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Liquidity and clientele effects in green debt markets[☆]

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ABSTRACT

We jointly model green and regular bond markets. Green bonds can improve allocative efficiency and lower financing costs for green projects, but economies of scale, like liquidity fragmentation, may cause friction. Consequently, profitable and welfare-enhancing projects, green and brown, can be rationed in equilibrium. Rationing green projects happens with a shortage of climate investors, large non-monetary offsets, and/or costly fragmentation. Rationing regular projects can happen with a shortage of regular investors, but also with an abundance, when more profitable green projects crowd out regular ones. We propose an alternative security design that preserves green earmarking but prevents fragmentation.

1. Introduction

In recent years, environmental concerns have led to a diverse array 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 their environmental footprint.[1] Given the urgency expressed during, for example, the COP28 meeting, the scrutiny, regulation, and taxation of environmental footprints of governments and firms 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 firms. The cash flow and collateral rights for green bonds 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 purposes. The market for green bonds has grown exponentially in recent years as evidenced by Fig. 1.

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

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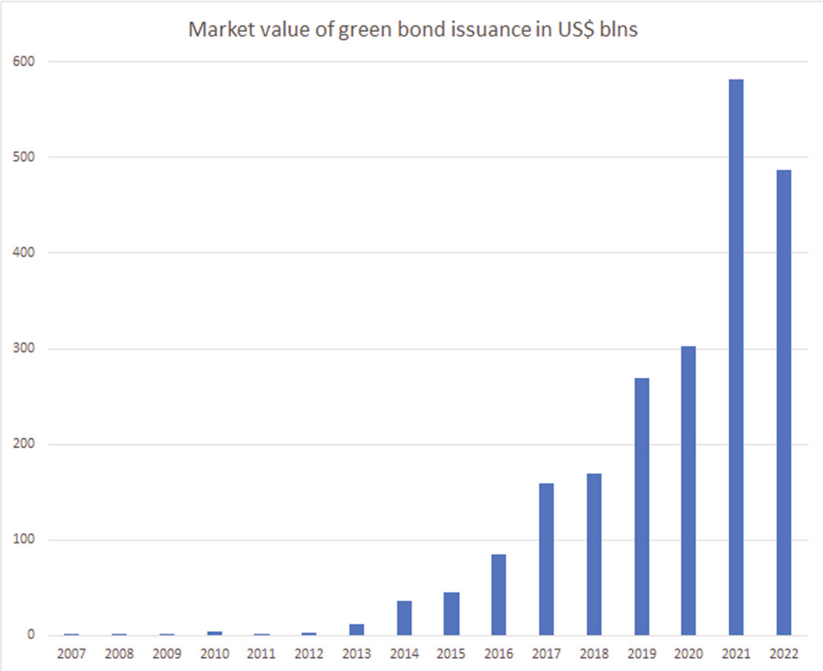

Fig. 1. The figure shows the global annual issuance volumes of green bonds.
Source: Source: Climate Bonds Initiative.

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. Survey evidence from Maltais and Nykvist (2020) indicates that the three main motivations for issuing green bonds are expanding the investor base, catering to investor preferences, and lowering capital costs. The model aims to capture these motivations in an as simple way as possible.

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 (green) and environmentally unfriendly (brown) projects and maximizes total profits. Investors maximize utility and are divided into two types: regular investors and climate investors. The two types of investors are identical, except for the fact that climate investors derive non-monetary utility from investing in securities solely tied to green projects and non-monetary disutility from investing in any other securities. We assume that the aggregate volume of available funding exactly matches the aggregate demand, but that there could be a mismatch in the composition (i.e., there may be too many or too few green projects to satisfy the aggregate demand of climate investors).

The issuer can issue green and regular bonds to investors in the primary market, each at a uniform price (i.e., the same price for each investor). The proceeds of green bonds can only be used to finance green projects. Climate investors are willing to accept a lower yield for green bonds because of their non-monetary benefit of investing in green bonds. Thereby, green bonds allow, at least conceptually, for the issuers to price-discriminate and obtain lower funding costs for green projects. We call this form of price discrimination the clientele effect and the associated yield reduction the clientele premium. Since all bonds in a given issue are offered to all investors at a uniform price, the clientele effect only manifests itself if a green bond issue is solely allocated to climate investors in the primary market.

There are also disadvantages of issuing green bonds in our model. Green bonds fragment bond issues and thereby reduce issuance volumes of individual bonds. We argue that such fragmentation increases funding costs for the issuer because there are economies of scale at the bond issue level. We focus on a specific type of economies of scale, namely in liquidity. The literature has found issuance volumes of bonds to be important for their liquidity (e.g., Houweling et al., 2005). Using the model by Duffie et al. (2005) on OTC market liquidity, we provide a theoretical micro-foundation for a bond-specific economy-of-scale-effect on liquidity. We empirically confirm the existence of such an effect for issuers of both green and regular bonds.[2] As theoretically proposed by Acharya and Pedersen (2005) and empirically validated by Bongaerts et al. (2017), investors rationally incorporate expected transaction costs in

[2] It is unlikely that regular and green bonds issued by the same issuer are perfect substitutes from a liquidity perspective. An increasing part of bond trading is conducted on Request for Quote (RFQ) platforms (see e.g., O'Hara and Zhou, 2021). To trade a bundle consisting of a green and regular bond, one would need to post two requests for quotes. Most dealers on those platforms cater to institutions and hence want meaningful volumes. However, two of such requests are not guaranteed to convert both into trades, which may make dealers reluctant to bid.

their decision-making process, and thus demand a liquidity premium to compensate for anticipated and realized transaction costs. Economies of scale in bond-specific issuance sizes naturally follow.

While liquidity fragmentation is a plausible and well-documented channel for economies of scale at the bond issue level, there are also other documented channels that lead to similar economies of scale and are hence also captured by our model. For example, there are costs related to the issuance, under-writing, and rating processes of bonds. Public disclosures of credit rating fee schedules show decreasing costs to scale.[3] Similarly, Altınkılıç and Hansen (2015) document that there is a fixed, bond-specific cost component in bond underwriting costs.

In the model, the issuer rationally trades off the clientele premium against the associated increase in bond liquidity premia due to fragmentation. Moreover, when there is a mismatch between climate preferences of investors and the supply of green and brown projects, issuers also trade off smaller project volumes against with lower (per dollar) funding costs (e.g., due to a clientele premium) against higher project volumes with higher (per dollar) funding costs. This latter trade-off results from the requirement to issue bonds at a uniform price which hampers price discrimination. Since green projects can also be financed with regular bonds, this trade-off only manifests itself for green projects when the fragmentation costs of financing green projects with a regular bond are prohibitive.

We derive and characterize equilibrium types that materialize in different parameter ranges. For each equilibrium type, investors accept any offer that makes them break even in terms of expected utility. The issuer maximizes her profits, and in doing so, trades off clientele premia against liquidity premia and (potentially) project volumes.

A key finding of our analysis is that for several equilibrium types, strictly profitable projects, both brown and green, are rationed. The intuition behind this result is as follows. For the issuer, rationing projects can prevent fragmentation costs. Moreover, rationing can also allow the issuer to maximize clientele premia at the expense of project volumes. The issuer optimally rations profitable projects when the benefits of preventing fragmentation and protecting clientele premia outweigh the benefits of larger project volumes. Since green projects can also be financed by regular bonds, green projects are less likely to be rationed than brown ones. Brown projects may be rationed even with a shortage of climate investors. For this to happen, green projects need to be more profitable than brown projects such that the latter are crowded out.

A key question our model can speak to is how the availability of green bonds affects equilibrium outcomes and welfare. To this end, we compare equilibrium types with and without the possibility of issuing green bonds. Intriguingly, we find that the effect of green bond availability on both the number of projects undertaken and welfare is ambiguous.

On the one hand, green bonds allow issuers to price-discriminate, thereby lowering funding costs and increasing the number of projects undertaken. This happens when green projects are only made profitable by the clientele premium. By catering to investor preferences, green bonds may also expand the total investor base and thereby reduce the rationing of brown projects that would otherwise be crowded out by more profitable green projects. This is particularly relevant when climate investors are in short supply and have very strong preferences against investing in brown projects.

On the other hand, the availability of green bonds may lead to profitable projects of either type being rationed. The intuition is that the clientele premium makes it less attractive for an issuer to fund all projects with a single bond issue (which must be a regular bond). For brown projects, this may lead to an increase in liquidity premia that potentially renders the project unprofitable. This effect is particularly likely if fragmentation costs are high. For green projects, the incentive to protect clientele premia may give rise to rationing that would not be there in the absence of green bonds. This effect is particularly present with a shortage of climate investors, strong preferences of climate investors, and unprofitable brown projects. The latter condition prevents excess green projects from being financed by a regular bond, since they cannot be part of a larger bond issue that also funds brown projects (since brown projects are unprofitable).

In the model, funding costs are zero-sum transfers between investors and the issuer. Similarly, transaction costs are zero-sum transfers between investors and dealers. Consequently, aggregate individual welfare increases in the number of projects as well as the economic surplus they create (project NPV net of the non-monetary utility components of investors). By contrast, the environmental welfare contribution increases in the number of green projects undertaken, but decreases in the number of brown projects undertaken. Combined with the fact that green bonds can increase and decrease the number of green and brown projects, it follows that the impact of the green bonds on market outcomes is ambiguous and dependent on model parameters.

The model also allows us to investigate the effects of changes in the prevalence of climate investors and the strength of their preferences. As such, we can use the model to evaluate policies and societal trends that affect the prevalence of climate investors and the strength of their preferences. Such policies and trends include regulations (e.g., coverage and strength of regulations) as well as social norms, movements, and stigmas (e.g., political correctness norms). The model shows that the impact of changes in the prevalence and strength of climate investors' preferences have ambiguous effects on individual and environmental welfare. For example, an increase in the strength of climate investors' preferences for financing green projects can lower the funding costs of green projects leading to more green projects being undertaken. However, it also increases clientele premia and may thereby incentivize the issuer to ration profitable green projects in certain situations.

