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Allocating to Green Bonds

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[Replaced Exhibit 14 with the correct version in June 2023]

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¹ Corresponding author. The views in this paper are not necessarily shared by Robeco. I would like to thank Gino Beteta Vejarano, Michiel de Bruin, Martin Martens, Lukasz Pomorski, Rikkert Scholten, and Thomas Walther for valuable discussions.

Allocating to Green Bonds

Abstract

Green bonds are about a decade old financial instrument with cash flows earmarked to improve the environment or combat climate change. We show the spectacular growth of the asset class over time, but note 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 were mainly very safe supranational institutions issuing in a variety of currencies with relatively short maturities. They were followed by corporates, especially utilities, and more recently also governments have started issuing green bonds. These sharp composition changes make historical data from before 2015 less representative for the future. Our returns- and characteristics-based analyses show that an investor 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.

Keywords: Asset allocation; Bonds; Climate change; Environmental, Social, and Governance (ESG); Fixed income; Green bonds; Portfolio management; Socially Responsible Investing (SRI); Sustainable investing.

JEL Classification: G11; G12; G14

1. Introduction

Risks stemming from climate change are on top of mind of policy makers. At the same time, institutional investors around the world are evaluating their investment policies with regard to 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 an underweight of about the same magnitude over the period 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.

A relatively new financial instrument that may facilitate the energy transition are green bonds, sometimes also referred to as climate bonds.² These instruments can be issued by governments, supranational and government-related institutions, or corporate entities. The issuance of green bonds are typically tied to specific green projects designed to avoiding or reduce climate change, such as renewable energy projects that facilitate the energy transition away from fossil fuels.³ 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

² A somewhat different financial instrument, a transition bond, was introduced in the United States, 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.

³ 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'.

to facilitate the energy transition.⁴ 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 investment 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 so far been mostly interested with 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

⁴ Ehlers, Mojon, and Packer (2020) suggest to rate 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.

also challenging because of two aspects. First, the green bond market has different characteristics from a typical fixed income benchmark, as it has different credit rating, currency, sector, and maturity composition. Second, since the market has seen a rapid development over the past years, historical data may not be representative for future risk and return characteristics. In this paper, we address these two issues in detail.

Our empirical analysis shows that the green bond market is predominantly a market with bond issues denominated in euro and with 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 using the entire available return history back to 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.

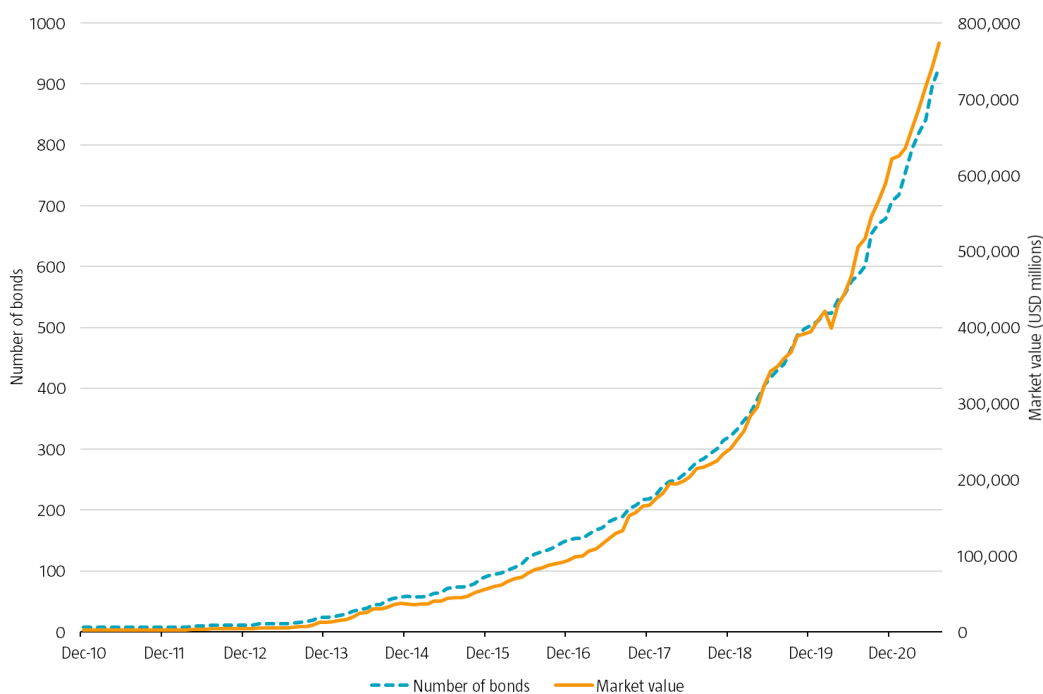
While investors could expand existing government bond mandates to now also include green government and government-related bonds and expand existing corporate bond mandates to also include green corporate bonds, they can also decide to allocate to a separate green bond strategy by a specialized manager. The advantage of the latter 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 risk-return profile of the portfolio will be least affected, while the sustainability of their portfolio is improved by contributing to the energy transition.

