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Allocating to Green Bonds

Laurens Swinkels

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Allocating to Green Bonds

Laurens Swinkels

Laurens Swinkels
is an associate professor of finance at Erasmus University in Rotterdam, The Netherlands, and executive director of sustainable multi-asset strategies at Robeco Institutional Asset Management in Rotterdam, The Netherlands.
lswinkels@ese.eur.nl; l.swinkels@robeco.com

KEY FINDINGS

- The green bond market is rapidly growing but still represents less than 1% of bonds outstanding.
- Composition changes of the green bond market make historical data from before 2015 less representative for the future.
- The green bond market is a mix of government and corporate bonds, with a tilt to issuers in euro.

ABSTRACT

Green bonds are about a decade old financial instrument with cash flows earmarked to improve the environment or combat climate change. The author shows the spectacular growth of the asset class over time but notes that it is currently still less than 1% of the investment grade fixed income market. The composition of the asset class has changed considerably over time. At the start, it was mainly very safe supranational institutions issuing in various currencies with relatively short maturities. Corporates, especially utilities, followed them, and more recently, governments have started issuing green bonds. These sharp composition changes make historical data from before 2015 less representative for the future. The author's returns- and characteristics-based analyses show that investors allocating to green bonds should finance this from an aggregate fixed income allocation if they want to reduce the impact on the risk and return characteristics of the existing portfolio.

Risks stemming from climate change are on the top policymakers' minds. At the same time, institutional investors worldwide are evaluating their investment policies concerning climate risks and opportunities. In a survey on climate risk perceptions among more than 400 such investors, 10% of respondents ranked the financial implications of climate risk for their portfolios first, and 55% said that climate risks had already begun to materialize; see Krueger, Sautner, and Starks (2020). Choi, Gao, and Jiang (2020) find that institutional investors have reduced their overweight to high carbon-emission stocks of 0.5% relative to a market-capitalization-weighted portfolio to underweight about the same magnitude over 2001 to 2015. Bolton and Kacperczyk (2021) document that institutional investors in Europe and Asia have started divesting from carbon-emitting companies after the Paris Agreement.

Green bonds are a relatively new financial instrument that may facilitate the energy transition, sometimes also referred to as climate bonds.[1] These instruments can be

[1] A somewhat different financial instrument, a transition bond, was introduced in the US to deal with regulatory changes in the utility industry. See Sidak (2019) for more detail on this financial instrument. Further innovations have been proposed by Bongaerts and Schoenmaker (2020), where the green bond can be split in a conventional bond and a green certificate that may trade separately. They indicate that this would improve bond liquidity and allow for more flexibility for sustainable investors.

issued by governments, supranational and government-related institutions, or corporate entities. The issuance of green bonds is typically tied to specific green projects designed to avoid or reduce climate change, such as renewable energy projects that facilitate the energy transition away from fossil fuels.[2] Hence, green bonds are particularly suited for investors concerned about climate change. See Kaminker and Stewart (2012), Inderst, Kaminker, and Stewart (2012), Kaminker (2015), Glomsrød and Wei (2018), Torvanger, Maltais, and Marginean (2021), and Maltais and Nykvist (2021) for analyses on how energy producers and institutional investors can together develop the green bond market to facilitate the energy transition.[3] Banga (2019) and Otek Ntsama et al. (2021) analyze how developing countries may use the green bond market to finance their energy transition. Tolliver, Keely, and Managi (2020) also show that national commitments to the Paris Agreement have spurred the further development of green bond markets. Fatica and Panzica (2021) find that following green bond issuance, corporates become less carbon-intensive, suggesting that green bonds have real-world implications for climate change mitigation. At least, the authors find that those green bonds that are not used for refinancing purposes have the largest impact on carbon emission reduction. However, it cannot be ruled out that these companies would have also undertaken these green projects without green bond issuance. In addition, institutional investors have intermediated to bring green bonds to the retail investing public by developing green bond mutual funds and exchange-traded funds; see Gyura (2020), Deschryver and de Mariz (2020), and Liaw (2020).

The academic literature on green bonds has been mostly interested in the pricing of green bonds relative to non-green bonds with similar characteristics. This difference is often referred to as the green bond premium or the 'greenium.' Empirical studies trying to identify the magnitude of this premium mostly find economically small premiums that vary between plus and minus 10 basis points. Differences are due to the sample period, the sample of green bonds studied, or the methodology to find appropriate matching non-green bonds; see Hachenberg and Schiereck (2018), Baker et al. (2018), Bachelet, Becchetti, and Manfredonia (2019), Gianfrate and Peri (2019), Nanayakkara and Colombage (2019), Zerbib (2019), Wang et al. (2020), Larcker and Watts (2020), Liaw (2020), Immel et al. (2021), and Fatica, Panzica, and Rancan (2021).

A research question that has not yet been addressed is the place of green bond investments in the overall fixed income portfolio. This research question is important but also challenging because of two aspects. First, the green bond market has different characteristics from a typical fixed income benchmark, as it has a different credit rating, currency, sector, and maturity composition. Second, since the market has seen rapid development over the past years, historical data may not be representative of future risk and return characteristics. In this article, we address these two issues in detail.

Our empirical analysis shows that the green bond market predominantly has bond issues denominated in euro and less credit risk than a corporate bond portfolio. The sector composition is also tilted to government-related securities and includes emerging markets issuers. We prefer to use data after October 2014 for historical return analyses instead of the entire available return history from 2010. Using this recent data, we find that a green bond allocation robustly resembles a global aggregate bond portfolio, with a tilt to corporate bonds and euro-denominated assets.

[2] González and Núñez (2021) provide data showing that the proceeds of green bonds over the period 2014–2020 are predominantly used for the categories 'energy,' 'buildings,' and 'transport.'

[3] Ehlers, Mojon, and Packer (2020) suggest rating corporate bond issuers on their 'greenness' to help institutional investors provide fresh capital not only to bonds with a green label, but to firms that are in the process of lowering their overall carbon emissions.

While investors could expand existing government bond mandates to include green government and government-related bonds and expand existing corporate bond mandates to include green corporate bonds, they can also decide to allocate to a separate green bond strategy by a specialized manager. The latter's advantage may be that the investor can better monitor and control the amount invested in green bonds, which may be an important element of its sustainability goals. Such investors should finance the green bond allocation by selling their aggregate investment grade fixed income portfolio, rather than only government or only corporate bonds. This way, the portfolio's risk-return profile will be least affected, while the sustainability of their portfolio is improved by contributing to the energy transition.

The next section shows the historical size and composition of the green bond market. In the third section, we compare the current composition with that of conventional fixed income assets. In the fourth section, we analyze which conventional fixed income assets best resemble the green bond market characteristics and returns. It also compares the effect of an allocation to green bonds on the risk-return profile of the fixed income portfolio. The final section concludes.

ARE HISTORICAL DATA ON GREEN BONDS REPRESENTATIVE FOR THE FUTURE?

In order to examine whether historical returns data are representative of the future return profile of green bonds, we start by analyzing the historical composition of the green bond market. We use the InterContinental Exchange (ICE) Bank of America (BofA) Green Bond Index.[4] We accessed this database through the ICE Data Services platform, where this index has the code GREN. The launch of this index was October 30, 2014, and it was at that time calculated back in time until December 31, 2010. We first examine the development of the size of the market, followed by its composition on the dimensions of credit rating, currency, sectors, and remaining maturity.

Exhibit 1 shows that at the launch of the green bond index in 2014, the number of qualifying bonds was 55 and adding up to a total of USD 36 billion in market value. At the starting date of the index in 2010, the number of included bonds was only seven, and its total market value was only USD 1.9 billion. In the beginning, the market lacked a standard, which was inconvenient for both issuers and investors. However, with the creation of the Green Bond Principles in January 2014, the market started taking off.[5] The number of green bonds increased considerably after the launch of the index in October 2014, but the increase had accelerated over the last couple of years of the sample period. While at the end of 2019, there were already 503 bonds in the index, this increased to 707 a year later. The market value increased from USD 395 billion to USD 622 billion over the same year. Even though its growth is fast and the market is expected to continue to grow fast, the global investment grade fixed income market is USD 65,513 billion in size at the end of 2020.[6] Hence, green bonds are currently still below 1% of the global fixed income market.

Credit Rating Composition

Green bonds qualifying for this index must have an investment grade credit rating. The seven green bonds in the index at the end of 2010 were all AAA-rated bonds

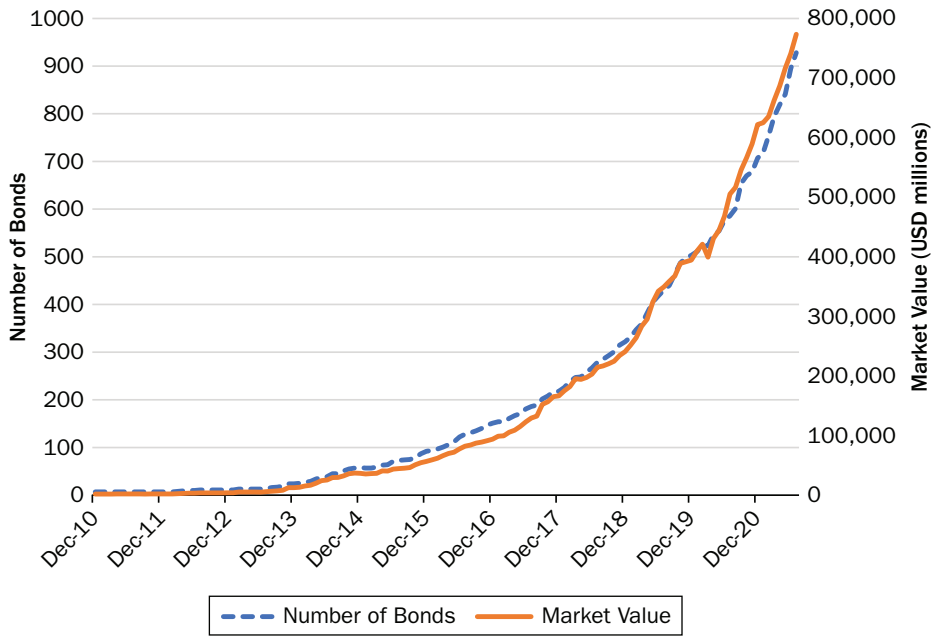
[4] The appendix contains Exhibit 1 (Exhibit A1) and Exhibit 10 (Exhibit A2) also for the Bloomberg Barclays MSCI Green Bond Index. Differences are small.

[5] See https://www.ceres.org/resources/reports/green-bond-principles-2014.

[6] Source: ICE BofA Global Broad Market Index (GBMI).

EXHIBIT 1

Size of the Green Bond Market



SOURCE: ICE BofA Green Bond Index. Index code: GREN. Sample period: December 31, 2010, to July 31, 2021.

issued by supranational institutions: the Asian Development Bank, the European Development Bank, and the International Bank for Reconstruction and Development.