The aforementioned discussion shows the limitations of the green bond security design. The trade-off of clientele premia against project volumes arises because of the requirement of a uniform price on a debt instrument, which impairs perfect price discrimination. The trade-off between issuance volume (and hence lower fragmentation) and clientele premia arises from the binary nature of earmarking (a green bond requires all of the money raised to be spent on green projects). We propose a different security

[3] See e.g., https://www.dothan.org/AgendaCenter/ViewFile/Item/8230?fileID=17855

design that reduces both frictions. Specifically, we recommend separating the cash flow and earmarking features of green bonds, essentially unbundling them. 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.

Specifically, we propose to have all or most projects financed by a single combined (and therefore large) bond issue. This way, fragmentation is avoided. The proceeds of this issue can be partially earmarked for environmentally friendly projects by issuing so called green certificates. These certificates solely certify that the notional amount stated in each certificate is used for environmentally friendly projects. These green certificates can be issued and traded separately and provide investors exclusive green reporting rights. This way, the issuer can capitalize on the clientele effect, while avoiding the costs of fragmentation (i.e., the issuer can engage in perfect and costless price discrimination based on positive environmental preferences).[4] Following the circulation of an early version of our paper, the Sovereign debt issuance office of the Danish Central Bank is seriously considering the use of green certificates. The office mentions liquidity fragmentation avoidance as an explicit motivation.[5]

We use our model to show that using green certificates instead of green bonds leads to equilibrium types with (often strictly) higher individual welfare. Environmental welfare with green certificates is, in most cases, also higher than with green bonds.[6] Yet, in certain situations, green certificates may increase the number of brown projects and thereby have a negative environmental contribution (relative to green bonds).

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 to theoretically 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 signaling devices for commitment to sustainable policies. Since the mechanisms at play in their paper are different from ours, the two papers are complementary to one another.

Our analyses can also, at least in part, explain the empirically documented low yield discount of green bonds[7] by pointing out fragmentation effects. Our results are also consistent with the limited documented effectiveness of green bonds as well as policies and regulations aimed at making investors care more about the environmental contribution of their investments (Berensmann et al., 2018; ElBannan and Löffler, 2024). In fact, we show that the security design of green bonds can actually decrease environmental welfare. 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 investor tastes and clienteles for different asset types. Dybvig and Ross (1986) provide the theoretical underpinnings for clientele effects in asset prices. There is a large literature on tax clienteles and asset prices, started by Elton and Gruber (1970). Several empirical studies provide evidence of such tax clientele effects in a variety of markets by looking at investor holdings (e.g., Graham and Kumar, 2006; Dahlquist et al., 2014), investor tax bills (e.g., Kawano, 2014), or prices, trading volume, and returns (e.g., Gay and Kim, 1991; Schaefer, 1982; Ferris and Reichenstein, 1988; Seida, 2001). Other studies investigate the empirical or theoretical impact of such clientele effects on the cost of capital (e.g., Kim and Stulz, 1988), capital structure decisions (e.g., Zechner, 1990), and dividend policy (e.g., Allen et al., 2000). Besides tax clienteles, the literature has also looked at risk clienteles (e.g. Blackburn et al., 2009), liquidity clienteles (e.g., Lipson and Mortal, 2006; Chen et al., 2020; Dhar et al., 2004; Amihud and Mendelson, 1986), bond maturity clienteles (e.g., Guibaud et al., 2013; Butler et al., 2019), religious alignment (e.g. Shafron, 2019), and, more recently, clienteles with respect to sustainability of security issuers (e.g., Friedman and Heinle, 2016).

We contribute to this literature by presenting a model in which both financing and business decisions depend on clientele effects. We let business decisions rely on clientele effects by linking revenues from green debt instruments to green projects and then include a volume versus clientele premium trade-off in the model. While the model could conceptually also be applied to some other forms of investor clienteles (e.g., dividend clienteles with high current cash-flow projects, bond maturity clienteles with project horizons, or liquidity clienteles with project opacity), we are unaware of any studies doing so.[8] Since we look at bond markets, an issuer

[4] Note that the ability to price-discriminate based on negative environmental preferences (i.e., reluctance to invest in brown projects) is unaffected by green certificates.

[5] See http://www.nationalbanken.dk/en/governmentdebt/IR/Pages/Model-for-sovereign-green-bonds.aspx and https://research.danskebank.com/abo/FIStrategyDenmarkDanishGreenbond051219/%24file/FIStrategy_Denmark_Danish_Green_bond_051219.pdf

[6] While similar to derivatives in terms of stripping, our green certificates are positive and not zero-net-supply assets. Our results therefore imply that in most situations green certificate financing should fully replace green bond financing. For the CDS market, however, full replacement is infeasible since CDS are in zero-net-supply and an underlying benchmark is needed. 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.

[7] See e.g., Baker et al. (2022), Zerbib (2019), Gianfrate and Peri (2019), Flammer (2021), Tang and Zhang (2020), Warmath (2021), Caramichael and Rapp (2022), Benincasa et al. (2023).

[8] Note that because projects are linked to financing instruments, the model does not extend to all settings with heterogeneity in investors' preferences. The clientele premium versus volume trade-off would, for example, be absent in a setting with A and B shares (with different voting rights) since there is no direct link between voting rights and the possibility to undertake certain types of projects.

trying to capitalize on the clientele effect is faced with increased fragmentation and hence trades off low transaction costs and the associated low liquidity premia against clientele premia. We are not aware of any study including or mentioning such a trade-off either.

2. Setup

We set up a model for the market for regular and green debt instruments. There is a profit-maximizing issuer with a total supply of projects equal to unity, split between a mass $\kappa_G \in [0,1]$ green projects and $1-\kappa_G$ brown projects. 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). We set the net profitability of brown projects to β. Green and brown projects are in all other aspects identical.

The issuer can finance her projects by making a one-time take-it-or-leave-it offer in the primary market for regular and/or green bonds. A green bond can only finance green projects, while a regular bond can finance brown and/or green projects. During the issuance process, the issuer sets the masses of green projects to be financed by green bonds ($V_{G,GB}$), brown projects to be financed by regular bonds ($V_{B,RB}$), and green projects to be financed by regular bonds ($V_{G,RB}$) (these are collected in the vector V). Simultaneously, she quotes take-it-or-leave-it yield offers y_{RB} and y_{GB} for the regular and green bonds, respectively (these are collected in the vector y). The issuer maximizes expected profits which are defined by

$$\Pi = V_{G,GB}(\beta+\xi-y_{GB}) + V_{G,RB}(\beta+\xi-y_{RB}) + V_{B,RB}(\beta-y_{RB}), \tag{1}$$

assuming all issued bonds are sold. There are negligible but strictly positive issuance costs that increase in issue volume to make sure that issuers do not issue larger volumes than can be expected to be bought.

The issuer offers her bonds to a continuum of atomistic investors. The continuum is again of unit size. The investor population is split into a mass $\pi_c \in [0,1]$ climate investors and a mass $1-\pi_c$. Hence, 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.[9] By assumption, investors are 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 (or have a distaste) of $\phi \geq 0$ when investing in a security that is not green. We also refer to ζ and ϕ as non-monetary preference offsets. Regular investors experience a negligible but strictly positive convenience yield from investing in a green debt security.[10] Expected utility for investors is linear and consists of expected returns, net of any anticipated costs, and non-monetary (dis)utility of investment choices. Investors optimize their expected utility with respect to their investment choices.

Green and regular bonds trade in secondary OTC markets which are not perfectly liquid. Following Acharya and Pedersen (2005) investors anticipate transaction costs s_j (on a per dollar per annum basis) for each bond j which are assumed to be inversely proportional to its issue size:

$$s_{GB} = \frac{b}{V_{G,GB}},$$
$$s_{RB} = \frac{b}{V_{G,RB}+V_{B,RB}}, \tag{2}$$

where b is a positive constant. We micro-found this assumption in Appendix A theoretically using a model for liquidity in OTC markets and validate it empirically in Appendix D. One can show that under this assumption, fragmenting a single large funding need by issuing two bonds increases total transaction costs by a factor of two.

3. Equilibrium analysis

In this section, we provide an equilibrium definition and subsequently solve for the equilibrium. We solve backwards. First, we derive optimal responses of investors that are faced with yield quotes y_{GB} and y_{RB}. 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 focus on symmetric equilibrium types in which all investors of the same type act identically. We assume that investors play a threshold strategy for accepting investment offers.[11] Each investor i decides on investment thresholds $\theta_{i,j}$ for yield y_j on each bond $j \in \{GB, RB\}$ so as to maximize utility. For notational convenience, all threshold levels for an investor i are collected in a vector θ_i.

The issuer allocates the funding needs of her projects to the different possible bond issues according to V and makes a take-it-or-leave-it offer with yields y so as to maximize expected profits. A (Nash) equilibrium is then defined as a tuple $((V^*, y^*), \theta^*)$, a point at which the issuer nor any of the investors finds it optimal to deviate from the chosen strategy given the strategy of the others.

[9] 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.

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

[11] We show in the proof of Lemma 1 that such trigger strategies are optimal.

3.2. Optimal investor strategies

We now solve for the equilibrium backwards. We start by solving for the optimal strategy of investors. Investors optimally accept bond offers if the expected utility resulting from doing so is positive. Their expected utility consists of monetary and non-monetary components. The monetary components are the 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 gives rise to a relatively simple optimal strategy for investors.

