The security design of green debt instruments*

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Abstract

We analyze the security design of environmentally friendly debt securities, such as green bonds, in the context of market frictions such as transaction costs. Our models show that green bonds fragment debt markets, which impairs liquidity, and thereby increases funding costs. Moreover, price transparency and price discovery related to environmental performance are poor for green bonds, even when frictions are small. An alternative design in which earmarking is separated from the debt security itself prevents fragmentation, preserves liquidity, lowers funding costs, improves price discovery and transparency, and stimulates issuers to undertake new environmental projects.

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1 Introduction

In recent years, environmental concerns have led to a widespread range of measures and developments to fight climate change and transition to environmentally friendly business models. One of the initiatives is the Bloomberg Taskforce on Climate-Related Financial Disclosures, which requires investment funds to report on the environmental footprint of their investments.[1]

The aforementioned initiatives have given rise to a new asset class, namely green bonds. Green bonds are very similar to regular bonds and can be issued by both (semi) governments as well as corporates. 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 Figure 1.

While green bonds have contributed significantly towards the transparency of investment mandates with regards to environmental impact, they are not undisputed (Berensmann et al. 2018, Zerbib 2019). There are three issues of dispute (explained in more detail in Section 2). First, most green bond issues refinance existing green projects that were previously financed with regular bonds. This lack of so called "additionality" compromises the promise of green bonds to increase the volume of environmentally friendly activities. Second, the economic benefits of issuing green bonds seem to be small. The estimated reductions in funding costs for green bonds vis-a-vis perfectly matched reference bonds range from 0 to 20 bps and cluster around 5 bps (Baker et al. 2018, Zerbib 2019, Gianfrate and Peri 2019, Flammer forthcoming). These benefits are (at least partially) offset by higher issuing and reporting costs (estimated at 5 bps per annum by Gianfrate and Peri 2019). The small yield discount is in line with claims made by the sell-side industry that one can invest in green bonds without additional cost.[2] Finally, there have been

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

[2] As an example, VanEck writes in a note on green bonds: "Given that there is *no clear systematic pricing difference between green bonds and conventional bonds*, the case for holding green bonds begins with the rationale for holding any fixed income investment"; see `https://www.vaneck.com/vaneck-green-bond-etf-guide-source.pdf`

various reports of green bonds that are not very green or that finance activities that do not materially affect the issuer's environmental footprint (i.e., issuers engaging in window dressing and greenwashing).[3] If markets aggregate information well and provide incentives to produce information, one would expect little benefit of greenwashing using greenbonds, since markets would find out about it and undo any reduction in funding costs. In well functioning markets, prices would also serve as alternatives for green ratings given by analysts, which have been shown to display relatively low correlations among different green rating providers.[4]

In this paper we analyze, from a theoretical angle, the extent to which these problems are associated with the security design of green bonds. To isolate the effects of security design from the effects of green earmarking, we compare green bonds to an alternative security design that incorporates earmarking in exactly the same way. In particular, we compare to a security design that entails a regular bond plus a separate certificate with the sole purpose of arranging the earmarking (we call this a "green certificate"). We show that both designs are equivalent in a frictionless market, but lead to very different economic outcomes in the presence of frictions, even if these are small.

In our analysis, the green certificate security design serves as a benchmark for green bonds. This design is novel and does not exist (yet). Some issuers, however, started to consider such a design after our paper had circulated for about a year.[5] As such, it can serve as a meaningful and realistic benchmark. The design of green certificates also fits in a tradition of separating special features from nominal cash flow rights in fixed income markets. For example, one can decompose a floating rate bond into a fixed rate bond and an interest rate swap, a credit risky bond into a risk-free bond plus a short position in a credit default swap, and an inflation-linked bond into a regular bond plus an inflation swap. Separating features from nominal cash flow rights to establish a benchmark is even

[3] An example of such a green bond for window dressing purposes is `https://www.reuters.com/article/us-china-greenbonds-coal/china-provides-1-billion-in-green-finance-to-coal-projects-in-first-half-of-the-year-idUSKCN1V90FY`

[4] For example, Berg et al. (2019) show an average correlation of 0.6, which is much lower than correlations among credit ratings produced by different credit rating agencies.

[5] See e.g., `https://www.nationalbanken.dk/en/governmentdebt/IR/Pages/Model-for-sovereign-green-bonds.aspx`.

more natural in the green debt market than in other markets since green certificates would be positive rather than zero net supply securities and thereby mimic green bonds exactly. As such, this design does not suffer from additional frictions like counterparty default risk.

Our theoretical analysis is split up into two parts. In the first part, we set up a simple model in which a firm has a refinancing need and in addition considers undertaking a project in either the traditional mode or an environmentally friendly mode. The firm needs external financing and plans to finance part of the project with debt. The firm can issue green debt securities but only if the project is undertaken in the green mode. We allow for either green bonds or regular bonds paired with green certificates. After issuance, bonds can be traded in the OTC market which features search frictions in the spirit of Duffie et al. (2005). In particular, we assume that the dealer bargaining power is inversely proportional to bond issue size. Financing for the project is provided by an over-supply of regular and impact investors, which are rational and identical except for the fact that impact investors derive a convenience yield from investing in green debt securities.

The convenience yield of impact investors creates scope for a clientele effect if the firm can get a lower financing cost when the project is undertaken in an environmentally friendly way. If the project is financed by a regular bond, be it paired with a green certificate or not, one large, combined bond could be issued to jointly refinance existing debt and finance the project. Since dealer bargaining power is inversely proportional to issue size and a combined bond issue is large, the combined bond issue is relatively liquid. Because less than perfectly liquid securities command a liquidity premium that is increasing in the degree of illiquidity (see e.g., Amihud and Mendelson 1986, Bongaerts et al. 2017), a larger issue size leads to a smaller liquidity premium. This in turn leads to a lower financing cost for the project (direct effect), but also to a lower refinancing cost of other debt (indirect effect). Because both effects result from the project choice and financing decisions, they both contribute to the *effective* financing costs of the project. By contrast, if a firm chooses to issue a green bond, it fragments its total demand for debt financing (a regular bond for the refinancing and a green bond for the project). As a result, the green bond issue is relatively small, therefore illiquid, and entails relatively high liquidity premium. In addition, the issue size of the regular bonds used for refinancing is also relatively small. Therefore, these bonds are also subject to a relatively large liquidity premium. Hence, we show that, both thrhough the direct as well as through the indirect channel, financing costs with green bonds are higher than with green certificates.

