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The economics of the greenium: How much is the world willing to pay to save the Earth?*

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Abstract

Sadly, not much. This paper provides a theoretical and empirical analysis of the greenium, the price premium the investor pays for green bonds over conventional bonds. We explain in simple economic terms why the price premium of a green bond essentially represents a combination of the non-pecuniary environmental benefit of the bond, as perceived by the investor, and the effective cost of issuing it, as measured by the additional issuing costs of the bond netted off a range of monetary and non-monetary benefits associated with the issuance. Our empirical model decomposes the greenium into a time-varying market component which is common to all green bonds and an idiosyncratic component which is specific to a certain green bond itself. Using a global green bond dataset larger than any previous studies, we find that the greenium on average amounts to, sadly, just over one basis point. However, it can vary quite significantly among individual green bonds and our result suggests that a key factor underlying the variation is that they are subject to the risk of greenwashing to different extents.

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1. Introduction

The planet's temperature has risen.[1] The ice sheets have retreated in mass.[2] The oceans have warmed. The global sea level has increased.[3] This list can go on and on. There is no shortage of hard evidence that human beings have done collateral damage to the environment following a protracted period of unchecked and unsustainable population and economic growth. Fortunately, with the world feeling the backlash, there has in recent years been a growing global consensus that it is high time human beings put their acts together to at least stop, if not to reverse, the climate change (Chiang, 2017; Orlov et al., 2017; Denchak, 2018; Heine et al., 2019; Krogstrup & Oman, 2019; Lagarde & Gaspar, 2019). In the global bond market, the intensity of this consensus has arguably been manifested into the greenium, which essentially represents the willingness of the world to pay for financing green projects over non-green projects. The objective of this paper is to analyse the economics of that intensity and measure it.

Green bonds differ from conventional bonds only in the way the proceeds are used (Bhatia, n.d.; Flaherty, 2017; Horsch & Richter, 2017; Reboredo, 2018; Sartzetakis, 2019). They are designated to fund green projects, projects that aim to deliver environmental and climate benefits (Climate Bond Initiative, 2015; Wang & Zhi, 2016; Asian Development Bank, 2018; International Capital Market Association, 2018; Kenny, 2019). The greenium or the premium of a green bond refers to the higher price that the green bond can command over its conventional counterpart (Partridge & Medda, 2018; Larcker & Watts, 2019). Alternatively, it can be seen as the spread of the yield of the green bond over the yield of its conventional counterpart. Hence, a greenium is said to exist if the price of the green bond is higher or its yield is lower.[4] However, whether or not the greenium exists at all in practice and how large it is are entirely empirical questions. Indeed, empirical results have so far been mixed. While most of the studies confirm that a negative yield spread does exist, some find it practically non-existent and a couple even find it positive.

Theoretically, the greenium exists only if there are benefits that green bonds can accrue to investors, but conventional bonds cannot. Perhaps, the most direct benefit to investors of green bonds is the satisfaction derived from a goal, one of supporting climate change solutions, being fulfilled (Bendersky et al., 2019). No doubt, it is possible that some institutional investors may act just out of the motive of trying to improve their image or reputation, or to meet an environmental protection criterion of their investment mandate (Wood, 2011; Kaminker & Majowski, 2018). However, it is

[1] According to the Annual Report of the National Oceanic and Atmospheric Administration (2019b), the yearly global land and ocean temperature has increased at an average rate of 0.07°C (0.13°F) per decade since 1880.

[2] With data from its satellites, the National Aeronautics and Space Administration (n.d.) shows that the land ice sheets in both Antarctica and Greenland have been retreating since 2002, with an acceleration of ice mass loss from 2009.

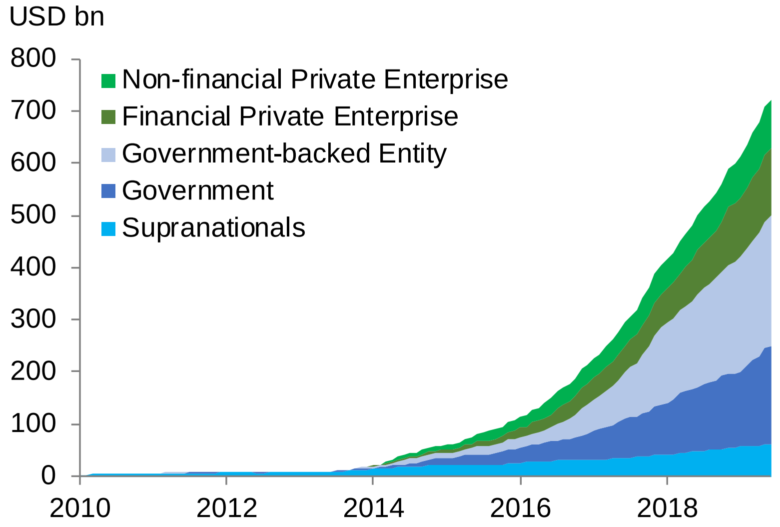
[3] According to the National Oceanic and Atmospheric Administration (2019a), the global sea level has been rising at an increasing rate in recent decades.

[4] The term, premium, generally carries a positive connotation. Green bonds are no exception, as the investor pays a premium for green bonds which are considered superior to conventional bonds. Therefore, the greenium, defined as the yield spread of green bonds over conventional bonds, is supposedly negative. We would like to define it clearly here as we find it confusing that some authors call it the negative greenium when their empirical results confirm that the greenium is negative.

important to note that such demand cannot sustain if it is not underscored by a growing desire among world citizens to protect the environment.

To the issuer, financing green initiatives is costly. It is conceivable that the public sector, including government and supranational organizations, has strong motivation to embark on green projects and issue green bonds.[5] From a social or political perspective, green projects funded by green financing increase the popularity of the issuer (Ross, 2015). Financial considerations are only secondary for this type of issuer. However, what is intriguing is the growing popularity of green bonds among private issuers (Chart 1). Why does a firm want to spend money to clean up its toxic waste in the first place when it can simply dispose it in a nearby river? A plausible answer is that its behaviour is bound by government regulations, a likely outcome of the political pressure coming from the people living downstream or the public opinion of the wider community (Currin, 2012; Gunther, 2015; Nielsen, 2018; IntelligentHQ, 2019). To put it in an economic perspective, as public opinion is formed and government policies are made in favour of internalizing the negative externalities caused by some economic activities to the environment, the private sector will have to abide by the society's values and rules to augment production processes accordingly (DeNyse, 2000; Centemeri, 2009).

Chart 1: Global outstanding amount of green bonds*



**The outstanding amount is estimated based on the assumption that bonds issued will mature on their maturity date.*
Source: Appendix A.

Still, the fact that firms need to devote resources to cleaning up their own mess is only a necessary but not a sufficient condition for green bond issuance. There is no requirement that green projects must be financed by green bonds. Firms are entirely free to issue conventional bonds (or use other means such as bank borrowing) to finance their green pursuits. Theoretically, being profit-maximizing entities, they would not issue green bonds unless the costs of issuing green bonds are more than compensated by the benefits, compared to issuing conventional bonds. The costs

[5] For example, according to As You Sow and Climate Bonds Initiative (n.d.), issuing green bonds help governments brand themselves as forward thinking, innovative, and sustainable, which is covered by the press favourably.

mainly refer to the compliance costs associated with green bond issuance.[6] The benefits can be monetary or non-monetary. Monetary benefits include government incentives, for example, direct subsidies in obtaining the "green label" and tax deductions.[7] Non-monetary benefits refer primarily to those of being crowned with the name of a green firm or, in other words, achieving a better corporate image or reputation, which may in the end also lead to monetary benefits in terms of, for example, lower cost of bank borrowing or higher stock prices (Goss & Roberts, 2011; Muller & Wikstrom, 2016; Norton Rose Fulbright, 2016; Ibrahim et al., 2017; ThriveHive, 2017; Tang & Zhang, 2018; Krebbers, 2019a; LaMacro, 2019).

This paper seeks to contribute to the literature by explaining the economics of the greenium and adopting a new approach to estimating it, utilising probably the most comprehensive global green bond dataset compared to any previous studies (Appendix A). We are unaware of any previous attempt in the literature to put forward a theory to analyse the economic concept of the greenium. Much of the literature has so far been empirical in nature, focusing on estimating it. However, in our view, it is important to develop a theoretical framework to help us understand the rationale underlying why investors are willing to pay for, and issuers willing to sell, a bond at a price different from another with totally the same characteristics except that the use of the proceeds is confined to serving pro-environmental purposes. The theory should lay bare what exactly constitutes the greenium, which is instrumental in the subsequent interpretation and analysis of the estimation results.

We propose to use a two-way fixed effects regression model as it allows us to dissect the greenium with a view to facilitating the distilling of implications for investors, issuers and policymakers. With this technique, two components of the greenium, namely, the market greenium and the idiosyncratic greenium, are specified in the model. The market component, which is time-varying, can help us monitor the market trend of the greenium in general, whereas the idiosyncratic component helps us gauge the greenium of a bond due to its own specificities. Being able to monitor the trend can aid policymaking, while knowing the attributes underlying the greenium of individual bonds can help investors make their investment decisions and issuers formulate their funding strategies. For example, a green bond that displays a smaller greenium than other green bonds does not necessarily mean that it represents a potentially better investment and, similarly, one that has a larger greenium makes no guarantee that all issuers would be able to tap it.[8]

[6] Getting the green bond label involves additional costs ranging from US$10,000 to US$100,000 and additional time for verification or certification (Kaminker et al., 2016; Hong Kong Exchanges and Clearing Limited, 2018).

[7] Taking China as an example, 120 policy measures were rolled out by the government to support the development of China's green bond market in 2018, which include policy support for the issuer of the market (Meng et al., 2019).

[8] As we shall see, this may be caused by the problem of greenwashing. Greenwashing, a term coined in the 1980s by an American environmentalist Jay Westerveld, refers to the action of misleading consumers regarding the environmental practices of a company or environmental benefits of a product (Romero, 2008; Gallicano, 2011). The smaller greenium, if attributable to a lower idiosyncratic greenium of the bond due possibly to a greater risk of greenwashing, does not at all mean that it is undervalued by the market. Also, issuers coming from an industry that is generally seen as being associated with a greater risk of greenwashing are unlikely to be able to harness the same total greenium for their bonds as other issuers.