Section 2 shows the historical size and composition of the green bond market. In Section 3, we compare the current composition with that of conventional fixed income assets. In Section 4, we analyze which conventional fixed income assets resemble best 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. Finally, Section 5 concludes.

2. Are historical data on green bonds representative for the future?

In order to examine whether historical returns data is 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.⁵ We accessed this data base through the ICE Data Services platform, where this index has the code GREN. The launch of this index was 30 October 2014 and it was at that time calculated back in time until 31 December 2010. We first examine the development of the size of the market, followed by its composition on the dimensions credit rating, currency, sectors, and remaining maturity.

Exhibit 1: Size of the green bond market



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

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

⁵ The appendix contains Exhibit 1 (Exhibit A1) and Exhibit 10 (Exhibit A2) also for the Bloomberg Barclays MSCI Green Bond Index. Differences are small.

the starting date of the index in 2010 the number of included bonds is only 7 and its total market value was only USD 1.9 billion. In the beginning, the market was lacking a standard, which was both inconvenient for issuers and investors. However, with the creation of the Green Bond Principles in January 2014, the market started taking off.⁶ The number of green bonds increased considerably after the launch of the index in October 2014, but the increase is accelerating 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 expected to continue to grow fast, the global investment grade fixed income market is USD 65,513 billion in size at the end of 2020.⁷ Hence, green bonds are currently still below 1% of the global fixed income market.

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

Exhibit 2 shows that at the launch date of the index in 2014, a little over half of the market value of the index was AAA-rated, and slightly less than 10% had a BBB-rating. After the launch, 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 represents about a quarter. This credit quality difference over this decade-long sample period is something to keep in mind for 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.⁸ At the end of the

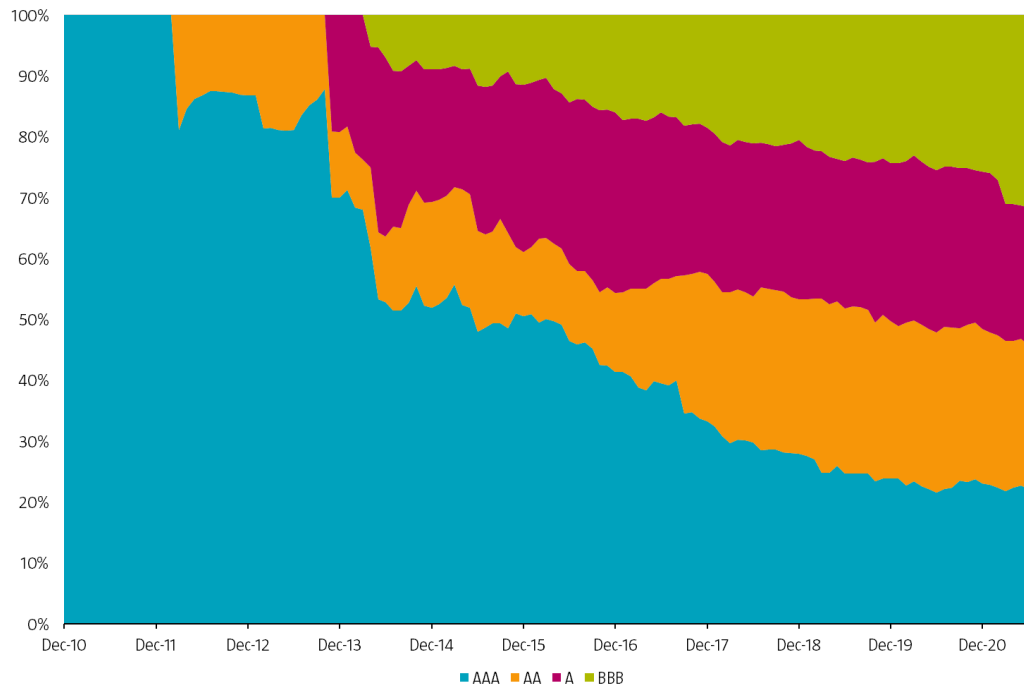
⁶ See <https://www.ceres.org/resources/reports/green-bond-principles-2014>

