

Green Bond Risk Premiums: A Twin-Bond ULFP Approach

Ulf G Erlandsson^{1,2}

Abstract

This paper explores the risk premium in green bonds and how it relates to the more frequently researched spread premium. The approach can reconcile the inherent conflict between issuers and investors in green bond markets where one basis point of spread premium gained for the issuer of a bond is one basis point lost for the investor. We illustrate that when green bonds trade with lower volatility than traditional bonds, issuers can issue greens at a lower cost-of-capital while at the same time investors can remain within their fiduciary duty limits if expected risk-return ratios do not deteriorate. Thus our understanding of bond spreads' statistical properties becomes important: using the Unibail-Rodamco (ULFP) bond curve with near identical twin bonds, we build a laboratory of sorts which allows for quite specific like-for-like analysis and avoids potential curve mis-specification. We explore how to use various econometric techniques including cointegration and time-varying volatility to arrive at conclusions both for absolute spread premiums as well as relative volatility between green and traditional bonds. This should be useful both for how to price bonds when issued into primary markets, as well as a support to evaluate secondary market pricing of already issued bonds. It also highlights the role volatility reductive measures from policy institutions could play to support lower cost-of-capital for green investment projects.

JEL Classification: G12, Q54

This version: June 2, 2020

¹This work has benefited from excellent research assistance and inputs by Linus Thand. Comments from Anastasiya Ostrovskaya, Caroline Harrison, Andreas Graflund and several others are gratefully acknowledged. This is not, and shall not in any way be construed to be, investment advice. The author has historically managed portfolios and traded some of the securities and bond curves discussed in the article and has received economic compensation for that. Views and remaining errors are the sole responsible of the author.

²Founder, Anthropocene Fixed Income Institute; Chief investment officer Diem Credit; Affiliated researcher, Knut Wicksell Centre for Financial Studies, Lund University. Corresponding address: ulf.erlandsson@hotmail.com.

1 Introduction

The green bond premium ("greenium")³ is often debated and central in a tug-of-war between the issuers of green bonds and the investors. From the issuer angle, the issuance of a green bond only makes sense if it brings some sort of benefit such as lower cost-of-capital. If the issuer can place a green bond at a lower credit spread than a traditional bond, he effectively achieves a lower funding cost through the green transaction. A slightly broader issuer perspective can be taken that is referred to as the halo effect. By this, the green bond in itself does not provide a direct lower cost-of-capital, but the goodwill achieved through the issuance rubs off on other bonds (or even traded equity) so that the issuer's capital structure in general gets a lower cost-of-capital.⁴ In this case, the green bond premium in itself (versus the issuer's other bonds) should be zero, but with a spread differential between issuers that have issued green bonds and those who have not.

On the other side, we have the investors looking to maximize their returns. In the early days of the green bond market, green bonds often came in smaller issuance sizes than traditional bonds, which would motivate a positive premium to compensate for lower liquidity⁵ and thus the argument to purchase green bonds was fairly simple to state. As time has progressed, the size-based risk-premium appears to have fallen or been diminished completely, also as a maturing market has brought more green bond deals with sizes in line with traditional bonds. It should be remembered in this context that bonds that are placed into the primary market command a new-issue premium in general, and it can be hard to identify whether a primary market spread differential is unique to a green-bond or just a general new issue premium. See Harrison (2020) for an example of this and a link to periodical update on the issuance of new green bonds. This has moved the recent debate to a somewhat infected point on whether green bonds price expensive (with negative spread premiums), implying that investors are deviating from traditional fiduciary duties when investing in them.

This paper adds to the debate by formalizing how a Pareto-optimal exchange between issuers and investors could happen in terms lower cost-of-capital versus lower volatility/higher return-risk ratios, which would potentially reconcile the different standpoints around the spread premium.⁶ Market participants anecdotally indicate that green bonds are well-held,⁷ meaning that investors in

³In this paper, we will make the distinction between green bond spread premium (difference in spread between a green bond and the counterfactual case) and the green bond risk premium (the difference but adjusted for volatility/risk). The generic term green bond premium will refer to the former case, as in earlier literature. The unit of measurement, unless otherwise stated, is basis points (bp) where 1bp = 0.01%.

⁴See Hyman et al. (2014) for an empirical study of this phenomenon.

⁵The general assumption is that liquidity is worse for bond issues with smaller amounts outstanding.

⁶Issuers are in general not financially affected by mark-to-market volatility, however, it does matter to them in a secondary way through marketing argument in future bond deals, as suggested in Harrison (2020). This suggests that there is an asymmetry in preferences of mark-to-market volatility between issuers and investors, which could enable a Pareto-effective exchange of spread versus volatility.

⁷This is a sentiment reflected in a number of individual conversations with market makers.

green bonds are less likely to sell those bonds compared to traditional investors and/or bonds. Issuers and syndicates propose they see more diverse primary market investors in greens compared to traditional bonds, see Climate Bonds Initiative (2020). This suggests that relative spread volatility could be lower for greens. We illustrate methodologies to measure and test this volatility hypothesis. Furthermore, we suggest how to price/relate lower volatility to the spread premium through a risk premium framework, so that given measurements or assumptions around relative volatility, we can derive what the spread premium should be. This has trading implications: "where is the spread premium versus where we believe it should be"; primary market implications: "we can motivate why this bond will trade with $X\%$ lower volatility, hence it is motivated to issue it a Y bp lower cost-of-capital" as well as policy implications: "by enacting this facility specifically for green bonds, we lower volatility and thus cost-of-capital for green funding."

Previous academic literature on green bonds spread premiums has not provided firm evidence on spread premiums, with evidence pointing toward a spectrum of higher, lower or neutral spreads on green bonds relative to traditional bonds. Zerbib (2019) provides a good survey of earlier results and structure of studies. Some of the results in the survey's referenced studies are surprising from a market participant standpoint: for example, Ehlers and Packers (2017) Bank of International Settlements study finding a green bond yield spread premium of -18bp in general, and -47bp for the BBB-rated segment seems to be particularly incredible to market participants.⁸ Zerbib's (2019) own study finds evidence of a more reasonable green bond yield spread premium in the region of -1.5 to -2bp for the main traded markets in EUR and USD, with clear differences depending on subsets such as in the division between corporate bonds and SSAs.⁹ Later studies, such as Larcker and Watts (2019) confidently reject the existence of any premium in the US municipal market.¹⁰ Bachelet et al. (2019) find a negative/positive spread premium in green bonds issued by institutional/corporate issuers, and is the first study to our knowledge also starting to explicitly look at volatility of green bonds vis-a-vis traditional bonds. Most earlier studies use matching requirements between green bonds and traditional bonds to find bond-pairs to compare, but from a practitioner standpoint the number of found matching pairs, e.g. 4,500 matching bond-pairs as in Kaprauns and Scheins (2019), sometimes seem like a stretch.¹¹

⁸We have asked for the data and/or ISINs of the studied bonds to replicate their results but that request was denied. As an alternative route, we have tried to find any liquid traded green bonds that price at such premium but have failed to do so. This may seem like an academic hair-splitting point to make, but the BIS study results were for example used to form conclusions in the Swedish government's Inquiry to promote the market of green bonds (2017). We make this point to illustrate how estimates can have policy importance.

⁹Supras, sovereigns and agencies (SSA), is a collective term for various non-corporate issuers that are not directly government debts, such as the European Investment Bank, the World Bank, covered bonds, some mortgage bonds, as well as sovereign issuance in foreign currency.

¹⁰Their results are based on a broad cross-section with close matching bonds giving the results good statistical power. The market is, however, a narrow specialist one with the average outstanding notional of USD 5mn. As a contrast, we do not consider any notionals below benchmark size (USD500mn) as such issues are generally not priced actively.

¹¹For example, we search the Bloomberg bond database and only find 2,201 green-flagged bonds in the corporate and government bond space. Out of those, only 1,035 bond have an

All this generates a number of interesting hypotheses to test around the nature of the green bond premium. The first is simply how specific or general the green bond premium is. At the extremes, we could argue around the existence of a green bond premium on the individual bond and issuer level at a specific time ("there exists a green bond risk premium for issuer X in Q2 2019"), and on the other extreme that there exists a well-defined spread premium for the whole market ("the green bond premium is Ybp "). The former approach necessitates a very specific knowledge about a single bond and issuer to avoid mis-specification and omitted variable issues, whereas the latter hypothetically can expect individual bond effects to be smoothed out by the law of large numbers in a panel/cross-section setting. It is probably fair to say that the former approach is more useful from a practitioner perspective, and the latter from an academic/policy perspective. Which one is more likely to show a correct answer may depend on the degree of heterogeneity between green bonds relative to the size and quality of the cross-section and control variables one can generate in a generalized approach. In this context, the contribution of this paper is to suggest a specific-to-general direction rather than the opposite: we analyze a small number of structurally very similar ("twins") green and non-green bond cases, allowing us to minimize mis-specification and omitted variables issues.

To start, the first part of this paper looks at how omitted variables or model misspecification could be a potential reason some of the earlier studies appear to yield almost random results, but often with very high statistical significance. We show in a simple model of the bond curve how very persistent deviations from estimated fair values (zero risk premiums) can arise when the curve model is misspecified, also for bonds that appear to be relatively close to each other in maturity. In conjunction with this persistence issue, we discuss non-stationarity of bond yields and credit spreads. If individual bond spreads are non-stationary, but they have strong mean-reverting relationship between them - as would be a case with a green bond and a matched traditional bond if it is only a static greenium difference in how they trade - then this dynamic describes a co-integration relationship. Not accounting for such non-stationarity¹² may lead to spurious regression results and invalid inference on point estimates of the green spread premium.