The rest of this paper is organized as follows. Section 2 introduces the theoretical framework to analyze the greenium. Using this framework, we discuss and scrutinize what exactly determines its magnitude and under what conditions the greenium exists (or disappears). In Section 3, we detail the meticulous process of how we select our sample bond triplets from the enormous dataset and explain how to interpret the specification of the two-way fixed effects model in analysing the greenium. In this section, we also present and discuss our findings alongside those of the previous studies. Section 4 concludes.

2. Theoretical framework

Our theoretical framework is adapted from the vertical differential models developed by Gabszewicz and Thisse (1979) and Shaked and Sutton (1982) which analyse the pricing behaviour of the firm with two differentiated products. The differentiated products here are green bonds (GB) and conventional bonds (CB).

First of all, we make three assumptions about investors:

1. Investors generally perceive a non-pecuniary environmental benefit associated with bond i to be $S_i \in [\underline{S}, \overline{S}] \subset R$, where $\underline{S}$ and $\overline{S}$ represent the lower and upper bounds of the benefit respectively, and are able to differentiate between the two bonds in terms of the benefit.
2. Each investor is different in the way they value the benefit, which can be represented by a preference parameter $\theta \in [\underline{\theta}, \overline{\theta}] \subset R_{\geq 0}$, where $\underline{\theta}$ and $\overline{\theta}$ denote the lower and upper bounds of the parameter respectively. Hence, some investors value the same benefit more than others.
3. Each investor can afford at least one unit of either of the bonds in the market. There are $\overline{\theta} - \underline{\theta}$ investors uniformly distributed in the market since each investor is different in their preference.

The indirect utility function of investor j with parameter θ_j investing in bond i can be written as:

$$V_i(P|\theta_j) = r + \theta_j S_i - P_i$$

where r is the willingness to pay for the conventional bond such that $r + \theta_j S_i$ represents the maximum willingness to pay for the bond i; and P_i is the price of bond i.

For a given perceived environmental benefit of the green bond and conventional bond, S_{GB} and S_{CB}, there exists an investor with preference $\hat{\theta}$ who is indifferent between the green bond and conventional bond. The indifferent investor satisfies:

$$r + \hat{\theta} S_{GB} - P_{GB} = r + \hat{\theta} S_{CB} - P_{CB} \qquad (1)$$

Solving equation (1) gives:

$$\hat{\theta} = \frac{P_{GB} - P_{CB}}{S_{GB} - S_{CB}} \text{ for } \hat{\theta} \in [\underline{\theta}, \overline{\theta}] \tag{2}$$

For simplicity, we further make two assumptions about issuers:

1. There are two types of issuers, one issuing only green bonds and the other only conventional bonds.
2. They have constant and exogenous effective cost of issuing green bonds (C_{GB}) and conventional bonds (C_{CB}).

The effective cost of issuing a green bond differs from that of a conventional bond mainly by the setting off the costs and benefits associated with obtaining the green label:

$$C_{GB} - C_{CB} = C_{GL} - S_{GL} \tag{3}$$

where C_{GL} and S_{GL} denote the costs and benefits of obtaining the green label. The costs refer to those of obtaining green certificates, paying for external reviews, preparing regular and additional reports, and so forth. The benefits can be monetary or non-monetary. Monetary benefits are mainly government incentives, which can take the form of direct subsidies or tax deductions, while non-monetary benefits are those of achieving an improved corporate image, which in the end is also expected to be translated into monetary ones such as stronger sales prospects, lower cost of bank borrowing, positive stock price reactions.[9]

The objective functions of the issuer of the conventional bond and green bond can be written as:

$$\pi_{GB}(P_{CB}, P_{GB} | S_{CB}, S_{GB}) = (P_{GB} - C_{GB})(\overline{\theta} - \hat{\theta}) \tag{4}$$

$$\pi_{CB}(P_{CB}, P_{GB} | S_{CB}, S_{GB}) = (P_{CB} - C_{CB})(\hat{\theta} - \underline{\theta}) \tag{5}$$

since there are $\overline{\theta} - \underline{\theta}$ investors in the market, with $\overline{\theta} - \hat{\theta}$ of them investing in green bonds and $\hat{\theta} - \underline{\theta}$ in conventional bonds. Substituting equation (2) into objective functions (4) and (5) gives:

$$\pi_{GB}(P_{CB}, P_{GB} | S_{CB}, S_{GB}) = (P_{GB} - C_{GB}) \left(\overline{\theta} - \frac{P_{GB} - P_{CB}}{S_{GB} - S_{CB}}\right) \tag{6}$$

$$\pi_{CB}(P_{CB}, P_{GB} | S_{CB}, S_{GB}) = (P_{CB} - C_{CB}) \left(\frac{P_{GB} - P_{CB}}{S_{GB} - S_{CB}} - \underline{\theta}\right) \tag{7}$$

[9] Hence, theoretically, the effective cost can be negative, i.e., when the issuing benefits more than offset the issuing costs, in which case the effective cost is in fact a net benefit.

Given the perceived environmental benefit and effective cost, the problem to the green and conventional bond issuers is to maximize their objective function with respect to the price of green bonds and that of conventional bonds respectively. After taking the first-order conditions of $\partial\pi_{GB}/\partial P_{GB} = 0$ and $\partial\pi_{CB}/\partial P_{CB} = 0$ in equation (6) and (7), we can obtain the following optimal pricing functions:

$$P_{GB}^* = \frac{1}{3}\Big((S_{GB} - S_{CB})(2\overline{\theta} - \underline{\theta}) + (C_{CB} + 2C_{GB})\Big) \tag{8}$$

$$P_{CB}^* = \frac{1}{3}\Big((S_{GB} - S_{CB})(\overline{\theta} - 2\underline{\theta}) + (2C_{CB} + C_{GB})\Big) \tag{9}$$

The optimal price differential between the green and conventional bonds can then be obtained by subtracting equation (8) from equation (9):

$$P_{GB}^* - P_{CB}^* = \frac{1}{3}\Big((S_{GB} - S_{CB})(\overline{\theta} + \underline{\theta}) + (C_{GB} - C_{CB})\Big) \tag{10}$$

In other words, the greenium is one-third of the sum of the relative (environmental) benefit of the green bond to the conventional bond from investors' perspective and the relative (effective) cost of the green bond to the conventional bond from issuers' perspective.

Generally speaking, we expect $S_{GB} > S_{CB}$ and hence the relative (non-pecuniary environmental) benefit of the green bond, $(S_{GB} - S_{CB})(\overline{\theta} + \underline{\theta})$, is positive.[10] However, for the relative (effective) cost of issuing the green bond, there are two scenarios since it comprises not only the costs of obtaining the green label, but also the monetary and non-monetary benefits attached to the label. Substituting (3) into (10) gives:

$$P_{GB}^* - P_{CB}^* = \frac{1}{3}\Big((S_{GB} - S_{CB})(\overline{\theta} + \underline{\theta}) + (C_{GL} - S_{GL})\Big)$$

In the first scenario, if $C_{GL} > S_{GL}$, then the greenium exists. The second scenario in which $C_{GL} < S_{GL}$ can happen only if the benefits of having the label are so large that they more than offset the costs of obtaining it such that the effective cost essentially becomes a net benefit. However, even if this happens, whether or not the greenium exists still depends on whether or not this net benefit to the issuer is greater than the benefit to the investor, i.e., whether or not $S_{GL} - C_{GL} \geq (S_{GB} - S_{CB})(\overline{\theta} + \underline{\theta})$ is true.

The second scenario seems highly unlikely, as it requires that obtaining a green label does not only make it more cost-efficient in producing a bond from the perspective of the issuer but the cost saving is so much that the issuer is willing to sell this supposedly better instrument to the investor at a price lower than what the investor is

[10] S_{CB} can possibly be negative in the sense that the firm operates in a way that damages the environment. Yet, by definition, S_{GB} has to be greater than S_{CB}. In the case of greenwashing, it is possible than the actual benefit to environment is lower than the original perceived environment but still higher than that from conventional bonds.

willing to pay. There are two possibilities this could happen. First, the net benefit to the issuer is a result of governments offering considerable incentives, such as direct subsidies or tax cuts for issuing green bonds. However, to date, such government incentives have been minimal globally.[11] Second, firms believe green bonds can help them improve their corporate image by so much that it can be turned into huge long-term savings or benefits.[12] Theoretically, this improvement must be a function of the environmental benefit as perceived by society at large, which should bear little difference from the same environmental benefit as perceived by the investor. When the former is considerable, so should be what is expected of the latter. In all, therefore, even in the event that the second scenario occurs, i.e., $C_{GL} < S_{GL}$, chances that the greenium is negative, i.e., $P_{GB}^{*} < P_{CB}^{*}$, are slim.

Finally, it is important to note that this theoretical framework is not only applicable to the seller and the buyer in the primary market, but also to those trading in the secondary market. While the seller in the primary market is the firm that issues the green bond, the seller in the secondary market is the investor who holds the green bond. Whoever holds it owns its perceived environmental benefit, which will act as part of the cost when it is sold, due to the fact that it will become a value foregone. Therefore, other things being equal, the effective cost of a green bond is also expected to be higher than the effective cost of a conventional bond in the secondary market.

3. Empirical model and estimation

3.1 Screening for sample bond triplets

Theoretically, the comparable conventional bond is a bond that has features identical to the green bond of the same issuer, except that its proceeds are not restricted to financing green projects. The features include currency denomination, maturity, credit risk, bond structure, coupon type, seniority, and so forth. Taking these features into account, the spread between the yields of the green bond and the comparable conventional bond ($\Delta y_{i,t}$) may be said to be attributable to the green label:

$$\Delta y_{i,t} = y_{i,t}^{GB} - y_{i,t}^{CB}$$

where $y_{i,t}^{GB}$ is the yield of the green bond and $y_{i,t}^{CB}$ is the yield of the comparable conventional bond.