Lemma 1. *An investor of type i optimally invests in a security j if the quoted yield y_j exceeds a threshold $\theta^*_{i,j}$ that ensures positive utility. The optimal threshold is given by*

$$\theta^*_{i,j} = s_j - \zeta I_{c,GB} + \phi I_{c,RB}. \tag{3}$$

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 C. ■

The intuition for the result in Lemma 1 is as follows. In order for an investor to have positive utility, the quoted yield must at least compensate for expected transaction costs (s_j) and disutility from investing in regular bonds if applicable ($\phi I_{c,RB}$). Any convenience yield from investing in green bonds ($\zeta I_{c,GB}$) lowers the threshold as the climate investor gets a benefit from investing in a green bond through a different channel than interest payments.

3.3. Optimal issuer strategies and equilibrium

In this section, we take the optimal investor strategies from Lemma 1 as given and derive optimal issuer strategies and thereby fully characterize an equilibrium. As we will see, equilibrium types differ depending on parameters related to liquidity, preferences of climate investors, and the degree to which demand and supply of capital are matched.

3.3.1. Optimal pricing

The issuer strategy consists of setting prices and volumes for the different types of bonds. We first derive the optimal pricing strategy of the issuer as a function of project-bond volume choices. In the next section, we optimize project volume choices of the issuer taking the optimal pricing strategy as given.

Because of the take-it-or-leave-it market structure, the issuer can capture all the surplus of the marginal investor in a given security, and optimally sets the yield such that the utility of the marginal investor equals zero. In other words, the issuer optimally quotes a yield y_j equal to the optimal investment threshold $\theta^*_{i,j}$ of the marginal investor (in this case i). Which investor is the marginal investor depends of course on the issuance volumes of both bond types relative to the population masses of both investor types.

Lemma 2. *The issuer optimally quotes yields equal to the acceptance thresholds of the corresponding marginal investors. That is,*

$$y^*_{GB} = \begin{cases} \theta^*_{c,GB}, & \text{if } V_{G,GB} \le \pi_c, \\ \theta^*_{r,GB}, & \text{otherwise}. \end{cases} \tag{4}$$

$$y^*_{RB} = \begin{cases} \theta^*_{c,RB}, & \text{if } V_{B,RB} + V_{G,RB} \ge 1 - \pi_c, \\ \theta^*_{r,RB}, & \text{otherwise}. \end{cases} \tag{5}$$

Proof. See Appendix C. ■

We continue by deriving optimal project volume and allocation decisions given optimal investment and pricing decisions derived in Lemmas 1 and 2.

3.3.2. Project allocations and equilibrium types

In this section, we derive the optimal project to bond allocation for the issuer given her optimal pricing rule and the optimal investment policy of investors. This completes the equilibrium derivation.

The issuer optimally allocates funding to projects so as to maximize aggregate profits. In the absence of fragmentation costs (or other economies of scale in issue size) the issuer would optimally use green and regular bonds to perfectly price-discriminate in obtaining funding for profitable projects. Liquidity fragmentation prevents the issuer from effectively doing this. As a result, funding costs increase due to liquidity premia and compensation payments for allocative mismatches. Moreover, the issuer could optimally engage in substantial degrees of project rationing. The following proposition spells out the effects on project financing and uptake.

Proposition 1. *The issuer optimally undertakes projects only if these are profitable net of funding costs. Profitable projects are optimally financed by a large regular bond if benefits from the lack of fragmentation outweigh clientele effects. Otherwise a combination of green and regular bonds are used.*

Profitable regular projects are rationed in equilibrium with

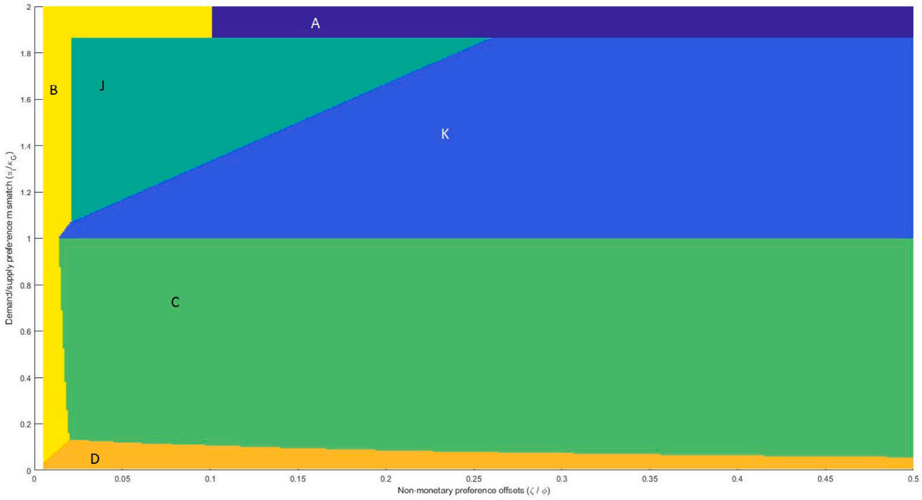

Fig. 2. Equilibrium regions with high profitability of all projects.
The graph displays the different equilibrium regions as a function of non-monetary preference offsets (ζ and ϕ, which are set equal to one another for exposition purposes) and the degree of preference mismatch in the demand and supply for green and brown projects (summarized by π_c/κ_G). The dark blue area (A) corresponds to equilibrium types with only climate investors investing in green bonds, the yellow area (B) to both investor types investing in a large regular bond financing all projects, the green area (C) to a green bond financing green bonds and a regular bond financing both types, the dark orange area (D) to a regular bond financing all brown projects and some green projects, the aqua area (J) to climate investors financing a green bond and climate and regular investors financing a regular bond, and the middle blue area (K) to climate investors financing a green bond and regular investors financing a regular bond with only brown projects. The other parameters are given by $\beta = 0.3$, $\xi = -0.0000001$, $\kappa_G = 0.5$, and $b = 0.02$.

1. *an excess of climate investors* ($\frac{\pi_c}{\kappa_G} > 1$) *and large* ϕ*, or*
2. *a shortage of climate investors* ($\frac{\pi_c}{\kappa_G} < 1$)*,* $\xi \geq 0$*, a large* ϕ*, and high costs of fragmentation.*

Profitable green projects are rationed in equilibrium with a shortage of climate investors ($\frac{\pi_c}{\kappa_G} < 1$) *and in addition*

1. *profitability purely resulting from clientele effects in funding, or*
2. *large clientele effects in funding, high costs of fragmentation, and brown projects being unprofitable, or*
3. $\xi < 0$ *and a large* ϕ*.*

Proof. See Appendix C. ■

The intuition for the results on rationing in Proposition 1 is as follows. With an excess of climate investors, the funding costs for all profitable brown projects increases by ϕ if the marginal investor in the regular bond is a climate investor. As a result, the issuer may be better off rationing brown projects to protect profit margins if the increase in number of projects financed at a funding rate increase of ϕ is only moderate (even if financing all projects is feasible and profitable). This effect is clearly illustrated in Fig. 2 (the rationing happens in the middle blue area K which expands with the strength of climate investors' preferences).

With a shortage of climate investors, the mechanism for green bonds is similar, but more subtle, since green projects can also be funded by regular bonds. This ability may allow the issuer to still capture clientele premia for some but not all green projects. As a result, rationing takes place in two cases. First, it happens when green projects are only profitable due to clientele effects resulting from ζ (which is a trivial case). Second, it happens when it is feasible and profitable to finance all green projects, but more profitable to ration green projects due to the opportunity to capture larger clientele premia. Since green projects can also be financed by regular bonds, high clientele premia and a shortage of climate investors are not enough to get such rationing. In addition, there should be no scope to combine the residual green projects with regular projects in a regular bond to contain fragmentation costs. This happens when brown projects are not profitable. The latter situation is depicted in Fig. 3. The figure clearly shows how higher green preferences lead to more severe rationing of green projects in this situation (the rationing happens in dark blue area A which expands with the strength of climate investors' preferences).

Finally, it could also be that π_c and/or ζ are so small that it makes no sense for the issuer to issue a separate green bond. In that case, a combined regular bond is an option. If also issued to climate investors, the funding costs of all projects increases with ϕ to offset climate investors' disutility. The issuer may therefore find it optimal to only issue it to regular investors and hence investment capacity is limited. The issuer optimally prioritizes the most profitable projects. Therefore, green projects are rationed if less profitable ($\xi < 0$) and brown projects are rationed otherwise ($\xi \geq 0$). This effect is illustrated in Fig. 4. In the figure, one can see that when ϕ is small, doing a combined regular bond to finance *all* projects (yellow area B) is optimal for the issuer. Yet, as ϕ grows, the costs for doing so become prohibitive. If ζ and/or π_c are low, giving up the clientele premium does not hurt much and projects are rationed (orange area D). If ξ is negative, green projects are rationed, and if ξ is positive, regular projects are rationed.