We illustrate this in the second part by applying a cointegration testing and estimation approach based on the Unibail-Rodamco (ULFP) bond curve, which has near identical twin-bonds available. Recent data, both in terms of general market volatility in 2020, as well as idiosyncratic factors hitting ULFP, highlight the importance of accounting for non-stationarity when estimating the spread premium. It also suggests that the spread premium is both time and spread dependent.

In the third part of the paper, we approach green bond valuation from outstanding notional of more than USD100mn, which from a practitioner perspective could be considered a bare minimum in order for a bond to be actively traded. Barclays (2020) managed to construct 67 matched pairs in corporate bonds and 38 pairs in SSAs.

¹²We have conducted a non-exhaustive search but struggled to find mention of non-stationarity issues in earlier green bond literature.

broader risk-premium perspective, where relative volatility between green and traditional bonds play a key role. In a simple modern portfolio framework, we show how the green bond spread premium can be inferred from relative volatility of the green and brown assets. To estimate such relative volatility, we use fat-tailed GARCH models to compare volatility and kurtosis between our twin bonds, and find some evidence of lower volatility in our green bond laboratory case. In the asset pricing framework, this could motivate a (negative) spread premium for green bonds, but without sacrificing Sharpe ratio for the investor. We furthermore investigate relative volatility in two more near-twin bond cases that illustrate the heterogeneity of the green bond market, and the difficulty in making general statements around a greenium. We also show how relative value trading signals could be constructed indicating when green bond trade cheap or expensive to estimated fair value.

The penultimate section briefly discusses the implications of the risk-return trade-off potential, for issuers, investors, intermediaries such as banks and policy institutions. As the reader will notice, this paper is focused on developing concepts rather than conducting broad cross-sectional analysis, as well as applying relatively standard econometric models. Hence, the final section suggests some rather straightforward extensions in terms of future research.

2 Model mis-specification and non-stationarity

Summary: *We show how bond curve mis-specification can drive persistent deviations between actual bond spreads and what would be expected from a model, and thus how statistical inference on a green bond spread premium easily can become incorrect. We suggest using a twin-bond approach to analyze the spread premium in a context of minimal potential model mis-specification. We show why we would consider two bonds from Unibail-Rodamco to be prime candidates for such a twin-bond pair.*

We start out by a simple example explaining how a credit scenario that is not parametrized in the model to be estimated can lead to substantially biased results of the green bond spread premium. In the northwest panel of Figure 1, denoted (a.1), we show the credit spread function of a bond issuer with a certain large repayment amount due in 5 years. The credit spread is linear up until then, assuming a 70bp per year increment in the spread and hence a 350bp spread before the repayment. The increase in spread is 150bp, up to 500bp, at the day of repayment. The credit risk thereafter stays at the 500bp level. This gives rise to a "kinked" spread curve depicted as a solid line.

Now, for our purposes, we assume that the 4yr bond is a green bond. If we apply a straight linear model to fit a curve to all the bonds, we see that this fitted curve estimates that bond spreads should be below their real value for the short end of the curve. The model infers that short end bonds are "cheap" to the curve at the original date. Thus the green bond, along with the other short-dated bonds, will appear to have a positive risk-premium. Table 1 indicates this premium to be 22.9bp.

Figure 1: Model bond curve. Bond maturities in years across the x-axis, credit spread in bps on the y-axis. Dots indicate individual traditional bonds, green squares the green bonds on the curve, solid line the underlying credit spread process, the dashed line a linear fit to the bond curve using only original bonds. The dotted line shows the fitted curve assuming new bonds filling up on the maturity curve as time passes. Panels (a.i), upper row show a fully populated bond curve with bond maturities every year, and panels (b.i) show a sparse bond curve. Columns 1, 2, 3 illustrate the bond curve at inception, after 1 year and after 2 years.

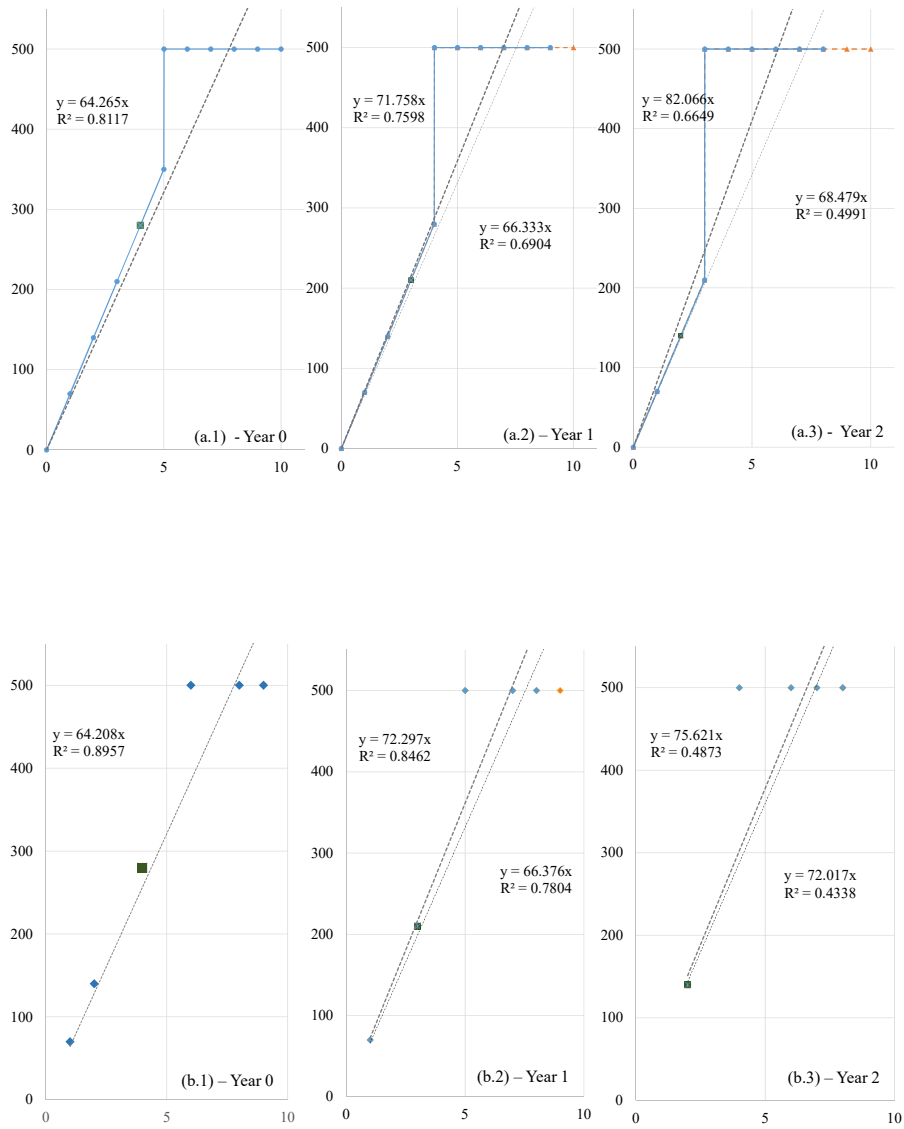


Table 1: Bond simulation: deviations between estimated curve and actual curve as the bond rolls down from 4yr to 2yr point. OC refers to original curve, where there is no new long-end issuance. EC - extended curve - refers to where 1 new 10yr bond is issued each year.

Bond curve	4yr	3yr OC	3y EC	2yr OC	2yr EC
Full (a.i)	22.9	-5.3	11.0	-24.1	3.0
Reduced (b.i)	23.2	-6.9	10.9	-11.2	-4.0

Now we consider the same well-defined credit curve but one year hence, just considering the original curve (OC, case a.2). If we assume that bonds are just rolling down linearly, we can note that fitted linear curve now lies above the actual curve for all the short-dated bonds. In the case of the green bond, we see the risk-premium to be -5.3bp. However, if we assume that the issuer has issued more debt in the long-end - a new 10yr bond - so as to have extended the curve (denoted EC), we see the risk-premium to be a positive 11.0bp. The interesting point here is that by only making a small adjustment to whether new long end bonds are fitted on the curve or not, we even get green bond premium estimates with different signs. The same pattern continues as we roll down the curve another year (a.3).

Our curve has so far been very well-specified: with up to 10 data points on the bond curve and no measurement errors or structural differences. In the bottom row of Figure 1, we illustrate a more likely scenario where maturities of the bonds actually issued are spread out across the curve. The bonds just on the 5yr point are gone and the best indication we have of the kink is the 6yr bond. It seems especially important to include this bond on the curve if we know the real data-generating process. However, for a researcher, it would be tempting to figure out if there is some structural factor that makes the 6yr bond trade so much higher in spreads than the model would suggest.¹³ If such a factor is found, we would then find our regression line with a lower slope and hence a bigger risk premium between the green bond and the interpolated curve.

The point here is that mis-specification of the credit curve can easily drive deviations from the actual bond and the estimated spread curve, which effectively constitutes the perceived green spread premium. The mis-specification is also likely to exhibit very persistent, even non-stationary, patterns.¹⁴ Consequently, we should be cautious of persistent deviations from fair-value levels of spreads as a sign of a mis-specified model. Note that the real credit process here has assumed that the green bond risk premium is zero.

