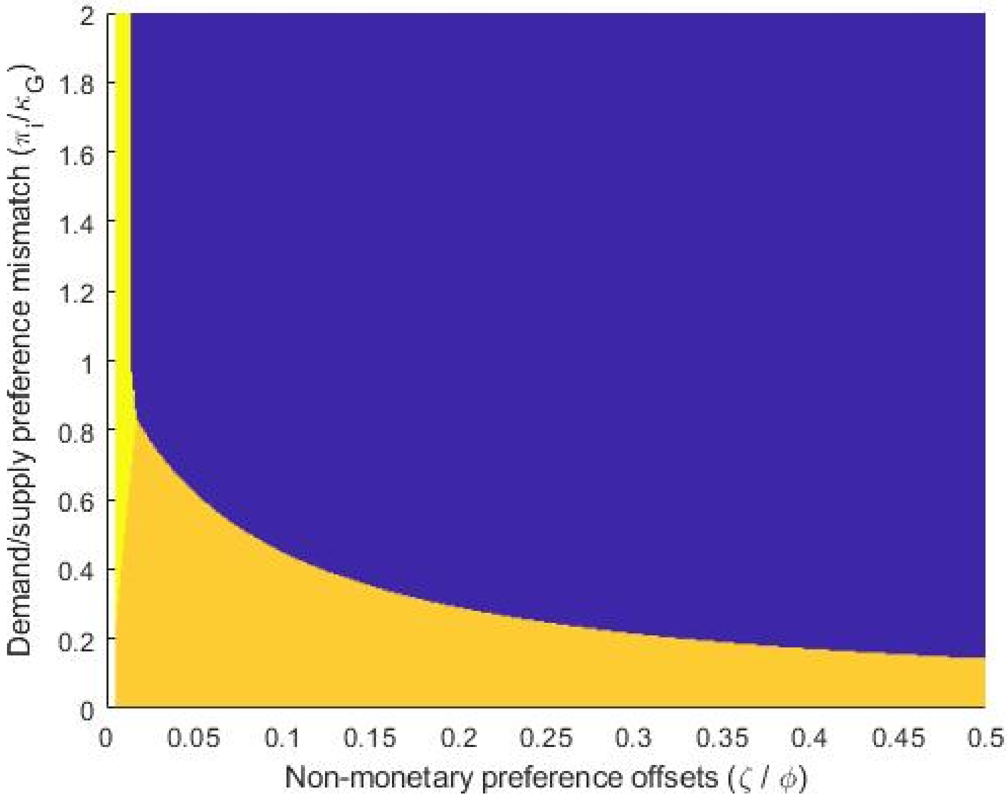
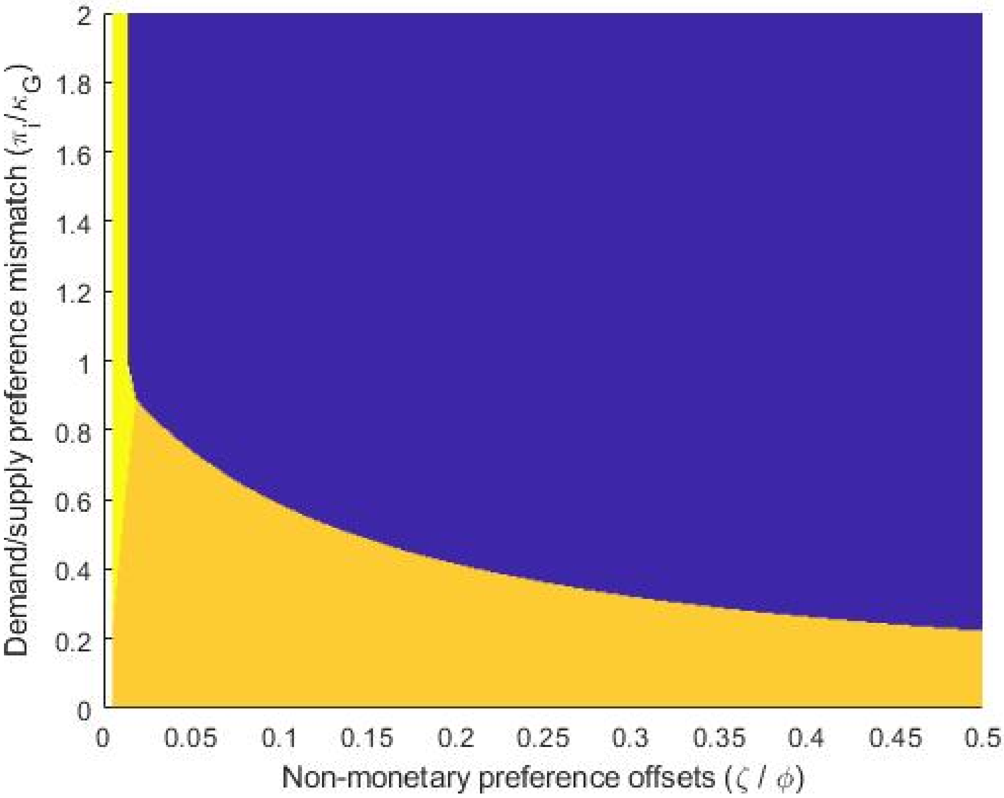


Figure 2: Equilibrium regions with low profitability of all projects



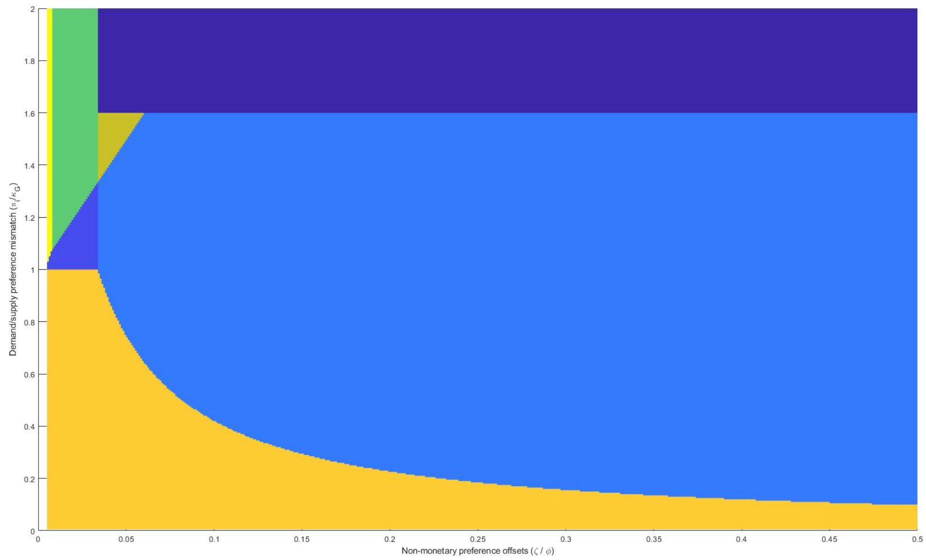
The graph displays the different equilibrium regions as a function of non-monetary preference offsets (ζ and ϕ, which are set equal to one another for exposition purposes) and the degree of preference mismatch in the demand and supply for green and brown projects (summarized by π_c/κ_G). The dark blue area corresponds to equilibria with only climate investors investing in green bonds, the orange area to climate and regular investors investing a combined bond financing both green and brown projects, and the yellow area to both investor types investing in a combined bond financing all projects. The other parameters are given by β =-0.04, ξ =0.1, Q =2, κ_G =0.5, μ =0.01, d =-0.002, σ_{GB} =0, and α =1.96.