Exhibit 2 shows that with the introduction of the Green Bond Principles in 2014, a little over half of the index's market value was AAA-rated, and slightly less than 10% had a BBB rating. Subsequently, the share of AAA-rated bonds slowly declined, and at the end of 2020, it is slightly less than a quarter of the total index value. At that point, each rating represented about a quarter. The credit quality differences over this decade-long sample period are to be considered when conducting historical analyses. The credit risk in the first years of the sample was low, indicated by the highest rating of the constituents, but at the same time, credit risk was also idiosyncratic as the number of bonds was limited.[7] At the end of the sample, idiosyncratic credit risk is much smaller, but the systematic credit risk has increased by lower ratings entering the index.

Currency Composition

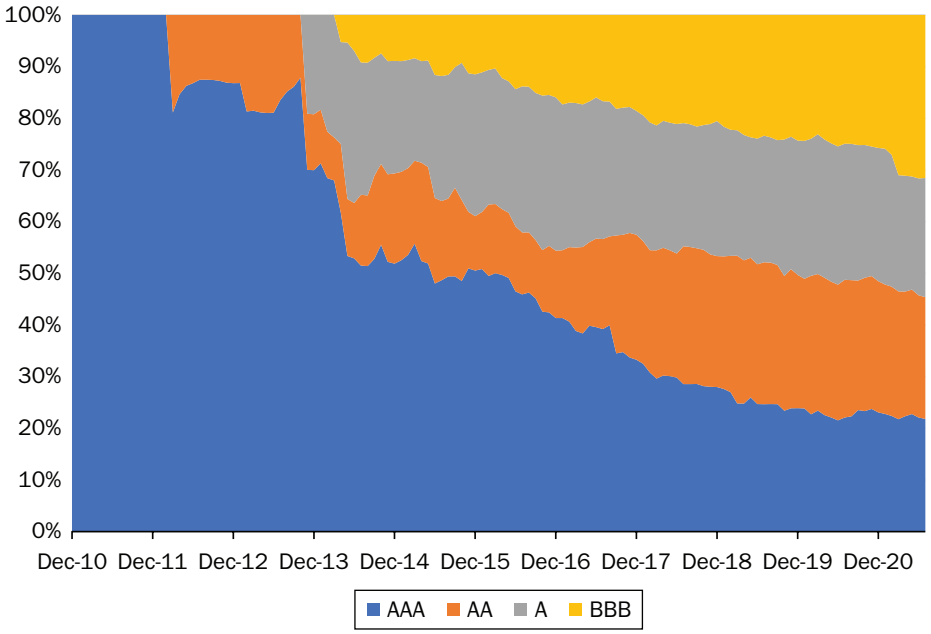
The green bond index is not limited to certain currency denominations. Exhibit 3 shows the currency composition of the index. At the start, it consisted of four relatively small currencies in the global fixed income markets: the Australian dollar, Brazilian real, South African rand, and Swedish krona.

At the index launch date, a little more than half of the market value was bonds denominated in European euro and a quarter by the US dollar. Smaller index shares

[7] The high credit quality can also be seen when the option-adjusted credit spread is examined for the first year of the index. From December 2010 to February 2012, this spread moved in the range of −32 to 5 basis points, suggesting that investing in those green bonds carried less or comparable risk to investing in US Treasuries. In the first 7 months of 2021, the option-adjusted credit spread moved in the range of 61 to 66 basis points.

EXHIBIT 2

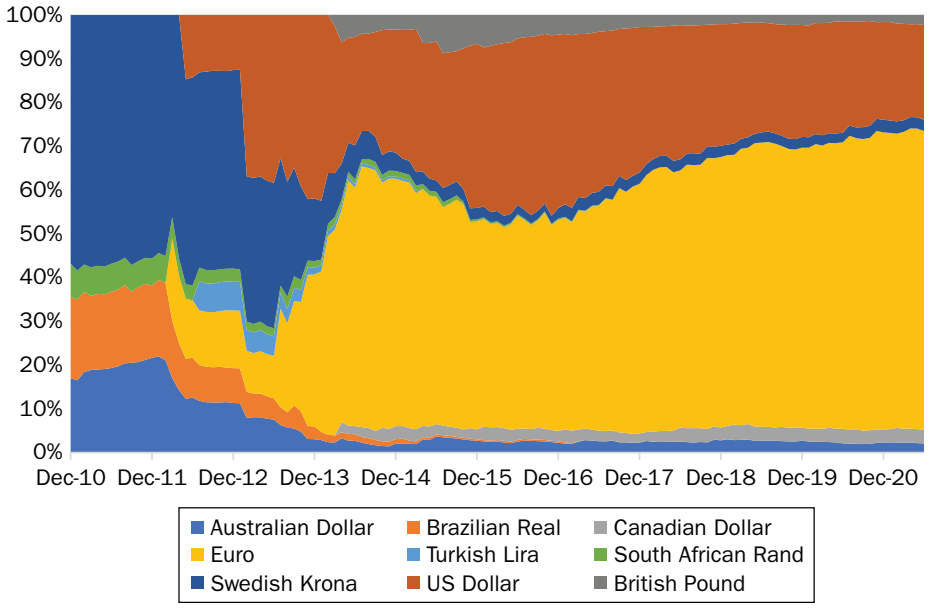
Credit Rating Composition of the Green Bond Market



SOURCE: ICE BofA Green Bond Index. Index code: GREN. Sample period: December 31, 2010, to July 31, 2021.

EXHIBIT 3

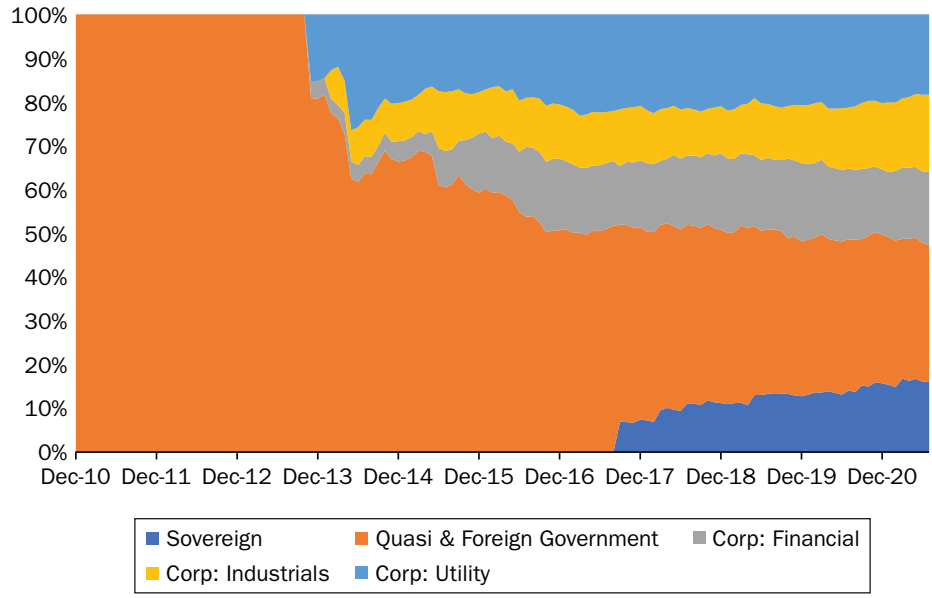
Currency Composition of the Green Bond Market



SOURCE: ICE BofA Green Bond Index. Index code: GREN. Sample period: December 31, 2010, to July 31, 2021.

EXHIBIT 4

Sector Composition of the Green Bond Market



SOURCE: ICE BofA Green Bond Index. Index code: GREN. Sample period: December 31, 2010, to July 31, 2021.

are in the Canadian dollar, Turkish lira, and British pound.[8] Perhaps because Eurozone investors or issuers have shown more interest in investing in or issuing green bonds, about two-thirds of the index is euro-denominated at the end of 2020.[9] The currency composition of the first years of the index is very different from that at the end. Therefore, one can question whether using the full index history of returns is representative for the future.

Sector Composition

We already mentioned that the first index-eligible green bonds were issued by supranational institutions, which are categorized in the 'Quasi and Foreign Government' sector definition. Exhibit 4 shows the sector composition of the green bond index over time. When the index was launched in 2014, there had been issuance by the corporate sector as well. Within the corporate bond sector, the 'Utilities' sector is relatively large. Flammer (2021) shows that stock markets react positively on green bond issuance of corporates, especially for first-time issues and those certified by third parties, and that the environmental performance of these companies improves after issuance of the green bond.[10]

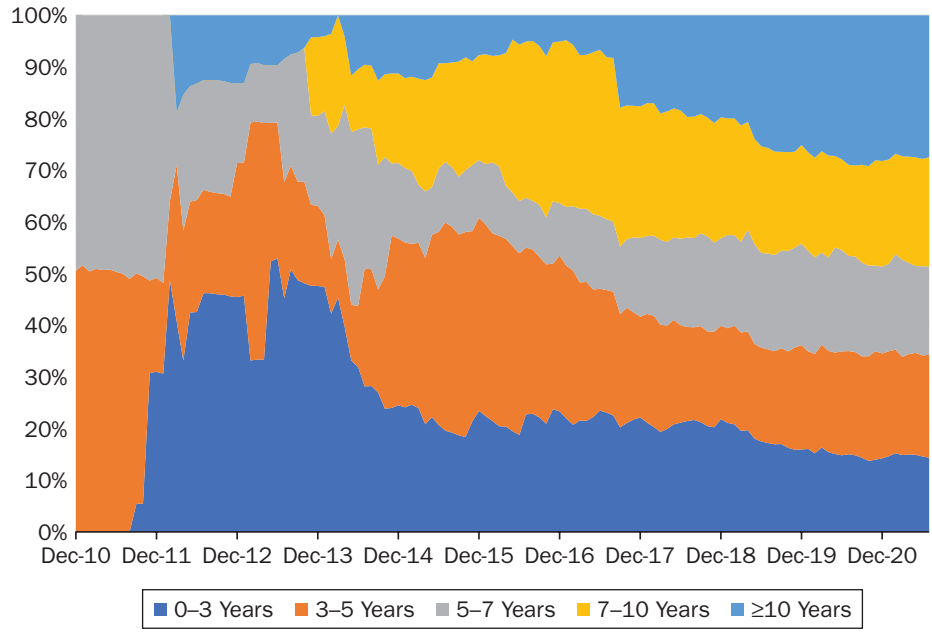
[8] Other currencies that are or were in the index, for such a small part that it is hardly visible in Exhibit 3, are the Chilean peso, Danish krone, Hong Kong dollar, Hungarian forint, Indian rupee, Indonesian rupiah, Japanese yen, Mexican peso, New Zealand dollar, Norwegian krone, Polish zloty, Singapore dollar, Swiss franc, and the Chinese offshore renminbi.