⁷ Source: ICE BofA Global Broad Market Index (GBMI).

⁸ 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

sample, idiosyncratic credit risk is much smaller, but the systematic credit risk has increased by lower ratings entering the index.

Exhibit 2: Credit rating composition of the green bond market



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

2.2 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 currencies that are relatively small in the global fixed income markets: the Australian dollar, Brazilian real, South African rand, and Swedish krona.

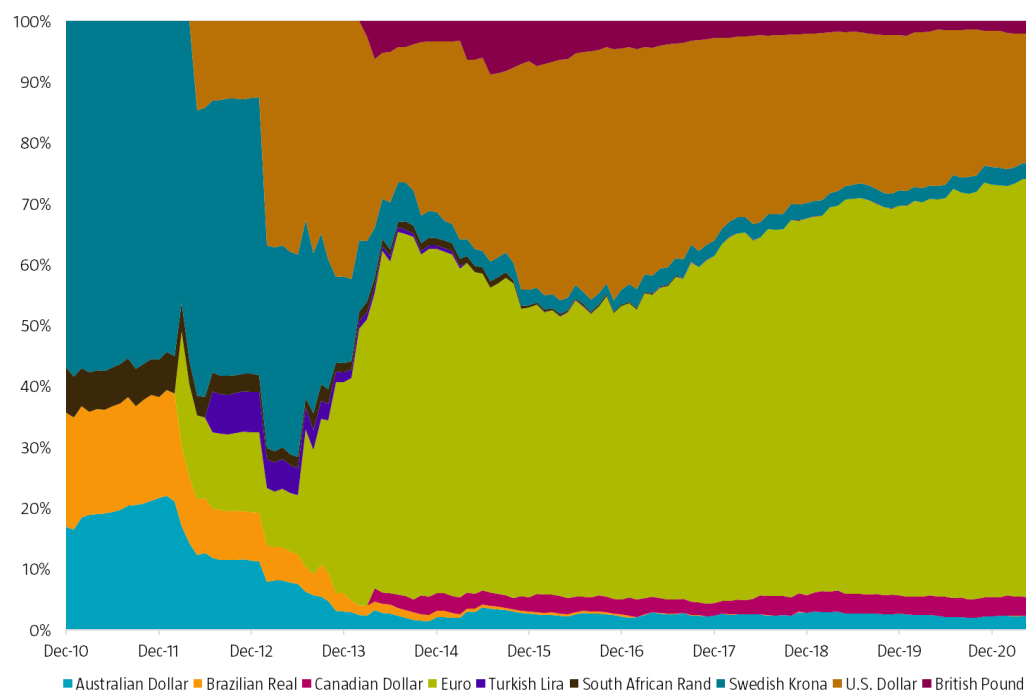
At the index launch date, a little more than half of the market value were bonds denominated in European euro and a quarter by the US dollar. Smaller shares of the index are in the Canadian dollar, Turkish lira, and British pound.⁹ Perhaps because Eurozone

Treasuries. In the first 7 months of 2021, the option-adjusted credit spread moved in the range of 61 to 66 basis points.