Figure 3: Equilibrium regions with low profitability of brown projects



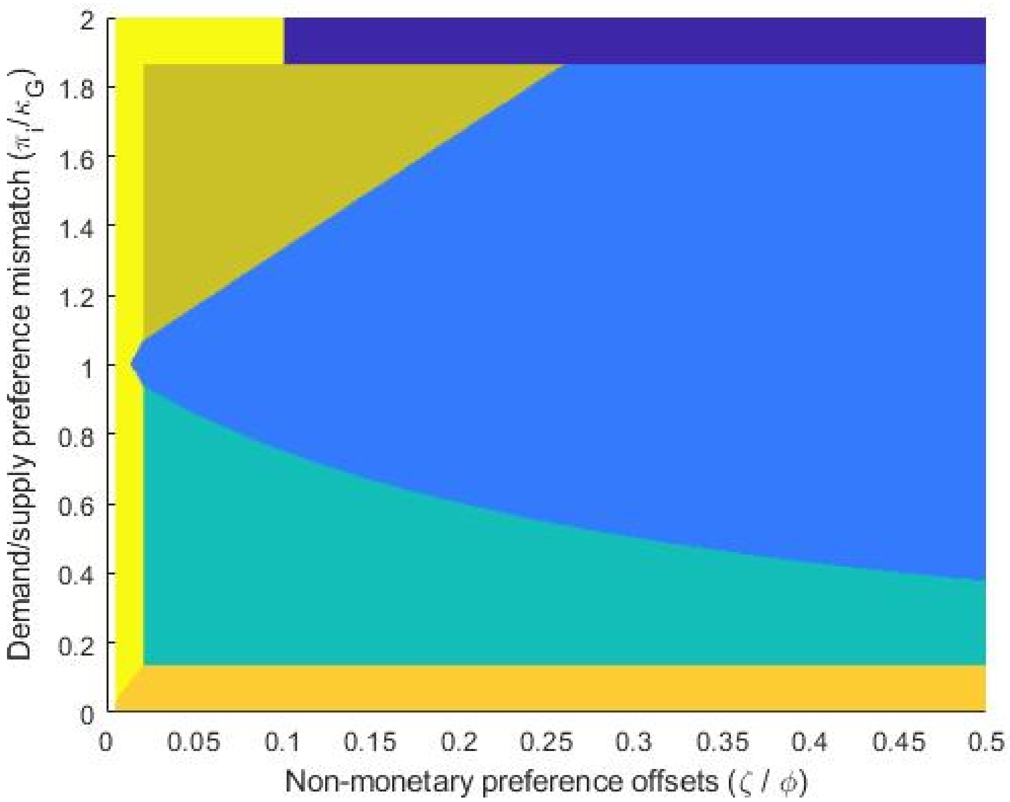
The graph displays the different equilibrium regions as a function of non-monetary preference offsets (ζ and ϕ, which are set equal to one another for exposition purposes) and the degree of preference mismatch in the demand and supply for green and brown projects (summarized by π_c/κ_G). The dark blue area corresponds to equilibria with only climate investors investing in green bonds, the light blue area to climate and regular investors investing in green bonds only, and the yellow area to both investor types investing in a combined bond financing all projects. The other parameters are given by β =0.04, ξ =0, Q =2, κ_G =0.5, μ =0.01, d =-0.002, σ_{GB} =0, and α =1.96.

Figure 4: Equilibrium regions with low profitability of green projects



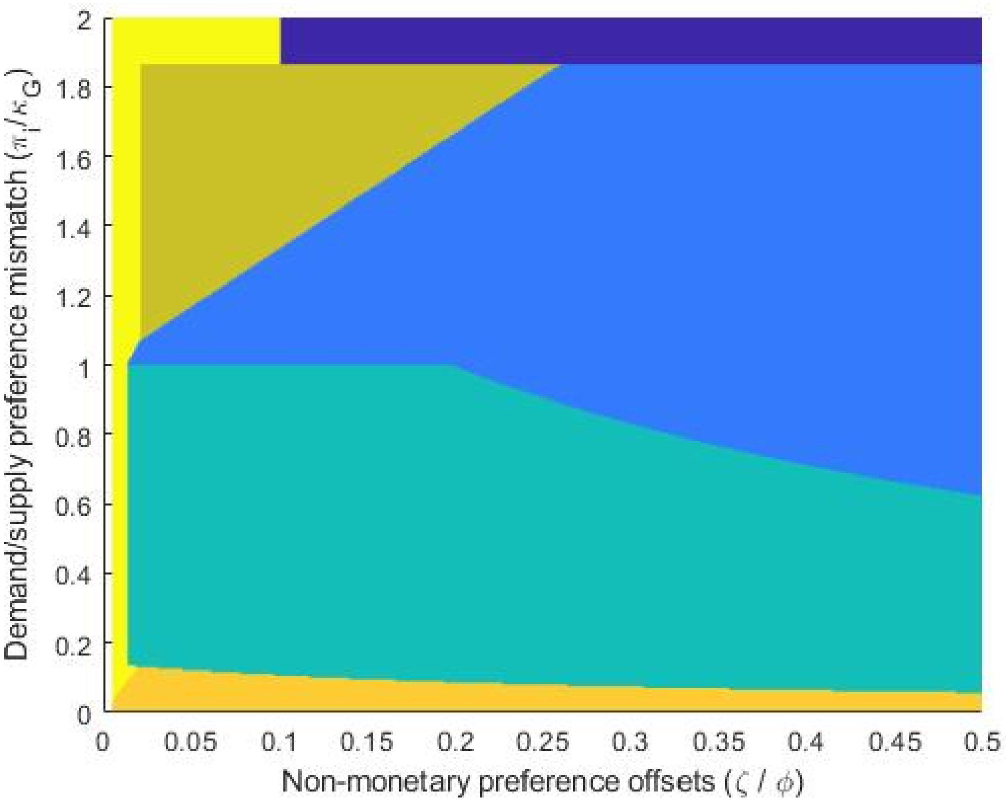
The graph displays the different equilibrium regions as a function of non-monetary preference offsets (ζ and ϕ, which are set equal to one another for exposition purposes) and the degree of preference mismatch in the demand and supply for green and brown projects (summarized by π_c/κ_G). The dark blue area corresponds to equilibria with only climate investors investing in green bonds, the light blue area to climate and regular investors investing in green bonds only, and the yellow area to both investor types investing in a combined bond financing all projects. The other parameters are given by β =0.1, ξ =-0.1, Q =2, κ_G =0.5, μ =0.01, d =-0.002, σ_{GB} =0, and α =1.96.

Figure 5: Equilibrium regions with high profitability of all projects



The graph displays the different equilibrium regions as a function of non-monetary preference offsets (ζ and ϕ, which are set equal to one another for exposition purposes) and the degree of preference mismatch in the demand and supply for green and brown projects (summarized by π_c/κ_G). The dark blue area corresponds to equilibria with only climate investors investing in green bonds, the orange area to climate and regular investors investing a combined bond financing both green and brown projects, and the yellow area to both investor types investing in a combined bond financing all projects. The other parameters are given by β =0.3, ξ =0, Q =2, κ_G =0.5, μ =0.01, d =-0.002, σ_{GB} =0, and α =1.96.