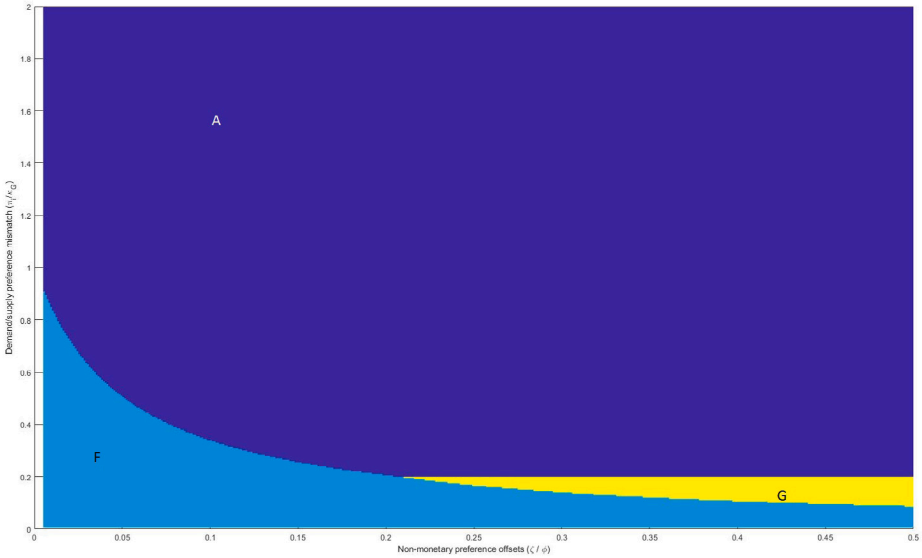

Fig. 3. Equilibrium regions with negative profitability of brown projects.
The graph displays the different equilibrium regions as a function of non-monetary preference offsets (ζ and ϕ, which are set equal to one another for exposition purposes) and the degree of preference mismatch in the demand and supply for green and brown projects (summarized by π_c/κ_G). The dark blue area (A) corresponds to equilibrium types with only climate investors investing in green bonds, the light blue area (F) to only green bonds being issued and financed by climate and regular investors, and the dark yellow area (G) to climate investors financing a green bond and regular investor financing a regular bond that finances green projects only. The other parameters are given by $\beta = -0.01$, $\xi = 0.06$, $\kappa_G = 0.5$, and $b = 0.02$.

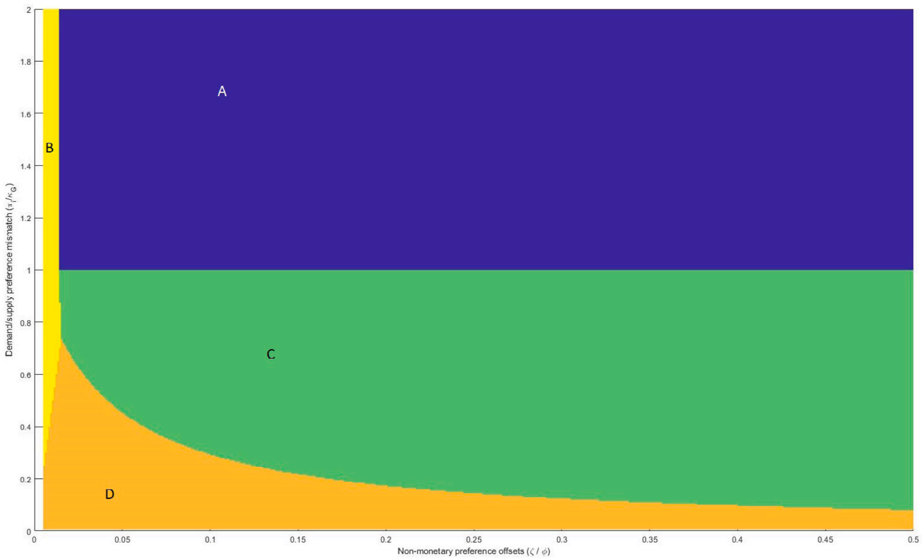

Fig. 4. Equilibrium regions with low profitability of all projects.
The graph displays the different equilibrium regions as a function of non-monetary preference offsets (ζ and ϕ, which are set equal to one another for exposition purposes) and the degree of preference mismatch in the demand and supply for green and brown projects (summarized by π_c/κ_G). The dark blue area (A) corresponds to equilibrium types with only climate investors investing in green bonds, the yellow area (B) to both investor types investing in a large regular bond financing all projects, the green area (C) to a green bond financing green bonds and a regular bond financing both types, and the dark orange area (D) to a regular bond financing all brown projects and some green projects. The other parameters are given by $\beta = 0.04$, $\xi = -0.000001$, $\kappa_G = 0.5$, and $b = 0.02$.

4. Welfare, trends, and policies

In this section, we evaluate the individual and environmental welfare effects resulting from the availability of green bonds and those resulting from changes in regulations and investor preferences. We start by splitting welfare into 'individual welfare' (related to agents' utility functions within the context of the model) and environmental welfare (related to the climate impact of projects undertaken). Next, we analyze how equilibrium outcomes in terms of individual and environmental welfare are affected by the availability of green bonds and by recent trends and regulations (which correspond to changes in model parameters).

4.1. Welfare definitions

We measure aggregate individual 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 the issuer (or the other way around if negative). Similarly, transaction costs are zero sum transfers from investors to dealers, in line with the micro-foundations provided in Appendix A. Since transaction costs are purely the result of dealer bargaining power, one should only consider the volume and operational profitability of projects as well as the non-monetary offsets for investors for individual welfare calculations. Hence, aggregate individual welfare is given by

$$WF = W_{c,G}(\beta + \xi + \zeta) + W_{r,G}(\beta + \xi) + W_{c,B}(\beta - \phi) + W_{r,B}\beta, \tag{6}$$

where $W_{i,k}$ denotes the amount of capital raised from investor type i which is allocated to project type k.

Similarly, we can measure environmental welfare as

$$EC = (W_{c,G} + W_{r,G}) - \tau(W_{c,B} + W_{r,B}), \tag{7}$$

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 is denoted by $\tau \geq 0$.[12]

4.2. Implications of the possibility to issue green bonds

We start by analyzing the individual welfare implications of the opportunity to issue green bonds. We can obtain a benchmark for the situation without green bonds by removing any benefit for climate investors to buy green bonds relative to regular bonds. In that situation there is no scope for clientele effects and hence, fragmentation is optimally minimized because it is costly. Below, we show that this situation is a special case of our model.

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

Proof. See Appendix C. ■

We can now compare the setting with and without green bonds to see how the availability of green bonds affects market outcomes. As it turn out, the impact of green bond availability on individual and environmental welfare is not always positive and more ambiguous than one would expect.

Proposition 2. *The possibility to issue green bonds has an ambiguous effect on the number of green and brown projects undertaken and therefore on individual and environmental welfare.*

In particular, the ability to issue green bonds can ***reduce*** *the number of green projects financed and thereby reduce individual and environmental welfare. It can also* ***increase*** *the number of brown projects financed and thereby increase individual welfare but reduce environmental welfare.*

Proof. See Appendix C. ■

One of the possible consequences of being able to issue green bonds is the (envisioned) increase in green projects due to lower funding costs that are in turn facilitated by the ability to price discriminate. In this case, individual and environmental welfare both increase. Yet, as Proposition 2 shows, there are also other possible outcomes. We discuss some of the more intriguing ones in more detail below.

First, with a shortage of climate investors, green bonds may lead to rationing of green projects, despite the possibility of green projects to be financed by regular bonds. Such rationing happens when the green clientele premium is high (and therefore not worth losing by issuing a green bond to regular investors) and a small regular bond issue is not profitable due to a fragmentation-induced liquidity premium. In the absence of green bonds, green projects would have been financed by a regular bond, and, since liquidity premia are decreasing in size, the issuer would in that case raise financing for all green projects at once.

Second, when climate investors strongly dislike regular bonds (high ϕ), but green projects are profitable, regular investors would, in the absence of green bonds, optimally finance all green projects and ration brown projects (even if these are also profitable). Yet, with green bonds, the green projects would be financed by climate investors and there is capacity freed up from regular investors that now finance all brown projects. Since projects are better allocated and more projects are financed, individual welfare increases. Yet, since the number of green projects is unchanged and more brown projects are undertaken, environmental welfare suffers.

Third, if brown projects are only profitable if financed by a large bond issue with a low liquidity premium, green bond-induced fragmentation reduces the number of brown projects. Thereby, it helps to increase environmental welfare potentially at the expense

[12] One should note that in our way of parameterizing individual and environmental welfare, we made the implicit assumption that the effects of ζ and ϕ are psychological and should be counted over and above the environmental welfare per se.

of individual welfare (which goes down due to fewer brown projects but up due to higher non-monetary benefits of climate investors).

Finally, 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. Interestingly, however, aggregate individual welfare is positively affected, since green bonds create additional (non-monetary) utility for climate investors.

4.3. Implications of regulations and preference changes

We can also analyze the effect of regulations and trends in society to promote environmentally friendly investments in a setting in which green bonds are available. Yet, as the previous section shows, the effects of the ability to issue green bonds on individual and environmental welfare are ambiguous. There is a similar ambiguity in the effects of the strength and prevalence of environmental preferences of investors.

Corollary 2. *An increase in the prevalence (π_c/κ_G) or strength (ζ, ϕ) of environmental preferences has an ambiguous effect on the number of green and brown projects undertaken and therefore on individual and environmental welfare.*

Proof. See Appendix C. ■

A regulator (or NGO) seeking to increase the volume of environmentally friendly projects through investments must look at π_c/κ_G, ζ, and ϕ together rather than in isolation. Regulators can change these model parameters as follows. The prevalence of climate investors can be increased by making the costs or revenues of regular business processes that involve debt securities climate dependent (this works particularly well for regulated financials). For example, one could give banks that pledge bonds with the central bank for a collateralized loan a better rate or lower haircut when the collateral is a green bond (which would correspond to ζ) and a higher rate or haircut when it is a regular bond (which would correspond to ϕ). Another example would be in Quantitative Easing (QE) programs to have an increased appetite and willingness to pay for green bonds and a decreased appetite and willingness to pay for regular bonds (see also Schoenmaker, 2021). Finally, NGOs could try to affect these parameters by the coverage breadth (for π_c/κ_G) and intensity (for ζ, and ϕ) of their media campaigns.