The firm may find it optimal to undertake the project in the green mode, even if the operational profitability of the project in the green mode is lower than in the regular mode if the difference in profitability (we call this the profitability deficit) is more than offset by the difference in funding costs. In our analysis, we quantify the maximum profitability deficit that can be compensated by either form of green debt financing. It naturally follows that maximum profitability deficit that can be compensated is much smaller for green bond financing than for green certificate financing. As such, we show that green bond financing has inferior additionality compared to green certificate financing.

While in the first part of the paper, secondary market liquidity is endogenized, in the second part, we take secondary market liquidity as given and derive additional results on how the green bond security design impairs price discovery and transparency. In particular, we focus on the informativeness of market price data about (changes in) environmental performance and the value of green earmarking. We split this up into (i) accuracy of information extraction in the presence of market frictions, (ii) incentives to trade on available information, and (iii) incentives to produce information.

In order to extract environmental performance information from green bond prices, one needs to clean the green bond of the nominal cash flow component by using a (regular) reference bond with similar credit risk, coupon, and maturity. This procedure is tends to be imperfect since a perfect match is typically unavailable, and one may need to resort to a yield curve that is estimated with error and thereby introduces measurement noise. This effect is absent for green certificates. Even when a perfect match is available, (proportional) transaction costs can contaminate price data and thereby introduce measurement error. The effect of such contamination is much larger for green bonds than for green certificates since the cost base for transaction costs is much larger. We calibrate our expressions for measurement noise to transaction costs and yield curve fitting error data in some of the most liquid sovereign bond markets. For these calibrated values we find that measurement error swamps any yield discount for green bonds. Moreover, we find that the vast majority of return differences (over long horizons) between green and reference bonds are due to measurement noise rather than changes in (environmental) fundamentals (i.e., environmental performance or the value of green earmarking).

We continue by analyzing the incentives to engage in informed trading based on environmental performance information. We assume that speculators wanting to do so face proportional transaction costs in addition to price impact. Speculating on such information using green bonds involves a trade in a green bond and an opposite trade in a reference bond. For both trades, the cost base is large compared to the value of the information (and the net position). This effect is much smaller for green certificates as only one trade is required with a small cost base. We show in our calibrations that transaction costs in order of a few basis points can already prevent speculators from trading on very strong information in the green and reference bond markets. Consequently, one would only expect the most liquid green sovereign bonds to impound information through trading and basically none of the corporate bonds. Naturally, if transaction costs are prohibitive for speculators to trade on their information, there is little incentive to produce information.

A natural policy implication of our findings is that issuers and market participants are better served with green debt securities that are better designed than green bonds. A green certificate design, as used for our benchmark would be a suitable candidate. We further elaborate on the practicalities that such a transition would require.

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 the first to investigate whether the current security design of green bonds serves the purposes of this security type well. Our analyses can also, at least in part, explain the empirically low yield discount (Baker et al. 2018, Zerbib 2019, Gianfrate and Peri 2019, Flammer forthcoming, Tang and Zhang 2018) and the apparent lack of market discipline in curbing greenwashing in green bonds (Flammer 2020, finds that green bonds are only effective if externally certified). Moreover, to the best of our knowledge, we are the first ones to point out issues with using green bond price data for analyzing environmental performance.

Our paper also contributes to the literature on security design. A large part of this literature has focused, from a theory standpoint, on security design in the context of agency conflicts between management and investors (see e.g., Fulghieri and Lukin 2001, Myers and Majluf 1984, Allen and Gale 1988, DeMarzo and Sannikov 2006). We show how security design in the context of earmarking can matter for the informativeness of prices and thereby can contribute to managerial governance. A smaller branch of this literature considers the choice of debt maturity spectrum, and thereby also incorporates fragmentation. Some of the theoretical studies in this field assume costs associated with fragmentation (e.g., Choi et al. 2018). We contribute by showing the relevance of such costs in the context of green bond issuance, by showing how the spillover effect on other bonds affects the *effective* funding costs in investment decisions, and by theoretically micro-founding fragmentation costs through illiquidity in the context of an OTC market with search costs.

We also contribute to a smaller literature on security design and price discovery. In this context, Oehmke and Zawadowski (2017) show empirically that CDS spreads lead credit spreads due to standardization and reduced fragmentation, which result in higher liquidity. We add to this by highlighting a different channel: the cost base. Speculative trades in decomposed features have a much lower cost base since the nominal cash flow part has been removed. Moreover, the consequences in the green debt market are different from any derivatives markets. For green debt markets, our results imply that green certificate financing should fully replace green bond financing, which we show to be inferior. For the CDS market, it is not feasible to do something similar since CDS are zero net supply derivatives. Even if CDS were issued by the issuer itself, the positions would still be exposed to counterparty default risk, in which case any risk mitigation would not be real.

Our paper also contributes to a large literature on market microstructure. First, we contribute to the literature on OTC markets with search frictions (Duffie et al. 2005, e.g.,) by showing that making market maker bargaining power inversely proportional in size generates the empirical observed pattern that larger bond issues are more liquid. Second, we show theoretically how transaction cost frictions are amplified in long-short strategies. Third, our calibrations highlight that market design and security design are complementary in fostering market transparency and price discovery.

2 Green bonds and green certificates as a benchmark

The exponential growth of the green bond market (see Figure 1) shows that there is market demand for debt instruments with revenues earmarked for environmentally friendly purposes. In this paper, we investigate the degree to which green bonds satisfy other criteria that are desirable in financial securities, such as being priced efficiently, information sensitivity with respect to distinguishing features, liquidity, and a low cost of funding.

Four our analysis, we need to benchmark green bonds to a reasonable alternative. To fulfil this role, we choose to use a bundle of a regular bond and a green certificate, a hypothetical security that only takes care of earmarking. We assume that the holder of a green certificate gets exactly the same earmarking and reporting benefits as the holder of a green bond derives from its earmarking aspect. The benefit of choosing this benchmark is that a green bond is exactly equivalent to this bundle in a frictionless market. As such, any deviations in pricing, liquidity, transparency, and price discovery in a market with frictions are due to security design. We acknowledge that a benchmark with similar features could also be constructed in different ways. Yet, one of the components of our benchmark, the regular bond, already exists. Moreover, decomposing cash flow from other features in fixed income markets is common, which makes our benchmark a natural choice. To the extent that other benchmarks perform even better on the dimensions indicated above, green bonds are even less efficient than we find.