One way to reduce the potential mis-specification is to interpolate the credit spread curve using nearest neighbours rather than trying to estimate a full credit

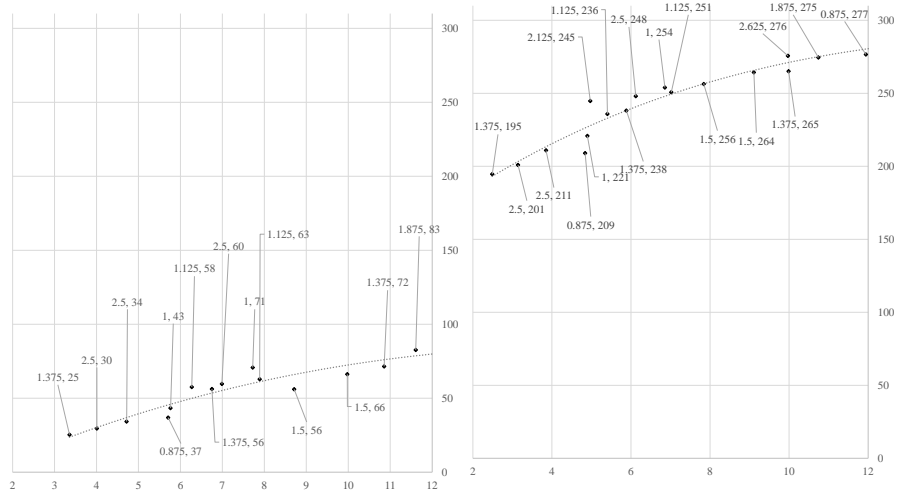
¹³We also illustrate that we achieve a higher explanatory value, R^2 , in the case of a sparse curve rather than a more granular one. Under a misspecified model, one may be incentivized to actually have less rather than more data using such measures.

¹⁴Arguably, spreads converge to zero as bonds mature (and assuming away default risk), but in practice most bond portfolio mandates, similar to the sample selection mechanisms in earlier studies, will cut-off bonds with shorter (< 1 -2yrs) maturities from their portfolios.

curve, and to also apply as large possible set of control factors for structural differences in bonds. Going through the studies highlighted in Zerbib (2019), a window of ± 2 years of the maturity of the green bonds seems to be the standard in order generate nearest neighbour triplets. Given the simple model above, such a window appears quite wide.¹⁵

We choose a different approach where we instead look at the dynamics in a case where a "twin-bond" with very closely matching characteristics exists. Twin studies are very useful in order to reduce omitted variable biases, as any omissions should be expected to have an identical effect on both twins. Unfortunately, finance provides very few perfect twins, but in the green bond space we have Uniibail-Rodamco, a Dutch company with holdings and operations of real-estate across Europe, and is one of the leading companies in the sector. The corporate ticker is ULFP.¹⁶ ULFP has been a frequent issuer in European bonds markets, both in terms of traditional bonds and green bonds. We illustrate the bond curve for the issuer in Figure 2. The sample selection of bonds is based on all bonds denominated in Euro currency, of at least benchmark size (EUR500mn) and with a remaining maturity of between 2-12 years. The y axis is in terms of basis points of z-spread. The interpolated curves have been produced using a third degree polynomial extrapolated from a full maturity curve. It is just a visual aid and does not suggest a structural form of the bond curve.

Figure 2: ULFP bond curve, 10 Jun 2019 (left) and 21 April 2020 (right). First number in the callout refers to the coupon of the bond, the second number to the z spread (y-value).



For the final date, 20 April 2020, we have 16 data-points in our sample. It is important to note that exclusion of sub-benchmark size issues ($< \text{EUR}500\text{mn}$) is due to a range of issues stemming such as liquidity (dealers are unlikely to make

¹⁵Barclays (2020) for example consider a ± 6 month window.

¹⁶The correlation between the ticker and the author's surname is entirely coincidental, however we feel obligated to make puns about it.

continuous markets in sub-benchmark size giving more erratic or matrix priced data points) as well as the investor base (sub-benchmark sizes can be issued as private placements which tend to end up with a few, or even a single, investors). Putting in the benchmark size constraint does however significantly reduce the size of a potential cross-sample. For example, we register¹⁷ 534/512 green bond issues in EUR/USD in total, but only 286/182 of those above benchmark-size.

Another important note on bond structure that we have not registered as controlled for in previous studies is actual bond-coupon levels. We would expect spreads and returns to be independent of bond-coupon, but this is not always the case, due to structural rigidities in the bond market as described in Hyman et al. (2014). Rather, a bond with a high coupon will have a higher price, which makes it more expensive from a capital cost perspective, e.g. for a hedge-fund, to hold compared to a bond with a lower coupon. Hence, one often sees higher-coupon bonds trade with a higher spread, to compensate for this cost. There is also an argument that certain income focused investors prefer higher coupon bonds when they do not mark-to-market the cash price of the bond. Hence, we should also try and distinguish between bonds based on their actual coupon level.

We highlight some of these as well as other potential structural features for the ULFP curve in Table 2. In the case of ULFP, we have two bonds with very similar features except that one is a green bond, ULFP 1 (henceforth denoted G), and a traditional bond, ULFP $\frac{7}{8}$ (henceforth denoted B). The Bloomberg DES screens for the bonds is available in 3. The coupon differential between G and B is a mere $\frac{1}{8}$ which should make any spread differentials based on capital efficiency minimal. The maturity of the bonds are within 1 month, the amount issued is similar. The main difference is time of issuance, where B was issued in April, 2015 and G in November, 2016. To correct any new-issue biases, we only conduct analysis of relative movements starting 2017. We have furthermore conducted checks with several market makers in the bonds and have recieved no objections to the similarity of these two bonds.¹⁸

We illustrate the z-spreads of the two bonds in 4. The graph conveys a visually close correlation between the two, albeit with a seemingly higher spread for G between July, 2018 and July, 2019. Measured over the sample, the average spreads are 35.67bp and 38.38bp respectively. This would imply that there is a positive spread-premium for the green bond indeed, at 2.7bp.¹⁹ In the words of the investors, bond G looks cheap vis-a-vis bond B . On the other side, as we saw in previous graphs, both G and B look expensive versus the implied bond curve. It is important to note that there is a substantial spread-widening happening in March 2020, as the corona virus implications started hitting markets

¹⁷Sample on May 1, 2020, using the Bloomberg terminal SRCH function.

¹⁸However, on closer inspection, we do find a difference between the syndicatings bank structure between the two deals, with a much stronger presence of Souther European (FRA, IT, ESP) banks in the $0\frac{7}{8}$ 25 bond. One could hypothesize that this means a higher degree of allocation to institutions across those geographies, which also would mean a potentially structurally different investor base than for the 1%25bond.

¹⁹For the sake of clarity, a positive spread premium indicates that the green bond offers a higher spread than the traditional bond, it trades "wide". A negative premium indicates that the green bond offers a lower spread (expected return), and it trades "tight".

Table 2: Structural bond factors with potential spread implications

Factor	Sample range	dSpread	Description and effect
Issue size	500-1000mn	+	Liquidity premium.
Time since issue	0-5yrs	+	Newer bonds have higher liquidity but can also exhibit higher volatility as they are the preferred trading vehicles for fast-money investors.
Coupon	0.875-2.5%	+	Cash price affects capital cost and trading efficiency of the bond.
CDS aligned	Varying	-	Hedging possibility: bonds with easily accessible CDS hedging should have a premium but can also have higher volatility.
CDS basis	Varying	+/-	The difference between bond spread and CDS spreads tends to differ across the curve and between issuers.
Central bank eligible	n.a.	-	Part of QE purchasing program will have a positive effect on credit spreads.
Syndicate quality	-	-	Balance sheet quality of original syndicate. Banks tend to offer better liquidity in bonds that they have syndicated themselves. The syndicate selection can indicate structure of the investors purchasing the bond originally.
Capital structure	Senior unsec	+/-	
Call structure	Bullet only	+/-	
Benchmark bond	-	+/-	Applies to studies using bond yields rather than spreads: underlying government bond technicals.
Swap rate dynamics	-	+/-	Applies to studies using bond spreads rather than yields: swap spreads will differ across the curve and can have important, persistent effects.

Figure 3: Bloomberg screens for ULFP bonds.

ULFP 1 03/14/25		ULFP 0 02/21/25	
ULFP 1 03/14/25	€194.84G	ULFP 0 02/21/25	€194.957
At 3:17	--003	At 3:18	--017
94.541/95.144	2.184/2.049	94.665/95.248	2.041/1.909
Source BGN		Source BGN	
ULFP 1 03/14/25 Corp	Settings	ULFP 0 02/21/25 Corp	Settings
Page 1/12	Security Description: Bond	Page 1/12	Security Description: Bond
94 No Notes	10 Buy 10 Sell	94 No Notes	10 Buy 10 Sell
Issuer Information Name: UNIBAIL-RODANCO SE Industry: Retail REITs (BCLASS) Country: FR Rank: S+ Unsecured Mkt Iss: Euro MTN Currency: EUR Coupon: 1.000000 Type: Fixed Gcn Freq: Annual Day Cnt: ACT/ACT Iss Price: 99.67200 Amort: 03/14/2025 Recoffer: 99.672 Issance & Trading Amt Issued/Outstanding: 500,000.00 (H) / 500,000.00 (H) EUR Calc Type: (1)STREET CONVENTION Min Piece/Increment: 100,000.00 / 1,000.00 Pricing Date: 04/08/2015 Interest Accrual Date: 04/15/2015 1st Settle Date: 04/15/2015 Book Runner: JOINT LEADS 1st Coupon Date: 03/14/2016 Exchange: Multiple		Issuer Information Name: UNIBAIL-RODANCO SE Industry: Retail REITs (BCLASS) Country: FR Rank: S+ Unsecured Mkt Iss: Euro MTN Currency: EUR Coupon: 0.875000 Type: Fixed Gcn Freq: Annual Day Cnt: ACT/ACT Iss Price: 99.04700 Amort: 02/21/2025 Recoffer: 99.047 Issance & Trading Amt Issued/Outstanding: 500,000.00 (H) / 500,000.00 (H) EUR Calc Type: (1)STREET CONVENTION Min Piece/Increment: 100,000.00 / 1,000.00 Pricing Date: 11/15/2016 Interest Accrual Date: 11/22/2016 1st Settle Date: 11/22/2016 Book Runner: JOINT LEADS 1st Coupon Date: 02/21/2017 Exchange: Multiple	

in general, and ULFP in particular with a business model highly dependent on retail sales. As we shall see, to have sampled this widening becomes important in terms of statistical analysis and results for the spread series.