⁹ Other currencies that are or were in the index, but for such 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,

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 2020.¹⁰ The currency composition of the first years of the index' is very different from that at the end, and therefore one can question whether using the full index history of returns is representative for the future.

Exhibit 3: Currency composition of the green bond market



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

2.3 Sector composition

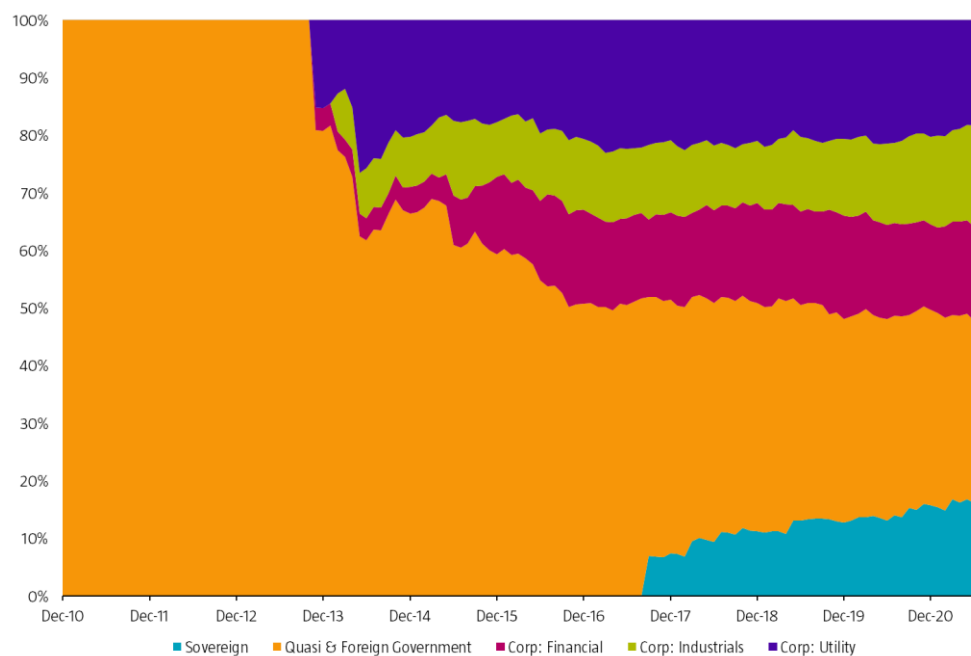
We already mentioned that the first index eligible green bonds were issued by supranational institutions, which are categorized in the 'Quasi and Foreign Government' sector definition. Exhibit 4 shows the sector composition of the green bond index over time. When the index was launched in 2014, there had been issuance by the corporate

Japanese yen, Mexican peso, New Zealand dollar, Norwegian krone, Polish zloty, Singapore dollar, Swiss franc, and the Chinese offshore renminbi.

¹⁰ There are entities from countries that have successfully issued green bonds outside their native currency, and including from these countries: Czech Republic, Iceland, India, Lithuania, Panama, Peru, Philippines, Romania, Russia, South Korea, Taiwan, British Virgin Islands, and United Arab Emirates.

sector as well. Within the corporate bond sector, it is the ‘Utilities’ sector that 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 environmental performance of these companies improves after issuance of the green bond.¹¹

Exhibit 4: Sector composition of the green bond market



ICE BofA Green Bond Index. Index code: GREN. Sample period: 31 December 2010 to 31 July 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 indeed is used for the energy transition. In September 2017 the first government bond, issued by the French treasury, also entered

¹¹ 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 stock market react 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 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.