3 A model of fragmentation, liquidity, and funding costs

In this section, we show, using an OTC model with search frictions, that the use of green bonds leads to fragmentation of bond issues and thereby deteriorates liquidity. Because more illiquid securities are in lower demand, they have higher yields and are therefore more expensive ways to finance investments. There is a direct effect because the issue sizes of green bonds themselves are relatively small. Moreover there is also an indirect effect because by issuing green bonds issuers miss out on economies of scale in making other bond issues larger and therefore more liquid. This is an indirect effect which is not visible from green bond yields. Yet, both the direct and indirect effect affect the bottom line of the issuer as a consequence of choice of financing mode. As such, both contribute the *effective* financing costs and should be taken into account in financing and project choice decisions. In the benchmark setting with green certificates, the economies of scale in liquidity create an incentive to start additional new projects and therefore contribute to additionality. These economies of scale are absent for green bonds.

3.1 Model Setup

Consider a firm with a project of a given size that can either be undertaken in the traditional (t) or green (g) mode. Project modes are mutually exclusive. One can think about building a power plant based on renewable energy instead of fossil fuels (oil, gas or coal). The green mode results in an expected annual CO_2 emission reduction. We assume that the project mode does not affect the risk profile of the project and the investments required to run the project. Moreover, we assume that the expected return on invested capital (ROIC) for the project, r^k is perpetual, constant in expectation, and depends on mode k. This allows for the green mode being more costly (and therefore less profitable) to operate. Finally, we assume that the project is of similar risk as the other projects in the firm, will be financed by the same mix of debt and equity as other projects in the firm, and needs debt financing of size S.

The firm is fully rational and maximizes the NPV of undertaking the project by choosing the size project mode k and financing mode l. This NPV is maximized by solving

$$\max_{k,l}(r^k - r^l_{WACC}), \tag{1}$$

where r^l_{WACC} corresponds to the weighted average cost of capital for the project that corresponds with financing mode l. There are three possible financing modes: traditional (b), green bond (GB), and traditional bonds combined with green certificates (GC). These translate into weighted average costs of capital equal to r^b_{WACC}, r^{GB}_{WACC}, and r^{GC}_{WACC}, respectively. To focus on financing channels in the debt market, we assume that

$$r^l_{WACC} = \frac{E}{V} r_e + \frac{D}{V} r^l_d, \tag{2}$$

where D, E and V are debt, equity and total firm value (without the project), respectively, r_e is the cost of equity capital, and r^l_d is the cost of debt corresponding to financing mode l. We assume the leverage ratios $\frac{D}{V}, \frac{E}{V}$ to remain constant going forward and the cost of equity and corporate credit risk to be unaffected by project mode k or financing mode l. By assumption, the firm cannot engage in greenwashing such that r^{GB}_{WACC}, and r^{GC}_{WACC} are only available for project mode g. The firm has a portfolio of other (legacy) projects that cannot be greened, which all need debt refinancing of aggregate size D.

There are two types of debt investors in the market: regular investors and impact investors. Both investor types have homogeneous preferences. Impact investors derive an additional convenience yield ζ from green earmarking, which could originate from regulatory requirements, preferences of investors/investment managers,[6] or PR-considerations. We also assume that there is an over-supply of capital among both types of investors such that the issuer can capture all surplus. This assumption maximizes the scope for green debt instruments to affect environmental outcomes.

We assume that green bonds and regular bonds are traded in an OTC market in which investors need to search for dealers (which is costly) and bargain with dealers over prices. Duffie et al. (2005) show that the steady-state bid-ask spread s^j for security j as a fraction of its fair value in an OTC market with search frictions is given by

$$s^j = \frac{\delta_j z_j}{r_f + (1 - z_j)\rho_j}, \tag{3}$$

[6]Some pension funds, for example, aim to reduce the carbon footprint of their portfolio. An example is the Dutch pension fund for health care PGGM: `https://www.ipe.com/esg-pggm-gets-serious-on-carbon-reduction/10013495.article`. Pension fund participants seem to support this (see Bauer et al. 2019)

where δ_j is a holding cost, z_j is the bargaining power of the market maker, r_f is the risk-free interest rate, and ρ_j is the intensity with which investors meet market makers.[7] We assume δ_j and ρ_j to be identical across security types and independent of issue size, such that bond turnover, denoted by Q, is unaffected by bond issue type or size. Importantly, we assume market maker bargaining power z_j to be inversely proportional to issue size:

$$z_j = \frac{a}{S_j} \tag{4}$$

where a is a positive constant and $S_j \in [a^{-1}, \infty)$ is the issue size of bond j. Intuitively, one would expect smaller markets to be more concentrated leading to higher market maker bargaining power.[8] Substituting (4) into (3) immediately gives that

$$s_j = \frac{\delta_j a / S_j}{r_f + (1 - a/S_j)\rho_j}, \tag{5}$$

$$= \frac{c}{d + S_j}, \tag{6}$$

where c is a strictly positive constant and d is a strictly negative constant. These constants are identical across bond types because δ_j and ρ_j are.

3.2 The effect of financing mode on cost of debt and project choice

We now derive the consequences of the choice of financing mode on the cost of debt.

Since there is an over-supply of capital among both investor groups, both types of investors break even in expectation. As a result, issuers can capture all surplus generated by impact investors' preferences. Therefore, the cost of debt in the absence of frictions equals $\hat{r}_d^b$ for brown financing, and $\hat{r}_d^b - \zeta$ for green bond and green certificate financing.

Since all investors break even in expectation, the yield increase that investors demand for any bond j due to illiquidity equals Qs^j, which corresponds to their expected losses due to transaction costs.[9]

[7] This result is obtained under the assumption that investors can only trade through market makers and not directly with one another, which conforms well to practice.

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

[9] This is similar to Amihud and Mendelson (1986) when liquidity-related clientele effects (relating to pa-

We can now derive the *effective* cost of debt for all three financing modes. With traditional and green certificate financing, the financing is raised along with all other debt financing in one large bond issue (LB). The direct cost of debt for traditional financing equals

$$r_d^b = \hat{r}_d^b + Qs^{LB}, \tag{7}$$

where

$$s^{LB} = \frac{c}{d + D + S}. \tag{8}$$

The cost of green certificate financing is identical to that of regular financing minus a clientele-induced discount:

$$r_d^{GC} = r_d^b - \zeta. \tag{9}$$

With regular and green certificate financing,r_d^b also equals the cost of debt for all other company-issued debt. With the project, this cost of debt is lower than without it, since the size of the combined debt issue is now larger than the small bond issue (SB) that would take place without it. Hence, there is a spillover effect of the project on the other debt. When the project at hand is the marginal investment, we can attribute these cost savings on all other corporate debt to this project. As a result, the *effective* cost of debt of the project is lower than the observed cost of debt. We can derive the additional spillover-induced reduction for the effective cost of debt analytically.