Figure 6: Equilibrium regions with high profitability of all projects and miss-selling



The graph displays the different equilibrium regions as a function of non-monetary preference offsets (ζ and ϕ, which are set equal to one another for exposition purposes) and the degree of preference mismatch in the demand and supply for green and brown projects (summarized by π_c/κ_G). The dark blue area corresponds to equilibria with only climate investors investing in green bonds, the orange area to climate and regular investors investing a combined bond financing both green and brown projects, and the yellow area to both investor types investing in a combined bond financing all projects. The other parameters are given by β =0.3, ξ =0, Q =2, κ_G =0.5, μ =0.01, d =-0.002, σ_{GB} =0.1, and α =1.96.

A Proofs

Proof of Lemma 1. Duffie et al. (2005) show that the steady-state bid-ask spread s_j for security j as a fraction of its fair value in an OTC market with search frictions is given by

$$s_j = \frac{\delta_j z_j}{r_f + (1 - z_j)\rho_j}, \tag{26}$$

where δ_j is a holding cost, z_j is the bargaining power of the market maker, r_f is the risk-free interest rate, and ρ_j is the intensity with which investors meet market makers. By assumption, $\delta_j = \delta$ and $\rho_j = \rho$ for all securities j. Substituting (1) into (26) immediately gives that

$$s_j = \frac{\delta a / S_j}{r_f + (1 - a/S_j)\rho}, \tag{27}$$

$$= \frac{\mu}{d + S_j}, \tag{28}$$

where μ is a strictly positive constant and d is a strictly negative constant. Since δ_j and ρ_j are identical across bond types and independent of issue size, bond turnover Q is unaffected by bond issue type or size. ■

Proof of lemma 2. From the proof of Lemma 1, note that turnover Q is independent of size. Average transaction costs are given by

$$\bar{s} = \frac{S_{GB}}{S_{GB} + S_{RB}} s_{GB} + \frac{S_{RB}}{S_{GB} + S_{RB}} s_{RB}. \tag{29}$$

We can derive a Taylor approximation of s_j around S_j:

$$s_j = \frac{\mu}{d + S_j} \approx \frac{\mu}{S_j} + d\left(-\frac{\mu}{S_j^2}\right). \tag{30}$$

Using this Taylor approximation, we have that

$$\bar{s} = \frac{S_{GB}}{S_{GB} + S_{RB}} \frac{\mu}{d + S_{GB}} + \frac{S_{RB}}{S_{GB} + S_{RB}} \frac{\mu}{d + S_{RB}} \approx 2\frac{\mu}{S_{GB} + S_{RB}} - \frac{d\mu}{S_{GB} + S_{RB}}\left(\frac{1}{S_{GB}} + \frac{1}{S_{RB}}\right). \tag{31}$$

Since $d < 0$ and $S_{GB}, S_{RB} > 0$, we have that

$$2\frac{\mu}{S_{GB}+S_{RB}} - \frac{d\mu}{S_{GB}+S_{RB}}\left(\frac{1}{S_{GB}}+\frac{1}{S_{RB}}\right) > \\ 2\left(\frac{\mu}{S_{GB}+S_{RB}} - \frac{d\mu}{(S_{GB}+S_{RB})^2}\right) \approx \frac{\mu}{d+S_{GB}+S_{RB}} = s_{LB}. \quad (32)$$

■

Proof of Lemma 3. Suppose an investor i receives a take-it-or-leave-it offer with yield y_j for bond j. It is optimal to accept when doing so maximizes (perceived) expected investor utility. Since it is a take-it-or-leave-it offer, there are no dynamic future consequences of the acceptance decision and such a decision cannot be revisited. Therefore, acceptance is optimal if

$$U(y_j) \geq 0, \Rightarrow \quad (33)$$

$$0 \leq y_j - Qs_j + \zeta I_{c,GB} - \phi(I_{c,RB} + I_{c,LB}) - I_{r,GB}\sigma_{GB}\alpha, \Rightarrow \quad (34)$$

$$y_j \geq \theta^*_{i,j} = Qs_j - \zeta I_{c,GB} + \phi(I_{c,RB} + I_{c,LB}) - I_{r,GB}\sigma_{GB}\alpha, \quad (35)$$

where $I_{i,j} \forall j$ are indicator functions that equal one if an climate investor of type i invests in security of type j and zero otherwise. ■

Proof of Proposition 1. From Lemma 3, we have with $\mu = 0$ that $\theta^*_{c,GB} < \min(\theta^*_{c,RB}, \theta^*_{c,LB})$, while $\theta^*_{r,GB} = \theta^*_{r,RB} = \theta^*_{r,LB}$. Hence, $y^*_{LB} = \emptyset$ is always at least weakly optimal.

From Lemma 3, we have that $\theta^*_{c,GB} < \theta^*_{r,GB}$ and $\theta^*_{c,RB} > \theta^*_{r,RB}$. Hence, $y^*_{GB} = \emptyset$ if (11) is violated and $y^*_{RB} = \emptyset$ if (10) is violated.

If $\pi_c \geq \kappa_G$, all green projects can be financed by climate investors, and hence, $y^*_{GB} = \theta^*_{c,GB}$. Similarly, if $\pi_r \geq \kappa_B$, all brown projects can be financed by regular investors, and hence, $y^*_{RB} = \theta^*_{r,RB}$.

If $\pi_c < \kappa_G$, there is scope for increasing the volume of financed projects by setting $y_{GB} = \theta^*_{r,GB}$. This is sub-optimal iff

$$\pi_c(\beta + \xi - \theta^*_{c,GB}) \geq \kappa_G(\beta + \xi - \theta^*_{r,GB}), \quad (36)$$

which is equivalent to Eq. (13).

Similarly, if $\pi_r < \kappa_B$, there is scope for increasing the volume of financed projects by setting $y_{RB} = \theta^*_{c,RB}$. This is sub-optimal iff

$$\pi_r(\beta - \theta^*_{r,RB}) \geq \kappa_B(\beta - \theta^*_{c,RB}), \tag{37}$$

which is equivalent to Eq. (12). ■

Proof of Proposition 2. By definition, the combined bond is to finance both green and brown projects. The issuer can choose from three mutually exclusive options: 1.) to not issue a combined bond, 2.) to issue a combined bond to regular investors only, or 3.) to issue a combined bond to all investors. Issuing a combined bond to climate investors only is never optimal because $\theta^*_{c,LB} \geq \theta^*_{r,LB}$, the issuer optimally sets in that case $y_{LB} = \theta^*_{c,LB}$, and $\theta^*_{c,LB}$ is decreasing in issue size. In other words, letting also regular investors invest in the large bond is always at least weakly optimal.

An option is optimally chosen if the associated issuer payoff is higher than that of the other two options. Condition (15) ensures that issuing to regular investors only yields a higher issuer payoff than not issuing a combined bond, while the violation of condition (17) ensures that issuing to regular investors only yields a higher issuer payoff than issuing a combined bond to all investors. Lemma 3 implies that $y_{LB} \geq \theta^*_{r,LB}$. Since interest is a cost for the issuer, setting $y_{LB} = \theta^*_{r,LB}$ is optimal.

Similarly, condition (16) ensures that issuing to all investors yields a higher issuer payoff than not issuing a combined bond, while condition (17) ensures that issuing to all investors yields a higher issuer payoff than issuing a combined bond to regular investors only. Lemma 3 implies that $y_{LB} \geq \max\left(\theta^*_{r,LB}, \theta^*_{c,LB}\right)$. Since interest is a cost for the issuer and $\theta^*_{c,LB} \geq \theta^*_{r,LB}$, setting $y_{LB} = \theta^*_{c,LB}$ is optimal.