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, but in addition to supranational 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).¹²

2.4 Maturity composition

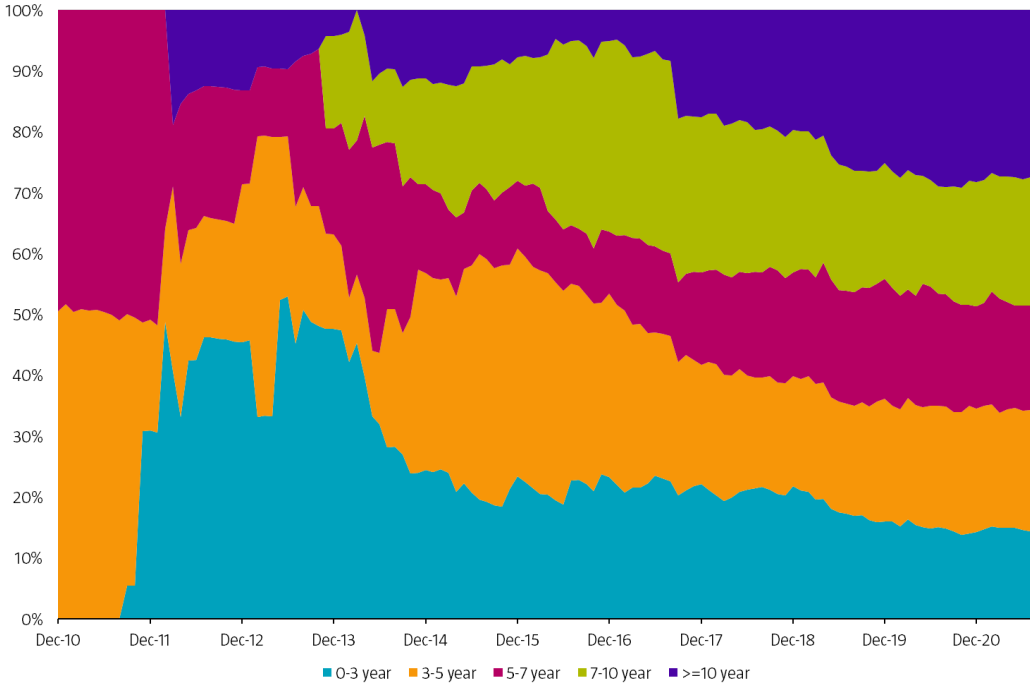
Part of the risk for an investor is reflected in the credit rating, but another dimension of risk is the maturity of the bond. Since investors have to wait longer to receive the payments of longer-dated bonds, it reduces their liquidity position and uncertainty about future credit worthiness or inflation rates can be considered additional risks on the long run. In addition, short-term changes in bond prices are the largest for bonds with longest maturities, all other things equal.¹³ Exhibit 5 shows the maturity 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 3 years, we also see 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 has been issued by the French local authority Soci t  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.

¹² Baker et al. (2018) examine in more detail green bonds issued by US municipal bonds.

¹³ 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 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 Lebellet, Lajili Jarjir, and Sassi (2021).

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 on 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 to better understand future risk and return of green bonds.

Exhibit 5: Maturity composition of the green bond market



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

3. Comparison with traditional fixed income instruments

Many institutional investors have stated ambitious climate policies for their investment portfolios. More than 500 of these investors who are 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 a 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 green bond affect the risk and return characteristics of the existing fixed income portfolio? In order 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 at 31 July 2021. Due to lack of data, we can neither examine how liquidity of green bonds has changed over time, nor can we 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.

For the existing fixed income allocations, we assume that these are either on an aggregate basis, i.e. including all fixed income securities ranging from government bonds, quasi government bonds, corporate bonds, and securitized bonds. Since investing in green bonds seems to be dominated by institutional investors from the Eurozone¹⁴, we also consider euro-only versions of these allocations (market cap at 31 July 2021):