The model shows that green projects are never rationed with an excess of climate investors. Therefore, if a regulator has sufficient control over π_c/κ_G, the number of green projects can be maximized by ensuring that $\pi_c/\kappa_G \geq 1$. Moreover, if the regulator also has sufficient control over ϕ, it can at the same time also ensure that ϕ is sufficiently large for brown projects to be rationed. These effects are the envisioned effects of green bonds.[13]

Yet, if there is insufficient control over π_c/κ_G and it remains at a level below unity, the effectiveness of various measures becomes less predictable, more subtle, and highly dependent on other model parameters. For example, giving a stronger disincentive to hold regular bonds (an increase in ϕ) in this situation could indeed lead to a rationing of brown projects if green projects are more profitable and fragmentation is costly. Yet, it could instead also lead to a rationing of green projects, with the opposite effect on environmental welfare when either ζ is large, fragmentation is costly, and brown projects are not profitable, or when green projects are less profitable than brown ones ($\xi < 0$).

One can of course also turn the discussion above around and try to learn about the deeper model parameters by observing market outcomes around regulatory changes (and then adjust policies where necessary). For example, if a regulatory increase in ϕ is followed by green project rationing (a decline in green bonds issued and green projects undertaken), one would infer that climate investors are in short supply ($\pi_c/\kappa_G < 1$). This important information as in such a situation supplementary measures that focus on green project profitability ξ could help in converting green rationing into brown rationing. Similarly, in case of a reduction in green projects following an increase in ζ, one would conclude that there is a shortage of climate investors, fragmentation costs are high and brown projects are unprofitable. It would also lead to the conclusion that ζ had become unnecessarily high. Hence, ζ could be lowered again. Alternatively, one could try to implement a supplementary policy that (sufficiently) increases the number of climate investors or reduces fragmentation costs. A supplementary policy that increases profitability of brown firms would also help, but would also increase the number of brown projects undertaken.

5. Alternative forms of green debt

The limitations of green bonds in achieving an optimal allocation of funds to projects originate from the inability of the issuer to effectively price discriminate across lenders within the same issuance.[14] With the availability of green bonds, the issuer is able to price discriminate, but price discrimination is imperfect if there is a demand/supply imbalance for green debt ($\pi_c/\kappa_G \neq 1$). Moreover, price discrimination achieved this way comes with costly fragmentation of debt issues.

[13] Note that there are typically individual welfare costs of rationing brown projects and a regulator would need to trade these off against the environmental welfare gains.

[14] Note that in reality, an issuer may be able to partially price-discriminate, for example by staged issuance. The non-monetary offsets ζ and ϕ in the model then reflect the net or residual scope for price discrimination.

In this section, we introduce a different type of financial contract that also achieves price-discrimination along the lines of environmental preferences of investors, but that we show achieves 1.) perfect price discrimination w.r.t. preference for green investments, and 2.) comes with lower or no fragmentation costs.[15]

The contract we propose we call a green certificate and would be issued in limited supply along with a regular bond issue. Each green certificate obliges the issuer to entirely dedicate the proceeds of one (unit of) bond to green projects. In essence we decompose, or strip, a green bond this way into a regular bond and a certificate that solely arranges green earmarking. The issuance of such green certificates can easily be incorporated into the regular issuance process.[16] Our proposed green certificates do not come with any direct cash flow rights, but do grant the holder green reporting rights (which may entitle the holder to indirect or derived cash flow rights such as subsidies or tax-breaks). Hence, the value of these certificates depreciates to zero over the maturity of the bond. These green certificates could in principle also be traded in the secondary market because of which it is still possible to realize capital gains on the certificates. The price of the certificate would then be an indication of the greenness of the project(s) financed by the bond issue, just like the price of a CDS is an indication of the credit quality of the issuer of the underlying bonds.

With this structure, all projects can be financed with a large regular bond issue with no or only minimal misaligning of climate investor preferences. Hence, the issuer can capture in most cases the full clientele premium without having to fragment bond issues or ration projects. We next formalize the impact of this security design on equilibrium types and market outcomes.

Proposition 3. *The issuer optimally sells green certificates with a yield discount equal to $y_{GC} = \theta^*_{c,GC} = -\zeta$ to climate investors only. With green certificates, there is no fragmentation, liquidity premia are smaller, and more projects, green and brown, are undertaken.*

Profitable brown projects can still be rationed with an excess of climate investors and a large ϕ, but not anymore with a shortage of climate investors.

Green projects are only rationed with a shortage of climate investors ($\frac{\pi_c}{\kappa_G} < 1$) and profitability of green projects purely resulting from clientele effects in funding.

Proof. See Appendix C. ■

The intuition for more projects being undertaken is as follows. Green certificates make green bonds redundant for price discrimination. In the presence of fragmentation, large regular bond issues with green certificates are always better for the issuer because these bonds are more liquid and hence liquidity premia are lower. As a result, more projects become profitable and are therefore undertaken.

The rationale for rationing regular projects is the same as before, namely the trade-off of between project volumes and avoiding yield mark-ups to compensate climate investors. Projects for which the profitability purely depends on clientele effects ζ are still be rationed with a shortage of climate investors as there is no way that price discrimination can generate funding for all projects such that investors at least break even and all projects are profitable for the issuers.

Since green certificates prevent fragmentation of bond issues, generally, more (or the same number of) projects will be undertaken, allocation is improved, and individual welfare will be higher than with green bonds. The associated increase in the volume of green projects is an improvement for the environmental welfare. The associated increase in the volume of brown projects reduces environmental welfare, which can outweigh the positive environmental contribution of the increased number of green projects if the environmental costs τ are sufficiently large.

Proposition 4. *Compared to a system with green bonds green certificates improve individual welfare but the effect on environmental welfare is ambiguous.*

Proof. See Appendix C. ■

The analysis above shows that using regular bonds paired with green certificates is conceptually optimal for the issuer. That said, there may be frictions that stand in the way of the adoption of green certificates as replacements for green bonds. One of the main concerns with green certificates is that they only derive value from the earmarking and depreciate in value to zero as the bond matures. This makes it very transparent to investors how much they pay for greening their debt investments. By contrast green bonds are often marketed as a costless way for greening investments since the clientele premium is hard to estimate and therefore intransparent. If regular investors indeed (incorrectly) believe green bonds to be equally profitable as regular bonds, issuers may be able to place green bonds with regular investors that have no fundamental demand for them. In this context, issuers may object to transparent green certificates, especially if they already issue large green and regular bond issues to begin with. Hence, an individual issuer may have private incentives to resist superior security design at the expense of aggregate individual and environmental welfare. This creates a potential scope for legislative and regulatory bodies to provide an institutional framework to counter such behavior. At the very least this would entail the same regulatory status of green bonds and regular bonds paired with green certificates. Other regulatory measures could include mandating more precise indications of yield discounts in green bond prospectuses or a mandatory move from green bonds to green certificates.

[15] For the purpose of our analysis, we assume that these contracts come with no fragmentation costs; results continue to hold when this assumption is relaxed as long as fragmentation costs do not become gigantic.

[16] Ultimately, we envision that it becomes a market standard for every bond prospectus to indicate for which fraction of the issue green certificates are issued. The ability to incorporate green certificates in the regular issuance flow would likely stimulate adoption. Being part of such a standard flow also justifies a relatively high liquidity for these certificates.

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.

6.2. Other issuer benefits of green bonds

In this study, we explore 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 in reduced form by adding a constant ν to the issuer utility when issuing a green bond, or equivalently by increasing ζ 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 and lead to supply-side rationing of green (and brown) projects. The existence of green bonds gives rise to trade-offs for issuers related to clientele, liquidity fragmentation, and market power effects on bond yields. As a consequence, we show that the availability of green bonds as a security type has an ambiguous effect on the volumes of green and brown projects undertaken in equilibrium and thereby on individual and environmental welfare. We also show that an alternative security design that decouples green earmarking from cash flow rights is in most situations superior to green bonds in terms of individual and environmental welfare because it reduces frictions related to fragmentation and the inability to set differentiated prices.

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.

CRediT authorship contribution statement

Dion Bongaerts: Writing – review & editing, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft. **Dirk Schoenmaker:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Only for Appenidx C and D data has been used. Code compatible with the appropriate data (given license) on WRDS will be made available.

Appendix A. Micro-foundations for fragmentation in OTC markets

The markets for green and regular bonds are OTC markets intermediated by dealers as described in Duffie et al. (2005). In this section, we provide micro-foundations for the reduced-form way of modeling OTC liquidity fragmentation in Section 2.

Let us start by assuming that any green or regular bond trades in a secondary OTC markets need to go through a dealer (which largely conforms to market practice). By assumption, the expected bond turnover rate Q is the same for all bond and investor types. Duffie et al. (2005), show that transaction costs in such markets depend on dealer bargaining power. Now assume that all regular and green bonds are homogeneous in this market except for their size and dealer bargaining power. In particular, assume that dealer bargaining power z_j for bond j is inversely proportional to bond size S_j:

$$z_j = \frac{a}{S_j}, \tag{8}$$

where a is a strictly positive constant. This way, dealer bargaining power and therefore bond liquidity only vary with bond size. Intuitively, one would indeed expect smaller markets to be more concentrated leading to higher dealer bargaining power.[17]

We can now combine the assumption that dealer bargaining power is inversely proportional to bond size (Eq. (8)) with the results from Duffie et al. (2005) to obtain closed-form expressions for round-trip transaction costs s in the secondary OTC market.

Lemma 3. *The round-trip transaction costs σ for a bond of size S are given by*

$$\sigma = \frac{\mu}{d + S}, \tag{9}$$

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

Proof. See Appendix C. ■

As one can see, transaction costs in Eq. (9) decrease in issue size. 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 $Q\sigma_j$ 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 single (and therefore large) regular bond issue. These projects could also be financed by a smaller 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. Under the micro-foundations provided here, fragmentation increases funding costs arising from liquidity premia by a factor of around 2.