The widening also has an important implication for the traditional usage of ratings as independent variable in the context of the green bond premium. There is always a certain degree of endogeneity in the ratings versus spread relationship, as it is essentially two ways of trying to infer underlying probability of default data generating process.²⁰ throughout the sample considered. Econometrically speaking, a model that tries to specify the green bond premium as a constant, e.g. saying it is 3bp, is making a rather strong implicit statement that the premium is equal when ULFP bonds were trading at $z+30\text{bp}$ as when it is trading at $z+300\text{bp}$. ULFP, including 2020, gives us a richness of data dynamics with both the twin-bond structure as well as realizations of the data-generating process on both the low-risk and high-risk spectrum of credit spreads.

2.1 Green spread premiums: econometric modelling

Summary: *We suggest that some of the seemingly spurious results in earlier studies may have been driven by non-stationarity issues, which easily arise when comparing bonds spreads between different bonds on the same curve. A remedy to this issue is to be found using cointegration and so called vector-error correction models, which also have the advantage of being intuitive from a trading/portfolio management viewpoint.*

Let us start with a simple expression for the green bond spread premium for two identical (except for the green bond use of proceeds) bonds G and B .

$$s_t^G = \mu + \beta s_t^B + \epsilon_t \quad (1)$$

where s_t^i denotes the credit spread for bond $i \in [G, B]$ at time t . In this context, μ would be the green bond spread premium. ϵ_t is a random error term, and the

²⁰ULFP has been rated Moody's A2 from 13 March 2017, and was downgraded to A3 on 27 March 2020. S&P has rated ULFP A from 10 April 2015 until 27 March 2020, when it was downgraded to A-. Fitch rated ULFP A+ from 16 April 2015 to 16 October 2018, to A, and then down to A- on 7 April 2020. The spread repricing adjusting for market beta happened in the preceding week. Between 18 March and 27 March, iTraxx Main S32 spreads tightened from 138bp to 92bp, whereas ULFP widened from 176bp to 207bp.

Figure 4: Spreads of the twin ULFP bonds.



term β indicating the spread move sensitivity between G and B . For the case of twin-bonds, we assume $\beta = 1$ but will be adjusting this assumption later on. A very simple re-arrangement then gives us:

$$s_t^G - s_t^B = \mu + \epsilon_t \quad (2)$$

We can see already in this simple representation²¹ that the nature of the error term is important in order to be able to measure μ . If the right hand side of the equation is not stationary, it effectively does not revert to a long-term mean μ , making traditional statistical inference on μ invalid. Specifically, the standard errors when estimating μ are deflated so as to give an overconfidence in that $\hat{\mu}$ is statistically significant.²²

An alternative way to express the spread premium in (2), is to consider some hypothetical bond curve so that the fair value spread for any point on the maturity curve can be expressed as:

$$s_t^G - s_t^{B*} = \mu + \epsilon_t \quad (3)$$

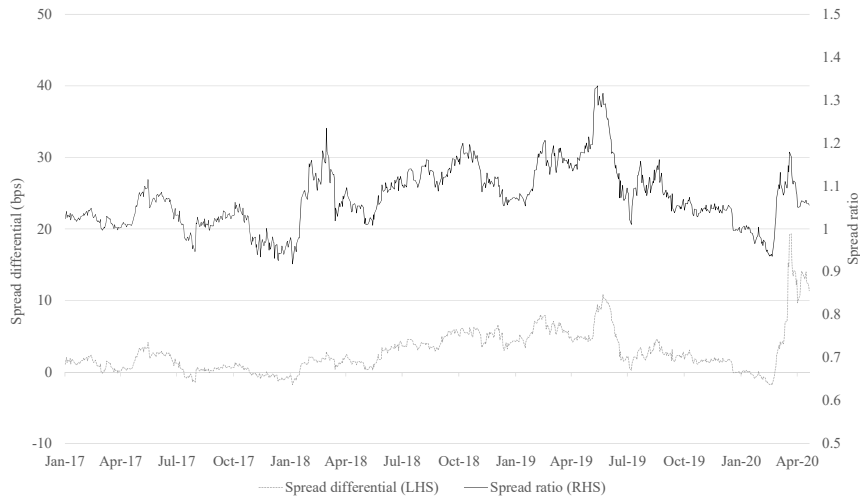
In this notation, we designate the ULFP 0 $\frac{7}{8}$ % Feb 2025 bond as B with spread time-series s_t^{B*} and the 1% Mar 2025 bond as G with spread series s_t^G . We plot (dotted-line) the spread differential $s_t^G - s_t^{B*}$ of these near twin-bonds in figure 5. Not surprisingly and in line with an initial ocular inspection, we

²¹There can be some confusion around notation here relative to earlier studies, where the difference in the left-hand side of Equation (2) sometime is annotated with a Δ such that $\Delta s_t = s_t^G - s_t^B$ would refer to the green bond spread premium rather than the daily change in the bonds spread. We use Δ to the latter effect, i.e. $\Delta s_t^i = s_t^i - \Delta s_{t-1}^i$.

²²For practitioners: The natural solution to non-stationary would be to estimate (1) in differences, however, by taking differences μ drops out and cannot be estimated which defeats the purpose of the estimation. Estimation of a constant in the differenced equations will relate to the existence of deterministic/time-trend in the level equation, rather than an intercept.

are unable to reject that the spread differential contains a unit root²³, or in other words, the expression in (2) is indeed non-stationary. Thus, the estimate of the spread premium $\hat{\mu}$ as a constant is not stable. The importance of this in a practical context is that even in a case where we have near identical bonds and thus are almost certain to not have misspecified the bond curve, we still are not able to make a long-term inference on the green bond premium from just observing some average spread differential.

Figure 5: ULFP twin-bond spread differential and spread ratio.



The figure does however appear to indicate that the ratio of the two bond spreads (solid line) might be a more stable combination. If this is the case, the interpretation is that the green bond spread premium would be proportional to underlying fair-value bond spread. This also runs very close to trading intuition around hedging for risks in bonds. A very common approach to neutralize/normalize two bonds is to use the spread ratio²⁴ as a beta factor. We have

$$\frac{s_t^G}{s_t^{B*}} = \mu + \epsilon_t \quad (4)$$

or equivalently in log terms:

$$\ln s_t^G - \ln s_t^{B*} = \ln(\mu + \epsilon_t) \quad (5)$$

Unfortunately the expressions in (4) and (5) are ill-behaved for credit spread purposes as spreads approach zero or go negative. Considering the nature of the

²³We apply both augmented Dickey-Fuller and Phillips-Perron test with various specifications and are unable to reject the null in all cases.

²⁴We set duration differentials to zero for the time being.

green bond market, where many issuers are high-quality, this problem may be more significant than traditionally assumed. We illustrate the point in Figure 6 where we show how two various ULFP bonds went negative in (i) credit spreads terms, as well as (ii) yield terms. Especially notable is the ULFP 2 $\frac{1}{2}$ % 2023 bond that as it showed a negative spread in late 2017 still had almost 6 years until maturity.²⁵ On point (ii), we see that our B bond traded with a negative yield for extended period of times in 2019.

If we look at the particular part of the green bond market issued from non-corporates such as supra- and sub-nationals (e.g. The European Investment Bank, EIB, or Kreditanstalt für Wiederaufbau, KfW), their bonds have been trading at both negative spreads and yields for a long-time. But the point here is that even for a corporate issuer with considerable credit risk, the numerical problems of the ratio/log approach can be considerable. So in order for arguing for a green bonds spread premium (expressed as a percentage of the current spread), one will need to make structural assumptions around credit spreads and especially on the shorter dated, higher quality part of the credit spectrum. We also conduct some testing of non-stationarity on the spread ratios and find conflicting evidence based on various tests and samples.²⁶

From this, we conclude that the issues in estimating a green bond risk premium as a fixed spread constant (in levels) can be significant even in the case of near-perfect twin bonds. Second, we find some evidence of stationarity in the ratio of spreads between our twin bonds, in line with trading intuition and an expression of the green bond risk premium as a percentage-of-spread expression, but the numerical issues with using spread ratios can be considerable.

We earlier indicated that in the original equation on spread differentials, we would need expression to be covariance stationary. We proceed to formalize this under the assumption that bond spreads s_t^i are non-stationary:

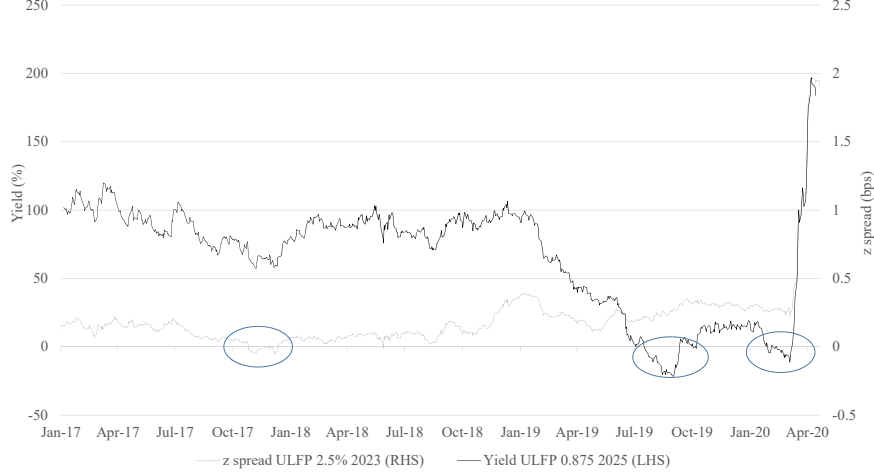
Proposition 1: In order to be able to estimate the spread premium μ for a bond G , we require that there exists some other bond B (real or generated through curve interpolation) such that we can form a stationary combination of spreads s_t^G and s_t^B

This simply describes a cointegration relationship, as originally proposed by Engle and Granger (1987). If there exists such a relationship, we can express

²⁵As we noted previously, the issuer was at the time rated single-A by Fitch, and put on negative watch in Dec-2017.