Ideally, the simplest way to estimate the greenium is to find a sufficiently large sample of green-bond-conventional-bond (GB-CB) twins and then compare their yields directly. However, this is almost impossible in practice. Often we can only find

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[11] According to the Green Bond Policy Data Set of Climate Bond Initiative, only six economies had offered subsidies or tax incentives as of 2018. They are China, Hong Kong, Japan, Malaysia, Netherlands, and Singapore.

[12] Long-term savings or benefits of the firm may take the form of lower cost of bank borrowing, higher stock prices, wider investor and customer bases, reduced risk of government control or regulations, and so forth (Goss & Roberts, 2009; Barney et al., 2007; Flammer, 2013; Liberatore et al., 2017; Climate Bonds Initiative, 2019).

some conventional bonds with features that are close to, but not identical to, the respective green bonds. Therefore, any conclusions drawn by comparing directly the yields of imperfect GB-CB pairs can be misleading since the spreads may be attributed to different features of the bonds as discussed, rather than the green label *per se*.

To take into account the heterogeneity of the green bonds and conventional bonds, we construct a synthetic conventional bond for each green bond following the methodology employed by Zerbib (2019). First, we match each green bond with two conventional bonds of similar features to form a sample of GB-CB triplets. Specifically, we require the two conventional bonds to have the same issuer, the same currency and the same rating as the green bond. In additional, they must have their issue dates within six years from (i.e., before or after) that of the green bond and their maturity dates within two years.[13] Finally, we restrict them to those having an issue amount of less than four times the green bond's issue amount and greater than one-quarter of this amount. The main difference between our matching and Zerbib's (2019) is that, for practical reasons, we exclude green bonds that are collateralized, option-embedded, or have a floating rate to keep the potential impurity of the matches to a minimum.[14] After the above much stricter screening and filtering process compared to Zerbib's, our considerably larger global green bond dataset still allows us to have a final sample that is richer in terms of size and variety. There are 267 GB-CB triplets with a 78,304-line unbalanced bond-day panel, covering 18 currencies. This is compared to Zerbib's 110 GB-CB triplets with a 37,503-line unbalanced bond-day panel, covering 12 currencies. The descriptive statistics of the 267 green bonds can be found in Table 1.[15]

Table 1: Descriptive statistics of the 267 green bonds with matched triplets

		AUD	CNY	EUR	JPY	SEK	USD	Others	*All*
Consumer Discretionary	**Average maturity (years)**			3.67	4.33	3.00	5.00	29.99	*7.81*
	Issued amount (USD bn)			0.71	0.24	0.02	0.50	0.04	*0.28*
	Number of green bonds			1	3	1	1	1	*7*
Financials	**Average maturity (years)**	4.75	3.00	6.17	5.07	4.10	4.74	3.40	*4.63*
	Issued amount (USD bn)	0.35	0.66	0.68	0.09	0.09	0.76	0.01	*0.33*
	Number of green bonds	4	9	25	16	19	7	18	*98*
Government/ Supranationals	**Average maturity (years)**	7.67		9.01		5.11	5.02	5.47	*6.16*
	Issued amount (USD bn)	0.25		0.75		0.19	0.59	0.11	*0.39*
	Number of green bonds	15		28		18	44	49	*154*
Industrials	**Average maturity (years)**			6.00	5.00				*5.34*
	Issued amount (USD bn)			0.68	0.09				*0.29*
	Number of green bonds			1	2				*3*

13 It is important to set a limit for the impurity of the sample caused by the differences in the maturity and issue dates between the two matched conventional bonds and the green bond. See Appendix F for a detailed discussion and analysis of the impact of the impurity on the greenium estimates.

14 It is important to match a collateralized green bond with two conventional bonds having the same underlying collaterals but we have no information about the collaterals used. It is also practically impossible to find two conventional bonds with the same benchmark/embedded option as a floating rate/option-embedded green bond.

15 See Appendix A for details on the construction methodology of our green bond database.

Materials	**Average maturity (years)**			5.00		*5.00*
	Issued amount (USD bn)			0.13		*0.13*
	Number of green bonds			1		*1*
Utilities	**Average maturity (years)**	5.00	7.96		10.01	*7.73*
	Issued amount (USD bn)	0.74	1.47		0.08	*0.94*
	Number of green bonds	1	2		1	*4*

Second, for each triplet collected, we estimate the yield of the synthetic conventional bond at time *t* ($\tilde{y}_{i,t}^{CB}$) as the maturity-adjusted yield of the two conventional bonds by linear interpolation or extrapolation. Denoting the slope and intercept of the linear function passing through ($Remaining\ Maturity_{CB1},\ y_{i,t}^{CB1}$) and ($Remaining\ Maturity_{CB2},\ y_{i,t}^{CB2}$) by m^* and c^*, we calculate the yield of the synthetic conventional bond at time *t* ($\tilde{y}_{i,t}^{CB}$) as:

$$\tilde{y}_{i,t}^{CB} = m^*(Remaining\ Maturity_{GB}) + c^*$$

and its spread with the green bond as:

$$\Delta\tilde{y}_{i,t} = y_{i,t}^{GB} - \tilde{y}_{i,t}^{CB}$$

3.2 Specifying the empirical model

Now, although the main features of the bonds are taken into account, a spread may still arise as a result of different market conditions, in particular with respect to liquidity and volatility (Febi et al., 2018; Bachelet et al., 2019). The investor is generally willing to pay a higher price for a more liquid or less volatile financial asset or, in the case of a bond, accept a lower yield, other things being equal. Hence, it is important to distinguish the effect on bond prices of the restriction of providing finances for green projects *per se* from the effects of market liquidity and volatility.

To estimate the sole impact of the green label, the yield spread between the green bond and the corresponding synthetic conventional bond is regressed on their liquidity and volatility differentials:

$$\Delta\tilde{y}_{i,t} = \alpha_i + \beta_t + \gamma\Delta L_{i,t} + \varphi\Delta\sigma_{i,t} + \varepsilon_{i,t} \qquad (11)$$

where α_i is the individual fixed effects, β_t is the time fixed effects, $\varepsilon_{i,t}$ is the error term, $\Delta L_{i,t}$ is the liquidity differential defined as the bid-ask spread (Bid/Ask) difference between the green bond and the corresponding synthetic conventional bond,

$$\Delta L_{i,t} = Bid/Ask_{i,t}^{GB} - Bid/Ask_{i,t}^{CB}$$

and $\Delta\sigma_{i,t}$ is the volatility differential defined as the difference in the past 10-day realized volatility of the yield between the green bond and the respective synthetic conventional bond.[16] A higher value of $\Delta L_{i,t}$ ($\Delta\sigma_{i,t}$) implies that the green bond is less liquid (more volatile) than its conventional counterpart and *vice versa*.

As can be seen in equation (11), instead of the one-way fixed effects regression model adopted by Zerbib (2019), we employ a two-way fixed effects regression model, which includes a green bond-specific factor and a time dummy. The advantage of the two-way fixed effects regression is that it allows us to decompose the greenium ($p_{i,t}$), of a green bond i at time t into two components: one can be called the market greenium (time fixed effects) as it is common to all green bonds; and the other the idiosyncratic greenium (individual fixed effects) as it varies among individual green bonds, such that

$$p_{i,t} = \alpha_i + \beta_t.$$

This is reminiscent of the decomposition of the yield spread of euro-area sovereign bonds by Gibson et al. (2016) into a regional market component (time fixed effect) and a country-specific component (individual fixed effect).

In practice, α_i and β_t cannot be estimated separately due to the inherent limitation of the regression model (Appendix B). To get around the econometric problem, we define an augmented version of the idiosyncratic and market greeniums, $\tilde{\alpha}_i$ and $\tilde{\beta}_t$, respectively:

$$\tilde{\alpha}_i = (\bar{\alpha} + \bar{\beta}) + (\alpha_i - \bar{\alpha}) \text{ and } \tilde{\beta}_t = (\bar{\alpha} + \bar{\beta}) + (\beta_t - \bar{\beta})$$

where $\bar{\alpha}$ and $\bar{\beta}$ are the average idiosyncratic and market greeniums respectively. The advantages of $\tilde{\alpha}_i$ and $\tilde{\beta}_t$ are multifaceted. Firstly, the shapes of their distributions are identical to those of α_i and β_t, except that their means differ by a constant.[17] Secondly, since $\tilde{\alpha}_i$ is just a monotonic transformation of α_i, the order is preserved, i.e., $\tilde{\alpha}_i > \tilde{\alpha}_j$ implies $\alpha_i > \alpha_j$. This means that we can rank the idiosyncratic greeniums among different green bonds equivalently by the augmented idiosyncratic greeniums (Nicholson & Snyder, 2012). Thirdly, the change in $\tilde{\beta}_t$ is the same as the change in β_t, i.e., $\tilde{\beta}_t - \tilde{\beta}_{t-1} = \beta_t - \beta_{t-1}$, because adding an extra constant ($\bar{\alpha}$) to β_t will not affect the value of its first difference. Most importantly, $\tilde{\alpha}_i$ and $\tilde{\beta}_t$ can be estimated separately (Appendix B). By delving into $\tilde{\alpha}_i$ and $\tilde{\beta}_t$, we can analyse how the greeniums are distributed within our sample and monitor how the market greenium changes over time.

3.3 Controlling for liquidity and volatility effects

[16] The bid-ask spread is calculated as the difference, expressed as a fraction of the ask price, between the ask price and the bid price. For the synthetic conventional bond, the spread is estimated as the distance-weighted average of the bid-ask spreads of the two conventional bonds. Let d_1 be the absolute value of the difference between the remaining maturities of $CB1$ and green bond, and d_2 be the absolute value of difference between remaining maturity of $CB2$ and green bond, such that $Bid/Ask_{i,t}^{CB} = [d_2/(d_1 + d_2)]Bid/Ask_{i,t}^{CB1} + [d_1/(d_1 + d_2)]Bid/Ask_{i,t}^{CB2}$. Analogously, the realized volatility of the yield of the synthetic conventional bond is estimated as the distance-weighted average of the realized volatility of the two conventional bonds.