- Aggregate fixed income

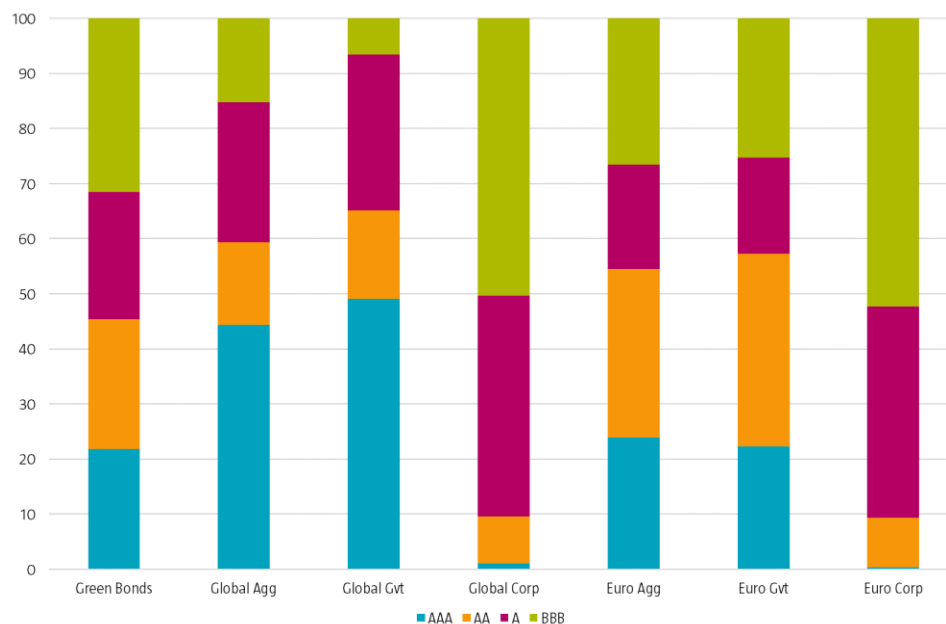
ICE BofA Global Broad Market Index	GBMI	USD 66.9 trillion
ICE BofA Euro Broad Market Index	EMU0	USD 16.3 trillion
- Government bonds

ICE BofA Global Government Index	W0G1	USD 36.0 trillion
ICE BofA Euro Government Index	EG00	USD 9.2 trillion
- Corporate bonds

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

¹⁴ 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

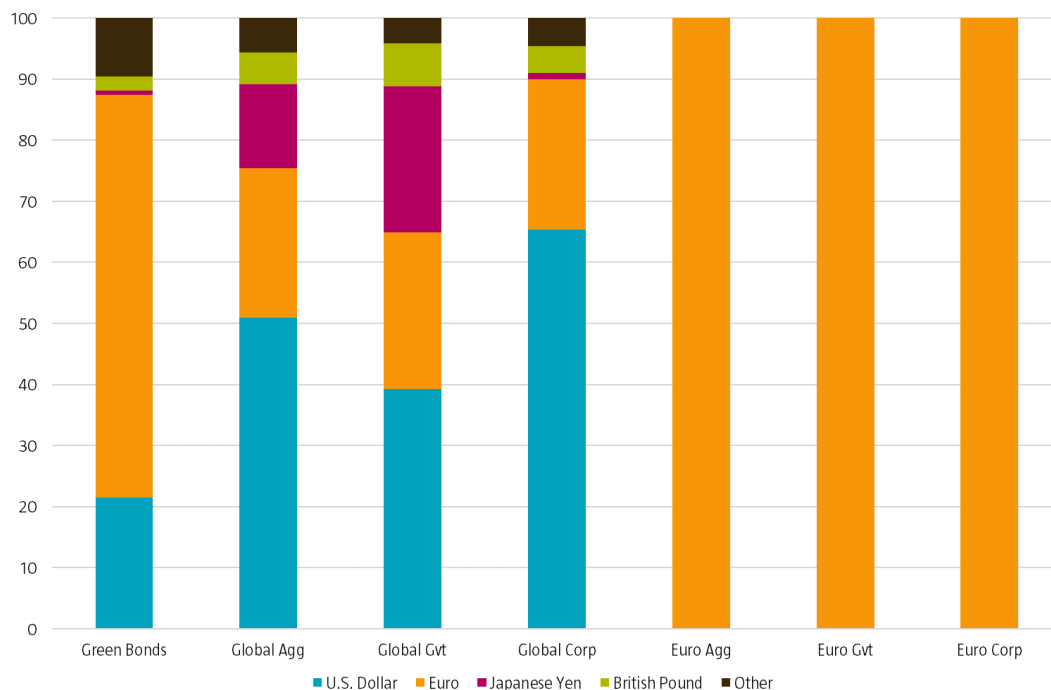


Date: 31 July 2021. Index codes: GREN, GBMI, W0G1, G0BC, EMU0, EG00, ER00.