²⁶Specifically, we find the ratio in nominal and in log terms to be non-stationary with an ADF test but not with the Phillips-Perron test. The latter test adjusts for unspecified auto-correlation and heteroskedasticity.

Figure 6: ULFP bonds exhibiting negative spreads and yields.



the spread dynamics in a vector error correction format so that:

$$\begin{aligned}
 \Delta s_t^G &= \alpha^G \underbrace{(\kappa + s_{t-1}^G - \beta s_{t-1}^B)}_{\text{Cointegration relationship}} + \sum_{p=1}^P \phi_p^G \cdot \Delta s_{t-p}^G + \epsilon_t^G \\
 \Delta s_t^B &= \alpha^B \underbrace{(\kappa + s_{t-1}^G - \beta s_{t-1}^B)}_{\text{Cointegration relationship}} + \sum_{p=1}^P \phi_p^B \cdot \Delta s_{t-p}^B + \epsilon_t^B
 \end{aligned} \tag{6}$$

where α^i is a speed-of-reversion parameter for the bond spread to the equilibrium level given by the long-term relationship $(\kappa + s_{t-1}^G - \beta s_{t-1}^B)$. To capture further auto-correlation in the changes in spreads, we have the AR(p) component with coefficients ϕ_p^i . This structure actually has a strong relationship to how bond traders would see a trade: they would expect the changes in a bond spread to adjust over time to some long-run beta-adjusted relationship with another bond: deviations from the bond curve should be mean-reverting over time. In fact, cointegration and VECM models are not uncommon in the literature looking at market neutral, "pairs"-trading in equities, see for example Huc and Afawubo (2015).

We proceed to test for cointegrating relationships between G and B as per the expression in (6), using the Johansen (1991) methodology.²⁷ For the full

²⁷In the bivariate case, such as ours, using Engle and Granger's (1987) approach is also

Table 3: VECM estimation. For brevity we only present the parameters directly related to the cointegrating relationship.

Parameter	Long sample		Short sample	
	Estimate	t-value	Estimate	t-value
κ	-2.521	-2.53	3.231	1.13
β	-0.994	-42.2	-1.182	-14.7
α^G	0.048	2.41	0.027	1.62
α^B	0.075	3.83	0.037	2.26
R_G^2	0.383		0.082	
R_B^2	0.380		0.085	

sample, and for various specification of the potential cointegration relationship, we find 1 cointegration vector. We note however, that the results are less convincing when testing for a subsample that ends by 31 December 2019 and thus does not include the spread widening and volatility for the issuer in March-April 2020. As earlier discussed, credit spreads may appear locally stationary in a statistical sense. Covering the right-most part of Figure 4 would make the shorter time-series appear as a highly persistent yet mean-reverting (and stationary) time-series. The richness of the data covering the latter part of the sample is a clear advantage here, in terms of testing these dynamics.

We estimate the model in (6), results available in Table 3 with subsamples results to check for stability pre- and post the 2020 spread blowout. For the longer sample, we estimate $\hat{\kappa}$ to -2.5bp, which translates to a 2.5bp spread premium on G versus B . The point estimate is statistically significant. To put this in trading terms, the model suggest that for a \$1mn position in G , one should short the beta-adjusted amount of \$994k of B to expect to have a market-neutral package, and the estimated alpha from that trade would be 2.5bp (per annum). The relevance of the speed-of-reversion parameter also has relevance for trading: with an estimated speed of reversion of 0.048 as in the G equation, we would expect any deviation (for example if G traded wider to B than suggested in the cointegration equation) to halve in 21 trading days.

Even with our relatively robust specification of the model, we are very dependent on realized data to estimate the relationships. The right-hand columns of Table 3 give quite another picture. Pre-2020 volatility estimates of the cointegration vector are quite different with a $\hat{\beta}$ indicating a different hedge-ratio, which in turn move the estimated green spread premium to -3.2bp. This estimate is, however, not statistically significantly different from zero. We further test, on the shorter sample, to restrict the cointegration vector to $[1, -1]$ and under that restriction which is not rejected statistically, the spread premium $\hat{\kappa}$ lands at 2.3bp. So the shorter sample eventually supports the first conclusion.

So how do these results differ from simply running the original Equation (3) under the condition that the spread differential is stationary? When estimating (3), we obtain a t-statistic for $\hat{\mu}$ which under standard distributional assump-

possible, with the advantage that it is easily applicable through standards software such as Excel.

tions would indicate that the probability that μ is equal to zero is 50% lower than that the probability of picking one particular atom in the know universe.²⁸ To contrast this, if we return to the data in Figure 5, we see that on 11% of the days in the sample, we actually observe a premium below 0. The VECM confidences estimates of $\hat{\kappa}$ are much more in line with this.

Furthermore, the VECM specification specifically outlines the time-variation of the spread differential between G and B through the reversion parameter. The drawback with the approach is that it requires a fairly high degree of specification in terms of the cointegration vector, and the original Johansen (1991) statistics to decide on the existence of cointegration in the presence of conditional heteroskedasticity can be non-standard, see Lee and Tse (1996). The natural extension of the above analysis would be to apply it in a panel cointegration setting, such as in Pedroni (2004).

3 Quantifying a green bond return-premium using asset volatility.

Summary: *We illustrate the distinction between green bond spread premium and risk premium by looking at green bond volatility relative to traditional bonds, and describe the portfolio theory relationship between the two. We suggest a standard volatility model to measure relative volatility, and find evidence of lower volatility for the green bond in our twin-bond study.*

So far, we have attempted to specify a robust econometric expression for the spread differential between the green bond and the traditional bond. This is often referred to as the "green bond premium" or "greenium". We have shown that it can be difficult, even in what appears to be fairly clear cut cases, to actually properly identify this premium.

To contrast this, we now focus on the green bond *risk* premium, i.e. the spread differential between the green and traditional bond adjusted for any differences in volatility between the two assets. There are indications that issuance of green bonds provide a broader investor base and a more sticky holding pattern, see Climate Bonds Initiative (2020), while pricing approximately at the same level as traditional bonds, which would indicate that the risk-premium in a green bond could come from different volatility rather than different returns. From a financial econometrics standpoint, volatility rather than deltas tend to be more predictable, with Engles' (1982) auto-regressive conditional heteroskedasticity (ARCH) model being a centre-piece for how to model time varying volatility. Earlier literature includes Pham (2016) who studies the interrelationship of volatility between standard and green bonds on an index-level.

We first illustrate the lower volatility, lower risk-premium thinking using modern portfolio theory, as previously discussed in the context of green bond

²⁸The corresponding p-value is down to the 117th digit, whereas there are approximately 10^{80} atoms in the universe. Still, that significance value is lower than some of the values presented for example in Barclays (2015).

pricing in Erlandsson (2019). To start out, return to our two (now generalized) assets G and B . with expected risk return vectors $rr_i = [r_i; \sigma_i, S_i]$ where r_i denotes the expected return for asset i , σ_i the volatility and $S_i = \frac{r_i}{\sigma_i}$ the (expected) Sharpe ratio. Given a correlation between the two assets $\rho_{G,B}$ and portfolio weights w_i ; $\sum w_i = 1$, we have the expected portfolio return and portfolio volatility as $r_{pf} = w_G r_G + w_T r_T$, $\sigma_{pf} = \sqrt{w_G^2 \sigma_G^2 + w_T^2 \sigma_T^2 + 2 \cdot w_G w_T \sigma_G \sigma_T \rho_{G,B}}$.

To simplify the analysis, we assume the absence of a risk-free asset, so that the portfolio allocation problem is simply between asset G and B . For starters, we assume risk-return vectors $rr_B = [2.5\%, 5\%, 2]$ and $rr_G = [2\%, 4\%, 2]$ meaning that the green asset has a lower expected return (4%) and a lower volatility (2%). However, both assets have an expected return/risk-ratio of 2, which can be interpreted such that the investor could replicate T by simply investing more/levering up on G . We assume a correlation $\rho_{G,T}$ of 0.2. The resulting efficient frontier/Markowitz bullet (Markowitz (1952)) is projected in Figure 7.

In this simple setting, we assume that the investor will select portfolio weights so as to maximize the Sharpe ratio of the portfolio. As we are in a two asset world, we note that the portfolio weight of G can simply be replaced such that $w_G = (1 - w_T)$. Hence, the maximization problem becomes:

$$\max S_{pf} = \frac{r_{pf}}{\sigma_{pf}} \quad (7)$$

with the maximum solution appearing where $\frac{\delta S_{pf}}{\delta w_B} = 0$. The optimization problem is graphically²⁹ depicted in Figure 8 where we plot the portfolio Sharpe ratio as a function of the allocation to asset B . The solution is the saddle point in the figure, appearing at a portfolio Sharpe ratio of 2.58 with an allocation to asset T of 44%. This example illustrates, as further discussed in Erlandsson (2019), how diversification benefits can make it difficult to switch a portfolio entirely to green assets. It is easy to show that even in cases where the green asset G has a higher expected return and lower volatility, i.e. strictly superior to B , there will still be significant allocations to B . This poses a clear problem to ESG minded investors, who would rather switch their whole portfolio into perceived better ESG assets, especially when they are expected to outperform in every way.