[9] There are entities from countries that have successfully issued green bonds outside their native currency, including from these countries: Czech Republic, Iceland, India, Lithuania, Panama, Peru, Philippines, Romania, Russia, South Korea, Taiwan, British Virgin Islands, and United Arab Emirates.

[10] Tang and Zhang (2018) also find that green bond issuance is advantageous for shareholders in the company. On the other hand, Lebelle, Lajili Jarjir, and Sassi (2020) find that the stock market reacts negatively on the announcement of green bond issuance. Using a sample of Chinese green bonds, Deng, Tang, and Zhang (2020) confirm that reputable third-party verification lowers the yield of the green bond issue. They also show that green bonds for which part of the proceeds can be used for

EXHIBIT 5

Maturity Composition of the Green Bond Market



SOURCE: ICE BofA Green Bond Index. Index code: GREN. Sample period: December 31, 2010, to July 31, 2021.

Among the first green utility bonds included in the index were Electricité de France and Engie from France, Hera from Italy, Iberdrola from Spain, and Verbund Öst in Austria. This suggests that part of the green bond market is indeed used for the energy transition. In September 2017, the French treasury issued the first government bond entering the index. Today, the index also contains green government bonds issued by Belgium, Germany, Ireland, Netherlands, and Sweden. Nevertheless, the sector 'Quasi and Foreign Government' is still dominating the index. Yet in addition to supranational, it also contains 'Agencies' (e.g., Autoridad del Canal de Panama), 'Local Authorities' (e.g., Auckland Council), 'Government Guaranteed' (e.g., Nederlandse Financierings-Maatschappij voor Ontwikkelingslanden), and 'Foreign Sovereigns' (e.g., Republic of Chile, whose bonds issued in Chilean pesos are in the 'Sovereign' sector, but its US dollar- and euro-denominated bonds are included here).[11]

Maturity Composition

Part of the risk for an investor is reflected in the credit rating, but another dimension of risk is the bond's maturity. Since investors have to wait longer to receive the payments of longer-dated bonds, they impact liquidity positions, and uncertainty about future creditworthiness and inflation rates can be considered additional risks in the long run. In addition, short-term changes in bond prices are the largest for bonds with the longest maturities, all other things equal.[12] Exhibit 5 shows the maturity

non-green investments are not considered green bonds by the market. Cao, Jin, and Ma (2021) suggest that commercial banks in China have issued green bonds predominantly for regulatory arbitrage reasons, not a reduction of financing costs.

[11] Baker et al. (2018) examine in more detail green bonds issued by US municipal bonds.

[12] The maturity of a bond is an easy and straightforward concept. For fixed income portfolio management, where sensitivities to interest and spread changes are important, a comparison of the option-adjusted duration profiles would be useful in addition to these maturity profiles. Another sign of

composition of the index. The bond issues first included in the green bond index were between 3 and 7 years. With several of these bonds maturing and dropping in the segment below three years, we also see the issuance of longer-dated green bonds. Since 2014, new issuance is regularly in the 7–10-year segment, and after 2017 there is regular issuance with maturities over 10 years. The green bond with the longest maturity at this moment was issued by the French local authority Societé du Grand Paris and matures only in February 2070. This maturity extension in the green bond market suggests that the market is coming of age.

The overall conclusion from this section is that historical analysis on, for example, the risk and return characteristics of green bonds, is challenging. Using returns data going back until 2010 may not be representative for the future. The number of green bonds was limited, making idiosyncratic risk much more important in the early part of the sample period. In addition, the composition of the dimensions rating, currency, sector, and maturity has changed considerably over time. Using return data prior to the launch date of the index, October 2014, is unlikely to help better understand the future risk and return of green bonds.

COMPARISON WITH TRADITIONAL FIXED INCOME INSTRUMENTS

Many institutional investors have stated ambitious climate policies for their investment portfolios. More than 500 of these investors responsible for more than USD 50 trillion in assets under management have become signatories of the Climate Action 100+ initiative. This implies that they want to help achieve the goals of the Paris Agreement and accelerate the transition to net-zero emissions by 2050. Financing the energy transition through investments in green bonds may be one of the actions on the agenda of these investors. How does an allocation to a green bond affect the existing fixed-income portfolio's risk and return characteristics? To examine this further, we first compare the rating, currency, sector, and maturity characteristics of several common fixed income allocations with those of the green bond market on July 31, 2021. Due to lack of data, we can neither examine how the liquidity of green bonds has changed over time nor compare the (il)liquidity of green bonds to conventional bonds. Existing research on corporate and municipal green bonds suggests that liquidity differences are limited (see, e.g., Febi et al. 2018 and Partridge and Medda 2020), but we have not been able to find comparisons between the liquidity of green and conventional government bonds.

We assume that existing fixed income allocations are on an aggregate basis, that is, including all fixed income securities ranging across government bonds, quasi-government bonds, corporate bonds, and securitized bonds. Since investing in green bonds seems to be dominated by institutional investors from the Eurozone,[13] we also consider euro-only versions of these allocations (market cap at July 31, 2021):

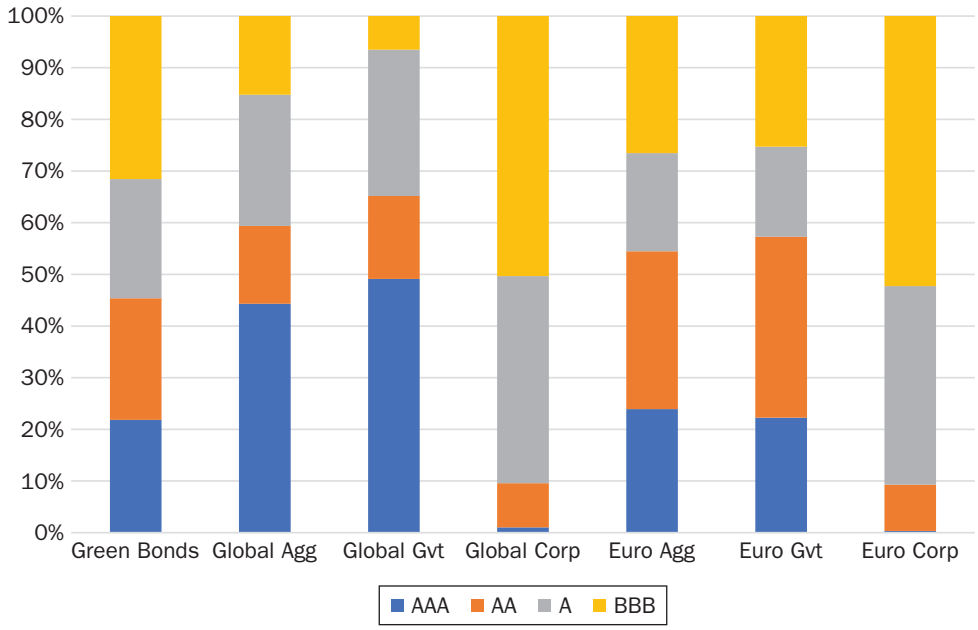
- Aggregate fixed income
  - ICE BofA Global Broad Market Index — GBMI — USD 66.9 trillion
  - ICE BofA Euro Broad Market Index — EMU0 — USD 16.3 trillion
- Government bonds
  - ICE BofA Global Government Index — W0G1 — USD 36.0 trillion
  - ICE BofA Euro Government Index — EG00 — USD 9.2 trillion

the development of the green bond market is the improved liquidity in more recent periods; see Febi et al. (2018). Liquidity is higher for green corporate bonds with more disclosure and higher readability; see Lebelle, Lajili Jarjir, and Sassi (2021).

[13] Sangiorgi and Schopohl (2021) report the results of a survey among European asset managers about their reasons to invest in green bonds.

EXHIBIT 6

Rating Composition of Selected Fixed Income Indexes



NOTES: Date: July 31, 2021. Index codes: GREN, GBMI, W0G1, G0BC, EMU0, EG00, ER00.

- Corporate bonds

ICE BofA Global Corporate Index	G0BC	USD 14.1 trillion
ICE BofA Euro Corporate Index	ER00	USD 3.5 trillion

Exhibit 6 shows that the rating profile of green bonds, with about equal shares in each of the four rating segments, is most similar to that of the euro aggregate and government indexes. The global aggregate and government indexes have almost double an allocation to the AAA-rating segment. The ratings from corporate bonds are concentrated in the A- and BBB-rating segments and are therefore much riskier than green bonds from this perspective.

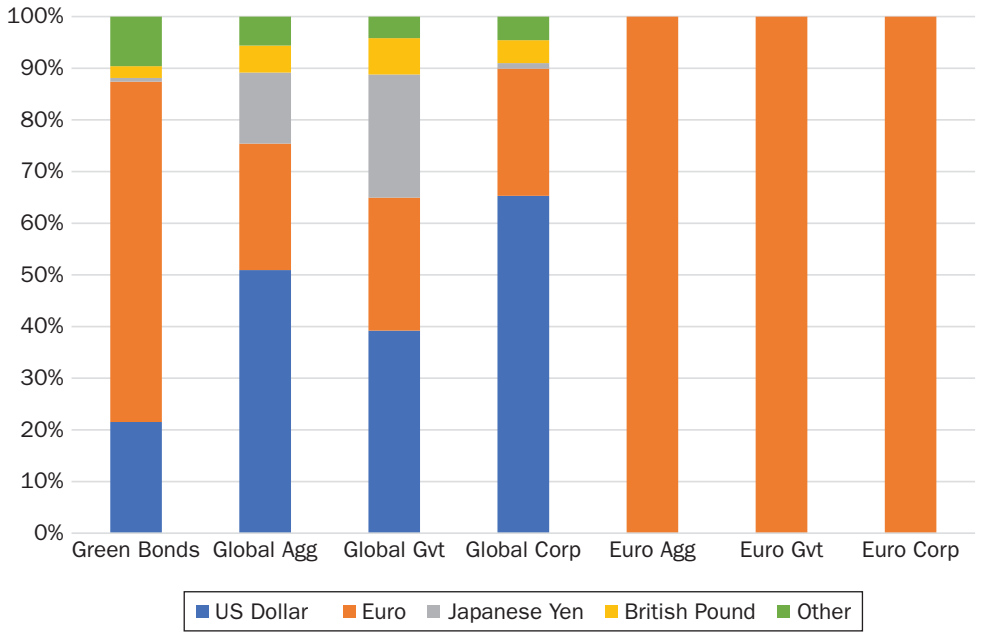
In the previous section, we already saw that the green bond index is heavily tilted to bonds denominated in euros. Exhibit 7 shows that the global indexes are dominated by issuance in US dollars. The Japanese yen is clearly visible because of the large government debt of Japan. The green bond index has a relatively large portion of 'other' currencies, with the Australian and Canadian dollars and Swedish krona taking up the largest portion of that. Note that the green bond index also contains a small portion of emerging markets currencies, which are excluded from the three global indexes.