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 as large 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 more risky 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 take 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 7: Currency composition of selected fixed income indexes

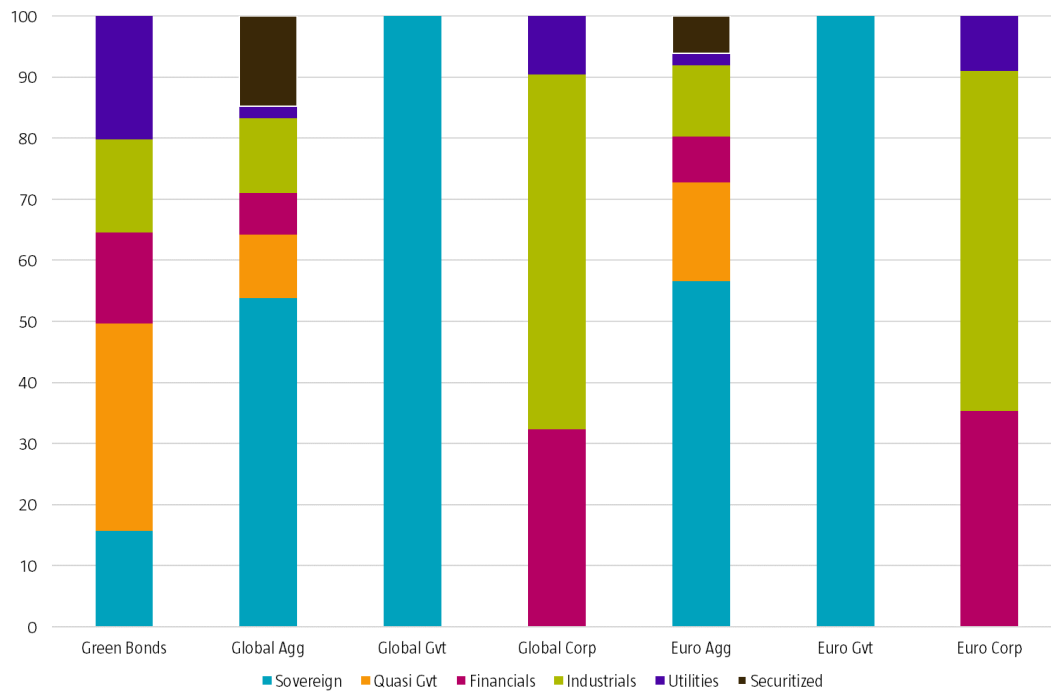


Date: 31 July 2021. Index codes: GREN, GBMI, WOG1, GOBC, EMU0, EG00, ER00.

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 these are not present in the green bonds index.