Lemma 1 *Under regular and green certificate financing, the reduction in effective financing cost of the project due to liquidity spillovers equals*

$$\frac{D}{d + D} Qs^{LB} \tag{10}$$

tient vs impatient investors) are ignored. Bongaerts et al. (2017) confirm this relationship in the corporate bond market.

Proof. See Appendix A. ■

Lemma 1 shows that spillover effects are project size invariant. Hence, even small projects generate sizable reductions in effective funding costs due to liquidity spillover effects. The reason is that even though small projects do not increase the size of the bond issue by much, the positive spillovers are applicable to a large capital base. These two effects exactlty offset each other, resulting in a size-independent reduction of the effective cost of debt for the project. Note that these costs savings are not reflected in lower direct financing costs of the project, but should be incorporated into the decision making process.

We now derive the financing costs for green bonds. Green bonds also allow to capture a yield discount due to clientele effects. Yet, the use of green bonds fragments bond issues. As a result, the green bonds themselves are relatively illiquid since the issue size is relatively small. The cost of debt is then given by

$$r_d^{GB} = \hat{r}_d^b - \zeta + Qs^{GB}, \tag{11}$$

where

$$s^{GB} = \frac{c}{d+S}. \tag{12}$$

In contrast to green certificate and regular bond financing, there are no positive liquidity spillovers on all the other debt. Therefore, Equation (12) also represents the *effective* cost of debt for the project.

Having derived the (*effective*) cost of debt financing for all debt instruments considered, we can now present the main result of this section.

Proposition 1 *The effective costs of debt for the project with regular bond, green bond,* *and green certificate financing are respectively given by*

$$r_d^b = \hat{r}_d^b + (1 - \frac{D}{d+D})Qs^{LB}, \tag{13}$$

$$r_d^{GB} = \hat{r}_d^b + Qs^{GB} - \zeta, \tag{14}$$

$$r_d^{GC} = \hat{r}_d^b + (1 - \frac{D}{d+D})Qs^{LB} - \zeta. \tag{15}$$

Proof. See Appendix A. ■

The mechanisms behind the cost of debt of different financing modes are also summarized in Table 4. It is immediately clear from Proposition 1 that green bond financing is strictly dominated by green certificate financing (everything else equal). It then follows that with green bond financing, a smaller green mode profitability deficit (defined as $\gamma = r^t - r^g$) can be overcome than by green certificate financing.

Corollary 1 *The maximum profitability deficits $\bar{\gamma}^x$ for $x \in \{GB, GC\}$ that can be overcome by green debt financing are given by*

$$\bar{\gamma}^{GC} = \frac{D}{V}\zeta,$$
$$\bar{\gamma}^{GB} = \frac{D}{V}(\zeta + (1 - \frac{D}{d+D})Qs^{LB} - Qs^{GB}) < \bar{\gamma}^{GC}. \tag{16}$$

Proof. See Appendix A. ■

4 Transparency and information efficiency

In the previous section, transaction costs were endogenous, the need for trading exogenously given, and we abstracted from information asymmetry across traders. In this section, we take transaction costs and other market imperfections as given and show how the security design of green bonds compromises the transparency and the informativeness of prices (and price changes) of green debt instruments in the context of market imperfections such as transaction costs.

If markets were perfectly liquid, holding a regular bond plus a green certificate would be equivalent to holding a green bond. As a result, prices would need to satisfy a no-arbitrage relationship. Let us denote the yield on a green bond at time t issued by issuer i as $r_{i,t}^{GB}$, the yield on a reference bond $r_{i,t}^{ref}$. The annualized discount $\xi_{i,t}^{GC}$ that would result from green certificate financing (also called the green certificate premium) is given by

$$\xi_{i,t}^{GC} = r_{i,t}^{ref} - r_{i,t}^{GB}. \tag{17}$$

We call the right hand side of Eq. (17) the green spread.

As before we assume that there is an oversupply of regular and impact investors where impact investors derive a per period convenience yield $\zeta_{i,t}$ from investing in environmentally friendly projects of issuer i. We have that the green spread equals the green certificate premium and the convenience yield of impact investors.

Lemma 2 *With more demand than supply for environmentally friendly projects, we have in frictionless markets that*

$$\xi_{i,t}^{GC} = r_{i,t}^{ref} - r_{i,t}^{GB} = \zeta_{i,t}. \tag{18}$$

Proof. See Appendix. ■

The convenience yield $\zeta_{i,t}$ is potentially time-varying. Throughout this section, we assume $\zeta_{i,t}$ to be proportional to the environmental performance of the projects the earmarked funds are used for. Under this assumption, all time variation in the convenience yield $\zeta_{i,t}$ is due to time variation in environmental performance. Lemma 2 then shows that in frictionless markets any information about environmental performance is fully incorporated in and perfectly visible from both the green certificate premium as well as the green spread. Below we relax the assumption of a frictionless market and show that the degree to which information about environmental performance is incorporated in and is visible from the green spread is very low compared to that of green certificates.

4.1 Informativeness of market prices (levels)

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

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

$$\tilde{r}_{i,t}^{ref} = r_{i,t}^{ref} + \epsilon_{i,t}. \tag{19}$$

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

$$\tilde{r}_{i,t}^{ref} - r_{i,t}^{GB} = r_{i,t}^{ref} - r_{i,t}^{GB} + \epsilon_{i,t}. \tag{20}$$

We calibrate these expressions to realistic numbers. We set $\zeta_{i,t} = 5$ bps per annum (the average green spread reported by Zerbib 2019) and $\sigma_i^{\epsilon} =$ of 4bps (the calibration error volatility in Nymand-Andersen 2018). The volatility of the fitting error is of similar magnitude as the convenience yield, which makes green spread estimates unsuitable as an environmental performance metrics. This calibration also confirms anecdotal evidence that the green bond yield is not significantly different from a matched reference bond yield. This problem is absent for green certificates since their entire value relates to earmarking and there is no need for reference bond matching.