[17] Mathematically, it can be shown that $var(\tilde{\alpha}_i) = var(\alpha_i)$ and $var(\tilde{\beta}_t) = var(\beta_t)$ since $\bar{\alpha}$ and $\bar{\beta}$ are constants.

The bond yields data are taken from Bloomberg.[18] Table 2 shows the descriptive statistics of variables used for regression. The sample comprises a 78,304-line unbalanced bond-day panel for the period between 2 January 2014 and 31 July 2019. Observations with values of $\Delta\tilde{y}_{i,t}$, $\Delta L_{i,t}$ or $\Delta\sigma_{i,t}$ lying outside the 5th to 95th percentile range of the sample are removed from the panel to alleviate the problem of potential outliers.

Table 2: Descriptive statistics of the data in the sample

	Sample values (in basis points)					
	Min	1st Quart.	Median	Mean	3rd Quart.	Max
$\Delta\tilde{y}_{i,t}$	-61.39	-3.48	-0.29	-1.67	1.56	46.09
$\Delta L_{i,t}$	-33.33	-2.35	0.26	0.33	3.31	29.81
$\Delta\sigma_{i,t}$	-278.93	-18.09	0.94	3.38	24.37	304.81

As an illustration, Charts 2A and 2B plot $\Delta\tilde{y}_{i,t}$ against $\Delta L_{i,t}$ and $\Delta\tilde{y}_{i,t}$ against $\Delta\sigma_{i,t}$ respectively, using the data from the largest ten GB-CB triplets (out of 267 triplets), which account for 13% of the 78,304-line unbalanced panel. The data of each GB-CB triplet are denoted by the same colour and a best-fitted line is drawn to each of these coloured clusters. As can be seen, two of the ten lines are downward sloping in Chart 2A and only one of the ten lines in Chart 2B. The rest of the sample bears basically the same picture. This suggests that the relationships between the yield spread and liquidity differential and between the yield spread and volatility differential are by and large positive.

Chart 2A: Scatterplot of $\Delta\tilde{y}_{i,t}$ versus $\Delta L_{i,t}$

[18] The pricing source used is BVAL from Bloomberg, which provides evaluated prices generated by quantitative pricing models based on direct market observations from multiple sources. When calculating the yield spreads, we use the bid yield instead of the ask yield used by Zerbib (2019). Since the bid price is the maximum amount of money an investor is willing to pay for a security, the bid yield serves as a better reference for potential issuers to gauge the maximum cost of borrowing to finance their spending (Dickson & Rowley, 2014).

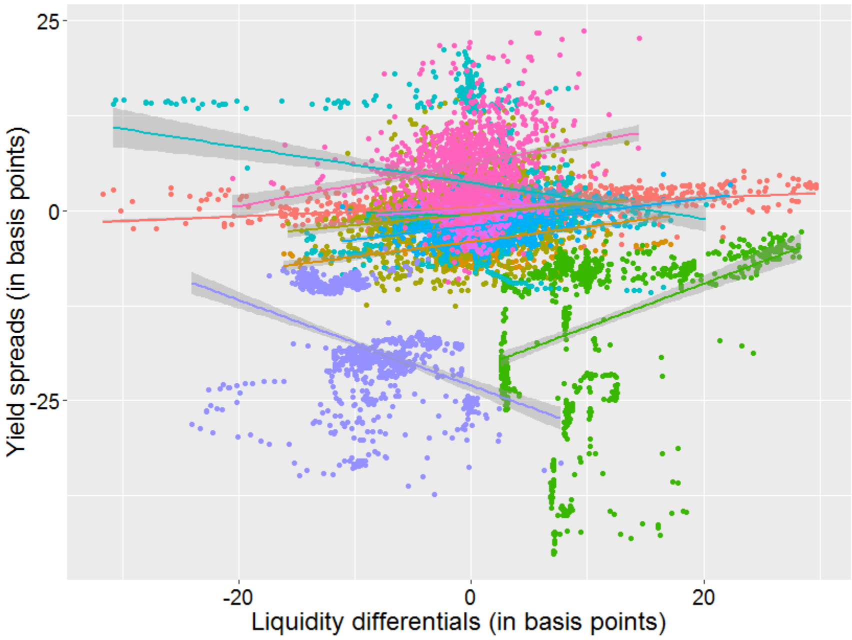


Chart 2B: Scatterplot of $\Delta\tilde{y}_{i,t}$ versus $\Delta\sigma_{i,t}$

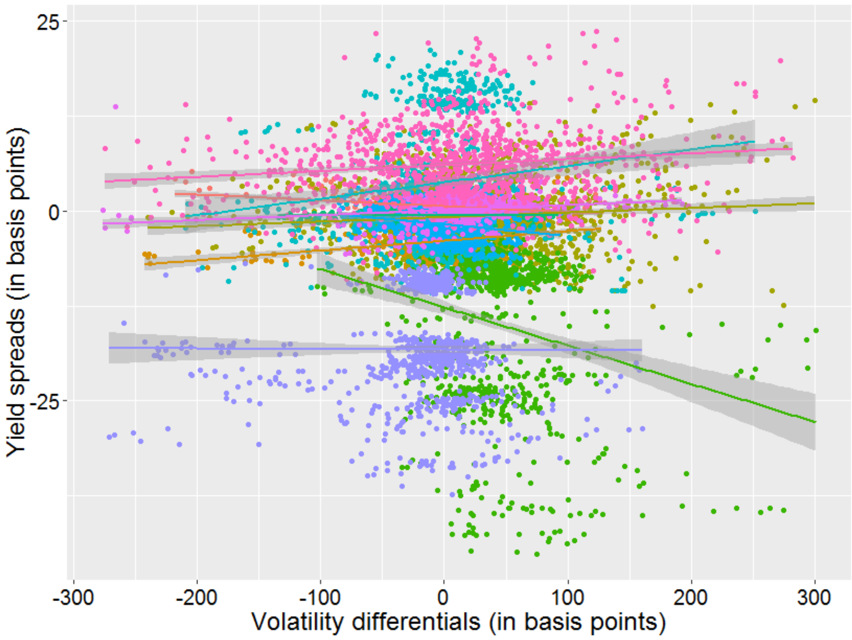


Table 3 summarizes the results of the regression using equation (11).[19] Although the R^2 of the two-way fixed effects model is low, the liquidity and volatility differentials are important factors whose effects need to be controlled for, as suggested by their highly statistically significant coefficients. The coefficient of $\Delta L_{i,t}$ (γ) is estimated to be 0.11, which suggests that a one basis-point widening in the liquidity differential indicator $(\Delta L_{i,t})$ will lead to an increase of 0.11 basis points in yield spread $(\Delta\tilde{y}_{i,t})$. The sign of γ estimated by our panel model takes the opposite sign of the one estimated by Zerbib (2019). In Zerbib's one-way fixed effects model, it is estimated that a one basis-point increase in $\Delta L_{i,t}$ will lead to a 9.9 basis point reduction in

[19] The panel model is estimated with the "plm" package in R (Croissant & Millio, 2008).

$\Delta\tilde{y}_{i,t}$. Comparatively speaking, it seems our results make more economic sense since a higher $\Delta L_{i,t}$ (i.e., the green bond being less liquid) should theoretically lead to an increase, rather than a reduction, in the yield spread between green bond and conventional bond ($\Delta\tilde{y}_{i,t}$). The coefficient of $\Delta\sigma_{i,t}$ (φ) is estimated at 0.002. Despite its small magnitude, $\hat{\varphi}$ is statistically significant and has a positive sign as expected.[20] More discussions on the magnitude and variation of the average liquidity and volatility premium differentials can be found in Appendix C.

Table 3: Results of the two-way fixed effects regression

	Dependent variable: $\Delta\tilde{y}_{i,t}$	
	Within	Newey-West Robust std. err.
$\Delta L_{i,t}$	0.111*** (0.005)	0.111*** (0.014)
$\Delta\sigma_{i,t}$	0.002*** (0.0004)	0.002* (0.001)
Observations	78,304	
R^2	0.007	
F Statistics	278.882*** (df = 1; 76668)	

*Note: *** and * denote statistical significance at 1% and 10% respectively.*

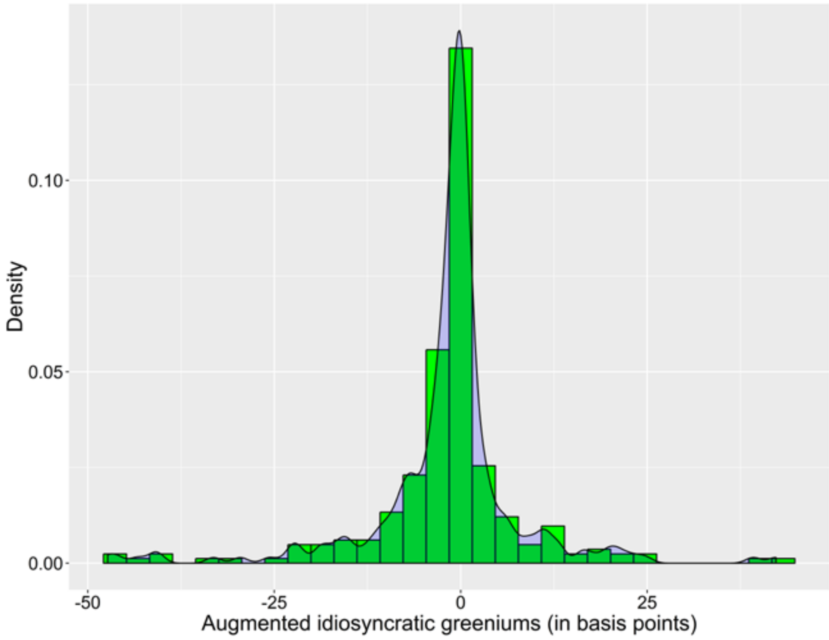
We perform two robustness checks on our results. First, we try different model specifications and the results are shown in Appendix D. The coefficients of $\Delta L_{i,t}$ and $\Delta\sigma_{i,t}$ are very similar across the models, suggesting that the estimates are plausible and robust. As a second check, we replicate Zerbib's results with his individual fixed effects model using our data but confining the sampling period to be the same as Zerbib's, i.e., July 2013 to December 2017. Appendix E summarizes the replication results, which are largely in line with Zerbib's findings, again except for the sign of the coefficient of the liquidity differential indicator.