We now turn to how the above system of asset metrics can be used to quantify volatility versus expected return trade offs. The basic idea is that if we see a traditional asset B price at a certain market level, and given the volatilities σ_G, σ_B and correlation $\rho_{G,B}$, we can calculate what the expected return on asset G should be. In order to do so, we assume that at the equilibrium pricing point, the investor would be equally allocated to each asset, i.e. $w_G = w_B = 0.5$. To phrase in the terms of the example above: what expected return r_G fulfils the condition $w_G = w_T = 0.5$? Again, this is something which is available, however not very elegant, analytically, but for multivariable cases, one might need to resort to numerical methods to find the solution.

²⁹There is an analytical solution, however, it is not very elegant. See Pedersen, Fitzgibbons and Pomorski (2020) for a similar definition of the optimization problem with an explicit ESG target function.

Figure 7: Hypothetical portfolio Markowitz bullet.

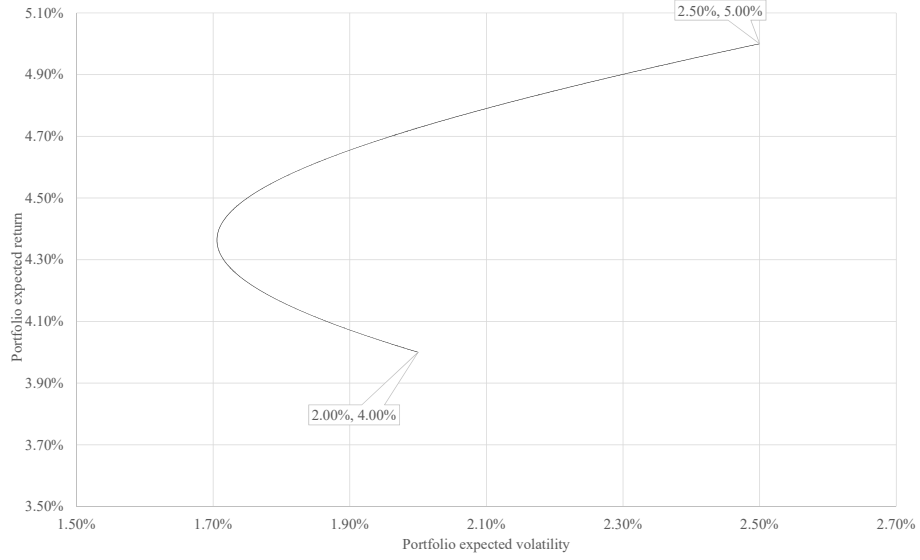
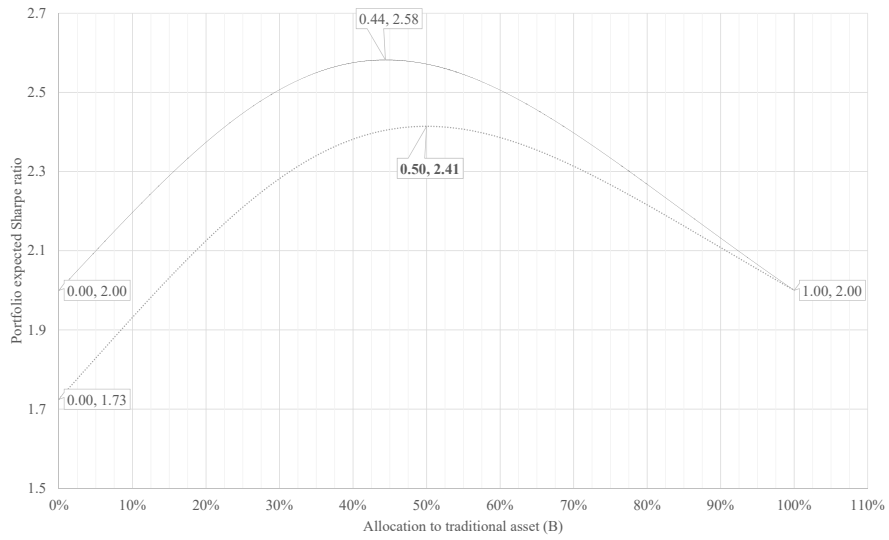


Figure 8: Portfolio Sharpe ratio as a function of allocation to asset B . Solid line indicates frontier using set values for risk and expected return, dashed line indicates the frontier where r^G has been set such that there is a 50/50 allocation to asset B and G .



Solving in our case for r_G yields a solution of $r_G^* = 3.45\%$. Hence, a Sharpe-optimizing investor would be indifferent between asset G and B if the respective risk-return metrics were $rr_G = [2\%, 3.45\%, 1.72]$ and $rr_B = [2.5\%, 5\%, 2]$ under our correlation assumption. In this context, we would refer to $r_G^* - r_B = 3.45\% - 5\% = -1.55\%$ as the green bond spread premium. In this low-correlation case, it is easy to see that this so called premium is not very meaningful. One way to make it slightly more meaningful would be to assume that you take on the same volatility in both asset: we would for example size up the position in G by 25% so that it has 2.5% volatility. Then we could write the green premium as $3.45\% * 1.25 - 5\% = 4.31\% - 5\% = -0.69\%$.

To further lead into the case on how to price green vs traditional assets, consider a case where volatilities are much closer to each other, $\sigma_G = 3\%$ and $\sigma_B = 3.1\%$. Solving for this case, we get a $r_G^* = 4.74\%$, clearly illustrating how equalizing volatility drives down the expected return differential between the assets.

We now proceed to create a re-weighted spread series such that $E(r_t^G) - E(r_t^B) = 0$ so that we can compare magnitudes of volatility under the condition that expected returns are equal. The market convention would be to construct this as $E(r_t^G) = \frac{s_{t-1}^G}{s_{t-1}^B} \cdot E(r_t^B)$, with the intuition that a hold-to-maturity investors solving this portfolio problem would weight their zero expected return portfolio as $\omega E(r^G) - E(r^B) = 0 \Leftrightarrow \omega s_t^G - s_t^B = 0 \Leftrightarrow \omega = \frac{s_t^B}{s_t^G}$.

The intuition behind this comes from the long-term assumption that the return (assuming an identical risk of default) will equal the spread of the bond. To compensate for any current spread differentials, i.e. make the investor neutral between the two assets from a first-moment perspective, the percentage weight on one of the assets will be adjusted according to the percentage spread ratio between the assets. In our ULFP example, the B generally trades tighter than G with the average spread ratio of 1.07x. In practice, an investor considering investing in the two would then *on average* rebalance so that the exposure to the higher yielding G would be 7% lower. However, we noted earlier that the spread ratio has considerable time-variation, which is why we normalize the spread series with 1 day lagged values of the spread ratio, as would be the case in a continuously hedged portfolio.

Given our normalized series, we can estimate time-series dynamics for the spreads of G and B and analyze differences in volatility, if any, to further lead to conclusions on the risk rather than just the spread premium. However, in order to do this, we need robust estimates of $\hat{\sigma}_i$. In case of credit spreads, we face some fairly classical issues with financial time-series in terms of persistent (auto-correlated) volatility as well as a high degree of fat-tailedness/leptokurtosis. We suggest the following GARCH specification (Bollerslev (1986)):

$$\Delta s_t^i = c_i + \phi_i \Delta s_{t-1}^i + \epsilon_{i,t} \quad (8)$$

where Δs_t^i is the change in the spread, ϕ captures auto-correlation in spreads and ϵ_t is IID error term with mean zero and variance σ_t^2 . The variance in turn

Table 4: GARCH estimation results, ULFP bonds.

Parameter	Bond G		Bond B	
	Estimate	p-value	Estimate	p-value
c_i	-0.073	(0.096)	-0.079	(0.086)
ϕ_i	0.272	(0.000)	0.240	(0.000)
ω_i	0.216	(0.000)	0.253	(0.000)
α_i	0.274	(0.000)	0.234	(0.000)
β_i	0.617	(0.000)	0.647	(0.000)
ν_i	4.961	(0.000)	4.649	(0.000)
σ_i^2	1.993	(0.006)	2.125	(0.018)
Log-Likelihood	-1283.8		-1343.0	

is driven by the process

$$\sigma_{i,t}^2 = \omega_i + \alpha_i \epsilon_{i,t-1}^2 + \beta_i \sigma_{i,t-1}^2 \quad (9)$$

In order to allow for further fat tails, we assume a Student t distribution for the underlying errors, where the degree-of-freedom parameter ν is estimated. As $\nu \rightarrow 4$ the fourth moment (kurtosis) tends toward infinity.³⁰

Equation 9 describes the conditional variance of the time-series s^i , but using estimates of the parameters, we can calculate the unconditional variance as

$$\sigma_i^2 = \frac{\omega_i}{1 - \alpha_i - \beta_i} \quad (10)$$

This eventually leads us to be able to test the hypothesis $\sigma_G^2 = \sigma_B^2$. As we have normalized returns so that $E(r^G) = E(r^B)$, the test becomes a test of the existence of a risk-premium. We produce model estimates in Table 4.

We test $\sigma_G^2 = \sigma_B^2$ using likelihood ratio tests with resulting p-values of 0.059 and 0.061³¹ We also estimate the mean of the difference in conditional variance/standard deviation time-series to be significantly negative, in favour for the green bond series. However, testing this for the shorter sample (up until Dec 31 2019), we find the differential to not be significant. A second test to be conducted can be to test the fat-tailedness of both series, to check if the green bond is less prone to outsized moves. We do this by testing the equality of ν across the series, but reject this hypothesis with p-values in the range of 0.7. Hence, and perhaps not too suprisingly as we only see one real tail-risk event in the data, we are unable to reject that the green and traditional bond exhibit the same leptokurtosis.