4.2 Informativeness of market prices (changes)

In this subsection we extend the analysis from the previous subsection in price or yield levels to one in changes. We show that green spread changes poorly reflect changes in environmental performance and that changes in green certificate premia fare much better. We do this in the context of yield curve fitting errors as well as transaction costs.

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

4.2.1 Yield curve fitting noise

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

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

$$IR_{i,t}^{GCP} = \frac{Var(\zeta_{i,t} - \zeta_{i,t-1})}{Var(\xi_{i,t} - \xi_{i,t-1})} = \frac{Var(\zeta_{i,t} - \zeta_{i,t-1})}{Var(\zeta_{i,t} - \zeta_{i,t-1})} = 1. \tag{21}$$

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

$$IR_{i,t}^{spread} = \frac{Var(\zeta_{i,t} - \zeta_{i,t-1})}{Var(\tilde{r}_{i,t}^{ref} - r_{i,t}^{GB} - \tilde{r}_{i,t-1}^{ref} - r_{i,t-1}^{GB})} = \frac{Var(\zeta_{i,t} - \zeta_{i,t-1})}{Var(\zeta_{i,t} - \zeta_{i,t-1}) + 2Var(\epsilon_{i,t})} < 1, \tag{22}$$

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

We calibrate Eqn. (22) to realistic values to quantify the information shortfall (see

Table 1). We set the annualized volatility of changes in $\zeta_{i,t}$ to 4 bps with zero autocorrelation[10] and σ_i^ϵ to 4bps (as before). With those values, 33% of the annualized variance and 11% of the quarterly variance of changes in estimated green spreads is driven by changes environmental performance and respectively 67% and 89% by yield curve fitting noise. Hence, changes in green spreads poorly reflect changes in environmental fundamentals, which is not the case for changes in green certificate premia. The information ratio for corporate green spread changes is most likely lower than our figures calibrated to sovereign bond data. The reason is that corporates typically have fewer bonds outstanding and have more heterogeneity across issues and issuers, resulting in more yield curve estimation noise.

4.2.2 Transaction costs

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

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

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

$$\tilde{p}_t^x = p_t^x(1 - s^x + 2s^x X_t^x), \qquad (23)$$

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

where s^x is the proportional transaction cost, $X_t^x \sim$ Bernoulli(0.5) is the trade sign indicator (1 for buy, 0 for sell), and p_t^x is the true value of security x at time t. One can use Eq. (23) to approximate (log) returns for green certificates and long-short positions in green and reference bonds based on observed transaction prices.

Lemma 3 *The returns for green certificates ($\tilde{ret}^{GC}$) and long-short positions in green and reference bonds ($\tilde{ret}^{ref-GB}$), both based on observed transaction prices are, by approximation, given by*

$$\tilde{ret}_t^{GC} \approx ret_t^{GC} + 2s^{GC}X_t^{GC} - 2s^{GC}X_{t-1}^{GC}, \tag{24}$$

$$\tilde{ret}_t^{ref-GB} \approx ret_t^{GC} + \frac{p_t^{ref}}{p_t^{GC}}2sX_t^{ref} - \frac{p_t^{GB}}{p_t^{GC}}2sX_t^{GB} - \frac{p_{t-1}^{ref}}{p_{t-1}^{GC}}2sX_{t-1}^{ref} + \frac{p_{t-1}^{GB}}{p_{t-1}^{GC}}2sX_{t-1}^{GB}, \tag{25}$$

where ret_t^{GC} is the fundamental (log) return of the green certificate.

Proof. See Appendix. ■

The transaction cost terms in (25) are multiplied with the price ratio of a bond and a green certificate, which is typically very large. This is due to the fact that in order to get a small net position that corresponds to the value of green earmarking, large long and short positions have to be taken in green and reference bonds. As a result, the transaction cost base for such a position is large. Consequently, transaction costs infuse much more noise into $\tilde{ret}^{ref-GB}$ than into $\tilde{ret}^{GC}$. For tractability reasons, we now use the approximation

$$p_t^{ref} \approx p_{t-1}^{ref} \approx p_t^{GB} \approx p_{t-1}^{GB}, \tag{26}$$

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

Proposition 2 *The information ratio of green certificate premium changes is higher than that of green spread change iff*

$$s^{GC} < \sqrt{2}\frac{p_t^{ref}}{p_t^{GC}}s. \tag{27}$$

Proof. See Appendix. ■

In Eq. (27) the square root of two shows up because a long and short position are required to construct the grean spread, and each of the two is subject to transaction costs. The ratio $\frac{p_t^{ref}}{p_t^{GC}}$ shows up because large positions in bonds are required to match a small position in a green certificate (cost base ratio).

We now calibrate (27) to realistic values in the sovereign debt market (See Table 2). We set face values for bonds and green certificates to 100, maturity to 5 years, reference bond yield and coupon rates to 1% per annum, convenience yield ζ_t of 5 bps per annum, and one-way transaction costs to 3.5 bps, which aligns with German Bund market estimates in de Roure et al. (2019). For these inputs, the information ratio of green spread changes is inferior to that of green certificate premium changes, unless one-way transaction costs for green certificates exceed 2042 bps (20%).

We can also calibrate (27) to realistic values in the corporate bond market. We change reference bond yields and coupon rates to 2% per annum and one-way transaction costs to 50 bps, in line with Bongaerts et al. (2017). It follows that the information ratio of green spread changes is inferior to that of green certificate premium changes, unless one-way transaction costs for green certificates exceed 30,050 bps (300%). This is unrealistic, since transaction costs would exceed the intrinsic value threefold.