Since not issuing any bond is one of the options in Proposition 1, condition (15) ensures that if a combined bond is optimally offered, the expected payoff is positive. ■

Proof of Corollary 1. If $\sigma_{GB} = 0$ and $\phi = -\zeta$, Lemma 3 implies that $\theta^*_{r,j} = Qs_j \forall j$ and $\theta^*_{c,j} = Qs_j + \phi \forall j$. Since s_j is strictly decreasing in issue size S_j, any project that can be profitably financed by a green bond can also be profitably financed by a regular or combined bond at the same or a lower yield. Hence, green bond financing is (weakly) dominated in this setting, and hence, the resulting equilibria with and without the option to use green bonds for financing are the same. ■

Proof of Proposition 3. The proof of the different cases is by examples.

Consider the case in which $Q = 0$, $\beta < 0$, $\beta + \xi < 0$, and $\zeta > \beta + \xi$. When funded in any other way than a green bond, investors would demand an interest of at least $\min_{i\in\{c,r\},j\in\{RB,LB\}} \theta^*_{i,j} = 0$. As a result, green projects are not profitable and are undertaken. With green bonds available, climate investors would require an interest rate of at least $\theta^*_{c,GB} = -\zeta$ for at least some green projects (assuming $\pi_c > 0$). Since, $\zeta > \beta + \xi$, green projects are profitable (net of funding costs), undertaken in equilibrium, and only funded by green bonds. As a result, the number of green projects undertaken in equilibrium increases due to the availability of green bonds. Since $\beta < 0$ and $Q = 0$, brown projects are still not undertaken. Since $V_{c,G}$ increases with green bonds being available while the other volumes stay constant, welfare and the environmental contribution improve as a result of being able to issue green bonds.

Consider the case in which $\pi_c/\kappa_G < 1$, $\xi = 0$, $\beta - Qs_{RB} < 0$, $\beta - Qs_{GB} < 0$, $\zeta > Qs_{GB} + \epsilon/\pi_c$, $\tau = 0$, and $\beta - Qs_{LB} - \phi = \epsilon > 0$. Since $\beta - Qs_{LB} - \phi = \epsilon > 0$, and $\beta - Q\min(s_{RB}, s_{GB}) < 0$, a large combined bond that finances all projects materializes in equilibrium when green bonds are not available. When green bonds are available, the issuer optimally issues only a green bond to climate investors since its payoff exceeds that of having regular investors co-fund a green bond (since $\beta - Qs_{GB} < 0$), or issuing a combined bond (as $\pi_c(\beta Q s_{GB} + \zeta) > \pi_c\beta + \epsilon > \epsilon$). As a result, the mass of both green and brown projects reduces. Since welfare is monotonically increasing in the number of green and brown projects undertaken in equilibrium (since $\beta > 0$ and $\xi = 0$), welfare suffers. Since $\tau = 0$, the reduction of brown projects is not associated with an environmental improvement, but the reduction of green projects is with an environmental deterioration. Hence, the environment suffers.

Consider the case in which $Q = 0$, $\beta > 0$, and $\xi < -\beta + \zeta$. In the absence of green bonds, green projects are always loss-making, so would not be funded in equilibrium, while brown projects are profitable and optimally undertaken by issuing regular bonds to regular investors. With the possibility of issuing green bonds, this is not changed as $\xi < -\beta + \zeta$ and green projects are still not profitable. Hence the possibility of issuing green bonds leaves the mass of green and brown projects unaffected, and hence, so are welfare and the environmental payoff.

Consider the case in which $\pi_c/\kappa_G < 1$, $Q > 0$, $\beta - Qs_{RB} > 0$, $\xi > 0$. In the absence of green bonds, a combined bond will be issued to only regular investors to finance both green and brown projects. Since green projects are more profitable than brown ones, brown projects are rationed (only a mass $\pi_r - \kappa_G$ is undertaken). With a green bond available, it is optimal to issue green bonds to climate investors and regular bonds to regular investors. Hence, all brown projects are funded and the availability of green bonds increases the mass of brown projects. ■

Proof of Corollary 2. The proof is by example of each of the mentioned cases.

Consider the case in which $Q = 0$, $\beta << 0$, $\beta + \xi < 0$, and $\zeta = \beta + \xi - \epsilon$, with $\epsilon > 0$. We have that $\theta^*_{c,GB} = -\zeta$ and that $\beta + \xi - \theta^*_{c,GB} < 0$. As a result, green projects would not be undertaken. When ζ increases by ϵ, we have that $\theta^*_{c,GB} = -\zeta = -\beta - \xi$ and that $\beta + \xi - \theta^*_{c,GB} = 0$, in which case at least some green projects are undertaken. As a result, the number of green projects undertaken in equilibrium increases due to an increase in ζ. Since $\beta < 0$ and $Q = 0$, brown projects are still not undertaken. Since $V_{c,G}$ increases, whereas the other quantities stay unaffected, welfare and the environmental contribution improve as a result of being able to issue green bonds.

Now consider the same example as above. If ζ increases by $\frac{1}{2}\epsilon$, we still have that $\beta + \xi - \theta^*_{c,GB} < 0$ and nothing changes.

Consider the case in which $\pi_c/\kappa_G < 1$, $\xi = 0$, $\beta - Qs_{RB} < 0$, $\beta - Qs_{GB} < 0$, $\zeta = 0$, $\tau = 0$, and $\beta - Qs_{LB} - \phi = \epsilon > 0$. Since $\beta - Qs_{GB} + \zeta < 0$, no green bond is issued. Since $\beta - Qs_{LB} - \phi = \epsilon > 0$, a large combined bond that finances all projects materializes in equilibrium. When ζ is increased to $\zeta > Qs_{GB} + \epsilon/\pi_c$, the issuer optimally issues only a green bond to climate investors since its payoff exceeds that of issuing a combined bond or have regular investors co-fund a green bond (see also proof of Proposition 3). As a result, the mass of both green and brown projects reduces (since $\pi_c/\kappa_G < 1$ and $\beta - Qs_{RB} < 0$). Because welfare is monotonically increasing in the number of green and brown projects undertaken in equilibrium, welfare suffers. As $\tau = 0$, the reduction of brown projects is not associated with an environmental improvement, but the reduction of green projects is with an environmental deterioration. Hence, the environmental contribution is negative.

Consider the case in which $\pi_c/\kappa_G < 1$, $Q > 0$, $\beta - Qs_{RB} > 0$, $\xi > 0$, $\phi >> 0$, and $\zeta = 0$. A combined bond will be issued to only regular investors to finance both green and brown projects. Since green projects are more profitable than brown ones, brown projects are rationed (only a mass $\pi_r - \kappa_G$ is undertaken). When ζ is increased to violate Eq. (13), it is optimal to issue green bonds to climate investors and regular bonds to regular investors. Hence, all brown projects are funded (since $\pi_c/\kappa_G < 1$) and the availability of green bonds increases the mass of brown projects. ■

Proof of Corollary 3. ϕ only shows up in conditions (12), (16), and (17). The violation of Condition (12) is a necessary condition for equilibria with maximum investment, as are Conditions (16), and (17). An increase in ϕ relaxes Condition (12) and tightens conditions (16), and (17). Therefore, the number of green and brown projects financed in equilibrium is decreasing in ϕ. Since Eq. (18) is increasing in the number of projects financed, welfare is deteriorating in ϕ. If $\tau = 0$, the associated environmental contribution deteriorates in ϕ, while it increases in ϕ when $\tau = \infty$. ■

Proof of Corollary 4. The proof of the different cases is by examples.