As a last step, how would we expect the green spread premium to look, under the assumption that the volatility in G is actually lower? We return to our investor-neutral allocation problem in the beginning, where we seek the

³⁰An advantage of the GARCH model is that it is straightforward to estimate through using numerical optimization available in software packages like Excel maximize the log likelihood function. Using a Student t distribution rather than a normal makes this a bit more difficult, but not impossible. For hypothesis testing, we would advice to use more advanced statistical software, however.

³¹We make the test two-sided such that in the first instance, we have normalized G spreads to match B and vice versa.

green bond spread $r_{G,t}^*$ that would make an investor indifferent (i.e. choose a 50/50) portfolio between G and B , given our volatility estimates $\hat{\sigma}_G^2 = 1.993$ and $\hat{\sigma}_B^2 = 2.125$, correlation coefficient between returns $\hat{\rho} = \text{Corr}(\Delta s_t^G, \Delta s_t^B)$ and return assumption $r_{B,t} = s_t^B$. Note the time-indexing t of the return term: as expected return is based on time-varying spreads, the green bond premium $r_{G,t}^* - r_{B,t}$ will also be time-varying, effectively dependent on spread level.³²

Given the estimation results, we find the long-term green bond spread premium at fair value to be -3.4% of the B spread, for example 1.7bp at a spread of 50bp or 6.8bp at a spread of 200bp. It is important to note that these are the long-run estimates, based on a hold-to-maturity investor profile, unconditional variance estimates, and identical default probabilities as under the assumption on the twin-bond relationship between G and B . Still, we find it illuminating that the original, off-the-cuff assertion of a green bond additional premium in this twin-bond case is fully rejected by looking through the relative volatility lens. In this case, the discrepancy between actual market pricing and the volatility-based fair value spread is considerable. To put it in direct terms, there seems to be little reason to hold the ULFP $\frac{7}{8}$ 2025 bond at lower expected return and higher expected volatility than its green twin ULFP 1 2025 bond. If anything, we could view this as cautionary tale of how corporat bonds markets can deviate from what appears theoretically correct.

4 Further twin-bond case studies.

Summary: *Our previous statistical analysis is extended to two more cases of near twin-bonds of issuers AAPL and EIB. We find weak indications of lower volatility in both issuers' green bonds, and discuss some green bond re-valuation dynamics for EIB bonds through the corona-crisis.*

Twins bonds are however quite rare in the traded bond space, often by design. Bond issuers tend to prefer to "tap" existing bonds rather than issue new bonds very close to the curve, in order to smooth their maturity profile.³³ However, we seek out two more cases to attempt to collect some further insight into the green risk-premium rather than spread premium approach. We have searched for other good twin-bond pairs in prominent green bond issuers such as NIB, EDF, ENI, TENN, HSBC, VODLN, ENGIFP, BAC, SOCGEN among others, but with lesser like-for-like qualities than for these bonds.

We first illustrate two Apple bonds in USD, the traditional (B) AAPL 2.4% Jan 2023 and the green (G) 2.5% Feb 2023. The bonds are similar in many ways, but with a smaller issue size for B , USD750mn vs USD 1.1bn, and the green bond being "older" with a difference in original issue date of 1 year and 9 months. These effects should be working in opposing directions. It shall be

³²Note that it will be approximately proportional to spread level such that $r_{G,t}^* - r_{B,t} = s_t^B \cdot \left(\frac{\sigma_G}{\sigma_B} - 1 \right)$ as $\rho_{G,B} \rightarrow 1$.

³³For an actual example of this, Iberdrola (IBESM) provided an interesting example, also with a large number of green bond issues over the curve, but where we do not find good twin-bond pairs.

Figure 9: Bloomberg screens for AAPL bonds.



Figure 10: Spreads of the twin AAPL bonds.



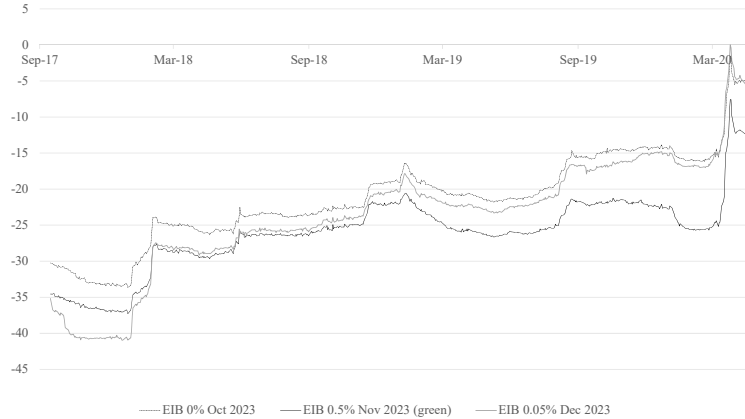
Table 5: GARCH estimation results, AAPL.

Parameter	Bond G		Bond B	
	Estimate	p-value	Estimate	p-value
c_i	-0.027	(0.71)	-0.022	(0.77)
ϕ_i	-0.086	(0.05)	-0.103	(0.02)
ω_i	0.616	(0.01)	0.482	(0.01)
α_i	0.202	(0.00)	0.190	(0.00)
β_i	0.729	(0.00)	0.764	(0.00)
ν_i	4.919	(0.00)	5.271	(0.00)
σ_i^2	8.870	0.032	10.434	x
Log-Likelihood	-1338.4		-1356.1	

noted at this point that USD and EUR corporate bonds markets tend to use different quoting conventions: in USD, most bonds will be priced over benchmark Treasuries, whereas in EUR quotation and pricing over swaps is more common. We show the difference in the green bonds spread premium based on swap spreads, government spreads and yield spreads in Figures 13 and 14 in the appendix.

We start our sample 2 months after issuance of the B bond. The bond info and spread time-series are depicted in Figure 9 and 10. The results from GARCH estimation is in Table 5, where considerable persistence in volatility ($\alpha_i + \beta_i$ is near 1) is shown. Moreover, we see considerable additional fat-tailedness in the distribution with low ν_i parameter estimate in both cases. When testing for equality of unconditional volatility $\hat{\sigma}_G^2 = \hat{\sigma}_B^2$, we are unable to reject the null that they are equal with a p-value 0.70. Hence, we conclude that although there superficially appears to be lower volatility in the green bond case, we do not have the statistical power to confirm it.

Figure 11: Spreads of the EIB bonds.



We continue to look at the green bonds of the European Investment Bank (corporate ticker EIB). EIB is a supranational issuer that has been a key player in that segment since 2013. With an extensive balance sheet, an issuer like EIB will have a large number of benchmark sized bonds across the maturity curve, making precise interpolation easier compared to more sparse corporate issuers.³⁴ Supranational issuers like EIB often "tap" existing bonds issues, i.e. rather than issue a new bond, they increase the nominal size of an already outstanding bond. Naturally, such taps occur opportunistically, as the issuer seeks to minimize their cost of capital, which can be hypothesized to happen when

³⁴Note that EIB has a guarantee structure such that refinancing risk is dissimilar from what we would see in a corporate issuer.

Table 6: GARCH estimation results, EIB. Short sample refers to data up until 31 Dec 2019.

Param	Full sample				Short sample			
	Bond G		Bond B		Bond G		Bond B	
	Estimate	p	Estimate	p	Estimate	p	Estimate	p
c_i	-0.008	(0.18)	0.001	(0.89)	-0.007	(0.29)	0.003	(0.65)
ω_i	0.010	(0.0)	0.006	(0.00)	0.014	(0.00)	0.007	(0.00)
α_i	0.529	(0.00)	0.590	(0.00)	0.522	(0.00)	0.509	(0.00)
β_i	0.386	(0.00)	0.422	(0.00)	0.244	(0.02)	0.414	(0.00)
ν_i	5.269	(0.00)	5.239	(0.00)	5.955	(0.00)	5.370	(0.00)
σ_i^2	0.116	(0.26)	n.a.	n.a.	0.060	(0.25)	0.085	(0.08)
Log-L	118.1		179.4		149.1		199.3	

spreads appear below fair-value.³⁵ It should also be noted that there are further policy making influences on an issuer like EIB. For example, EIB obtained a preferred status in the Greek government debt restructuring of 2012. EIB debt is also generally be treated as 0% risk-weight assets, making the investor base larger in terms of institutions looking to optimize capital ratios.

The best match we can find on the EIB curve is the triplet of EIB 0% Oct 2023, EIB 0.5% Nov 2023 (green) and EIB 0.05% Dec 2023. These bonds have some divergence in coupons and relative issue sizes varying over time due to taps³⁶, but we find fairly similar, such that a combination of of the EIB 0% and EIB 0.05% should approximately match the EIB 0.5%.³⁷ We graph the z-spreads of the three bonds in Figure 11.

It is quite clear that the EIB 0.05% bond starts out tighter than both the green and traditional bond, but that there is an almost deterministic trend through which this bond converges to the spread of the EIB 0% bond. This illustrates our point in the first section: the green bond spread premium can exhibit quite persistent deviations over time. Had we estimated the premium as an average in Sep 2017-Sep 2018, we would have gotten a very different results from, for example, March 2019-March 2020.³⁸ But visually speaking, it seems quite clear that the green 0.5% is trading at a lower spread than the traditional bonds.

To proceed, we construct a synthetic twin bond to the green bond G as a 50/50 portfolio of the EIB 0% and EIB 0.05% $\rightarrow B$. Even with this near combination, and given that we find unit roots in all of the EIB spread series, we do not find evidence of cointegration between G and B irrespective of a number of

³⁵For example, EIB issued a GBP500mn 2 $\frac{1}{4}$ % 2020 bond in March 2014, and tapped that bond at a tighter level than original issue for another GBP500mn even before the original transaction had settled. illustrating an issuance pattern that would not be seen in corporate bond markets.