4.3 Incentives for informed trading and information acquisition

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

We assume that a risk-neutral speculator is privately informed about an issuer engaging in greenwashing, which means that the value of a green certificate/price difference between a green and reference bond equals $\hat{p}^{GC}$ instead of the market consensus price $p^{GC} = p^{GB} - p^{ref} > \hat{p}^{GC}$. We assume the same proportional transaction cost structure as before and in addition assume linear price impact $\lambda^{ref-GB} = \lambda^{GC} = \lambda > 0$.[11]

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

$$q^{GB} = -q^{ref} = -\frac{\max((p^{GC} - \hat{p}^{GC}) - s(p^{GB} + p^{ref}), 0)}{2\lambda}, \tag{28}$$

$$\approx -\frac{\max((p^{GC} - \hat{p}^{GC}) - 2sp^{ref}, 0)}{2\lambda}, \tag{29}$$

where the approximation results from $s\tilde{p}^{GB} \approx sp^{ref}$. The demand for green and reference bonds is nonzero if

$$p^{GC} - \hat{p}^{GC} > 2sp^{ref}. \tag{30}$$

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

$$q^{GC} = -\frac{\max((p^{GC} - \hat{p}^{GC}) - s^{GC}p^{GC}, 0)}{2\lambda}, \tag{31}$$

which is nonzero if

$$p^{GC} - \hat{p}^{GC} > s^{GC}p^{GC}. \tag{32}$$

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

We calibrate again to realistic numbers to quantify the difference in thresholds (see Table 3). We set all face values to 100, a maturity of 5 years, a yield and coupon rate on reference bonds of 1%, and the market consensus on $\zeta_{i,t}$ to 5 bps (based on public information). With these values, the green certificate has a price of 24 cents. It follows that a speculator that is privately informed that $\zeta_{i,t}$ equals 0 bps[12] trades in the green certificate market if one-way transaction costs do not exceed 100% and in green and regular bond markets if one-way transaction costs do not exceed 12 bps. This condition is typically met in developed sovereign bond markets (e.g., 3.5 bps in German Bund markets), but not in

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

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

corporate bond markets (50 bps). For a smaller informational advantage (private information that $\zeta_{i,t}$ equals 1 bps) the respective thresholds equal 20% and 2.4 bps, preventing the speculator to trade on his information in even one of the most developed sovereign bond markets.

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

5 Welfare and policy implications

5.1 Welfare

We start by deriving welfare implications for the results in Section 3 on fragmentation. Eqn. (16) derives the thresholds on the maximum profitability deficit for green bond and green certificate financing, respectively, for which the firm still optimally chooses to undertake the project in the green mode. Any projects with a profitability deficit γ exceeding $\bar{\gamma}^{GC}$ will not be undertaken in the green mode, irrespective of green debt instruments available. Similarly, any projects with a profitability deficit smaller than $\bar{\gamma}^{GB}$ will optimally by undertaken in the green mode, irrespective of green debt instruments available. In those situations, the choice for green bonds (instead of green certificates) simply implies a wealth transfer from equity holders to bond dealers. However, for projects with a profitability deficit in the interval $(\bar{\gamma}^{GB}, \bar{\gamma}^{GC})$, the choice for green bonds lowers welfare as projects are not undertaken in the green mode. There is a welfare loss due to the convenience yield ζ not being realized. The size of this loss equals ζS. If the environmental gain from undertaking the project in the green mode exceeds the welfare gain (which is likely since it is a public good, but not embedded in the model), the welfare loss of being constrained to green bonds is even larger.

Proposition 3 *The use of green bonds prevents projects with a moderate profitability deficit from being undertaken in the green mode and leads to an associated annual welfare loss (compared to the use of green certificate financing) of at least ζS.*

Proof. See Appendix. ■

The problems of green bonds with regards to transparency, price informativeness, and price discovery do not have direct policy implications in the context of the model. One reason is that the information ratio is not used for any purposes that generate value in the context of the model. Similarly, informed trading in the context of the model is a zero-sum activity. Yet, there is an extensive literature on the role of informed trading in fostering governance on management (see e.g., Massa et al. 2015, Chang et al. 2019). If market price informativeness and transparency reduce the need for external certification of green bonds, the associated certification costs, which are dead-weight losses, can be saved. For the firms for which external certification costs are prohibitively high to consider undertaking the project in the green mode, such cost reduction leads to more projects being undertaken in the green mode. The resulting convenience yield and/or environmental gain are additional welfare benefits.

5.2 Policy implications

A natural policy implication of the analyses conducted in this paper is to switch to a different security design for green debt securities. The combination of regular bonds with green certificates as used in this paper as a benchmark is one of the options, and a natural one. Yet, it may be possible that other designs deliver even better economic outcomes. In the subsection below, we provide some practical details on how a transition from green bonds to green certificates could be organized.

5.3 A common institutional language and treatment

A common language and agreement on definitions of what is green and what is not constitute a starting point. The current process of establishing green standards at the EU level is a major contributor to this process. Having a common framework for green investments allows to report on a more consistent basis on those, improve environmental ratings, and helps in developing a consensus view on the value of green investment earmarking. This is a precondition for speculative trading on environmental performance information and the associated welfare gains described in Subsection 4.3. A similar standardization in the form of the 1999 ISDA Credit Derivatives Definitions helped the CDS market to establish itself.

5.4 Reporting allocation of green earmarking

A second important issue is the question who can include the green earmarking benefit in reporting. To fully separate the earmarking rights from the cash flow rights, the holder of the green certificates should receive the sole right to report the face value of the underlying bond as invested in an environmentally friendly way. To achieve this, green reporting standards need to be modified.

5.5 Attaining critical mass

Third, green certificates will be most successful if there is a flourishing and liquid market. For a market to function well, one typically needs sufficient demand and supply (critical mass), as well as sufficient intermediation activity by dealers or market makers. We describe below which parties would be most influential in getting a market for green certificates started.

5.5.1 Supply side

In order to gain critical mass quickly, large issuers that commit to this security design are needed. Sovereigns are among the largest issuers and therefore natural candidates. Moreover, sovereigns issues are special (Feldhütter and Lando 2008) and safe. In view of the scarcity of safe assets (Caballero et al. 2017), it is hard to ignore sovereigns as issuers. Finally, sovereigns have a certain amount of discretion in their allocation decisions in case of over-subscriptions (which are common). As such, they can reward primary dealers that are more willing to purchase, underwrite, and/or make a market in green certificates. In view of these arguments, it is therefore no surprise that the first party (to our knowledge) to seriously consider green certificates is the Sovereign debt issuance office of the Danish

Central Bank.[13]

5.5.2 Demand side

Similar to the supply side, the involvement of large investors is likely to help this market attain critical mass quickly. Naturally, investors with a fundamental demand for green investment instruments, in particular with debt features, would be good candidates to drive this transition. Pension funds and large insurance companies would be natural candidates due to their natural demand to hedge interest rate risk originating from their liability side. Sovereign wealth funds would also be candidates with a sufficiently large impact to accelerate this market. Especially those funded by cash flow with a high environmental footprint such as Norway's Oil Fund, may find this appealing because environmentally friendly investments may partially hedge their cash flow risk originating from climate policies.