Exhibit 8 shows that the portion of 'Quasi and Foreign Government' is a relatively large component of the green bond index compared to the other indexes. Much of the energy transition is financed through supranational institutions, agencies, and local authorities. However, Exhibit 8 also shows that the 'Utilities' segment of the corporate bond market is a relatively large part of the green bond index. The aggregate indexes also contain 'Securitized' debt, but this is not present in the green bonds index.

In the previous section, we indicated that the green bond market has come of age, evidenced by the increase in bond maturities. Exhibit 9 shows that the share of the green bond index that has a maturity below 10 years is similar to that of most other indexes, even though for the euro government index, this share is lower, while

EXHIBIT 7

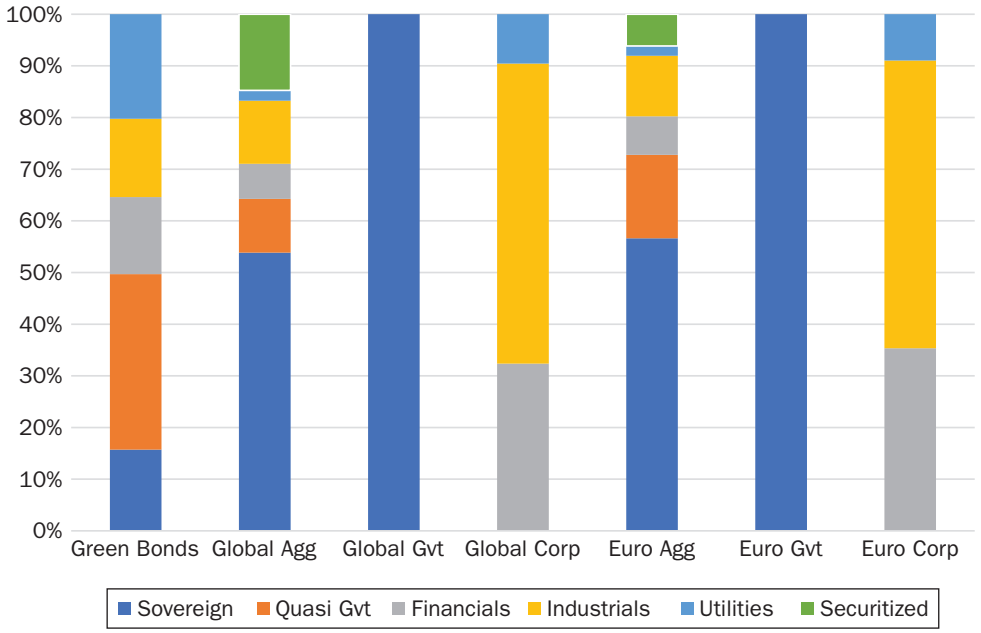
Currency Composition of Selected Fixed Income Indexes



NOTES: Date: July 31, 2021. Index codes: GREN, GBMI, W0G1, G0BC, EMU0, EG00, ER00.

EXHIBIT 8

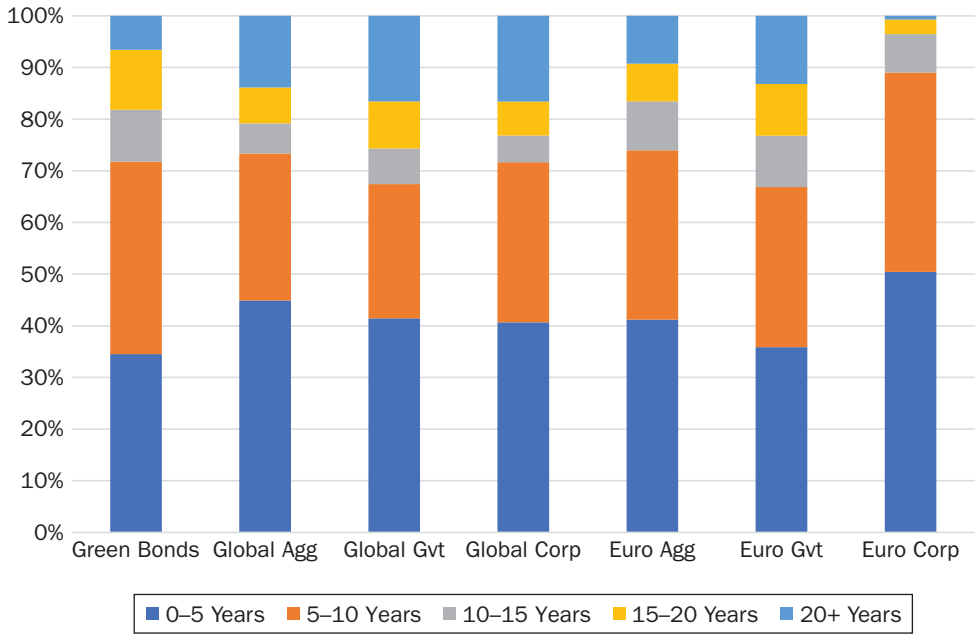
Sector Composition of Selected Fixed Income Indexes



NOTES: Date: July 31, 2021. Index codes: GREN, GBMI, W0G1, G0BC, EMU0, EG00, ER00.

EXHIBIT 9

Maturity Composition of Selected Fixed Income Indexes



NOTES: Date: July 31, 2021. Index codes: GREN, GBMI, W0G1, G0BC, EMU0, EG00, ER00.

for euro corporate bonds, this is higher. Green bond issuance with maturities above 20 years is relatively small at this moment.

In the next section, we evaluate which fixed income asset allocation resembles most the green bond allocation. This allocation could be sold when allocating to green bonds, leaving the overall portfolio characteristics similar.

EMPIRICAL ANALYSES

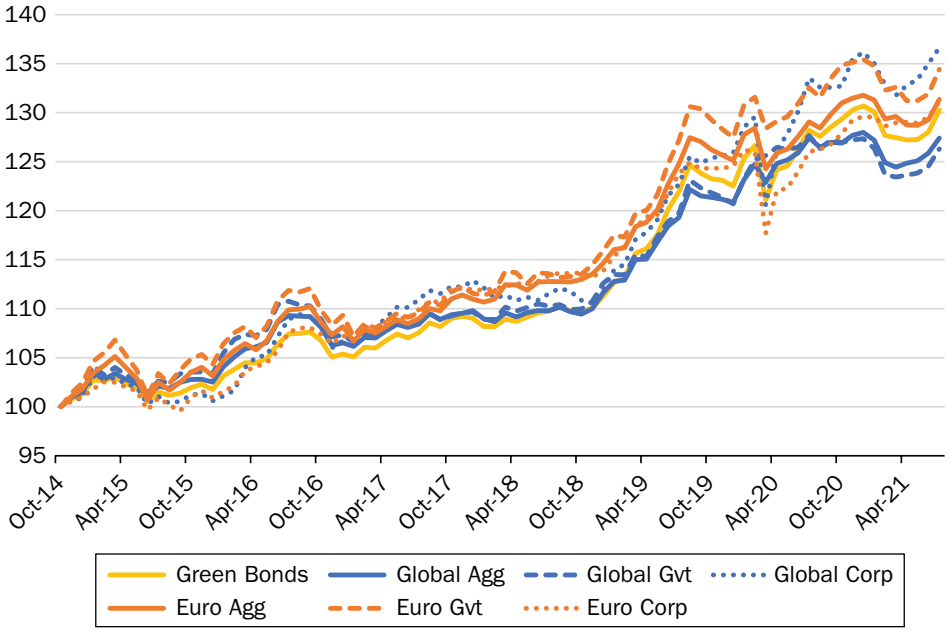
Historical Returns

In Exhibit 10, the total return index of the green bond market and the other asset classes is displayed over the period October 31, 2014, to July 31, 2021. We show the series hedged to US dollars. Based on the earlier analyses, we decided not to use the historical returns before the launch date of the green bond index in 2014. The returns of the fixed income assets move together, and the green bond index ends up in the middle in between the other indexes. Exhibit A3 in the appendix contains the full history, comparison between hedging to the US dollar and euro, and the option-adjusted spread at the index level. The ordering of these lines also depends on the currency composition of the index, as hedging currency risks to the US dollar is sensitive to the difference in the short-term interest rate in the US and the Eurozone.[14] Exhibit A4 in the appendix highlights the time-varying correlations between excess returns of green bonds and the other fixed income assets. That exhibit also shows why the data between January 2011 to October 2014 may not be representative of the future.

[14] We only compare green bonds to fixed income asset classes. Reboredo, Ugolini, and Aiube (2020) show that these are the most important asset classes and the relation with high-yield bonds and equities is low. Nguyen et al. (2021) also find low correlation between green bonds and other asset classes.

EXHIBIT 10

Historical Total Returns



NOTES: Total returns hedged to USD. Sample period: October 31, 2014, to July 31, 2021. GREN: Green Bonds, GBMI: Global Agg, W0G1: Global Gvt, G0BC: Global Corp, EMU0: Euro Agg, EG00: Euro Gvt, ER00: Euro Corp.

For credit investors, the excess return relative to duration-matched government bonds may be more important, as it reflects the additional return on top of a safe investment in government bonds. Exhibit 11 shows that the excess returns of the global and euro corporate credit series are virtually the same. While excess returns for government bond indexes should be close to zero, this does not hold for the Eurozone market, where the risk-free government bond curve is taken from Germany instead of a weighted average of the Eurozone government bond index.[15] Hence, this series also contains a default risk component related to the risk of other Eurozone governments. From Exhibit 11, we can also see that the green bond index has less downside risk during the COVID-19 crisis in March 2020 compared to a corporate bond index but that aggregate portfolios that contain a large allocation to liquid government bonds perform slightly better than green bonds during this crisis month.