Lemma 4. *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. This result is independent of the relative sizes of the green and brown projects.*

Proof. See Appendix C. ■

Lemma 4 shows that there is a costs of fragmentation that results from the economies of scale in individual bond issue sizes. In Appendix D, we verify empirically that liquidity is indeed increasing with issue size for both green and regular bonds in a sample of bonds issued by issuers that use both types of bonds. In this OTC market framework, changing the market power of dealers leaves the bond turnover unaffected. The functional form we adopt in Section 2 corresponds to the limit of $Q\sigma_j$ as d goes to zero. In this limit, the factor by which transaction costs increase with fragmentation converges to 2.

Appendix B. Supplementary lemmas

This section contains supplementary lemmas that are used in the proofs for Propositions 1 and 3. These lemmas contain all technical details behind Propositions 1 and 3 and allow these propositions to remain informal and intuitive.

For Proposition 1, we first derive optimal volume allocations if we restrict green projects from being financed by regular bonds in Lemma 5. Lemma 6 then shows what happens when this constraint is relaxed.

With the availability of green certificates, the result in Lemma 5 remains the unchanged. Hence, it is sufficient for Lemma 8 to show how the result of Lemma 6 changes.

[17] This could, for example, be the result of fixed operating costs for dealers to be present in a market for a given security.

Lemma 5. *Assume the constraint $V_{G,RB} = 0$. In equilibrium, investors act according to Lemma 1 and the issuer optimally offer yields y as in Lemma 2 and sets $V = V^*$, where*

$$V^* = \begin{cases} (0,0,0), & \text{if (13) to (16) violated} \\ (\min(\pi_c,\kappa_G),0,0), & \text{if (14) and [(12) or (18)] satisfied and (13) violated} \\ (0,\min(1-\pi_c,1-\kappa_G),0), & \text{if (13) and [(11) or (17)] satisfied and (14) violated} \\ (\min(\pi_c,\kappa_G),\min(1-\pi_c,1-\kappa_G),0), & \text{if (13), (14), [(11) or (17)] and[(12) or (18)] satisfied} \\ (\kappa_G,0,0), & \text{if (13), (12), (18) violated and (16) satisfied} \\ (0,1-\kappa_G,0), & \text{if (14), (11), (17) violated and (15) satisfied} \\ (\kappa_G,1-\kappa_G,0), & \text{otherwise.} \end{cases} \tag{10}$$

with conditions

$$1-\pi_c \geq 1-\kappa_G \qquad \text{[Capacity brown]} \tag{11}$$

$$\pi_c \geq \kappa_G \qquad \text{[Capacity green]} \tag{12}$$

$$\beta - \frac{b}{\min(1-\pi_c,1-\kappa_G)} \geq 0, \qquad \text{[Profit brown]} \tag{13}$$

$$\beta + \xi - \frac{b}{\min(\pi_c,\kappa_G)} + \zeta \geq 0, \qquad \text{[Profit green]} \tag{14}$$

$$\beta - \frac{b}{1-\kappa_G} - \phi \geq 0, \qquad \text{[Profit mix brown]} \tag{15}$$

$$\beta + \xi - \frac{b}{\kappa_G} \geq 0, \qquad \text{[Profit mix green]} \tag{16}$$

$$(1-\pi_c)\beta - b \geq (1-\kappa_G)(\beta\phi) - b, \qquad \text{[Size/ROI brown]} \tag{17}$$

$$\pi_c(\beta+\xi+\zeta) - b \geq \kappa_G(\beta+\xi) - b. \qquad \text{[Size/ROI green]} \tag{18}$$

Proof. By assumption $V_{G,RB} = 0$. Since liquidity premia are decreasing with size, the optimal issue sizes equal 0, π_c, or κ_G for green bonds and 0, $1-\pi_c$, or $1-\kappa_G$ for regular bonds. Conditions (14) and (16) correspond, respectively, to issuer profitability with regular and climate investors as marginal investors, for issuing green bonds to be positive. If not, the issuer optimally sets $V_{G,GB} = 0$. Similarly, conditions (13) and (15) correspond, respectively, to issuer profitability with regular and climate investors as marginal investors, to issuer profitability for issuing regular bonds to be positive. If not, the issuer optimally sets $V_{B,RB} = 0$.

If condition (14) or (16) is satisfied, a green bond is optimally issued. If condition (12) is satisfied, the marginal investor is a climate investor and $V_{G,GB} = \kappa_G$. If condition (18) is satisfied and (12) violated, rationing green projects is more profitable than increasing volume and therefore optimal. The marginal investor is a climate investor and $V_{G,GB} = \pi_c$. If conditions (12) and (18) are violated, rationing green projects is less profitable than increasing volume and therefore sub-optimal. The marginal investor is a regular investor and $V_{G,GB} = \kappa_G$.

Similarly, if condition (13) or (15) is satisfied, a regular bond is optimally issued. If condition (11) is satisfied, the marginal investor is a regular investor and $V_{B,RB} = 1-\kappa_G$. If condition (17) is satisfied and (11) violated, rationing brown projects is more profitable than increasing volume and therefore optimal. The marginal investor is a regular investor and $V_{B,RB} = 1-\pi_c$. If conditions (11) and (17) are violated, rationing brown projects is less profitable than increasing volume and therefore sub-optimal. The marginal investor is a climate investor and $V_{B,RB} = 1-\kappa_G$. ■

Lemma 6. *With the opportunity to issue a combined bond, investors' and issuer's equilibrium behavior is as in Lemma 5, except that the issuer now optimally sets*

$$\begin{pmatrix} V_{G,GB}, \\ V_{B,RB}, \\ V_{G,RB} \end{pmatrix}' = \begin{cases} (\pi_c, 1-\kappa_G, \kappa_G-\pi_c), & \text{if (11), (14), (20) satisfied,} \\ (\pi_c, 0, \kappa_G-\pi_c), & \text{if (11), (14), (21) satisfied,} \\ (0, 1-\kappa_G, \kappa_G-\pi_c), & \text{if (11), (22) satisfied and (14) violated,} \\ (0, 1-\pi_c-\kappa_G, \kappa_G), & \text{if (11), (23) satisfied,} \\ (0, 1-\kappa_G, \kappa_G), & \text{if (24) satisfied,} \end{cases} \tag{19}$$

with conditions

$$\beta + \kappa_G\xi + \pi_c\zeta - 2b = \Pi_1 \geq \max\left(\Pi^*, \Pi_2, \Pi_4, \Pi_5\right) \tag{20}$$

$$\kappa_G(\beta+\xi) + \pi_c\zeta - 2b = \Pi_2 \geq \max\left(\Pi^*, \Pi_1, \Pi_4, \Pi_5\right), \tag{21}$$

$$(1-\pi_c)\beta + (\kappa_G-\pi_c)\xi - b = \Pi_3 \geq \max\left(\Pi^*, \Pi_4, \Pi_5\right), \tag{22}$$

$$(1-\pi_c)\beta + \kappa_G\xi - b = \Pi_4 \geq \max\left(\Pi^*, \Pi_1, \Pi_2, \Pi_3, \Pi_5\right), \tag{23}$$

$$\beta + \kappa_G\xi - \phi - b = \Pi_5 \geq \max\left(\Pi^*, \Pi_1, \Pi_2, \Pi_3, \Pi_4\right), \tag{24}$$

where

$$\Pi^* = \max_{\{V|V_{G,RB}=0\}} \Pi(V, y^*, \theta^*). \tag{25}$$

Proof. The LHS of conditions (20) to (24) correspond to the issuer utility functions with the respective values for V. By definition of optimality, setting $V = V^*$ should (weakly) improve issuer utility compared to setting $V = \tilde{V} \neq V^*$. Since the first two scenarios rule out the third and vice versa, Π_3 does not show up in conditions (20) and (21) and Π_1 and Π_2 not in condition (22). ■

Lemma 7. *The optimal threshold $\theta^*_{c,j}$ for climate investors to accept a quote y_{RB} on a regular bond is given by*

$$\theta^*_{c,RB} = \frac{b}{V_{G,RB} + V_{B,RB}} + \phi(1 - I_{c,GC}), \tag{26}$$

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

$$\theta^*_{c,GC} = -\zeta. \tag{27}$$

The other optimal trigger thresholds are as in Lemma 1.

Proof. The utility of regular investors is unaffected by green certificates given a price offer y_{RB}. For a climate investor, accepting offer y_{RB} without a green certificate yields expected utility

$$y_{RB} - \frac{b}{V_{G,RB} + V_{B,RB}} - \phi. \tag{28}$$

Hence, it is optimal to accept if

$$y_{RB} \geq \theta^*_{c,RB} = \frac{b}{V_{G,RB} + V_{B,RB}} + \phi. \tag{29}$$

For a climate investor, accepting offer y_{RB} with a green certificate offered at y_{GC} yields expected utility

$$y_{RB} - \frac{b}{V_{G,RB} + V_{B,RB}} + y_{GC} + \zeta. \tag{30}$$

Hence, it is optimal to accept if

$$y_{RB} \geq \theta^*_{c,RB} = \frac{b}{V_{G,RB} + V_{B,RB}}, \text{and} \tag{31}$$

$$y_{GC} \geq \theta^*_{c,GC} = -\zeta. \quad ■ \tag{32}$$

Lemma 8. *With the opportunity to issue a regular bond with green certificates, investors' and issuer's equilibrium behavior is as in Lemma 5, except that issuer now sets*

$$\begin{pmatrix} V_{c,GB}, \\ V_{r,RB}, \\ V_{c,RB} \end{pmatrix}' = \begin{cases} (0, 1-\kappa_G, \kappa_G), & \textit{if (34) is satisfied,} \\ (0, 1-\pi_c, \kappa_G), & \textit{if (35) and (12) are satisfied,} \\ (0, 1-\kappa_G, \pi_c), & \textit{if (36) and (11) are satisfied,} \\ (0, 0, \kappa_G), & \textit{if (37) and (11) are satisfied,} \end{cases} \tag{33}$$

with conditions

$$\beta - \phi I_{\pi_c > \kappa_G} + \kappa_G \xi + \min(\pi_c, \kappa_G)\zeta - b = \Pi_1^{GC} \geq \max\left(\Pi^*, \Pi_2^{GC}, \Pi_3^{GC}, \Pi_4^{GC}\right), \tag{34}$$

$$(\kappa_G + 1 - \pi_c)\beta + \kappa_G(\xi + \zeta) - b = \Pi_2^{GC} \geq \max\left(\Pi^*, \Pi_1^{GC}\right), \tag{35}$$

$$(1 - \kappa_G + \pi_c)\beta + \pi_c(\xi + \zeta) - b = \Pi_3^{GC} \geq \max\left(\Pi^*, \Pi_1^{GC}, \Pi_4^{GC}\right). \tag{36}$$

$$\kappa_G(\beta + \xi) + \pi_c\zeta - b = \Pi_4^{GC} \geq \max\left(\Pi^*, \Pi_1^{GC}, \Pi_3^{GC}\right). \tag{37}$$