5.6 Converting outstanding green bonds

Issuers could consider offers to convert existing green bonds to corresponding regular bonds plus green certificates. This could be done in order to help the green certificate market grow further, to pool with a new issue (and thereby let the new issue benefit from liquidity improvements as in Section 3), or simply as a service to investors to not let them feel left out and mitigate costs related to legacy products. In view of the superior properties of green certificate financing compared to green bond financing, investors should have little to no objections. To the extent that a minority of investors for whatever reason would object, such a conversion would impair the liquidity of outstanding green bonds even further, providing additional incentives for them to convert.

[13] See `http://www.nationalbanken.dk/en/governmentdebt/IR/Pages/Model-for-sovereign-green-bonds.aspx`

6 Conclusion

In this paper, we show from a theoretical angle that the security design of the popular asset class of green bonds stands in the way of fully capitalizing on the benefits of green debt securities. Compared to a simple to constuct hypothetical benchmark security, green bonds are illiquid, carry excessively high funding costs, impair additionality, and have prices that poorly reflect environmental fundamentals. Calibration exercises show that the effects on price transparency and price discovery are economically very large.

The mechanisms we put forward in this paper show clear advantages of abandoning green bonds in favor of other green debt instruments like the green certificates that we use as a benchmark. That having said, we are aware of some resistance against this idea, in particular because the lack of transparency inherent to green bonds makes the cost of green earmarking less explicit and therefore easier to sell. We would encourage a further discussion on potential advantages and disadvantages of changing the design of green debt securities that have not been covered in this paper as well as a further discussion on implementation details. Together with the experience from the Danish experiment to issue green certificates we hope to see green debt securities play a positive role in reducing the environmental footprint of humanity.

Tables and Figures

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

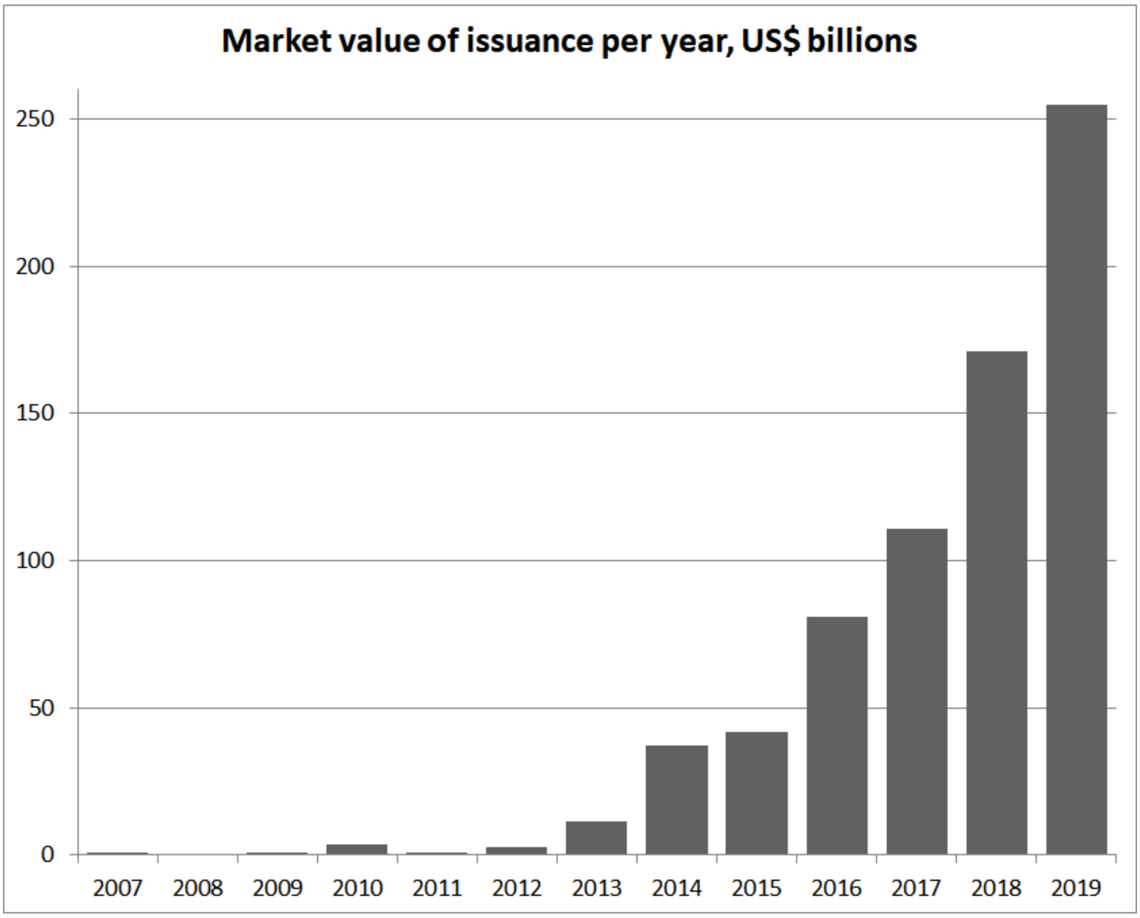

Table 1: Information ratios of changes in green spreads vs green certificate premia

	Green spread	Green certificate premium
Annual	33.33%	100%
Quarterly	11.11%	100%

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

Table 2: Transaction cost hurdles for green certificates to be less informative

	Green certificate hurdle
Sovereign	20.42%
Corporate	300%

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

Table 3: Transaction cost hurdle to trade on information

Information advantage	Green and reference bonds	Green certificates
2 bps	4.8 bps	40%
5 bps	12 bps	100%

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

Table 4: Summary of model results

	Project financing	Clientele effect	Liquidity improvement project bonds	Liquidity improvement other bonds
	Separate green bond	✓	×	×
	Part of large issue with green certificates	✓	✓	✓
	Part of large issue	×	✓	✓