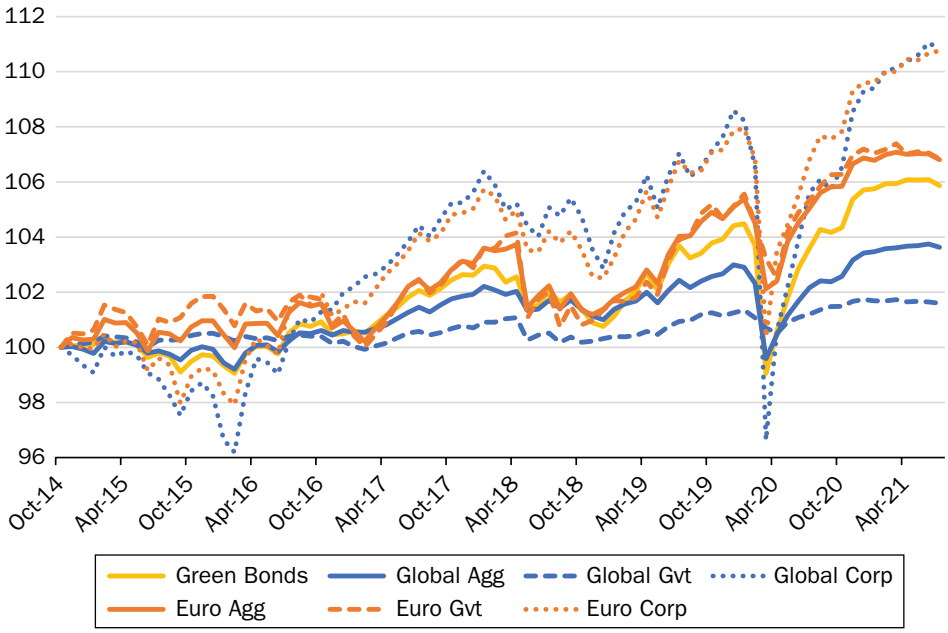
Returns-Based Mimicking Portfolio

In order to determine which part of the existing portfolio needs to be sold so that with the proceeds, the green bond allocation can be purchased, we continue by examining which portfolio has excess returns close to those of the green bond index. Of course, there are several choices to be made for this analysis: which historical period, what are the basic assets, and how do we measure whether the return is close. For the sample period, we take the period starting November 2014 until July 2021 and, for robustness, also the last 36 months, August 2018 to July 2021. For the basic assets, we assume that these are the six assets described above, or only the three Eurozone assets, or only the three global assets. It seems most likely that the

[15] See for documentation page 29 of the data manual ICE (February 7, 2020) *Bond Index Methodologies*.

EXHIBIT 11

Historical Excess Returns



NOTES: Excess returns relative to duration-matched government bonds. Sample period: October 31, 2014, to July 31, 2021. GREN: Green bonds, GBMI: Global Agg, W0G1: Global Gvt, G0BC: Global Corp, EMU0: Euro Agg, EG00: Euro Gvt, ER00: Euro Corp.

investor either has a Eurozone allocation or a global allocation, but we do not exclude that she can choose between all of them. For evaluation, we choose the square of the return difference of the mimicking portfolio and the green bond index, but for robustness, we also consider the mean absolute deviation of returns.[16] Alternatively stated, we solve for the coefficients β_k in the following equation

$$R_t^{green} = \sum_{k=1}^{K} \beta_k \cdot R_t^{index\ k} + \varepsilon_t$$

such that $\sum_{t=1}^{T} \varepsilon_t^2$ (or, alternatively, $\sum_{t=1}^{T} |\varepsilon_t|$) is minimized. We further require that for each k, $\beta_k \geq 0$ and $\sum_{k=1}^{K} \beta_k = 1$, such that the coefficients can be interpreted as portfolio weights in a fully invested portfolio with short-sale constraints; see Sharpe (1992). The return-based optimal mimicking portfolios are displayed in Exhibit 12.

Exhibit 12 shows that the portfolio mimicking the green bond index best over the full sample when the return differences are squared consists of 47% global aggregate, 10% global corporate bonds, 16% Eurozone aggregate, and 27% Eurozone corporate bonds. This results in a portfolio with an average excess return of 1.00% per year and volatility of 2.30%, compared to the 0.87% average excess return for the green bond index, with a volatility of 2.34%. The excess return correlation is 0.98. This result is consistent with Horsch and Richter (2017), who find that the risk-return profile of green bonds is similar to that of regular bonds. The tracking error between the two

[16] Using the squared returns gives also a small penalty to average return differences, as we think that the same tracking error with a closer average return is a better approximation. The mean absolute deviation penalizes differences the same, while with the squared error, large deviations receive more weight.

EXHIBIT 12

Returns-Based Mimicking Portfolios

	Green		Mimicking Portfolios											
Sample	Full	36M		Full			36M			Full			36M	
Criterion	–	–		Square			Squared			Absolute			Absolute	
Global agg	–	–	47	5	–	31	14	–	51	23	–	41	0	–
Global gov	–	–	0	53	–	0	44	–	0	37	–	0	54	–
Global corp	–	–	10	42	–	16	42	–	2	39	–	10	46	–
Euro agg	–	–	16	–	50	31	–	47	16	–	55	14	–	55
Euro gov	–	–	0	–	0	0	–	0	0	–	0	0	–	0
Euro corp	–	–	27	–	50	22	–	53	31	–	45	36	–	45
Average	0.87	1.28	1.00	0.84	1.28	1.45	1.83	1.08	0.95	0.86	1.25	1.42	1.11	1.78
Volatility	2.34	3.27	2.30	2.22	2.56	3.24	3.29	3.20	2.14	2.30	2.49	3.30	3.22	3.10
Tr error	–	–	0.43	0.57	0.67	0.35	0.45	0.51	0.47	0.58	0.69	0.40	0.51	0.51
Correlation	–	–	0.98	0.97	0.97	0.99	0.99	0.99	0.98	0.97	0.96	0.99	0.99	0.99

NOTES: Full sample refers to November 2014, to July 2021. 36M refers to the last 36 months of the sample, August 2018, to July 2021.

return series is 0.43% per annum. All in all, this is a very close match. When we are only allowed to invest in the three global assets, the optimal mimicking portfolio consists of 5% aggregate, 53% government bonds, and 42% corporate credits. When the existing assets are the three Eurozone assets, the optimal mimicking portfolio is 50% government bonds and 50% corporate credits. Each of the other variations, examining the last 36 months or using absolute deviations instead of squared deviations, shows that these results are robust and hardly depend on any of our choices.

All in all, the green bond index resembles an allocation of 50% in government bonds and 50% in corporate credits closely, with a tilt to euro-denominated bonds and, more recently, a tilt to corporate bonds.

Characteristics-Based Mimicking Portfolio

Instead of using *historical returns* of the relevant assets, an investor can also try to approximate the *current characteristics* as well as possible with the available set of assets. The advantage is that changing index compositions or coincidental past return patterns do not influence the portfolio construction. The disadvantage is that by matching characteristics, we might restrict the portfolio on irrelevant dimensions from a future excess return and risk perspective. The investor needs to specify which characteristics she finds important to match closely and which features are less important. We examine the mimicking portfolios based on the four characteristics discussed earlier and consider several variations of tastes. We do this again for the three global assets, three Eurozone assets, and the combination of both. As an evaluation criterion, we take the squared differences of the weight in a characteristic segment and sum these across all segments and characteristics. The resulting characteristics-based mimicking portfolios are displayed in Exhibit 13. We always include maturity and rating as close proxies for the duration and spread that are important to calculate the market risk of credit portfolios; see Ben Dor et al. (2007). In addition, we include the sector or currency dimension, or both.

Exhibit 13 also shows that a Eurozone aggregate portfolio (59% weight) supplemented with a global corporate bond portfolio (35% weight) leads to a good matching of bond characteristics with green bonds. When the sector composition is deemed

EXHIBIT 13

Characteristics-Based Mimicking Portfolios

	All			Global			Eurozone		
Rating	☑	☑	☑	☑	☑	☑	☑	☑	☑
Currency	☑	☐	☐	☑	☐	☐	☑	☐	☐
Sector	☑	☑	☐	☑	☑	☐	☑	☑	☐
Maturity	☑	☑	☑	☑	☑	☑	☑	☑	☑
Global agg	6	0	0	62	58	56	0	0	0
Global gov	0	0	11	0	0	0	0	0	0
Global corp	35	22	0	38	42	44	0	0	0
Euro agg	59	65	0	0	0	0	66	66	35
Euro gov	0	0	63	0	0	0	0	0	44
Euro corp	1	13	26	0	0	0	34	34	21

NOTE: Data from July 31, 2021.

irrelevant, we see that the global and Eurozone government bond portfolios suddenly receive a positive weight. Government bonds did not receive a positive weight before because they do not contribute to the 'Quasi and Foreign Government' segment, and since this also holds for the corporate bonds, the aggregate portfolio is the only one that can help reduce the weight difference in that segment. Contrary to the global portfolio, for the Eurozone-only portfolio, government bonds do not crowd out the aggregate allocation in the final column because it has a very similar rating distribution as the aggregate portfolio, but its maturity profile does not fit well.

These characteristics-based mimicking portfolios give a similar result as the return-based mimicking portfolios. Again, a tilt to the Eurozone and corporate bonds is required to obtain a good fit between the existing assets and the green bond index.

Implications for Fixed Income Portfolio Risk

In a final step of our analysis, we compare the risk and return of conventional fixed income portfolios with portfolios that include an allocation to the green bond index. We replace 20% of the conventional portfolio, which is a large enough allocation to see an effect but not too large for an investor that requires broad diversification across issuers. Exhibit 14 contains the volatility of the credit return (i.e., the return of the bond in excess of the duration-matched risk-free rate) on the horizontal axis and the average credit return on the vertical axis, while Exhibit 15 shows the volatility (i.e., tracking error) and average excess return of the allocation with 20% green bonds relative to a conventional fixed income allocation. The sample period ranges from November 2014 to July 2021, but the results over the last three years of our sample are similar.[17] The green bond index is a green diamond in Exhibit 14. The conventional indexes are orange circles, while the allocations where 20% is replaced with green bonds are blue triangles.

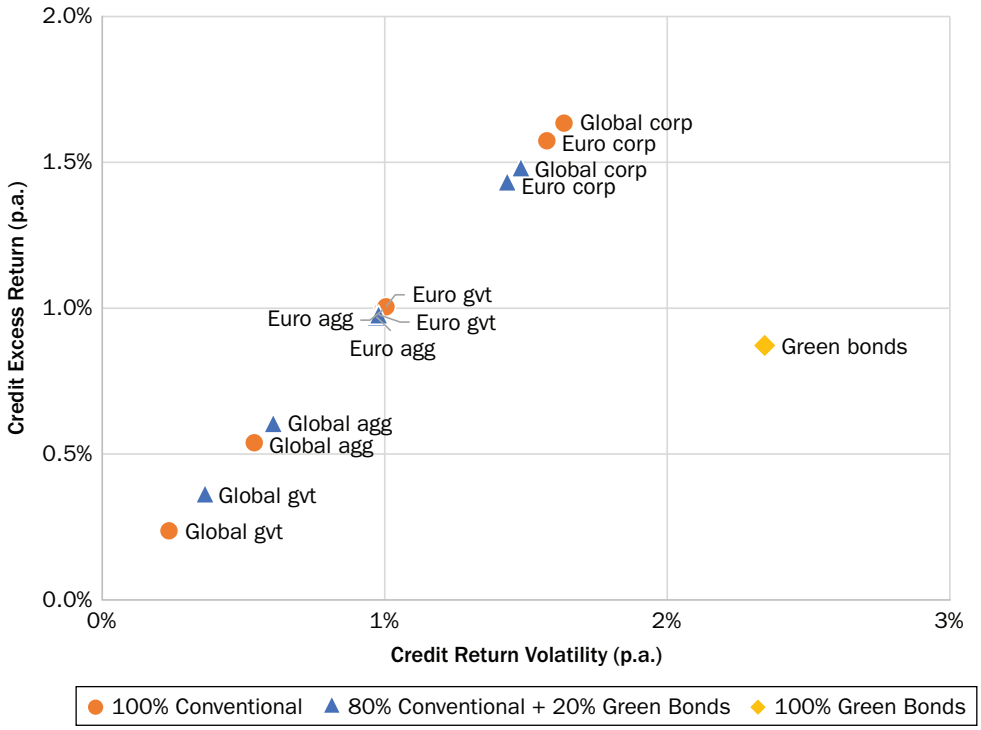
During this period, corporate bond excess returns were relatively high with 1.6% per annum for both the global and Eurozone index.[18] The global government bond index had a low excess return, as only a small part of those returns is due to credit spreads relative to risk-free government bonds. Excess returns for Eurozone government bonds

[17] See Appendix Exhibits A5 and A6 that correspond to Exhibits 14 and 15 in the main text.