Assume that Eqns. (8), (10), and (11) are satisfied and that Eqns. (13), (15), and (16) are violated. By Proposition 2, all projects are funded, so the number of green and brown projects are maximized, as is welfare. Now increase $\frac{\pi_c}{\kappa_G}$ so that the same constraints are satisfied and violated. Since all projects are still funded, nothing changes with regards to green and brown projects, welfare, and environmental contribution. Now increase $\frac{\pi_c}{\kappa_G}$ such that Eqn. (13) is satisfied and the other constraints are unaffected. By Proposition 2, the number of green projects decreases while the number of brown projects stays constant. As a result, welfare and the environmental contribution deteriorate. Now increase $\frac{\pi_c}{\kappa_G}$ further, such that Eq. (8) is violated and (9) is satisfied and the other conditions are unaffected. By Proposition 2, the number of green projects increases while the number of brown decreases. As a result, the environmental contribution increases. Now increase $\frac{\pi_c}{\kappa_G}$ further, such that Eq. (12) is violated, while all other constraints are unaffected. By Proposition 2, the number of green projects stays constant while the number of brown increases. As a result, the environmental contribution deteriorates while welfare improves. ■

Proof of Lemma 4. By definition, the only difference between a regular and a green bond is that the proceeds of a green bond are earmarked. A green certificates earmarks the proceeds of one bond. Hence, it trivially follows that the combination of a regular bond and a green certificate is equivalent to a green bond. ■

Proof of Lemma 5. Because of Lemma 4, expected utility of regular investors is unaffected by green certificates given a price offer y_j. For an climate investor, accepting offer y_j for $j \in \{RB, LB\}$ without a green certificate yields expected utility

$$y_j - \frac{Q\mu}{d + S_j} - \phi. \tag{38}$$

Hence, it is optimal to accept if

$$y_j \geq \theta^*_{i,j} = \frac{Q\mu}{d + S_j} + \phi. \tag{39}$$

For an climate investor, accepting offer y_j for $j \in \{RB, LB\}$ with a green certificate offered at y_{GC} yields expected utility

$$y_j - \frac{Q\mu}{d + S_j} + y_{GC} + \zeta. \tag{40}$$

Hence, it is optimal to accept if

$$y_j \geq \theta^*_{c,j} = \frac{Q\mu}{d + S_j}, \text{ and} \tag{41}$$

$$y_{GC} \geq \theta^*_{c,GC} = -\zeta. \tag{42}$$

■

Proof of Proposition 4. Since a green bond and a bond paired with a green certificate are equivalent, the results in Proposition 1 still apply. An issuer optimally issues a combined bond paired with green certificates if it maximizes profits. If all projects are financed with a combined bond, issuer profits are given by project profits $(\beta + \xi)$ minus financing costs (which equal the liquidity premium $\frac{Q\mu}{d+1}$ on the large bond plus a compensation for ϕ for the disutility of climate investors financing any brown project, if any), plus the revenues of green certificates $(\min(\pi_c, \kappa_G)\zeta)$. This defines Π_1^{GC}. If, in order to avoid climate investor disutility (with $\pi_c > \kappa_G$), brown projects are only financed by regular investors and all green projects are financed by climate investors, issuer profits are given by project profits $((\kappa_G + \pi_r)\beta + \kappa_G\xi)$ minus financing costs (which equal the liquidity premium $\frac{Q\mu}{d+\kappa_G+\pi_r}$) on the large bond) plus the revenues of green certificates $(\kappa_G\zeta)$. This defines Π_2^{GC}. If it is not profitable for regular investors to invest in green projects (with $\pi_c < \kappa_G$), issuer profits are given by project profits $((\kappa_R + \pi_c)\beta + \pi_c\xi)$ minus financing costs (which equal the liquidity premium $\frac{Q\mu}{d+\kappa_B+\pi_c}$) on the large bond) plus the revenues of green certificates $(\pi_c\zeta)$. This defines Π_3^{GC}. ■

Proof of Proposition 5. Assume d is small and $\beta + \xi \geq 0$. The LHS of Condition (23) exceeds the LHS of Condition (16) and the LHS of Condition (15) is always smaller than either the LHS of Condition (23) or (25). As a result, whenever there is a combined bond in the setting with green bonds, there would also be one in the setting with green certificates. The term related to transaction costs in all these conditions equals (by approximation; for small d) $Q\mu$. This term relates to zero-sum transfers while all other terms are relevant for welfare. It follows that welfare must improve with green certificates. Now assume that d is small, but that $\beta + \xi < 0$. Since the term related to transaction costs equals (by approximation) $Q\mu$, it is optimal for the issuer not to undertake green projects, irrespective of the financing options available. In this case, green certificates weakly improve welfare. Similarly, when d is small and $\xi > -\beta > 0$, it is optimal to only undertake green projects, irrespective of the financing options available and green certificates weakly improve welfare..

The proof for environmental contributions is by example. Assume that Condition (16) is satisfied and that $\beta\xi \geq 0$ and $\pi_c < \kappa_G$. It follows that Condition (23) must be satisfied. As all projects are undertaken under either financing option, the environmental contribution is unaffected.

Next, assume that Condition (15) is satisfied and that $\xi \in (-\beta, 0)$ and that $\zeta > \beta + \xi$. It must be that either Condition (23) or (25) is satisfied. In either situation, the number of green projects undertaken is increased while the number of brown projects is at most kept constant. Hence the environmental contribution improves as a result of the green certificate financing option.

Finally, assume that $\tau > 0$, $\phi = \infty$, $\pi_c = \kappa_G$, $\beta \in (0, \frac{Q\mu}{d+S_R})$, and that Condition (11) is satisfied. Proposition 2 implies that with only green bonds available, all green projects would be financed with green bonds and no brown projects would be financed. Proposition 4 implies that with green certificates all projects are financed with a large bonds and for all green projects green certificates are issued. Since $\tau > 0$, the environmental contribution with green bonds is higher than with green certificates. ■

Proof of Corollary 5. Let us assume that there is a shortage of climate investors (i.e., $\pi_c/\kappa_G < 1$). It is optimal for an issuer to use green bonds instead of green certificates when their profitability with green bonds is higher, that is

$$\kappa_B(\beta - \frac{Q\mu}{d+\kappa_B}) + \kappa_G(\beta + \xi - \frac{Q\mu}{d+\kappa_G} + \sigma_{GB}\alpha) \geq \beta + \kappa_G\xi - \frac{Q\mu}{d+1} + \pi_c\zeta, \quad (43)$$

and

$$\kappa_B(\beta - \frac{Q\mu}{d+\kappa_B}) + \kappa_G(\beta + \xi - \frac{Q\mu}{d+\kappa_G} + \sigma_{GB}\alpha) \geq$$
$$(\pi_c + \kappa_B)\beta + \pi_c(\xi + \zeta) - \frac{Q\mu}{d + \pi_c + \kappa_B}. \quad (44)$$

Re-writing and imposing the approximation $d \approx 0$, yields

$$\kappa_G \sigma_{GB} \alpha - Q\mu \geq \pi_c \zeta, \text{and} \quad (45)$$
$$(\kappa_G - \pi_c)(\beta + \xi) + \kappa_G \sigma_{GB} \alpha - Q\mu \geq \pi_c \zeta. \quad (46)$$

■

B Micro-foundations on intransparency

In this Appendix section, we derive micro-foundations for green bonds being intransparent about the return given up for green earmarking. We show such intransparency in price levels as well as in trade to trade return data (as provided by e.g., TRACE). Along with providing these micro-foundations, we also show that in general, the transparency of green certificates (developed in Section 5 as alternative green debt securities) is much higher. Finally, we show that beside low transparency on pricing, the green bond design also impairs the possibility of trading on environmental performance information of the issuer. Consequently, such information is not efficiently impounded into security prices and ex-ante incentives to produce such information are low. This creates a governance problem w.r.t. the commitment to environmental investment policies. We also show that such problems are much less prevalent with green certificates.