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. The issuer allocates V so as to maximize the associated profits. Since a green bond and a bond paired with a green certificate are equivalent, the results in Lemma 5 still apply. An issuer optimally issues a large regular bond paired with green certificates if it maximizes profits. If all projects are financed with such a bond, issuer profits are given by project profits $(\beta + \xi)$ minus financing costs (which equal a liquidity premium of b on the bond plus a compensation for ϕ for the disutility of climate investors financing any brown project, if any), plus the revenues $\min(\pi_c, \kappa_G)\zeta$ of green certificates (all due to Lemma 8). 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 ($(\kappa_G + 1 - \pi_c)\beta + \kappa_G\xi$) minus financing costs (which equal the liquidity premium times issue size and amounts to b) 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 ($(1-\kappa_G+\pi_c)\beta+\pi_c\xi$) minus financing costs (again b) plus the revenues of green certificates ($\pi_c\zeta$). This defines Π_3^{GC}. If all green projects, but no brown projects are financed with a regular bond, there is a shortage of climate investors, and for a mass π_c green certificates are issued, issuer profits are given by project profits ($\kappa_G(\beta + \xi)$) minus financing costs equal to b plus the revenues of green certificates ($\pi_c\zeta$). This defines Π_4^{GC}. ■

Appendix C. Proofs

Proof of Lemma 1. 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

$$U(y_j) \geq 0, \Rightarrow \tag{38}$$

$$0 \leq y_j - s_j + \zeta I_{c,GB} - \phi I_{c,RB}, \Rightarrow \tag{39}$$

$$y_j \geq \theta^*_{i,j} = s_j - \zeta I_{c,GB} + \phi I_{c,RB}, \tag{40}$$

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 Lemma 2. Given the chosen volume, a total mass of investors at least equal to the issuance volume needs to find it optimal to invest. Hence, the yield for a given bond needs to weakly exceed the investment threshold for the marginal investor. Lemma 1 implies that yields need to at least equal the optimal investment threshold of the marginal investor to get funding. When $0 < V_{G,GB} \leq \pi_c$, the marginal investor in a green bond is a climate investor and hence $y^*_{GB} = \theta^*_{c,GB}$. Otherwise, the marginal investor is a regular investor and $y^*_{GB} = \theta^*_{r,GB}$. When $0 < V_{B,RB} + V_{G,RB}$ and $V_{B,RB} + V_{G,RB} \geq 1 - \pi_c$, the marginal investor in a regular bond is a climate investor and hence $y^*_{RB} = \theta^*_{c,RB}$. Otherwise, the marginal investor is a regular investor and $y^*_{RB} = \theta^*_{r,RB}$. ■

Proof of Proposition 1. The proof of this proposition relies heavily on supplementary Lemma 6 in Appendix B.

The profitability requirement is ensured by requiring at least one of the conditions (13) to (16) to be satisfied when $V_{G,RB} = 0$ and the lower bound of $\Pi^* \geq 0$ on profits otherwise.

The last three scenarios in Eq. (19) involve a regular bond of a size $V_{G,RB} + V_{B,RB}$ that exceeds $\max(\kappa_G, 1 - \kappa_G)$. Hence, the associated fragmentation costs must be lower than if two separate bonds were used. Yet, $V_{G,GB} = 0$ which implies that the clientele premium ζ is given up and potentially an additional disutility ϕ is incurred. Optimality implies that for a large regular bond to be used the former must outweigh the latter.

Rationing of profitable projects happens when $V_{G,GB} + V_{G,RB} < \kappa_G$ and green projects are profitable or when $V_{B,RB} < 1 - \kappa_G$ and brown projects are profitable. Lemma 6 spells out that the former happens among others when Eqs. (11) and (22) hold and in addition Eq. (14) is violated. Eq. (22) only holds when $\xi < 0$ as otherwise Eq. (23) would hold. Eq. (22) only holds when ϕ is large as otherwise Eq. (24) would hold. Supplementary Lemma 6 shows that Rationing green projects also happens when Eqs. (11) and (14) are satisfied, but Eqs. (20) and (21) are not. This is only possible if funding a mass $V_{G,RB}$ of green projects by a regular bond adds negatively to profitability. This can happen in two cases. First, the fragmentation costs are excessively high. This only happens when brown projects are not profitable as otherwise excess green projects could be pooled with brown ones. One needs to also ensure that regular investors do not buy green bonds, so Eq. (18) also needs to hold, which corresponds to large clientele effects for green bonds. Second, funding a mass $V_{G,RB}$ by a regular bond adds negatively to profitability when profitability of green projects purely depends on ζ and is negative without.

Supplementary Lemma 6 spells out that the rationing of regular projects happens among others when Eq. (11) is violated and (17) satisfied; the latter only happens when ϕ is large. In addition, Eq. (24) needs to be violated, which can only happen if ϕ is large or ξ is very negative. The other scenario with rationing of regular projects is when Eq. (11) and (23) are satisfied. This happens only if Eqs. (22) and (24) are violated. This happens only when $\xi \geq 0$ and ϕ is large, respectively. It is also imperative that no green bond is offered (as green projects than no longer crowd out regular ones), which is only the case when fragmentation costs are large. ■

Proof of Corollary 1. If $\phi = -\zeta$, Lemma 1 implies that $\theta^*_{r,j} = s_j$, $\forall j$ and $\theta^*_{c,j} = s_j + \phi$, $\forall j$. Since s_j is strictly decreasing in issue size, 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 equilibrium types with and without the option to use green bonds for financing are the same. ■

Proof of Proposition 2. The proof of the different cases is by examples.

Consider the case in which $b = 0$, $\beta < 0$, $\beta + \xi < 0$, and $\zeta > \beta + \xi$. When funded by a regular bond, investors would demand an interest of at least $\theta^*_{r,RB} \geq 0$. 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 $b = 0$, brown projects are still not undertaken. Since $W_{c,G}$ increases with green bonds being available while the other volumes stay constant, individual and environmental welfare improve as a result of being able to issue green bonds.

Consider the case in which $\pi_c/\kappa_G < 1$, $\xi = 0$, $\beta - \frac{b}{1-\pi_c} < 0$, $\beta - \frac{b}{\pi_c} < 0$, $\zeta > \frac{b}{\pi_c} + \epsilon/\pi_c$, $\tau = 0$, and $\beta - b - \phi = \epsilon > 0$. Since $\beta - b - \phi = \epsilon > 0$, and $\beta - \min(\frac{b}{1-\pi_c}, \frac{b}{\pi_c}) < 0$, 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 $\beta - s_{GB} < 0$), or issuing a combined bond (as $\pi_c(\beta - s_{GB} + \zeta) > \pi_c\beta + \epsilon > \epsilon$). 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 $\xi = 0$), individual welfare suffers. Since $\tau = 0$, the reduction of brown projects is not associated with an environmental welfare improvement, but the reduction of green projects is with an environmental welfare deterioration. Hence, environmental welfare suffers.

Consider the case in which $b = 0$, $\beta > 0$, 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 individual and environmental welfare.

Consider the case in which $\pi_c/\kappa_G < 1$, $b > 0$, $\beta - s_{RB} > 0$, $\xi > 0$. 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 $1 - \pi_c - \kappa_G$ 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. We start by showing an ambiguous effect of an increase in ϕ.

ϕ only shows up in conditions (15), (17), and (24). Conditions (15), (24), or the violation of condition (17) constitute a necessary condition for equilibrium types with maximum investment. An increase in ϕ relaxes Condition (17) and tightens conditions (15) and (24). Therefore, the number of green and brown projects financed in equilibrium is decreasing in ϕ. Since Eq. (6) is increasing in the number of projects financed, individual welfare is deteriorating in ϕ. If $\tau = 0$, environmental welfare deteriorates in ϕ (since also the number of green projects decreases), while it increases in ϕ when $\tau = \infty$.

The proofs for ζ and $\frac{\pi_c}{\kappa_G}$ are by providing examples. We start with ζ.

Consider the case in which $b = 0$, $\beta \ll 0$, $\beta + \xi < 0$, 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 $b = 0$, brown projects are still not undertaken. Since $W_{c,G}$ increases, whereas the other quantities stay unaffected, individual and environmental welfare improve as a result of an increase in ζ.