[18] This is relatively high compared to investment grade credit premium estimates of 0.42% per annum by Ng and Phelps (2011) over the period 1990–2009 and the 0.80% per annum by Giesecke et al. (2011) over the period 1866–2008.

EXHIBIT 14

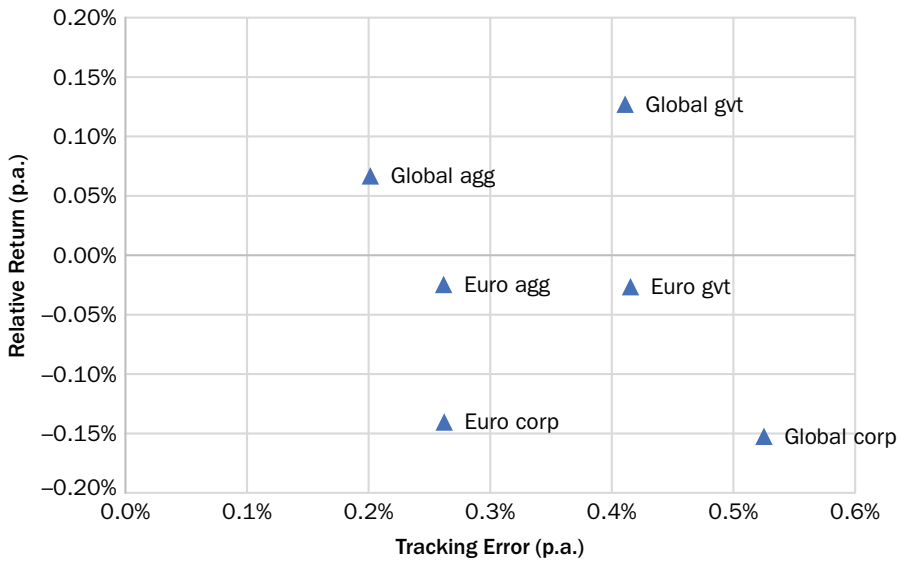
Impact on Credit Risk-Return Profile of Adding 20% Green Bonds



NOTES: Excess returns relative to government bonds. Orange circles are conventional allocations; blue triangles have 20% replaced with the green bond index (green diamond). Sample period: November 2014, to July 2021.

EXHIBIT 15

Impact on the Tracking Error of Adding 20% Green Bonds



NOTES: Excess returns relative to conventional fixed income allocation. Blue triangles have 20% of the portfolio replaced with the green bond index. Sample period: November 2014, to July 2021.

are higher because of the positive credit spread of many Eurozone governments relative to the German interest rate. We need to be careful interpreting the level of excess returns, as they are estimated over a short sample period, and there tends to be a substantial variation of realized credit returns over such short periods. The goal of this analysis is to compare differences in realized returns over this period and not to extrapolate these realizations as predictions for future returns.

Exhibit 14 confirms what we have seen in the previous two subsections: The impact on the credit-risk return profile is lowest for the aggregate fixed income portfolios, and even smaller for Euro aggregate than for global aggregate, as can be seen by comparing the distance between the orange circles and blue triangles. The larger distance between the orange circles and blue triangles for the credit-only or government bond-only allocations shows that these assets are not well suited to finance a green bond allocation for investors who prefer no change to the risk-return profile of their investments. Note that the orange circles and blue triangles are very close for Eurozone government bonds because of the earlier-mentioned credit return of Eurozone governments versus Germany. However, Exhibit 14 shows only the average credit return and volatility but does not consider the correlation between the series. A high correlation between the return series will end up in less relative risk on a month-by-month basis. Exhibit 15 displays the average and volatility (i.e., tracking error) of the return differences between the orange circles and blue triangles, representing current and greener fixed income allocation.

Exhibit 15 shows clearly that the tracking error is low for the global and Eurozone aggregate portfolios, with 0.20% and 0.26% per annum, respectively. The tracking error with the Euro corporate index is also low, with only 0.26%. However, adding green bonds to the corporate bond index comes at a 0.14% per year lower average return over this period, whereas the difference in returns with the Eurozone aggregate portfolio is only 0.02%. The tracking errors with the other three indexes are about twice as high. This may be most surprising for the tracking error relative to the Eurozone government bond index, which in Exhibit 14 had a similar credit return volatility. The credit returns of both portfolios are equally volatile, but they are only 0.58 correlated. For Eurozone corporate bonds, the correlation is much higher with 0.98.

Asset Pricing Tests

We can also statistically test whether green bonds expand the mean-variance frontier for a fixed income investor. De Roon and Nijman (2001) explain how a t-test on the intercept of a spanning regression achieves this. Similarly to Fama and French (1993), we use the US term factor and the US default factor as the two relevant pricing factors. We proxy the term factor by the return on the Bloomberg Barclays US Treasury Index minus the Bloomberg Barclays US 1–3 Month Treasury Bill Index and proxy the credit factor by the excess return of the Bloomberg Barclays US Corporate Investment Grade Index relative to duration-matched US Treasuries. Since these asset pricing factors are in US dollars, we use the US dollar hedged return series of our green bond index as the asset that needs to be priced. The mean-variance spanning regression is:

$$R_t^{green} - R_{f,t} = \alpha + \beta_{term} R_t^{term} + \beta_{def} R_t^{def} + \varepsilon_t$$

If the intercept α is statistically significantly larger than zero, the green bond market has an additional return relative to the two asset pricing factors, and optimal mean-variance portfolio weights to green bonds would be statistically significantly positive. In contrast, a negative intercept would imply a 'greenium,' that is, that returns of green bonds are statistically significantly lower than those on conventional bonds.

Exhibit 16 contains the results of the mean-variance spanning test. In addition to the term and default factor, we also added an inflation factor and an equity factor.

EXHIBIT 16

Mean-Variance Spanning Tests

	Coeff	*t*-Stat	Coeff	*t*-Stat	Coeff	*t*-Stat	Coeff	*t*-Stat	Coeff	*t*-Stat
Alpha	2.24	1.86	2.67	2.20	0.76	1.08	0.72	1.02	1.04	1.42
Term	0.44	4.90	–	–	0.75	13.21	0.70	6.84	0.65	6.10
Default	–	–	0.29	4.43	0.52	12.80	0.49	8.51	0.54	8.31
Inflation	–	–	–	–	–	–	0.06	0.59	0.10	1.00
Equities	–	–	–	–	–	–	–	–	–0.03	–1.46
R^2 (adj)	0.22	–	0.19	–	0.75	–	0.74	–	0.75	–

NOTES: Data: November 2014 to July 2021, monthly frequency. The dependent variable is the US-dollar-hedged return on green bond market (ICE BofA Green Bond Index minus Bloomberg Barclays US 1–3 Month Treasury Bill Index). Alpha is the intercept in the regression, annualized in percentages. Included are the return factors 'term' (Bloomberg Barclays US Treasury Index minus the Bloomberg Barclays US 1–3 Month Treasury Bill Index), 'default' (excess return of the Bloomberg Barclays US Corporate Investment Grade Index relative to duration-matched US Treasuries, 'inflation' (Bloomberg Barclays US Treasury Inflation-Protected Securities Index minus the Bloomberg Barclays US 1–3 Month Treasury Bill Index), and equities (Fama-French US equity market excess return).

The former is the Bloomberg Barclays US Treasury Inflation-Protected Securities Index minus the Bloomberg Barclays US 1–3 Month Treasury Bill Index, and the latter is the US equity market excess return factor from Kenneth French's online data library.

The first two columns of Exhibit 16 show the separate effect from the term and default factors. Clearly, both these models are incomplete. While the beta coefficients are significant with t-statistics 4.90 and 4.43, respectively, the explanatory power as measured by the adjusted R-squared is only 0.22 and 0.19, respectively. The alphas are economically sizeable with 2.24% and 2.67% per year and statistically significant at the 10% level as t-statistics are above 1.65. The main reason is that the term and default premium are negatively correlated, with a correlation of –0.43 over this sample period. A model with both pricing factors gives higher betas that have substantially higher t-statistics, and the adjusted R-squared increases to 0.75. The alpha is still positive with 0.76% per year but no longer statistically significant. Adding the two additional factors does not improve the explanatory power of the model, and both regression coefficients are close to zero and not statistically significant. We conclude that during our sample period, exposures to term and default risks have been the main determinants of the returns on the green bond market.

CONCLUSION

This article shows that the green bond market has grown spectacularly over the past decade. This rapid development has also meant that the composition of the green bond market has changed considerably since the end of 2010, which limits the use of historical return data for portfolio analysis. We prefer to leave the first five years of the available sample out of a historical analysis that is designed to be representative of the future.

We examine which fixed income assets investors should sell in order to have the least impact on the risk-return of their existing portfolio. Our results robustly indicate that investors should see the current green bond market as a combination of a global aggregate portfolio with additional tilts to Eurozone assets and corporate bonds. By replacing these existing assets, the risk-return profile is likely to be largely similar, while the sustainability of the fixed income portfolio substantially increases by contributing to the energy transition that is required to adhere to the Paris Agreement. In case bond issuers that are lagging in the energy transition will experience higher default rates going forward, the risk-return relation of an asset allocation including green bonds may even improve.