We assume again that the aggregate demand supply of capital are perfectly matched, but that there may be a mismatch in composition. For tractability, we set $Q = 0$ such that there is no liquidity premium. Moreover, we assume that conditions (11) and (9) or (13) are satisfied. Let us denote the friction-free yield on a green bond at time t issued by issuer i as $y_{GB,t}$ and the friction-free yield on a reference bond $y_{ref,t}$. The difference between the two, $y_{ref,t} - y_{GB,t}$, we call the green spread. Finally, we define the annualized discount $\xi_{GC,t}$ that would result from green certificate financing as the green certificate premium.

We have that the green spread equals the green certificate premium, which in turn equals the convenience yield of climate investors ζ_t.

Lemma 6 *With more demand than supply for environmentally friendly projects, we have in frictionless markets that*

$$\xi_{GC,t} = y_{ref,t} - y_{GB,t} = \zeta_t. \tag{47}$$

Proof. See Appendix. ■

B.1 Informativeness of market prices (levels)

The green certificates premium, $\xi_{GC,t}$ (an annualized expected return discount) can be derived from the prices of the green certificate and its associated bond (which by design is perfectly matched). The green spread however needs to be constructed from a green bond and a perfectly matched reference bond. Since perfectly matched reference bonds are often not available, one typically looks at an estimate that either involves the closest available match (as in e.g., Flammer 2021) or takes the reference bond yield from a yield curve. For sovereign bonds, the latter method is normally deemed most accurate if a perfect match is unavailable. We continue by deriving analytical expressions for the uncertainty of green spread estimates when yield curves are used to extract yields on reference bonds.

We assume that the green bond yield is observed without error, but that the matched yield obtained from the yield curve, $\tilde{y}_{ref,t}$, is an unbiased, but noisy estimate of the true matched yield. Specifically, we assume that yield curves are estimated with IID measurement error with standard deviation σ^{ϵ}:

$$\tilde{y}_{ref,t} = y_{ref,t} + \epsilon_t. \tag{48}$$

It follows that the green spread estimate is unbiased, but inherits the estimation noise

$$\tilde{y}_{ref,t} - y_{GB,t} = y_{ref,t} - y_{GB,t} + \epsilon_t. \tag{49}$$

We calibrate these expressions to realistic numbers. We set $\zeta_t = 5$ bps per annum (the average green spread reported by Zerbib 2019) and $\sigma^{\epsilon} = 6$bps (equal to the root mean squared error for fitting Euro yield curves using high quality European sovereign bonds, averaged over all considered methods, in Nymand-Andersen 2018, Table D.1). The volatility of the fitting error is even larger than the convenience yield. This calibration confirms anecdotal evidence that the green bond yield is not significantly different from a matched reference bond yield. This problem is absent for green certificates since their entire value solely relates to earmarking and there is no need for reference bond matching. As a result, green spread estimates are also unsuitable as environmental performance metrics.

B.2 Informativeness of market prices (changes)

In this subsection we extend the analysis from the previous subsection in price or yield levels to one in changes. In particular, we investigate how well changes in observed green spreads and green certificate premia reflect environmental performance changes of the issuer. We now make the convenience yield ζ_t time-varying. Throughout the rest of Appendix B, we now assume ζ_t to be proportional to the environmental performance of the projects the earmarked funds are used for. Under this assumption, all time variation in the convenience yield ζ_t is due to time variation in environmental performance. Lemma 6 then shows that in frictionless markets any information about environmental performance is fully incorporated in and perfectly visible from both the green certificate premium as well as the green spread. In this section and Sections B.3, we relax the assumption of a frictionless market and show that the degree to which information about environmental performance is visible from and is incorporated in the green spread is very low compared to that of green certificates. In this section, we incorporate yield curve fitting errors as well as transaction costs as frictions.

In our analysis, we employ a measure that we call the "information ratio." It is defined as the ratio of the variance of environmental performance changes (i.e., changes in ζ_t) over the variance of empirically observed changes in green spreads or green certificate premia. We denote the information ratio by IR. In a frictionless market, all price changes are driven by information on environmental performance and the information ratio equals one. Yet, frictions such as transaction costs or yield curve fitting errors infuse noise into empirically observed price changes, thereby lowering the information ratio.

B.2.1 Yield curve fitting noise

We first consider the situation with yield curve fitting errors as in the previous subsection. We make the additional assumption that innovations in environmental performance are independent of yield curve fitting errors.

Green certificates do not require the estimation of reference bond yields. Hence, green certificate premium changes are noise-free and purely reflect changes in fundamentals:

$$IR_t^{GCP} = \frac{Var(\zeta_t - \zeta_{t-1})}{Var(\xi_t - \xi_{t-1})} = \frac{Var(\zeta_t - \zeta_{t-1})}{Var(\zeta_t - \zeta_{t-1})} = 1. \tag{50}$$

By contrast, the information ratio of the green spread changes is given by

$$IR_t^{spread} = \frac{Var(\zeta_t - \zeta_{t-1})}{Var(\tilde{y}_{ref,t} - y_{GB,t} - \tilde{y}_{ref,t-1} - y_{GB,t-1})} = \frac{Var(\zeta_t - \zeta_{t-1})}{Var(\zeta_t - \zeta_{t-1}) + 2Var(\epsilon_t)} < 1, \tag{51}$$

where the last term in the denominator is due to the zero mean and IID assumptions. This expression contains a noise component in the denominator and will therefore be strictly smaller than one.

We calibrate Eqn. (51) to realistic values to quantify the information shortfall (see Table 3). We set the annualized volatility of changes in ζ_t to 4 bps with zero autocorrelation[6] and σ^ϵ to 6bps (as before). With those values, 18% of the annualized variance and 5% of the quarterly variance of changes in estimated green spreads is driven by changes environmental performance and respectively 82% and 95% by yield curve fitting noise. Hence, changes in green spreads poorly reflect changes in environmental fundamentals, which is not the case for changes in green certificate premia. The information ratio for corporate green spread changes is most likely lower than our figures calibrated to sovereign bond data. The reason is that corporates typically have fewer bonds outstanding and have more heterogeneity across issues and issuers, resulting in more yield curve estimation noise.

B.2.2 Transaction costs

We now analyze the effect of transaction costs on information ratios. Transaction costs generate noise in returns because transactions take place at the bid (ask) may be followed by transactions taking place at the ask (bid). As a result, a fraction of the observed returns is (at least partially) driven by changes in trade direction. This phenomenon is called the bid-ask bounce (see e.g., Roll 1984). We show that bid-ask bounce-induced noise reduces the information ratios of observed green spread changes much more than those of changes in green certificate premia.

[6] We deem this order of magnitude very large in view of the mean of 5bps.