3.4 Estimating and analysing the greenium

Chart 3 shows the distribution of the augmented idiosyncratic greeniums ($\hat{\hat{\alpha}}_i$) of all the green bonds covered by this study, which reveals how greeniums are distributed within our sample. Although the interquartile range of $\hat{\hat{\alpha}}_i$ is narrow (-3.7 to 0.9 basis points), many of the $\hat{\hat{\alpha}}_i$ lie far away from the range. This suggests that the greenium of different green bonds can differ significantly depending on the characteristics of the bond itself. As discussed, these characteristics can be wide-ranging given the idiosyncratic nature of the bond.

Chart 3: Distribution of the augmented idiosyncratic greeniums ($\hat{\hat{\alpha}}_i$)

[20] The expected sign of φ is positive since high volatility should be associated with a decline in price (i.e. an increase in yield) to compensate investors (Fama & French, 2008).



To understand what possibly underscores the variations, we slice and dice the sample based on two groups of features of the green bonds, which can be connected to the determinants of greenium in our theoretical model. The median and mean greeniums for each subsample are calculated based on (i) the sector the issuer belongs to, namely, financials, non-financials, and government/supranationals;[21] and (ii) whether the bond is certified by CBI or externally reviewed.[22] Since we cannot assume the idiosyncratic greeniums in all the subsamples are normally distributed, we therefore adopt the non-parametric Wilcoxon signed-rank test with continuity correction to assess the significance of the idiosyncratic greeniums in our subsamples.[23] Table 4 summarizes the results.

Of the three sectors, financials and government/supranationals distinctively have the smallest greeniums. This may be attributable to the possibility that investing in green bonds issued by financials and government/supranationals is subject to a greater risk of greenwashing, as money is fungible. As a result, the perceived environmental benefit of their green bonds is, other things being equal, smaller. This finding is consistent with Tang and Zhang (2018) that positive stock market reactions are found only for non-financial corporations, but not for financial corporations.

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[21] We identify the issuer's sector based on the level 1 Bloomberg Industry Classification Systems (BICS), which is a proprietary hierarchical classification system used by Bloomberg to classify firms' general business activities. We group consumer discretionary, industrials, materials, and utilities together and name it as "non-financials" because the GB-CB triplets in each of these sectors are relatively scarce.

[22] Refer to Climate Bond Initiative (2017, 2019) for details on CBI certification and external reviews.

[23] The null hypothesis is whether or not the median augmented idiosyncratic greenium is zero. In each subsample, we rank the absolute value of the n premiums in ascending order and assign them a rank R_i, from 1 to n. The Wilcoxon statistic can be found by equation $W = \sum_{i=1}^{n} sgn(\widehat{\alpha_i}) R_i$. Under the null hypothesis, the Wilcoxon statistic converges to a normal distribution, with $\sigma_W^2 = [n(n+1)(2n+1)]/6$. We also add (subtract) 0.5 if W<0 (W>0) as a continuity correction since we compare discrete data to a continuous probability function.

Indeed, when we break the sample based on their green credentials, we find that green bonds that are certified by CBI or externally reviewed have a much larger idiosyncratic greenium compared to those that are not, suggesting that the latter is probably subject to a greater risk of greenwashing and, in the context of our theoretical model, a smaller perceived environmental benefit. This lends support to a growing demand for independent assessment of the greenness of green bonds due to the risk of greenwashing (Carbon Trust, n.d.; Krebbers, 2019b). The results are also in line with the finding of Deng et al. (2019) that Chinese green bonds verified by a third party have a higher greenium, the finding of Bachelet et al. (2019) that third party verifications are necessary to eliminate or reduce the suspicion of a bond being greenwashed, and the finding of Flammer (2018) that positive reputation effect on stock prices exists only for green bonds that are certified by independent third parties.

Table 4: Augmented idiosyncratic green premiums across subsamples

		Median *(Mean)* ($\hat{\hat{\alpha}}_i$)	**p-value ($\hat{\hat{\alpha}}_i \neq 0$)**	**Number of GBs**
Sector	Financials	-0.5 *(-0.8)*	**	98
	Non-financials	-2.2 *(-2.1)*	***	15
	Government/Supranationals	-0.4 *(-2.2)*	**	154
Green credentials	Yes	-0.8 *(-2.3)*	***	171
	No	-0.1 *(-0.6)*		96

****** and ** denote statistical significance at the 1% and 5% levels respectively.*

Chart 4 plots the augmented market greenium ($\hat{\hat{\beta}}_t$) over time, which depicts how the greenium changes over time. As can be seen, it stays negative most of the time and stabilises at around -0.8 basis points recently, with a median of -1.6 basis points within the sample period. Hence, the market is willing to pay a premium for green bonds, but unfortunately the premium is pretty small. This implies that in the context of our theoretical model, if the perceived environmental benefit is reasonably close to the actual environmental benefit (i.e., the actual environmental benefit not too heavily discounted by the risk of greenwashing for green bonds as a whole), the preference parameter is unlikely to be significant. In other words, investors generally do not value the non-pecuniary environmental benefit much-or to the extent they should-albeit a growing environmental awareness worldwide in recent years (Allen, 2018; Climate Policy Watcher, 2019). Worse still, the greenium can be vulnerable to the world's determination and commitment to achieving sustainable economic growth and development from an environmental perspective. The sharp decline from mid-2017 to mid-2018 may be attributable to the announcement by the US of its withdrawal from the Paris Agreement (Climate Analytics, 2017).

Chart 4: Time series plot of the augmented market greenium ($\hat{\hat{\beta}}_t$)

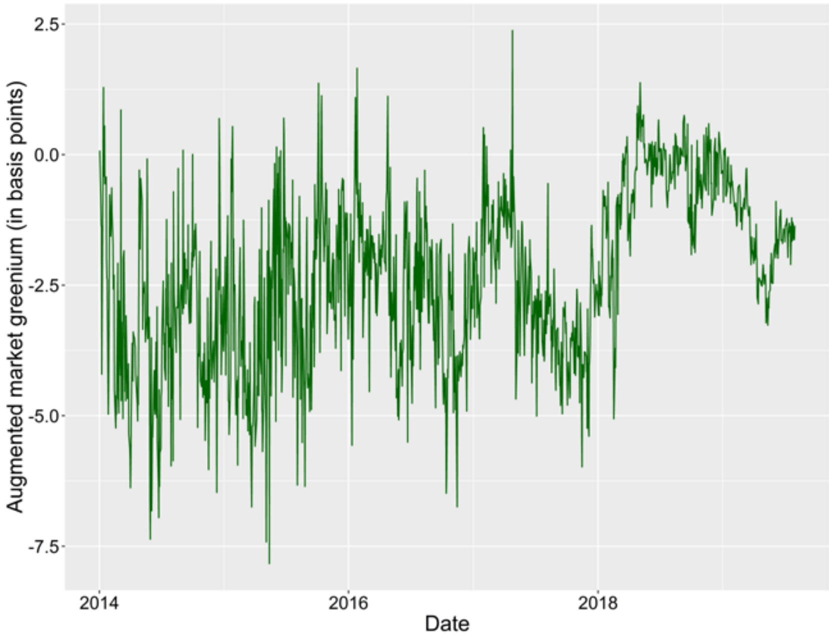


Chart 5 shows the distribution of the total greeniums ($\hat{p}_{i,t}$) of all the green bonds included in this study. The mean of the total greeniums is -1.2 basis points and the median is 0.0 basis point. A concern of the estimation is that the estimated greeniums are potentially affected by the fact that the synthetic conventional bond yield comes from two best-matched conventional bonds that have only similar, but not identical, features as those of the green bond. Therefore, as a robustness check, we re-estimate the greeniums by reducing the sample 267 bonds one by one in order of their impurity (see Appendix F). We find that the mean and median of the estimated greeniums stay very close to zero in all the subsamples, which suggests the finding that the greenium is on average negligible is robust.

Chart 5: Distribution of the total greeniums ($\hat{p}_{i,t}$)

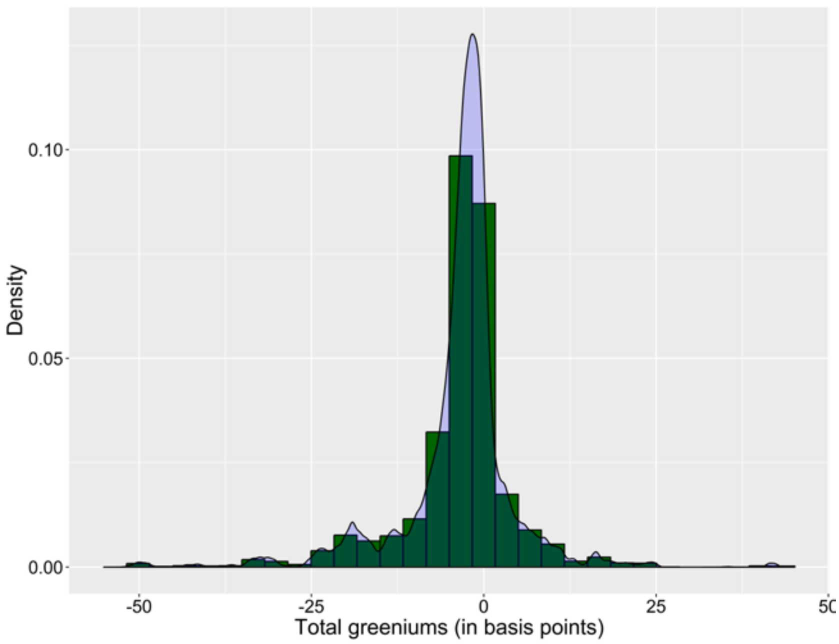


Table 5: Summary on the empirical techniques and findings of recent green bond studies#