APPENDIX A

EXHIBIT A1

Green Bond Index Comparison—Number of Bonds and Market Value

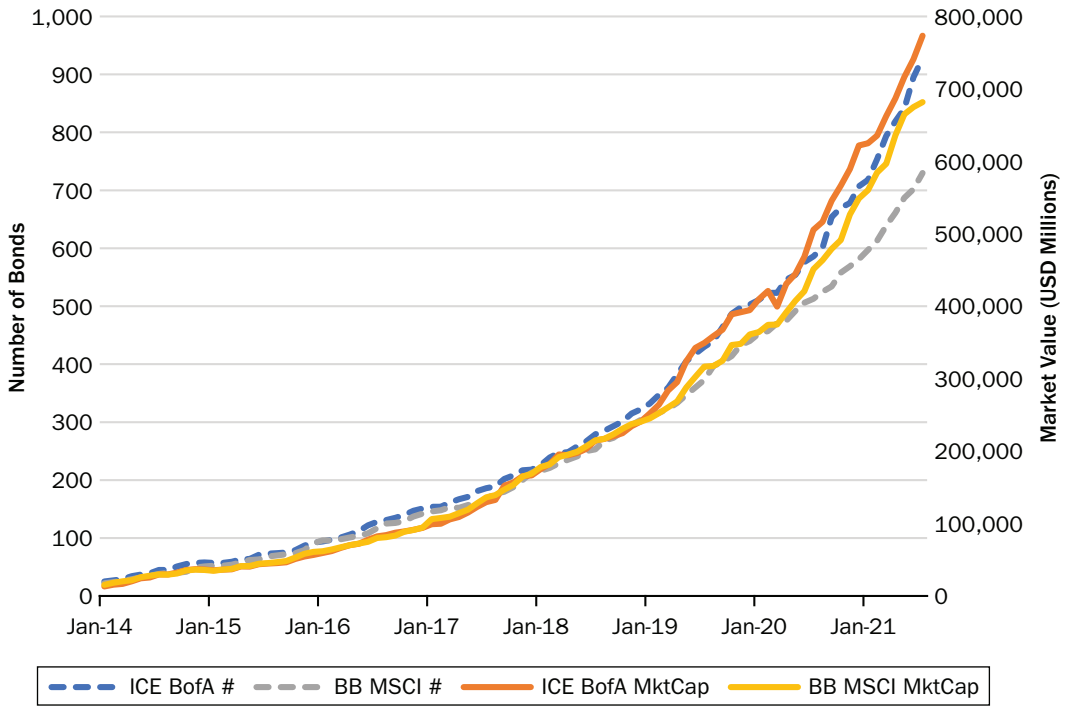


EXHIBIT A2

Green Bond Index Comparison—Total Return Index (USD Hedged)

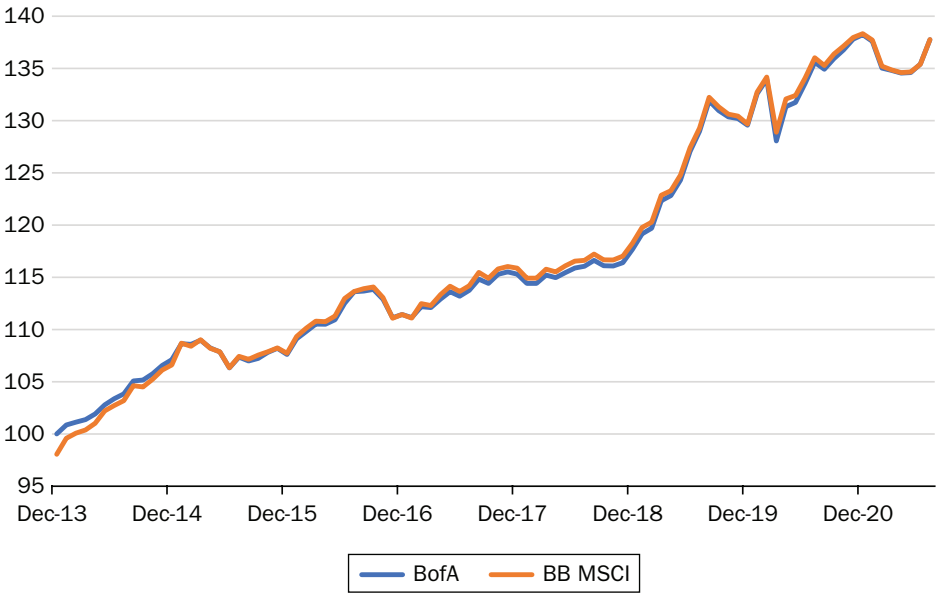


EXHIBIT A3

Green Bond Index from December 2010

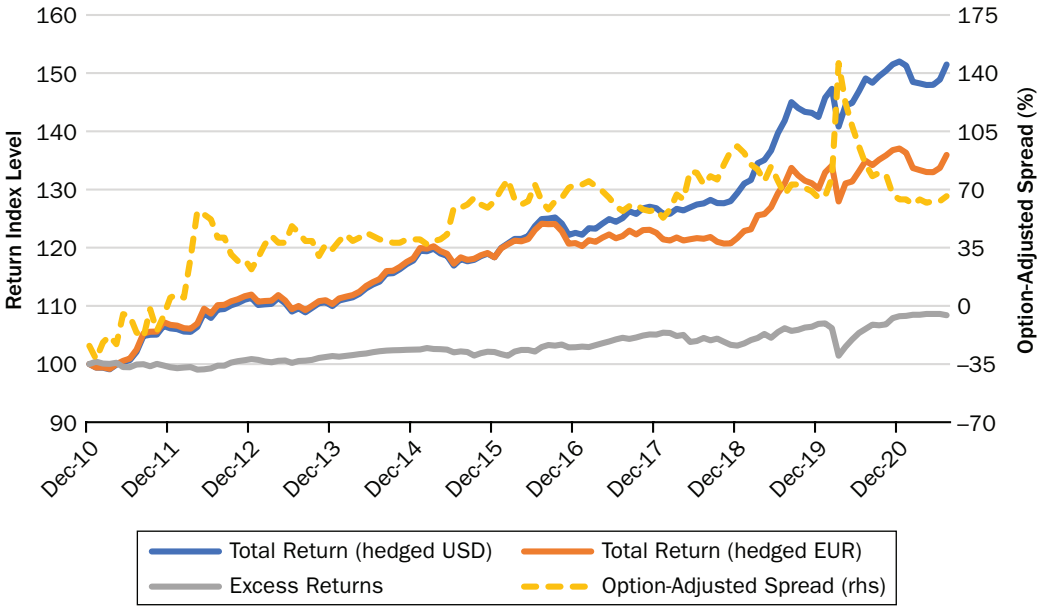
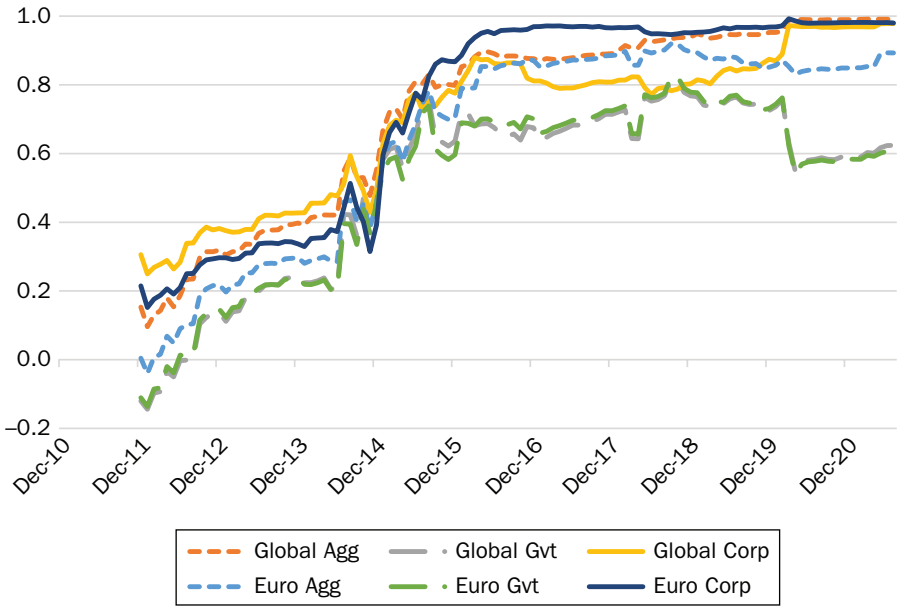


EXHIBIT A4

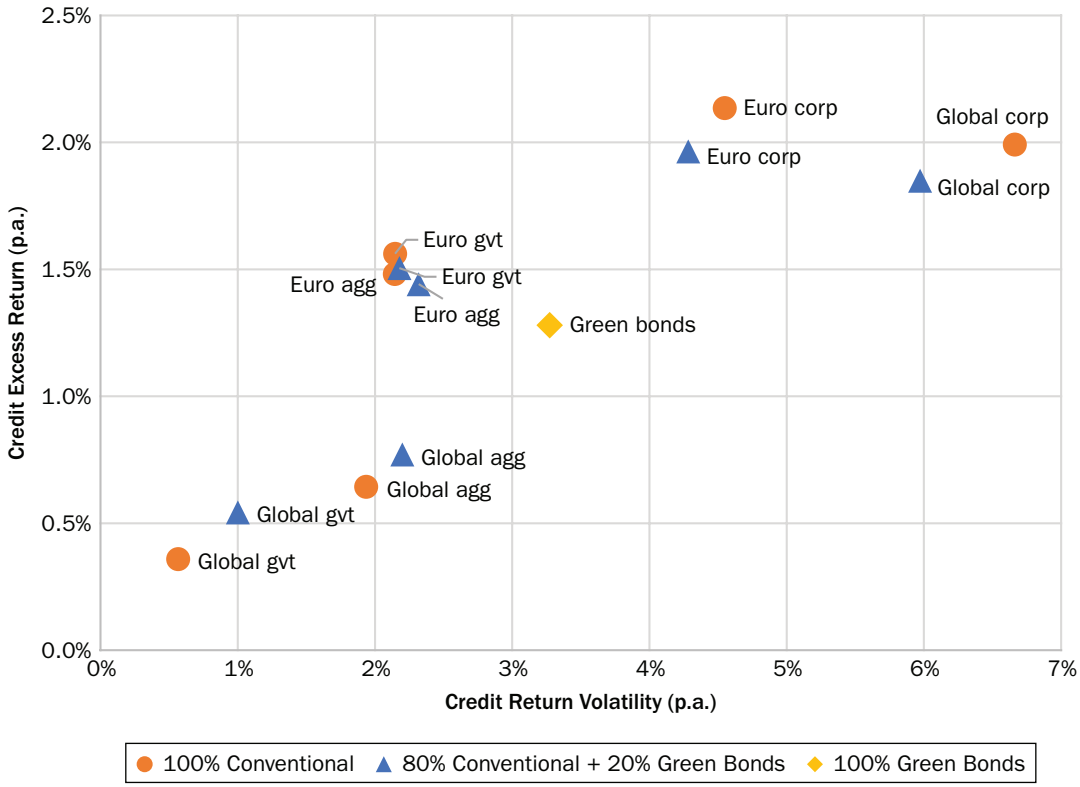
Rolling Correlation of Green Bonds with Other Fixed Income Assets



NOTES: First observation uses the first 12 monthly observations, then expanding window to 36 monthly observations. Thereafter a 36-month rolling window.