For our analysis we assume that 1.) each security is subject to time-invariant transaction costs that are proportional to its market value, 2.) only transaction-based price data are available (as in e.g., TRACE), 3.) proportional transaction costs for green bonds equal those for reference bonds (denoted by s), but transaction costs for green certificates can be different (denoted by s_{GC}), and 4.) buys and sells are equally likely and trade directions are serially uncorrelated. To focus on the effects of transaction costs, we abstract from matching problems for reference bonds and assume that a perfect match is available.

The observed transaction price $\tilde{p}_{x,t}$ of each security x at time t is given by

$$\tilde{p}_{x,t} = p_{x,t}(1 - s_x + 2s_x X_{x,t}), \tag{52}$$

where s_x is the proportional transaction cost, $X_{x,t} \sim \text{Bernoulli}(0.5)$ is the trade sign indicator (1 for buy, 0 for sell), and $p_{x,t}$ is the true value of security x at time t. One can use Eq. (52) to approximate (log) returns for green certificates and long-short positions in green and reference bonds based on observed transaction prices.

Lemma 7 *The returns for green certificates ($\tilde{r}_{GC,t}$) and long-short positions in green and reference bonds ($\tilde{r}_{ref-GB,t}$), both based on observed transaction prices are, by approximation, given by*

$$\tilde{r}_{GC,t} \approx r_{GC,t} + 2s_{GC}X_{GC,t} - 2s_{GC}X_{GC,t-1}, \tag{53}$$

$$\tilde{r}_{ref-GB,t} \approx r_{GC,t} + \frac{p_{ref,t}}{p_{GC,t}}2sX_{ref,t} - \frac{p_{GB,t}}{p_{GC,t}}2sX_{GB,t} - \frac{p_{ref,t-1}}{p_{GC,t-1}}2sX_{ref,t-1} + \frac{p_{GB,t-1}}{p_{GC,t-1}}2sX_{GB,t-1}, \tag{54}$$

where $r_{GC,t}$ is the fundamental (but unobservable) log return of the green certificate.

Proof. See Appendix. ■

The transaction cost terms in (54) are multiplied with the price ratio of a bond and a green certificate, which is typically very large. The reason is that in order to establish a net position that corresponds to the value of green earmarking only, large long and short positions have to be taken in green and reference bonds. As a result, the transaction cost base for such a long-short position is large. Consequently, transaction costs infuse much more noise into $\tilde{r}_{ref-GB}$ than into $\tilde{r}_{GC}$. For tractability reasons, we now use the approximation

$$p_{ref,t} \approx p_{ref,t-1} \approx p_{GB,t} \approx p_{GB,t-1}, \tag{55}$$

since p_{GC}, and its innovations are small. We can now analyze the differential effect of transaction costs on information ratios.

Proposition 6 *The information ratio of green certificate premium changes is higher than that of green spread change iff*

$$s_{GC} < \sqrt{2}\frac{p_{ref,t}}{p_{GC,t}}s. \tag{56}$$

Proof. See Appendix. ■

In Eq. (56) the square root of two shows up because a long and short position are required to construct the green spread, and each of the two is subject to transaction costs. The ratio $\frac{p_{ref,t}}{p_{GC,t}}$ shows up because large positions in bonds are required to match a small position in a green certificate (cost base ratio).

We now calibrate (56) to realistic values in the sovereign debt market (See Table 4). We set face values for bonds and green certificates to 100, maturity to 5 years, reference bond yield and coupon rates to 1% per annum, convenience yield ζ_t of 5 bps per annum, and one-way transaction costs to 3.5 bps, which aligns with German Bund market estimates in de Roure et al. (2019). For these inputs, the information ratio of green spread changes is inferior to that of green certificate premium changes, unless one-way transaction costs for green certificates exceed 2042 bps (20%).

We can also calibrate (56) to realistic values in the corporate bond market. We change reference bond yields and coupon rates to 2% per annum and one-way transaction costs to 50 bps, in line with Bongaerts et al. (2017). It follows that the information ratio of green spread changes is inferior to that of green certificate premium changes, unless one-way transaction costs for green certificates exceed 30,050 bps (300%). This is unrealistic, since transaction costs would exceed the fundamental value of the green certificate threefold.

B.3 Incentives for informed trading

In this section, we show that investors are much less likely to exploit and produce (private) information on environmental performance when they need to trade green (and reference) bonds as compared to the situation in which they can trade green certificates. This analysis is important, as it shows the degree of price discovery and information production that can be expected in markets.

We assume that a risk-neutral speculator is privately informed about an issuer engaging in greenwashing, which means that the value of a green certificate/price difference between a green and reference bond equals $\hat{p}_{GC}$ instead of the market consensus price $p_{GC} = p_{GB} - p_{ref} > \hat{p}_{GC}$. We assume the same proportional transaction cost structure as before and in addition assume linear price impact $\lambda_{ref-GB} = \lambda_{GC} = \lambda > 0$.[7]

Following Kyle (1985), the speculator's (green) bond market demand equals

$$q_{GB} = -q_{ref} = -\frac{\max((p_{GC} - \hat{p}_{GC}) - s(p_{GB} + p_{ref}), 0)}{2\lambda}, \tag{57}$$

$$\approx -\frac{\max((p_{GC} - \hat{p}_{GC}) - 2sp_{ref}, 0)}{2\lambda}, \tag{58}$$

where the approximation results from $sp_{GB} \approx sp_{ref}$. The demand for green and reference bonds is nonzero if

$$p_{GC} - \hat{p}_{GC} > 2sp_{ref}. \tag{59}$$

Similarly, the speculator's demand for green certificates is given by

$$q_{GC} = -\frac{\max((p_{GC} - \hat{p}_{GC}) - s_{GC}p_{GC}, 0)}{2\lambda}, \tag{60}$$

which is nonzero if

$$p_{GC} - \hat{p}_{GC} > s_{GC}p_{GC}. \tag{61}$$

Since $p_{ref} >> p_{GC}$, this threshold is much lower for green/reference bond pairs than for green certificates.

We calibrate again to realistic numbers to quantify the difference in thresholds (see Table 5). We set all face values to 100, a maturity of 5 years, a yield and coupon rate on reference bonds of 1%, and the market consensus on ζ_t to 5 bps (based on public information). With these values, the green certificate has a price of 24 cents. It follows that a speculator that is privately informed that ζ_t equals 0 bps[8] trades in the green certificate market if one-way transaction costs do not exceed 100% and in green and regular bond markets if one-way transaction costs do not exceed 12 bps. This condition is typically met in developed sovereign bond markets (e.g., 3.5 bps in German Bund markets), but not in corporate bond markets (on average 50 bps). For a smaller informational advantage (private information that ζ_t equals 4 bps) the

[7] Price impact is necessary as otherwise information is not incorporated into prices through trading. The exact size of the price impact is irrelevant for the rest of the analysis.

[8] i.e., issuer only engages in greenwashing

respective thresholds equal 20% and 2.4 bps, preventing the speculator to trade on his information in even one of the most developed sovereign bond markets.

The aforementioned hurdles to informed trading create a disincentive to produce or purchase environmental performance information, since it is likely to be costly to obtain. This problem is much more severe in green bond than in green certificate markets.