Author	Scope	Market	Matching	Number of GBs	Sample	Method	Greenium (bps)
With greenium							
Preclaw and Bakshi (2015)	Global	Secondary	Yes	7	Jan 2014 - Aug 2015	OLS model	-16.7
Ehlers and Packer (2017)	USD and EUR denominated	Primary	Yes	21	2014 – 2017	Comparison of yields	-18.0
Schmitt (2017)	Global	Secondary	Yes	160	Jan 2015 - May 2017	Individual fixed effects model	-3.2
Baker et al. (2018)	US corporate and municipal	Primary	No	2083*	2010 – 2016	OLS model	-5.4 to -7.4
Hachenberg and Schiereck (2018)	Global	Secondary	Yes	63	Oct 2015 - Mar 2016	Panel data regression	-1.0
Gianfrate and Peri (2019)	EUR denominated	Primary	Yes	121	2013 – 2017	Propensity score matching	-18.5
Nanayakkara and Colombage (2019)	Global	Secondary	Yes	82	2016 – 2017	Panel data regression with hybrid model	-62.7
Zerbib (2019)	Global	Secondary	Yes	110	Jul 2013 - Dec 2017	Individual fixed effects model	-1.8
Without greenium							
Ostlund (2015)	Global	Secondary	Yes	28	Jan 2011 - Mar 2015	Comparison of yields	0
Karpf and Mandel (2018)	US municipal	Secondary	No	1880*	2010 – 2016	Oaxaca-Blinder decomposition	7.8
Bachelet et al. (2019)	Global	Secondary	Yes	89	2013 – 2017	OLS model	2.1 to 5.9
Hyun et al. (2019)	Global	Secondary	Yes	60	2010 – 2017	Fixed-effects generalized least squares	0
Larcker and Watts (2019)	US municipal	Primary	Yes	640**	Jun 2013 - Jul 2018	Exact matching and comparison of yields	0

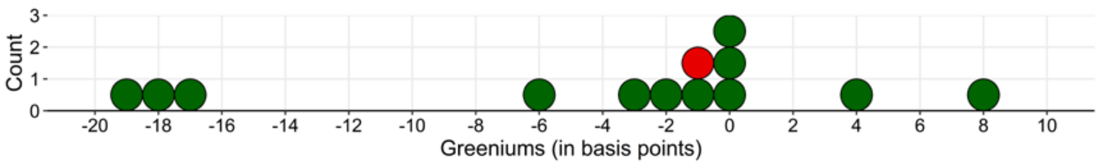
 # The two studies done by Partridge and Medda (2018) and Kapraun and Scheins (2019) are not shown here because they do not give a single point/range estimate of greenium. Partridge and Medda (2018) use multiple methodologies and different samples to study the US municipal green bonds. They find that there is greenium in both primary and secondary market. Kapraun and Scheins (2019) also use various approaches to analyze the global green bond market. They conclude that there is greenium in the primary market, but not secondary market.

** A GB-CB matching process is not used to ensure a fair comparison of the green bonds and conventional bonds.*

*** The researchers make use of the unique institutional features of the U.S. municipal bonds to achieve exact matching, i.e. forming GB-CB twins for doing true apple-to-apple comparison. Their sample includes revenue bonds, i.e. secured municipal bonds, which are in fact excluded in our sample.*

Table 5 provides a summary of the previous studies and their estimates of the greenium.[24] Chart 6 compares the estimates (represented by green dots) with ours (represented by the red dot). As can be seen, the majority of the studies, including ours, confirm that a negative yield spread does exist and that many of the estimates are very close, if not equal, to zero. As discussed, a positive yield spread rarely exists in the real world. Indeed, as pointed out by Baker et al. (2018), the estimated positive yield spread of 7.8 basis points by Karpf and Mandel (2018) is a result of the study not taking into account the effect of taxation in the US municipal securities market. The few studies that find a relatively larger estimated greenium tend to suffer from at least one of the following problems: sample size being too small, sample selection being biased, direct yield comparison without a sound GB-CB matching process and lack of control for liquidity and volatility impacts.

Chart 6: Summary distribution of estimated greeniums



Note: The dots represent the estimated greeniums from the studies listed in Table 5. The estimate of -63.0 basis points by Nanayakkara and Colombage (2019) is omitted due to scaling reasons. The red dot is ours at -1.1 basis points. The dots of 4.0 and -6.0 basis points represent the mid-point of the range of the greenium estimated by Bachelet et al. (2019) and Baker et al. (2018) respectively.

In our opinion, Larcker and Watts (2019) and Zerbib (2019) are so far the best two studies among all. Larcker and Watts make use of the unique institutional features of the US municipal bonds to achieve exact matching, i.e., forming GB-CB twins for doing true apple-to-apple comparison. From our perspective, the only problem of their work is that focusing on a particular green bond market makes their inference indefensible to be generalized to the global green bond market. The pros and cons of Zerbib's methodology and empirical results are mentioned and discussed throughout this section. In fact, our estimated greenium of -1.2 basis points is very close to the estimates of these two studies, which are 0 and -1.8 basis points.

Our empirical finding of a trivial greenium is also in line with the feedback of the market participants from a listening tour held by the California State Treasurer John Chiang (2017).[25] He points out that institutional investors, including both SRI and traditional fund managers, are reluctant to accept a lower return for investing in green bonds while, interestingly, some high-net-worth individuals are willing to pay a premium, albeit only a small one.[26] In addition, there are plenty of financial market commentaries and practitioner interviews suggesting that institutional investors and retail investors alike are generally unwilling to sacrifice financial returns for

[24] In total, there are 15 studies, of which Partridge and Medda (2018) and Kapraun and Scheins (2019) are not shown in the table because they do not give a single point/range estimate of greenium.

[25] He interviewed investors and bond underwriters in Sacramento, San Francisco, New York, Boston, and Los Angeles in 2016 in order to learn the views of market participants and identify the impediments to the development of the US green bond market.

[26] SRI refers to socially responsible investing which removes companies from the investment universe based on the environmental, social and governance (ESG) factors (MSCI, 2018; RBC Global Asset Management, 2019).

environmental benefits (Dupont et al., 2015; McLellan, 2016; Shishlov et al., 2016; Allen, 2018; Basar, 2018; Brenna & MacLean, 2018; Bowman, 2019; Reed et al., 2019).[27] Hence, anecdotal evidence also reinforces the validity of our finding of a close-to-zero greenium.

4. Conclusion

The facts speak for themselves. If green bonds are of no value, they would have not come into being and sustain in the first place, let alone experiencing the phenomenal growth in the past decade. The fact that the green bond market exists and continues to enjoy unparalleled popularity itself is perhaps the best testimony to the financial instrument being valued by investors and issuers. However, having said that, it does not necessarily mean that green bonds are seen by investors as a superior investment vehicle or product that deserves a higher price.

The choice between green bonds and conventional bonds from the investor's perspectives is actually little different from how the consumer chooses between two differentiated goods. The intrinsic value of green bonds lies in the restriction that the proceeds obtained are dedicated to serving the purpose of helping achieve a sustainable environment. We show that, in theory, the greenium is a fraction of the sum of the environmental benefit of the green bond as perceived by the investor and the effective cost incurred in issuing it for the issuer. As discussed, it is likely to be non-negative in terms of the price premium of the green bond over the conventional bond, or non-positive in terms of the yield spread. The question is how large.

Using the largest possible sample of green bonds globally, we find that the mean estimate of the greenium amounts to just slightly more than one basis point. Worse still, if there is any concern about the shape of the distribution, the median estimate, which may be more representative of the central tendency, even suggests that the greenium is practically non-existent. This result broadly agrees well with those of Zerbib (2019) and Larcker and Watts (2019) which are, as discussed, of the best quality among all the empirical studies we know of on this subject. The small greenium estimated essentially reflects that investors, and therefore also society at large, remain quite unwilling to pay for conserving the environment, despite the increased recognition of the pressing need worldwide in recent years. We find that part of the unwillingness may be attributable to the risk that some green bonds may be greenwashed, causing a risk premium that offsets the greenium. This calls for more forceful policies to reduce the rent-seeking behaviour. However, even if this can be done, our results overall still suggest that the awareness of society at large, which reflects the efforts of governments from around the world on public education, about the benefits of achieving sustainable growth and development is far from enough.

Therefore, all in all, how much is the world willing to pay to save the Earth? Sadly, not much.

[27] For example, the global head of fixed-income ESG portfolio management of a leading investment bank also reportedly opines that the ability to pay up for green bonds is very limited (Allen, 2018).

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Appendix A: Construction methodology of our green bond database

To facilitate our study of green bonds, we construct a global green bond database with raw data sourced from Bloomberg, Climate Bond Initiative, and Dealogic, which include green bonds issued from the date of the first issuance to June 2019. According to the GBP-SBP Databases & Indices Working Group (2018), there are five major green bond data providers, namely, Bloomberg, Climate Bonds Initiative, Dealogic, Cbonds and Environmental Finance. Data from Cbonds and Environmental Finance are not included as we have no access to them. However, given their relatively smaller size and considerable potential overlaps with the other sources, any missing bonds are likely to be immaterial to the comprehensive coverage of our proprietary green bond database. Interested readers can refer to GBP-SBP Databases & Indices Working Group (2018) for the details on the taxonomy, coverage, and governance process of the five data providers.

After collecting the raw data, we consolidate them based on the International Securities Identification Numbers (ISIN) of each green bond. This apparently straight forward task is quite formidable because the green bond information, such as the issue date, issuer name, credit rating, and issuer industry, can be missing and inconsistent among the three data sources. Therefore, we resort to a proprietary data massage algorithm, which validates the bond information, fills in missing values, standardizes values in different attributes, performs resolution strategies for inconsistent records among the three data sources, and removes duplicative records. Manual inspection is also performed on some subtle cases which cannot be rectified by the machine. Green bonds without ISIN are dropped to ensure no duplication.

Our green bond database has 6,031 bonds with a total face value of USD767 billion, covering over 50 economies.[28] These numbers are much larger than Zerbib (2019), in which his database has 1,065 bonds with a total face value of USD72 billion.