EXHIBIT A5

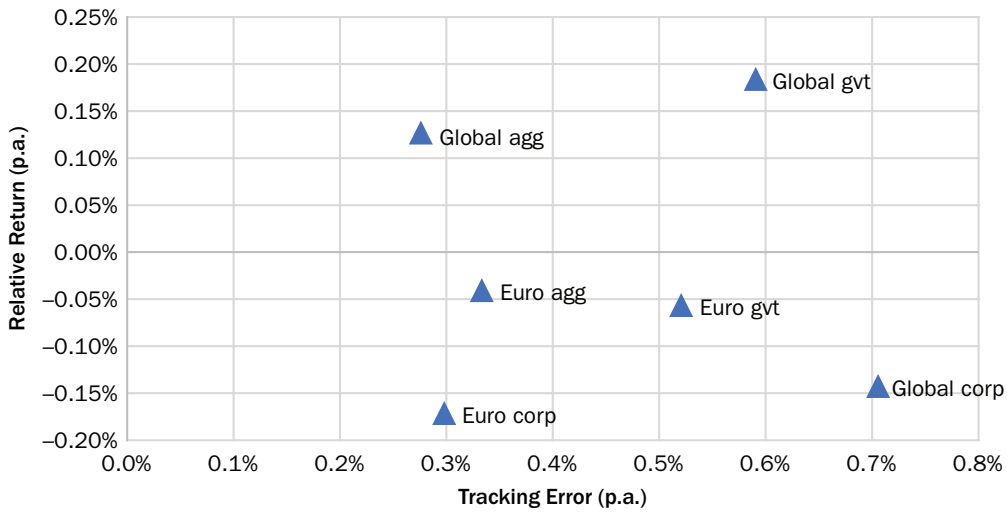
Impact on Credit Risk-Return Profile of Adding 20% Green Bonds: Last 3 Years



NOTES: Excess returns relative to government bonds. Orange circles are conventional allocations; blue triangles have 20% replaced with the green bond index (green diamond). Sample period: August 2018, to July 2021.

EXHIBIT A6

Impact on the Tracking Error of Adding 20% Green Bonds: Last 3 Years



NOTES: Excess returns relative to conventional fixed income allocation. Blue triangles have 20% of the portfolio replaced with the green bond index. Sample period: August 2018, to July 2021.

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REFERENCES

Bachelet, M., L. Becchetti, and S. Manfredonia. 2019. "The Green Bonds Premium Puzzle: The Role of Issuer Characteristics and Third-Party Verification." *Sustainability* 11 (4): 1098.

Baker, M., D. Bergstresser, G. Serafeim, and J. Wurgler. 2018. "Financing the Response to Climate Change: The Pricing and Ownership of US Green Bonds." *NBER Working Paper* 25194.

Banga, J. 2019. "The Green Bond Market: A Potential Source of Climate Finance for Developing Countries." *Journal of Sustainable Finance and Investment* 9 (1): 17–32.

Ben Dor, A., L. Dynkin, J. Hyman, P. Houweling, E. Van Leeuwen, and O. Penninga. 2007. "DTS (Duration Times Spread)." *The Journal of Portfolio Management* 33 (2): 77–100.

Bolton, P., and M. Kacperczyk. 2021. "Do Investors Care About Carbon Risk?" *Journal of Financial Economics* 142 (2): 517–549.

Bongaerts, D., and D. Schoenmaker. 2020. "Green Certificates: A Better Version of Green Bonds." *Bruegel Policy Contribution* 20.

Cao, X., C. Jin, and W. Ma. 2021. "Motivation of Chinese Commercial Banks to Issue Green Bonds: Financing Costs or Regulatory Arbitrage?" *China Economic Review* 66: 101582.

Choi, D., Z. Gao, and W. Jiang. 2020. "Measuring the Carbon Exposure of Institutional Investors." *The Journal of Alternative Investments* 22 (4): 1–12.

Deng, Z., D. Tang, and Y. Zhang. 2020. "Is 'Greenness' Priced in the Market? Evidence from Green Bond Issuance in China." *The Journal of Alternative Investments* 23 (1): 57–70.

De Roon, F., and T. Nijman. 2001. "Testing for Mean-Variance Spanning: A Survey." *Journal of Empirical Finance* 8 (2): 111–155.

Deschryver, P., and F. de Mariz. 2020. "What Future for the Green Bond Market? How Can Policymakers, Companies, and Investors Unlock the Potential of the Green Bond Market?" *Journal of Risk and Financial Management* 13 (3): 61.

Ehlers, T., B. Mojon, and F. Packer. 2020. "Green Bonds and Carbon Emissions: Exploring the Case for a Rating System at the Firm Level." *BIS Quarterly Review*: 31–47.

Fama, E., and K. French. 1993. "Common Risk Factors in the Returns on Stocks and Bonds." *Journal of Financial Economics* 33 (1): 3–56.

Fatica, S., and R. Panzica. 2021. "Green Bonds as a Tool Against Climate Change?" *Business Strategy and the Environment* 30 (5): 2688–2701.

Fatica, S., R. Panzica, and M. Rancan. 2021. "The Pricing of Green Bonds: Are Financial Institutions Special?" *Journal of Financial Stability* 54: 100873.

Febi, W., D. Schäfer, A. Stephan, and C. Sun. 2018. "The Impact of Liquidity Risk on the Yield Spread of Green Bonds." *Finance Research Letters* 27: 53–59.

Flammer, C. 2021. "Corporate Green Bonds." *Journal of Financial Economics* 142 (2): 499–516.

Gianfrate, G., and M. Peri. 2019. "The Green Advantage: Exploring the Convenience of Issuing Green Bonds." *Journal of Cleaner Production* 219: 127–135.

Giesecke, K., F. Longstaff, S. Schaefer, and I. Strebulaev. 2011. "Corporate Bond Default Risk: A 150-Year Perspective." *Journal of Financial Economics* 102 (2): 233–250.

Glomsrød, S., and T. Wei. 2018. "Business as Unusual: The Implications of Fossil Divestment and Green Bonds for Financial Flows, Economic Growth and Energy Market." *Energy for Sustainable Development* 44: 1–10.

González, C., and S. Núñez. 2021. "Markets, Financial Institutions and Central Banks in the Face of Climate Change: Challenges and Opportunities." *Banco de España Occasional Paper* 2126.

Gyura, G. 2020. "Green Bonds and Green Bond Funds: The Quest for the Real Impact." *The Journal of Alternative Investments* 23 (1): 71–79.

Hachenberg, B., and D. Schiereck. 2018. "Are Green Bonds Priced Differently from Conventional Bonds?" *Journal of Asset Management* 19: 371–383.

Horsch, A., and S. Richter. 2017. "Climate Change Driving Financial Innovation: The Case of Green Bonds." *The Journal of Structured Finance* 23 (1): 79–90.

Immel, M., B. Hachenberg, F. Kiesel, and D. Schiereck. 2021. "Green Bonds: Shades of Green and Brown." *Journal of Asset Management* 22 (2): 96–109.

Inderst, G., C. Kaminker, and F. Stewart. 2012. "Defining and Measuring Green Investments: Implications for Institutional Investors Asset Allocations." *OECD Working Papers on Finance, Insurance and Private Pensions*.

Kaminker, C. 2015. "Green Bonds: Mobilizing the Debt Capital Markets for a Low-Carbon Transition." *OECD Policy Perspectives*.

Kaminker, C., and F. Stewart. 2012. "The Role of Institutional Investors in Financing Clean Energy." *OECD Working Papers on Finance, Insurance and Private Pensions*.

Krueger, P., Z. Sautner, and L. Starks. 2020. "The Importance of Climate Risks for Institutional Investors." *The Review of Financial Studies* 33 (3): 1067–1111.

Larcker, D., and E. Watts. 2020. "Where's the Greenium?" *Journal of Accounting and Economics* 69 (2–3): 101312.

Lebelle, M., S. Lajili Jarjir, and S. Sassi. 2020. "Corporate Green Bond Issuances: An International Evidence." *The Journal of Risk and Financial Management* 13 (2): 1–21.

——. 2021. "The Effect of Issuance Documentation Disclosure and Readability on Liquidity: Evidence from Green Bonds." *Global Finance Journal* 51 (2).

Liaw, K. 2020. "Survey of Green Bond Pricing and Investment Performance." *The Journal of Risk and Financial Management* 13 (9): 193.

Maltais, A., and B. Nykvist. 2020. "Understanding the Role of Green Bonds in Advancing Sustainability." *Journal of Sustainable Finance and Investment* 11 (3).

Nanayakkara, M., and S. Colombage. 2019. "Do Investors in Green Bond Market Pay a Premium? Global Evidence." *Applied Economics* 51: 1–13.

Ng, K., and B. Phelps. 2011. "Capturing Credit Spread Premium." *Financial Analysts Journal* 67 (3): 63–75.

Nguyen, T., M. Naeem, F. Balli, H. Balli, and X. Vo. 2021. "Time-Frequency Co-Movement among Green Bonds, Stocks, Commodities, Clean Energy, and Conventional Bonds." *Finance Research Letters* 40: 101739.

Otek Ntsama, U., C. Yan, A. Nasiri, and A. Mbouombouo Mboungam. 2021. "Green Bonds Issuance: Insights in Low- and Middle-Income Countries." *International Journal of Corporate Social Responsibility* 6: 2.

Partridge, C., and F. Medda. 2020. "The Evolution of Pricing Performance of Green Municipal Bonds." *Journal of Sustainable Finance and Investments* 10 (1): 44–64.

Reboredo, J., A. Ugolini, and F. Aiube. 2020. "Network Connectedness of Green Bonds and Asset Classes." *Energy Economics* 86: 104629.

Sangiorgi, I., and L. Schopohl. 2021. "Why Do Institutional Investors Buy Green Bonds: Evidence from a Survey of European Asset Managers." *International Review of Financial Analysis* 75: 101738.

Sharpe, W. 1992. "Asset Allocation: Management Style and Performance Evaluation." *The Journal of Portfolio Management* 18 (2): 7–19.

Sidak, J. 2019. "Transition Bonds for Stranded Costs." *Criterion Journal on Innovation* 4: 601–623.

Tang, D., and Y. Zhang. 2018. "Do Shareholders Benefit from Green Bonds?" *Journal of Corporate Finance* 61: 101427.

Tolliver, C., A. Keely, and S. Managi. 2020. "Policy Targets behind Green Bonds for Renewable Energy: Do Climate Commitments Matter?" *Technological Forecasting and Social Change* 157: 120051.

Torvanger, A., A. Maltais, and I. Marginean. 2021. "Green Bonds in Sweden and Norway: What Are the Success Factors?" *Journal of Cleaner Production* 324: 129177.

Wang, J., X. Chen, X. Li, J. Yu, and R. Zhong. 2020. "The Market Reaction to Green Bond Issuance: Evidence from China." *Pacific-Basin Finance Journal* 60: 101294.

Zerbib, O. 2019. "The Effect of Pro-Environmental Preferences on Bond Prices: Evidence from Green Bonds." *Journal of Banking and Finance* 98: 39–60.

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