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 $\pi_c/\kappa_G < 1$, $\xi = 0$, $\beta - \frac{b}{1-\pi_c} < 0$, $\beta - \frac{b}{\kappa_G} < 0$, $\zeta = 0$, $\tau = 0$, and $\beta - b - \phi = \epsilon > 0$. Since $\beta - \frac{b}{\kappa_G} < 0$, no green bond is issued. Since $\beta - b - \phi = \epsilon > 0$, a large regular bond that finances all projects materializes in equilibrium. When ζ is increased to $\zeta > \frac{b}{\kappa_G} + \epsilon/\pi_c$, the issuer optimally issues only a green bond to climate investors since its payoff exceeds that of issuing a combined regular bond or have regular investors co-fund a green bond (see also proof of Proposition 2). As a result, the mass of both green and brown projects reduces (since $\pi_c/\kappa_G < 1$ and $\beta - \frac{b}{1-\pi_c} < 0$). Because individual welfare is monotonically increasing in the number of green and brown projects undertaken in equilibrium, it now suffers with an increase in ζ. As $\tau = 0$, the reduction of brown projects is not associated with an environmental welfare improvement, but the reduction of green projects constitutes an environmental welfare deterioration. Hence, the environmental welfare deteriorates.

Consider the case in which $\pi_c/\kappa_G < 1$, $b > 0$, $\beta - s_{RB} > 0$, $\xi > 0$, $\phi \gg 0$, and $\zeta = 0$. A regular 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 $1 - \pi_c - \kappa_G$ is undertaken). When ζ is increased to violate Eq. (18), it is optimal to issue green bonds to climate investors and regular bonds to regular investors. Hence, all brown projects are now funded (since $\pi_c/\kappa_G < 1$) and an increase in ζ increases the mass of brown projects.

We finalize the proof for by showing ambiguity in the effect of $\frac{\pi_c}{\kappa_G}$.

Assume that Eqs. (11), (13), and (14) are satisfied and that Eqs. (18) and (20) to (24) are violated. By Lemma 6, all projects are funded, so the number of green and brown projects are maximized, as is individual 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 the number of green and brown projects and individual and environmental welfare. Now increase $\frac{\pi_c}{\kappa_G}$, such that Eq. (11) is violated and (12) is satisfied and the other conditions are unaffected. By Lemma 6, the number of green projects increases while the number of brown decreases. As a result, environmental welfare improves. Now increase $\frac{\pi_c}{\kappa_G}$ further, such that Eq. (17) is violated, while all other constraints are unaffected. By Lemma 6, the number of green projects stays constant while the number of brown increases. As a result, environmental welfare deteriorates while individual welfare improves.

Now assume that Eqs. (11) and (14) are satisfied and that Eqs. (18), (13), and (20) to (24) are violated. By Lemma 6, all green and only green projects are funded. Now increase $\frac{\pi_c}{\kappa_G}$ such that Eq. (18) is satisfied and the other constraints are unaffected. By

Lemma 6, the number of green projects is now rationed and hence decreases, while the number of brown projects stays constant at zero. As a result, individual and environmental welfare deteriorate. ■

Proof of Proposition 3. This proof heavily relies on supplementary Lemma 8.

Interest paid is a cash outflow for the issuer and hence she optimally sells green certificates with a yield equal to either $\theta^*_{c,GC}$ to climate investors only or with a yield of $\theta^*_{r,GC}$ to both climate and regular investors. Since $\theta^*_{r,GC} = 0$ and $\theta^*_{c,GC} = -\zeta < 0$, it is optimal for the issuer to only sell to climate investors at $y_{GC} = \theta^*_{c,GC} = -\zeta$.

We now first prove the result on the rationing of regular projects. Supplementary Lemma 8 shows that rationing of profitable regular projects still happens with an excess of climate investors and high ϕ. Yet, for this to happen, Eqs. (34) and (36) need to be violated. The equivalent of Eq. (35) does not exist in the absence of green certificates. Moreover, Eq. (34) is less tight than Eq. (24) due to the terms involving ζ and ϕ. Hence, rationing of regular projects with an excess of climate investors can still happen, but in smaller parameter regions.

Now suppose there is a shortage of climate investors and $\xi \geq 0$. Supplementary Lemma 8 shows that brown projects are rationed only if these are not profitable (the scenarios in Lemma 5), or if Eq. (37) holds. But for Eq. (37) to hold, Eq. (34) must be violated. This can only be when brown projects are not profitable.

Supplementary Lemma 8 shows that profitable green projects are rationed only if there is a shortage of climate investors. Moreover, for this to happen, Eqs. (34) and (37) must be violated. This implies that green projects are only rationed when regular investors find them not profitable to invest in and hence, they depend on ζ to be profitable. Therefore, there is only rationing of profitable green projects in the second scenario of Eq. (10) rationing or the third in Eq. (33).

Since rationing for both green and brown projects now happens in smaller parameter ranges, more projects are undertaken in equilibrium than without green certificates.

We now prove that fragmentation is eliminated by green certificates. Whenever Eqs. (20), (22), (23), or (24) holds, Eq. (34) holds, while in the latter case there is no fragmentation since only one instead of two bonds are used. Whenever Eq. (21) holds, either Eq. (34) or Eq. (37) holds. In any of the latter two, there is no fragmentation since only one instead of two bonds are used. Finally, due to Lemma 4, the only equilibrium types in Lemma 5 that can survive are those in which only green or only brown projects are funded with only one bond issue as otherwise these are dominated by one of the equilibrium types from Lemma 8. Hence, in any equilibrium at most one bond is used and hence, there is no fragmentation.

Since there is less rationing and no fragmentation, liquidity premia must be smaller in equilibrium than without green certificates. ■

Proof of Proposition 4. Assume that $\beta + \xi \geq 0$. We have that $\Pi_1^{GC} \geq \max(\Pi_1, \Pi_5)$, $\Pi_2^{GC} \geq \Pi_4$, $\Pi_3^{GC} \geq \Pi_3$, and $\Pi_4^{GC} \geq \Pi_2$. As a result, the issuer strategies for V in Lemma 6 are dominated by those in Lemma 8.

The term related to liquidity premia in the expressions for Π_1^{GC} to Π_4^{GC} and Π_1 to Π_5 equals b. This term relates to zero-sum transfers while all other terms are relevant for individual welfare. It follows that individual welfare must improve with green certificates.

Now assume that $\beta + \xi < 0$. Since the term related to liquidity premia equals $b > 0$, it is optimal for the issuer not to undertake green projects, irrespective of the financing options available. In this case, green certificates only weakly improve individual welfare. Similarly, when $\xi > -\beta > 0$, it is optimal to only undertake green projects, irrespective of the financing options available and green certificates only weakly improve individual welfare.

The proof for environmental welfare is by example. Assume that Condition (24) is satisfied and that $\beta, \xi \geq 0$ and $\pi_c < \kappa_G$. It follows that Condition (34) must be satisfied. As all projects are undertaken under either financing option, environmental welfare is unaffected.

Next, assume that Condition (22) is satisfied and that $\xi \in (-\beta, 0)$ and that $\zeta > \beta + \xi$. It must be that either Condition (34) or (36) 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 environmental welfare improves as a result of the green certificate financing option.

Finally, assume that $\tau > 0$, $\phi = \infty$, $\pi_c = \kappa_G$, $\beta \in (b, \frac{b}{1-\kappa_G})$, and that Condition (14) is satisfied. Lemma 6 implies that with only green bonds available, all green projects would be financed with green bonds and no brown projects would be financed. Lemma 8 implies that with green certificates all projects are financed with a large regular bond and for all green projects green certificates are issued. Since $\tau > 0$, environmental welfare with green bonds only is higher than with green certificates. ■

Appendix D. 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 of Duffie et al. (2005) 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. For 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

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
$ILLIQ$	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
$ILLIQ$	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, $ILLIQ$ represents the Amihud (2002) liquidity measure based on clean price returns (i.e., excluding accrued interest), and $Size$ represents the bond issue size. IRC_{VW} and IRC_{EW}, are expressed in basis points, $ILLIQ$ in percentage points per $1mln, and size in $mln.

Table 2
Regressions of liquidity on log issue size.

	All bonds			Excluding small bonds		
	(1) IRC_{VW}	(2) IRC_{EW}	(3) $ILLIQ$	(4) IRC_{VW}	(5) IRC_{EW}	(6) $ILLIQ$
$Ln(Size)$	−7.347***	−4.117***	−1.681***	−6.475***	−1.395	−1.225***
	[−13.73]	[−4.70]	[−16.39]	[−5.84]	[−0.99]	[−5.54]
$Green$	5.084	−1.261	−6.620	6.362	11.75	−3.142
	[0.17]	[−0.02]	[−1.40]	[0.21]	[0.22]	[−0.62]
$Ln(Size) * Green$	−0.560	−0.125	0.447	−0.653	−1.061	0.193
	[−0.24]	[−0.03]	[1.26]	[−0.29]	[−0.26]	[0.51]
Firm-month FEs	Yes	Yes	Yes	Yes	Yes	Yes
Observations	28 200	28 200	29 644	25 670	25 670	27 518
Adjusted R-squared	0.234	0.152	0.569	0.098	0.111	0.269

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. Models (1) to (3) are estimated on all observations and Models (4) to (6) on all observations of bonds with an offering size of at least $10 mln. 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.

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 min). 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 min interval, but with different prices. Feldhütter (2012) indicates that about 90% of such trades involve 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. In addition, we also create the Amihud (2002) (il)liquidity measure ($ILLIQ$) for all (green and non-green) bonds. We winsorize both IRC and the $ILLIQ$ measures at the 5% and 95% level.

Panel A of Table 1 reports the summary statistics for green bond issues. Mean roundtrip cost estimates vary from 17.9 bps (value-weighted IRC) to 27.3 bps (equally weighted IRC). 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 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. Hence, the empirically observed relationship between liquidity and bond issue size is consistent with the implications of our model. To be sure that these results are not driven purely by small bond issues, we also repeat this analysis on all bonds with an offering amount over $ 10 mln. The results are similar, albeit slightly weaker.

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