[28] We count the number of bonds based on the number of unique ISIN. Taps of the same bond are excluded and individual constituent tranches are counted separately.

Appendix B: Inseparable individual and time fixed effects in a two-way fixed effects model

Consider the following two-way fixed effects model with both entity fixed effects and time fixed effects:

$$Y_{it} = \alpha_i + \beta_t + \gamma X_{it} + u_{it},\ i = 1,2,\dots,N,\ t = 1,2,\dots,T \tag{B1}$$

where α_i and β_t denote the individual and time fixed effects respectively.

From (B1), we can derive the following three mean equations:

$$\overline{Y}_{i.} = \alpha_i + \overline{\beta} + \gamma\overline{X}_{i.} + \overline{u}_{i.} \tag{B2}$$

$$\overline{Y}_{.t} = \bar{\alpha} + \beta_t + \gamma\overline{X}_{.t} + \overline{u}_{.t} \tag{B3}$$

$$\overline{Y} = \bar{\alpha} + \overline{\beta} + \gamma\overline{X} + \overline{u} \tag{B4}$$

where

$$\overline{Y}_{i.} = \frac{1}{T}\sum_{t=1}^{T} Y_{it},\ \overline{Y}_{.t} = \frac{1}{n}\sum_{i=1}^{N} Y_{it},\ \overline{Y} = \frac{1}{nT}\sum_{t=1}^{T}\sum_{i=1}^{N} Y_{it}$$

$$\overline{X}_{i.} = \frac{1}{T}\sum_{t=1}^{T} X_{it},\ \overline{X}_{.t} = \frac{1}{n}\sum_{i=1}^{N} X_{it},\ \overline{X} = \frac{1}{nT}\sum_{t=1}^{T}\sum_{i=1}^{N} X_{it}$$

$$\overline{u}_{i.} = \frac{1}{T}\sum_{t=1}^{T} u_{it},\ \overline{u}_{.t} = \frac{1}{n}\sum_{i=1}^{N} u_{it},\ \overline{u} = \frac{1}{nT}\sum_{t=1}^{T}\sum_{i=1}^{N} u_{it}$$

With $\hat{\gamma}$, we can derive the following three estimators:

1. $\bar{\alpha} + \bar{\beta} = \overline{Y} - \hat{\gamma}\overline{X}$ derived from (B4)
2. $\widehat{\alpha_i} + \bar{\beta} = (\widehat{\alpha_i} - \bar{\alpha}) + (\bar{\alpha} + \bar{\beta}) = \overline{Y}_{i.} - \hat{\gamma}\overline{X}_{i.}$ derived from (B2)
3. $\bar{\alpha} + \widehat{\beta_t} = (\widehat{\beta_t} - \bar{\beta}) + (\bar{\alpha} + \bar{\beta}) = \overline{Y}_{.t} - \hat{\gamma}\overline{X}_{.t}$ derived from (B3)

Practically, there is no way to tease out $\bar{\alpha}$ and $\bar{\beta}$ individually, so we cannot estimate α_i and β_t, i.e. the individual fixed effects cannot be separately identified from the time effects, and vice versa (Hansen, 2019).

Appendix C: Average liquidity and volatility premium differentials over time

Chart C1 and C2 plot the average liquidity premium differential ($\hat{\gamma}\overline{\Delta L_t}$) and the average volatility premium differential ($\hat{\varphi}\overline{\Delta\sigma_t}$) over time respectively. $\overline{\Delta L_t}$ and $\overline{\Delta\sigma_t}$ are calculated as $(\sum_i^{n_t} \Delta L_{i,t})/n_t$ and $(\sum_i^{n_t} \Delta\sigma_{i,t})/n_t$ respectively, with n_t equals to the available number of observations at time t.

As can been seen, $\hat{\gamma}\overline{\Delta L_t}$ has decreased in recent years, which means that green bonds have become more liquid compared to their conventional counterparts. This is consistent with the fact that green bond liquidity has improved due to growing average deal size, rising proportion of green bonds listed on exchanges, and increasing green bond exchange-traded funds (Meng et al., 2017; Filkova et al., 2019). Regarding $\hat{\varphi}\overline{\Delta\sigma_t}$, it fluctuates around zero and no obvious trend is observed. Both $\hat{\gamma}\overline{\Delta L_t}$ and $\hat{\varphi}\overline{\Delta\sigma_t}$ are very small in magnitude, implying that they play a negligible role in determining the yield spreads between green bond and conventional bond.

Chart C1: Time series plot of the average liquidity premium differential ($\hat{\gamma}\overline{\Delta L_t}$)

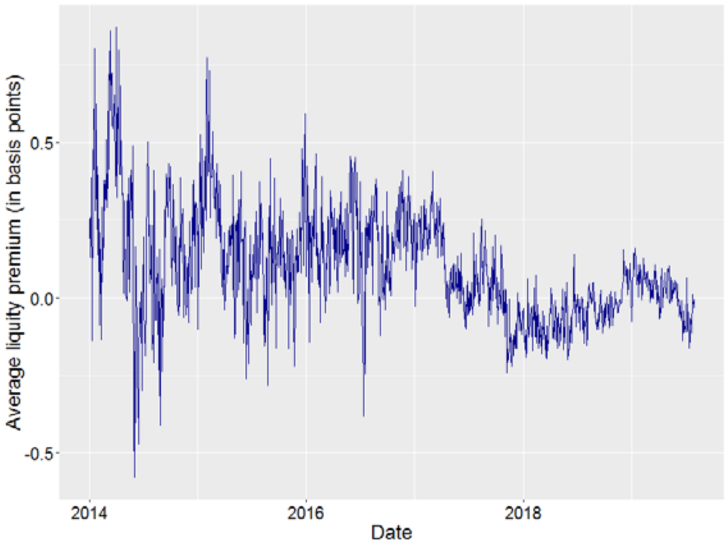
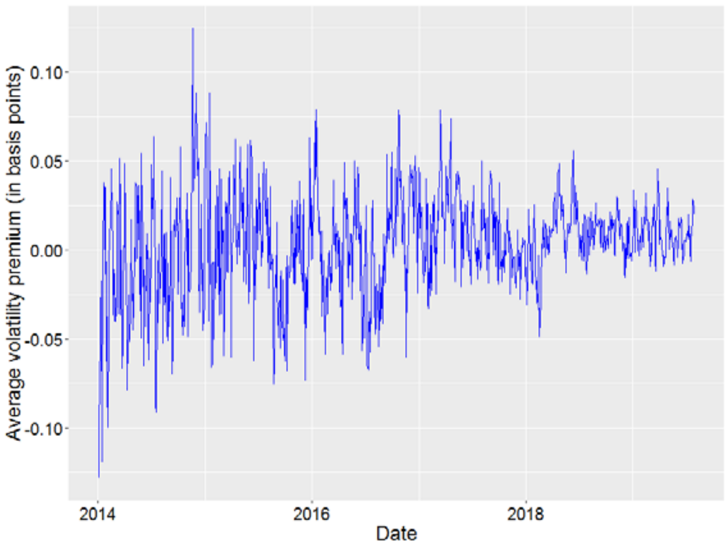


Chart C2: Time series plot of the average volatility premium differential ($\hat{\varphi}\overline{\Delta\sigma_t}$)



Appendix D: Regression results for robustness check

	Dependent variable: $\Delta\tilde{y}_{i,t}$					
	Pooled OLS (1)	Pooled OLS (2)	Pooled OLS (3)	Two-way FE (4)	Two-way FE (5)	Two-way FE (6)
$\Delta L_{i,t}$	0.092*** (0.005)		0.091*** (0.005)	0.111*** (0.005)		0.111*** (0.005)
$\Delta\sigma_{i,t}$		0.007*** (0.001)	0.006*** (0.001)		0.002*** (0.0004)	0.002*** (0.0004)
Constant	-1.703*** (0.039)	-1.695*** (0.039)	-1.724*** (0.039)			
Obs.	78,304	78,304	78,304	78,304	78,304	78,304
R^2	0.005	0.002	0.006	0.007	0.003	0.007
F Statistics	378.863*** (df = 1; 78302)	124.675*** (df = 1; 78302)	246.279*** (df = 2; 78301)	533.973*** (df = 1; 76669)	22.603*** (df = 1; 76669)	278.882*** (df = 2; 76668)

*Note: *** denotes statistical significance at 1%.*

Appendix E: Replication of Zerbib (2019)'s individual fixed effects model

In order to compare our estimates with those of Zerbib (2019), we re-estimate his individual fixed effects model with our data:

$$\Delta\tilde{y}_{i,t} = \alpha_i + \gamma\Delta L_{i,t} + \varepsilon_{i,t}$$

Table E1 shows the descriptive statistics of the data available from July 2013 to December 2017, which is the sampling period used by Zerbib. In total, there are 134 GB-CB triplets and 37,675 observations in the sample, as compared with Zerbib's 110 triplets and 37,504 observations.

Table E1: Descriptive statistics of the variables in the sample for replicating Zerbib's empirical results (July 2013 to December 2017)

	Sample values (in basis points)					
	Min	1st Quart.	Median	Mean	3rd Quart.	Max
$\Delta\tilde{y}_{i,t}$	-104.64	-6.10	-0.3	-2.754	2.90	75.30
$\Delta L_{i,t}$	-39.17	-2.52	0.81	1.42	5.40	40.20

Table E2 summarizes the results of the individual fixed effects model. The coefficient of $\Delta L_{i,t}$ (γ) is estimated at 0.174, which suggests that a one basis-point widening in the liquidity differential ($\Delta L_{i,t}$) will lead to an increase of 0.174 basis points in the yield spread ($\Delta\tilde{y}_{i,t}$). As mentioned, we believe our estimation is more intuitive as a higher $\Delta L_{i,t}$ (green bond being less liquid) should lead to an increase, instead of a decrease (suggested by Zerbib's results), in the yield spread between green bond and conventional bond ($\Delta\tilde{y}_{i,t}$).