C Empirical validation of fragmentation for dual issuers

Our assumption on market power of investors (vs dealers) being inversely proportional to issue size, in combination with the search and bargain market structure implies that bond liquidity improves with issue size. As an (implicit) test on our model setup, we empirically validate that bond liquidity improves with issue size for regular and green bonds alike. For this test, we only consider issuers of both green bonds and regular bonds (we call these dual issuers), as these certainly have the possibility to pick any mix of green and regular bonds. Moreover, this way we keep the composition of issuer characteristics equal across green and regular bonds. To this test, we construct a similar sample as Yang (2021). First, we download from Bloomberg the CUSIP identifiers of all U.S. dollar-denominated green bonds issued since 2013. We merge these identifiers with the Mergent FISD database to obtain issue sizes for these bond issues. We also merge these data with the TRACE Enhanced trading data, which contain all U.S. corporate bond trades. We clean these data according to the procedures outlined in Dick-Nielsen (2014). Following Bongaerts et al. (2017), we also exclude very small trades ($ 10,000 and smaller) due to those being unrepresentative and bonds that have a maturity left of less than a year. We discard any green bonds from our sample that are issued by issuers that only issue green bonds. Moreover, we discard any bonds that are putable, exchangeable, convertible, or can be paid in kind.

We then construct the Imputed Roundtrip Cost measure, IRC, from Feldhütter (2012), which is constructed from trades that quickly follow one another (within 30 minutes). The IRC measure is then defined as the difference between the highest and the lowest price observed for trades in the same bond, with the same quantity, within the 30 minute interval, but with different prices. Feldhütter (2012) indicates that about 90% of such trades involves a dealer. Hence, our IRC measure is an approximation of the half spread and should be multiplied by two to obtain the cost for a roundtrip trade. We average the IRC measure first within each trading day and then across all trading days in a month. We construct equally and volume-weighted averages of the IRC measure.

Since the IRC measure is only available when multiple trades cluster together, the coverage of this measure is limited. Therefore, we also construct a different, related measure, the high-low measure of Corwin and Schultz (2012), which is defined as the highest minus the lowest price within a trading day (provided that these do not coincide), divided by the average of the two. Under the assumption of zero price volatility within the trading day, this measure can be directly interpreted as the cost of a roundtrip trade (price volatility within the day will never exactly equal zero, and hence, this measure is slightly upward biased). We average the high-low measure across all trading days in a month. We also construct turnover at the monthly level as the aggregate reported par trading volume divided by the par amount outstanding. In addition, we also create the Amihud (2002) (il)liquidity measure (ILLIQ) for all (green and non-green) bonds. We winsorize turnover, ILLIQ, and all three bid-ask spread estimates at the 5% and 95% level.

Panel A of Table 1 reports the summary statistics for green bond issues. The mean turnover of the green bonds equals about 9.7% per month or 116.4% per year. Mean roundtrip cost estimates vary from 35.7 bps (value-weighted IRC) to 62.3 bps (high-low). Panel B reports the same liquidity measures for all other bonds (non-green) issued by green bond issuers.

Next, we regress liquidity measures on log issue size, a green bond dummy and the interaction of log issue size with the green bond dummy. These regressions are done at the bond-month level and the model is saturated with firm-month fixed effects. We double-cluster standard errors by issuer and month.

Table 2 presents the results. For all liquidity measures except the high-low measure, liquidity increases significantly with issue size. The interaction term between the green indicator variable and issue size is never statistically significant at conventional levels. Moreover, it varies in sign across liquidity measures, and is economically much smaller than the coefficient on issue size (except for the high-low measure). Hence, the empirically observed relationship between liquidity and bond issue size is consistent with the implications of our model.

D Appendix Tables

Table 1: Summary statistics green and non-green bonds issued by green bond issuers

Panel A: Green bonds

Variable	N	Mean	Median	SD
IRC_{VW}	1,647	17.9	10.3	21.7
IRC_{EW}	1,647	27.3	17.6	27.0
$high - low$	1,717	62.3	48.3	51.2
$Turnover$	1,809	9.70%	4.23%	20.66%
$Amihud$	1,712	0.365	0.048	1.650
$Size$	1,809	559	500	277

Panel B: Non-green bonds

Variable	N	Mean	Median	SD
IRC_{VW}	26,681	22.3	10.8	31.8
IRC_{EW}	26,681	33.7	21.3	34.8
$high - low$	29,076	70.7	51.1	61.7
$Turnover$	33,048	12.03%	3.86%	25.70%
$Amihud$	28,029	1.460	0.030	4.200
$Size$	33,048	951	500	1,338

The table presents summary statistics for samples of regular green bonds and non-green bonds issued between 2013 and 2020 by all issuers of U.S. dollar-denominated green bonds at the monthly level. IRC_{VW} and IRC_{EW} represent the value- and equally-weighted monthly average Imputed Roundtrip Cost measures from Feldhütter (2012), respectively, $high - low$ represents the monthly average high-low measure of Corwin and Schultz (2012), $Turnover$ represents monthly bond turnover, $Amihud$ the Amihud (2002) liquidity measures based on clean price returns (i.e., excluding accrued interest), and $Size$ represents the bond issue size. IRC_{VW}, IRC_{EW}, and $high-low$ are expressed in basis points, $Amihud$ as percentage point per \$1mln, and size in \$mln.

Table 2: Regressions of liquidity on log issue size

	(1) IRC_{VW}	(2) IRC_{EW}	(3) $high - low$	(4) $Amihud$
$Ln(Size)$	-7.35***	-4.12***	1.24	-1.68***
	[-13.73]	[-4.70]	[0.52]	[-16.39]
$Green$	5.08	-1.26	-39.4	-6.62
	[0.17]	[-0.02]	[-0.31]	[-1.40]
$Ln(Size) * Green$	-0.560	-0.125	2.65	0.447
	[-0.24]	[-0.03]	[0.27]	[1.26]
Firm-month FEs	Yes	Yes	Yes	Yes
Observations	28,200	28,200	30,675	29,644
Adjusted R^2	0.234	0.152	0.195	0.569

The table presents regression results from regressing different liquidity measures on the natural logarithm of size ($Ln(Size)$), an indicator variable that equals one if a bond is a green bond and zero otherwise ($Green$), and the interaction between these two. All specifications are saturated with issuer-month fixed effects. We double cluster standard errors by issuer and month and report t-statistics in brackets. Respectively, *, **, and *** denote statistical significance at the 10%, 5%, and 1% level. The sample description and variable definitions are in Table 1.

Table 3: Information ratios of changes in green spreads vs green certificate premia

	Green spread	Green certificate premium
Annual	18.17%	100%
Quarterly	5.26%	100%

The table shows the ratio of the variance in environmental performance over the variance of observed green spread and green certificate premia changes at a an annual and quarterly horizon. Reference bond yields are used to construct green spreads and are assumed to have a fitting error standard deviation of 4bps. The annualized standard deviation of environmental performance is set to 4 bps per annum.

Table 4: Transaction cost hurdles for green certificates to be less informative

	Green certificate hurdle
Sovereign	20.42%
Corporate	300%

The table shows the minimal relative (one-way) transaction costs on green certificates that are required to make observed price changes of green certificates less informative about changes in environmental performance than observed changes in green spreads. Sovereign green and reference bonds are assumed to have average one-way transaction and shorting costs of 3.5 bps. Corporate green and reference bonds are assumed to have average one-way transaction and shorting costs of 50 bps. Figures are for reference bonds priced at par with a maturity of 5 years and a yield of 1% for sovereign and 2% for corporate bonds.

Table 5: Transaction cost hurdle to trade on information

Information advantage	Green and reference bonds	Green certificates
1 bps	2.4 bps	20%
5 bps	12 bps	100%

The table shows the proportional fixed transaction and shorting costs beyond which it is suboptimal to trade on information regarding environmental performance for green and reference bonds and for green certificates.