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Appendices

A Proofs

Proof of Lemma 1. The monetary amount of annual interest savings on the regular debt equals

$$DQ(s^{SB} - s^{LB}), \tag{1}$$

where s^{SB} is the bond illiquidity if the project had not been undertaken. Dividing by project size gives the spillover-induced savings per dollar of debt financing raised for the project:

$$\frac{D}{S}Q(s^{SB} - s^{LB}). \tag{2}$$

We have that

$$s^{SB} = \frac{c}{d+D}, \qquad s^{LB} = \frac{c}{d+D+S}. \tag{3}$$

Substituting gives

$$\frac{D}{S}Q(s^{SB} - s^{LB}) = -\frac{D}{S}Q\frac{c(d+D) - c(d+D+S)}{(d+D)(d+D+S)}, \tag{4}$$

$$= \frac{D}{S}Q\frac{cS}{(d+D)(d+D+S)}, \tag{5}$$

$$= \frac{D}{d+D}Qs^{LB}. \tag{6}$$

■

Proof of Proposition 1. Since investors break even, each investor needs to earn at least $\hat{r}_d^b$ to be compensated for opportunity costs. Since issuers can capture all surplus, green bonds and green certificates can reduce the financing costs by ζ. Additionally, investors need to be compensated for expected transaction costs. For a security j, expected per period transaction costs are given by Qs^j. s^j is given by (8) for regular and green certificate financing, and by (12) for green bond financing. Finally, the per dollar spillover cost savings, if any, need to be subtracted. These are given by Lemma 1 for regular and green certificate financing and absent for green bond financing. Putting all these elements together yield (13) to (15). ■

Proof of Corollary 1. The green mode of running a project with green bond and green certificate financing is optimal if respectively

$$r^g - r^t - r^{GB}_{WACC} + r^b_{WACC} \geq 0, \tag{7}$$

$$r^g - r^t - r^{GC}_{WACC} + r^b_{WACC} \geq 0. \tag{8}$$

Substituting for $r^{GB}_{WACC}, r^b_{WACC}, r^{GC}_{WACC}$ yields

$$r^g - r^t \geq \frac{D}{V}(r^{GB}_d - r^b_d), \tag{9}$$

$$r^g - r^t \geq \frac{D}{V}(r^{GC}_d - r^b_d). \tag{10}$$

Substituting for $r^l_d \forall l$ from Proposition 1 yields

$$r^g - r^t \geq -\frac{D}{V}(\zeta - Q(s^{GB} - (1 - \frac{D}{d + D}s^{LB}))) = \gamma^{GB}, \tag{11}$$

$$r^g - r^t \geq -\frac{D}{V}\zeta = \gamma^{GC}. \tag{12}$$

■

Proof of Lemma 2. By no arbitrage, we have that

$$\xi^{GC}_{i,t} = r^{ref}_{i,t} - r^{GB}_{i,t}. \tag{13}$$

Since there is an over-supply of impact investors and regular investors, investors compete for all investment opportunities. As a result any impact investor must be indifferent among investing in a green project and a regular project. At time t, the expected per period utility of investing a dollar a project of mode t equals $r_{i,t}^{ref}$, while the expected per period utility of investing a dollar in a project in the green mode equals $\zeta_{i,t} + r_{i,t}^{GB}$. We have that

$$r_{i,t}^{ref} = \zeta_{i,t} + r_{i,t}^{GB}, \Rightarrow \tag{14}$$

$$r_{i,t}^{ref} - r_{i,t}^{GB} = \zeta_{i,t}. \tag{15}$$

■

Proof of Lemma 3. Taking log returns of (23) yields

$$\tilde{ret}_t^x = \log(\tilde{p}_t^x) - \log(\tilde{p}_{t-1}^x), \tag{16}$$

$$\approx \log(p_t^x) - \log(p_{t-1}^x) + 2s^x(X_t^x - X_{t-1}^x), \tag{17}$$

because $s^x X_t^x$ is small. This proves (24) for $x = GC$.

For the long-short position, we have that

$$\tilde{p}_t^{ref} - \tilde{p}_t^{GB} = p_t^{ref}(1 - s + 2sX_t^{ref}) - p_t^{GB}(1 - s + 2sX_t^{GB}), \tag{18}$$

$$= (p_t^{ref} - p_t^{GB}) \left(1 - \frac{p_t^{ref}}{p_t^{GC}} s(1 - 2X_t^{ref}) + \frac{p_t^{GB}}{p_t^{GC}} s(1 - 2X_t^{GB}) \right). \tag{19}$$

Using approximation (17) yields

$$\tilde{ret}_t^{ref-GB} \approx \log(p_t^{ref} - p_t^{GB}) - \log(p_{t-1}^{ref} - p_{t-1}^{GB}) + s\left(\frac{p_t^{ref} - p_t^{GB}}{p_t^{GC}} - \frac{p_{t-1}^{ref} - p_{t-1}^{GB}}{p_{t-1}^{GC}} \right) + 2s\left(\frac{p^{ref}}{p_t^{GC}} X_t^{ref} - \frac{p_t^{GB}}{p_t^{GC}} X_t^{GB} - \frac{p_{t-1}^{ref}}{p_{t-1}^{GC}} X_{t-1}^{ref} + \frac{p_{t-1}^{GB}}{p_{t-1}^{GC}} X_{t-1}^{GB} \right). \tag{20}$$

Simplifying using $p_t^{ref} - p_t^{GB} = p_t^{GC}$ yields (25). ■

Proof of Proposition 2. The information ratio of the green certificate premia changes is higher than that of green spread changes iff

$$Var(\tilde{ret}^{GC}) < Var(\tilde{ret}^{ref-GB}) \Rightarrow \tag{21}$$

$$2(s^{GC})^2 < Var(\frac{p_t^{ref}}{p_t^{GC}}2sX_t - \frac{p_t^{GB}}{p_t^{GC}}2sX_t - \frac{p_{t-1}^{ref}}{p_{t-1}^{GC}}2sX_{t-1} + \frac{p_{t-1}^{GB}}{p_{t-1}^{GC}}2sX_{t-1}), \tag{22}$$

since the numerator of the information ratio in both cases is the same. Using (26), we can approximate (22) by

$$2(s^{GC})^2 < 4\left(\frac{p_t^{ref}}{p_t^{GC}}\right)^2 s^2, \Rightarrow \tag{23}$$

$$s^{GC} < \sqrt{2}\frac{p_t^{ref}}{p_t^{GC}}s. \tag{24}$$

■

Proof of Proposition 3. Projects with $\gamma > \bar{\gamma}^{GC}$ are optimally not undertaken in the green mode. Projects with $\gamma < \bar{\gamma}^{GB}$ are optimally undertaken in the green mode. In both cases, the convenience yield ζ is unaffected by the choice between green bonds or green certificates. Projects with $\gamma \in (\bar{\gamma}^{GB}, \bar{\gamma}^{GC})$ are optimally not undertaken in the green mode when financed with green bonds, but are optimally undertaken when financed with green certificates. Hence, using green bonds instead of green certificates prevents a convenience yield of ζ per dollar invested from being generated. Multiplying with project size gives an aggregate utility loss of ζS. ■