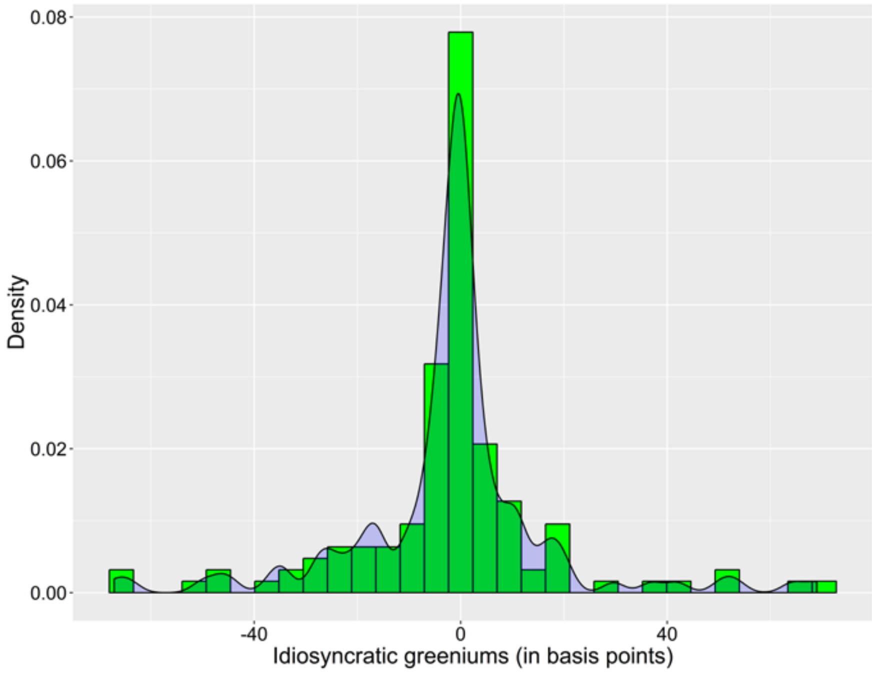
Table E2: Results of the individual fixed effects regression

	Dependent variable: $\Delta\tilde{y}_{i,t}$	
	Within	Newey-West Robust std. err.
$\Delta L_{i,t}$	0.174*** (0.009)	0.174*** (0.023)
Observations	37,675	
R^2	0.011	
F Statistics	410.908*** (df = 1; 37540)	

*Note: *** denotes statistical significance at 1%.*

Chart E1 shows the distribution of the idiosyncratic greeniums ($\hat{\alpha}_i$) estimated. The mean and median are -1.7 and -0.4 basis points respectively, which is very close to the estimates of Zerbib (-1.8 and -1.0 basis points).

Chart E1: Distribution of the idiosyncratic greeniums ($\hat{\alpha}_i$) using Zerbib's model



Appendix F: Robustness check on the impact of the triplet impurity

The Achilles heel of adopting a GB-CB triplet matching approach to estimating the yield spread between a green bond and its synthetic conventional counterpart is the potential errors caused by the impure matches of the bonds. Since it is almost impossible to find conventional bonds having identical features as the green bond, the GB-CB triplets are often impure, which may result in estimation errors in the yields of the synthetic conventional bonds ($\tilde{y}_{i,t}^{CB}$). Given that the two matched conventional bonds do not share the same maturity date as the green bond, $\tilde{y}_{i,t}^{CB}$ may be over- or under-estimated by linearly interpolating or extrapolating the yields of the conventional bonds, as the curvature of the yield curve is not taken account. Different issue dates can also contaminate the estimation of $\tilde{y}_{i,t}^{CB}$. For example, bonds issued in different interest rate cycles, despite having similar remaining maturities, can arguably have very different coupon rates and sharply different degrees of convexity.

A simple solution to the problem is to remove the GB-CB triplets of higher impurity from our sample. However, doing so will inevitably reduce the sample size, as well as the variety of green bonds. For instance, if half of the GB-CB triplets are removed from our sample, green bonds from a number of countries and sectors will be completely excluded, rendering potentially a huge loss in important information. Hence, there is a trade-off between triplet purity and sample size. In view of this, we conduct a robustness check to examine the extent to which the inclusion of impure triplets distorts the estimates of the greenium.

First, we introduce two major impurity measures based on the maturity date (MD) and the issue date (ID) differences for each GB-CB triplet. For the former, the impurity is measured by the sum of the absolute values of the maturity date difference between the green bond and each of the two conventional bonds.[29] The impurity arising from different issue dates is measured the same way.

$$Impurity_i^{MD} = \left|MD_i^{GB} - MD_i^{CB1}\right| + \left|MD_i^{GB} - MD_i^{CB2}\right|$$

$$Impurity_i^{ID} = \left|ID_i^{GB} - ID_i^{CB1}\right| + \left|ID_i^{GB} - ID_i^{CB2}\right|$$

With these measures, we rank the 267 GB-CB triplets by their impurity from the highest to the lowest and remove them one by one, starting with the most impure triplet, and we stop when there are only 10 triplets left. Each time when a triplet is removed, we re-estimate the augmented idiosyncratic greeniums ($\tilde{\alpha}_i$) with our fixed effects model. Charts F1, F2, and F3 show the trajectories of the mean, median, maximum, and minimum values of $\hat{\tilde{\alpha}}_i$ estimated by the aforementioned approach, with the impurity of the triplets measured by $Impurity_i^{MD}$, $Impurity_i^{ID}$, and the average impurity respectively.[30] As can been seen, the mean and median of $\hat{\tilde{\alpha}}_i$ are very stable and close to zero. This suggests that our key finding of a negligible

[29] The maturity date difference is defined as the number of days between the maturity dates of the green bond and the conventional bond.

[30] We do not have an explicit formula for the average impurity. The average of the ranks for $Impurity_i^{MD}$ and $Impurity_i^{ID}$ of a GB-CB triplet is taken as the rank of its average impurity. The GB-CB triplets with the highest rank of average impurity are removed first.

greenium on average is robust regardless of the degree of impurity of the sample.[31] However, the absolute values of the maximum and minimum $\hat{\hat{\alpha}}_i$ decrease substantially when impure triplets are removed, i.e., the distribution of $\hat{\hat{\alpha}}_i$ become more concentrated around zero. This indicates that the outliers in the distribution of $\hat{\hat{\alpha}}_i$ are possibly due to the inclusion of the impure GB-CB triplets.[32]

Chart F1: Trajectories of the augmented idiosyncratic greeniums ($\hat{\hat{\alpha}}_i$) with the GB-CB triplets of the highest $Impurity_i^{MD}$ removed one by one

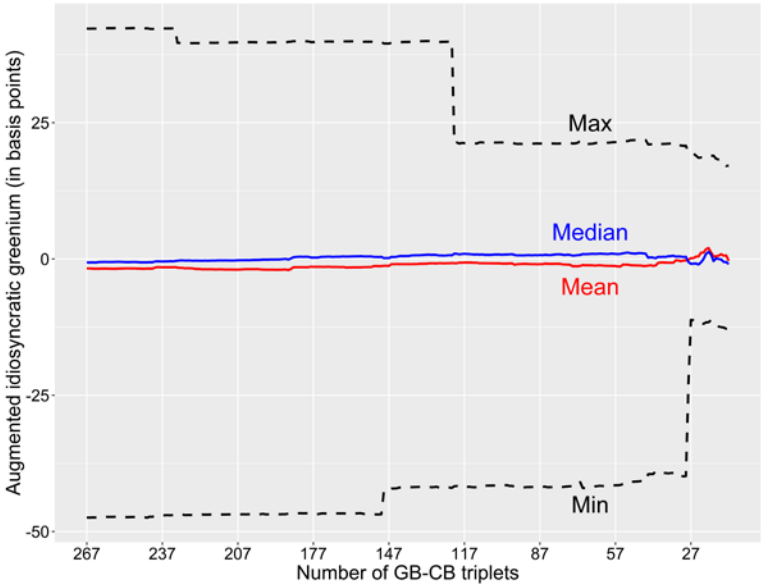
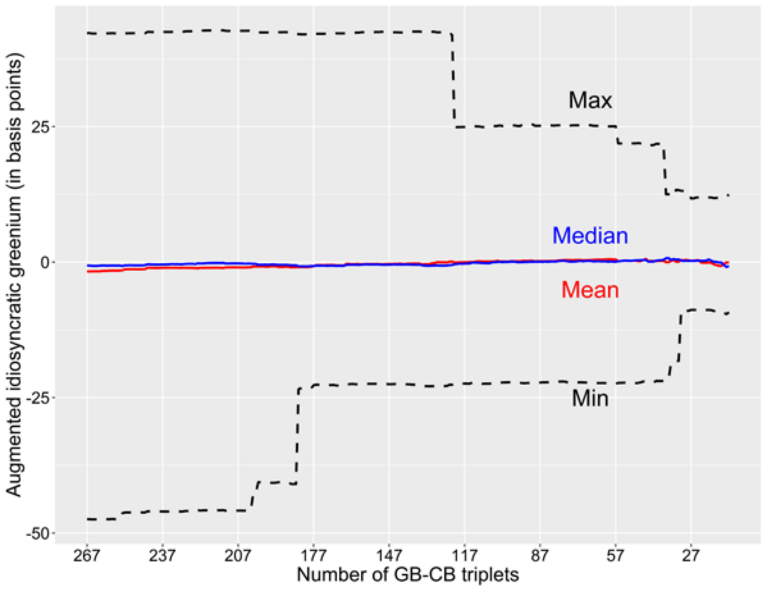


Chart F2: Trajectories of the augmented idiosyncratic greeniums ($\hat{\hat{\alpha}}_i$) with the GB-CB triplets of the highest $Impurity_i^{ID}$ removed one by one



[31] By definition, the average value of the augmented idiosyncratic greenium equals to the average value of the total greenium.

[32] This argument is supported by a similar exercise conducted from the opposite direction. That is, we remove the triplets one by one, starting with the least impure one and re-estimate the trajectories. We find that the absolute values of the maximum and minimum $\hat{\hat{\alpha}}_i$ change little even if the first 200 least impure triplets are removed.

Chart F3: Trajectories of the augmented idiosyncratic greeniums ($\hat{\tilde{\alpha}}_i$) with the GB-CB triplets of the highest average impurity removed one by one