³⁶For example, the green 0.5% was issued with original issue size EUR600mn in Aug-15, then tapped for EUR400m (Oct-15), EUR500mn (Jan-16), EUR400mn (Jan-17) and EUR150mn (Nov-19). The last tap in particular appears to on reverse inquiry, i.e. by direct demand from an investor.

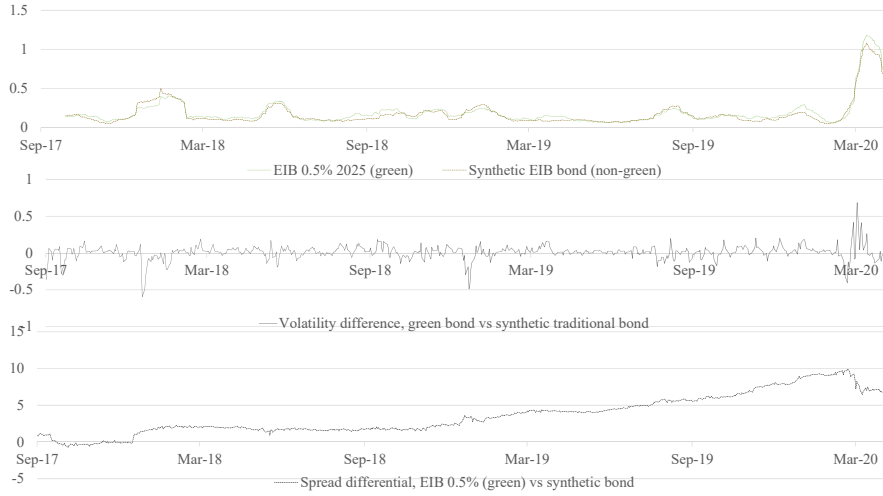
³⁷All three bonds mature on the 15th of the respective months, effectively making the EIB 0.5% a perfect mid-point for the non-green pari.

³⁸Average spread differential during these periods were 1.26bp/5.9bp respectively.

specifications. Analogously to earlier cases, the volatility models estimates are presented in Table 6. When estimating the full sample (including the corona crisis volatility), we run into specification difficulties, as the parameters estimates of B imply an IGARCH process³⁹ for which the unconditional variance σ_i^2 is not bounded.⁴⁰ Thus, we cannot compare variances between the two series. From ocular inspection, it appears that the corona volatility is a regime shift rather than well-fitted into a single distribution, suggesting a differing way to model volatility such as in Gray (1996).

We test instead if volatility is similar for G and B for a shorter sample instead, where the GARCH parameters for B are less than unity, right hand panel of Table 6. We find the point estimates such that $\sigma_G^2 < \sigma_B^2$, but similarly to the AAPL case, they are not statistically significantly different from each other.⁴¹

Figure 12: EIB bonds' relative volatility. Upper panel: 20-day moving average of absolute changes in bond spreads. Middle panel: difference in conditional volatility estimates based on GARCH model. Lower panel: green bond spread premium based on levels.



The EIB case piques our curiosity with regards to evolution during the corona crisis, and we believe it is illustrative to use (conditional) volatility estimates to see if the green bond trading dynamics look different during a risk-off event. If we look at the spread premium derived from levels equations, shown

³⁹An integrated GARCH(1,1) arises when $\alpha_i + \beta_i = 1$.

⁴⁰When $\alpha_i + \beta_i = 1$, the denominator in Equation eq:condvariance is zero, making the expression meaningless.

⁴¹If we still would proceed to plug the volatility numbers into our pricing framework, we find a greenium (negative spread premium) of 4.2bp is motivated by the lower volatility in G in this case.

in Figure 14 in the appendix, we can observe that the premium well exceeded the 4.2bp from 2019H2 and onwards. Prior to the onset of the corona crisis, it appeared to be almost 10bp, but as shown in the figure, the premium appears to almost halve very quickly during the crisis.

We graph the corresponding volatility estimates in Figure 12, where we can see that the green bond exhibited higher volatility than the traditional bond in March-2020. It appears that the heightened green volatility coincided with the reduction in the spread premium back toward the volatility inferred 4bp fair-value level. From a valuation perspective, this suggests that investors may not always accept greeniums to grow indefinitely, and that volatility events in overvaluation cases could drive excess volatility in green bonds. An explanation to this last effect offered by a market participant is that some green bond investors may only invest in green bonds, and that bond issuers such as EIB operate as the liquidity buffer for such investors. In times of higher market stress, they will sell the most liquid bonds (EIB) in order to raise cash for other green investments or for fund outflows. Again, this point illustrates the heterogeneity within the green bond space warranting caution in expressing a uniform green bond spread premium.

5 From a green bond spread premium to a green bond risk premium: Implications and suggestions

Summary: *Focusing on the green bond risk-premium rather than spread premium could reconcile the gap between seeking lower cost of capital for green projects vis-a-vis the fiduciary duty of the investors. Volatility is key to solving that equation and we suggest a number of considerations issuers, investors, policy institutions and regulators could make without deviating from a non-subsidization approach to climate investments.*

Following these results, focusing on volatility reduction in the burgeoning green bond asset class may be a better way to argue for it, rather than trying to argue for it through a pure reduced spread risk premium motivation. The implications for investors and issuers of green bonds in terms of "giving up" spread is very similar: a dollar won or lost is similarly valued by both. However, they may have very different valuations of mark-to-market volatility of a green bond.

For issuers: Mark-to-market volatility of the green bonds is not a material factor for the issuers of those bonds. Thus, issuers that can argue why their green bonds trade at a volatility discount to other bonds can make the argument why they should be able to issue green bonds with lower spreads (=lower cost-of-capital) than if they were issuing traditional bonds. This can be achieved in a number of ways. The first and most obvious one is to assure that primary market investors are dedicated to holding the bonds, especially across the full market cycle. The latter specification is important: the ULFP story tells us that

it is important to be able to hold the position through market volatility periods like March 2020, suggesting that "preferred" investors might actually be those that are able to hedge market beta moves rather than just outright long-only. The pattern shown in the EIB case study was the opposite: as negative spread moves across the curve filtered through, green bond volatility exceeded that of the traditional bond.

For investors: For many investors, investing in green bonds has been constrained by the suggestions that some green bonds trade with a lower return potential than traditional bonds. With a paradigm of strong fiduciary duty, ie. not being allowed to make a trade-off between returns and non-pecuniary values (such as saving the world), green bond investments have thus been controversial at some places. We believe that properly accounting for volatility allows investors to switch back to the alignment of a green bond strategy with their own fiduciary duty risk-return obligations, rather than just a returns based perspective. Our approach also suggests way to value the green bond risk premium for trading purposes.

For policy institutions: Certain institutions with clear policy objectives, such as the Nordic Investment Bank and KfW, have set up green bond mandates to support the market, explicitly with the target to lower funding costs for green projects. We believe their role should be predominantly as counter-rather than pro-cyclical buyers of green bonds. Simply put, they should design their investment plans to be activated when other buyers are absent and deactivate them when markets are more balanced. In this way, they could provide better liquidity (and lower volatility) in green bonds vis-a-vis traditional bonds specifically in downside scenarios, and through this channel provide arguments for issuers of green bonds to get a lower cost-of-capital. If the green bond market would also achieve a lower volatility, especially with diminished tail-risks through counter-cyclical investors, there could be further reasons to consider lower risk-weights on dedicated green bonds and how to quantify such divergence from traditional bonds (e.g. see Thomä and Gibhardt (2019) for a discussion of risk-weight in a European context).

6 Suggestions for further research

The twin bond analysis is a useful laboratory to understand and test some basic hypotheses around green bond vs traditional, but for a further generalization, a bigger cross-section is needed. On the cointegration test of the green bond spread premium, Pedroni (2004) and a number of subsequent papers explore how to do this in a panel setting.

Curve algorithms for creating the spread premium are fairly well researched, but we see an interesting avenue of research where we create a bond volatility curve rather than just the spread premium. Ben Dor et al (2007) for example illustrate the empirical relationship between credit spreads and volatility. This would enable us to potentially expand the cross-section of bonds where we could test for premiums.

Furthermore, we could model the interaction between the spread- and volatility premium more explicitly. A first step would be to consider multivariate GARCH models, such as the BEKK model (see Engle and Kroner (1995))⁴², as well as various GARCH-in-Mean specifications where the conditional volatility enters into the spread level equation. In terms of being able to capture even fatter tails in the variance, such as seems to have crystallized for some spreads during the corona crisis, regime shifting models might be considered.

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⁴²The original model presented in 1990 was named after Baba, Engle, Kraft and Kroner.

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8 Appendix

Figure 13: Green bonds vs traditional bond differential for AAP 2.4% and 2.85%.

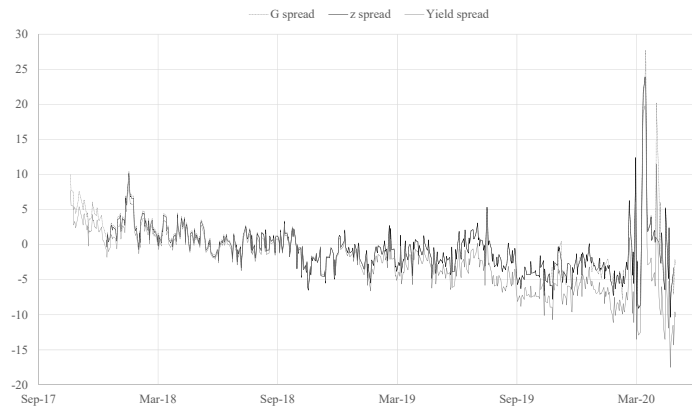


Figure 14: Green bonds vs traditional bond differential for EIB 0% and 0.5%.