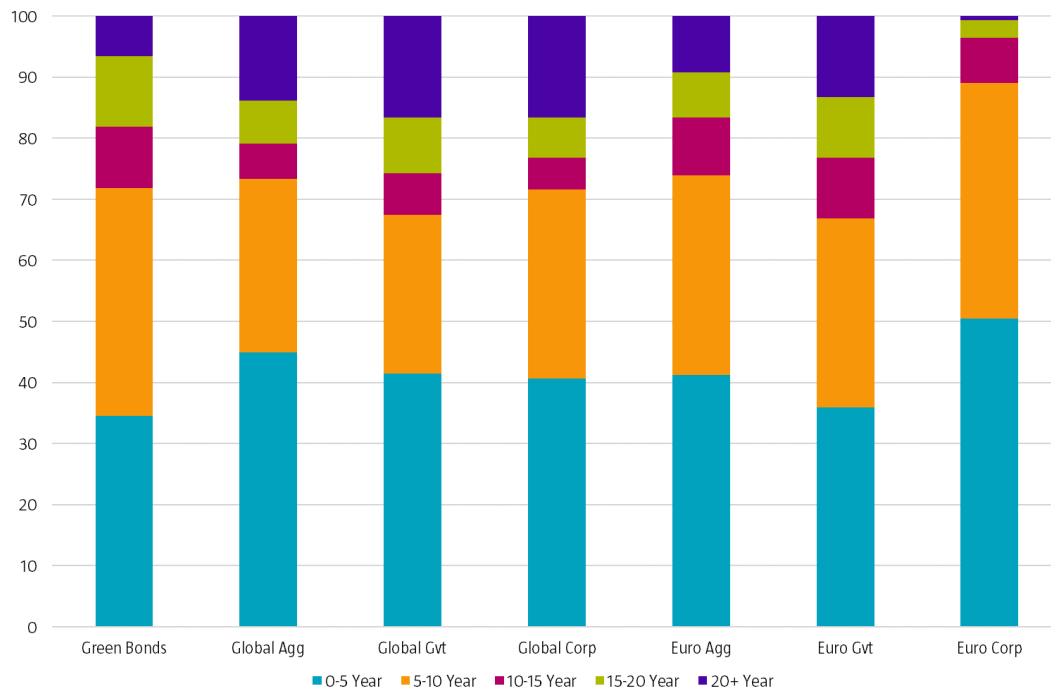
In the previous section, we indicated that the green bond market has come of age, evidenced by the increase in bond maturities. Exhibit 9 shows that the share of the green bond index that has a maturity below 10 years is similar to that of most other indexes, even though for the euro government index this share is lower, while for euro corporate bonds this is higher. Green bond issuance with maturities above 20 years are relatively small at this moment.

Exhibit 8: Sector composition of selected fixed income indexes



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

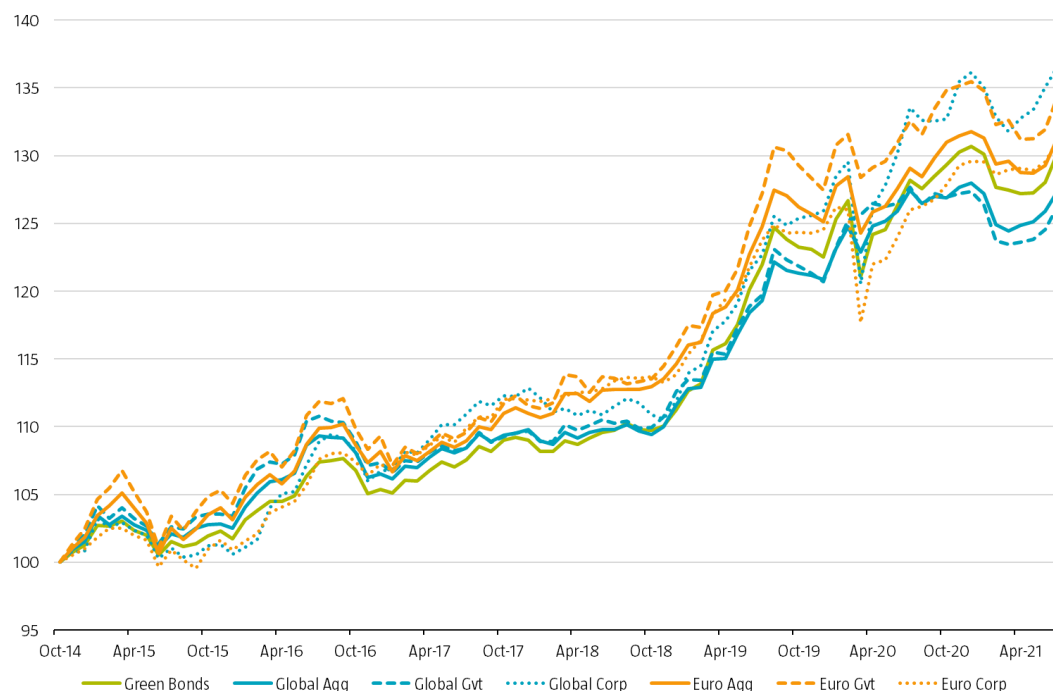
Exhibit 9: Maturity composition of selected fixed income indexes



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

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

Exhibit 10: Historical total returns



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

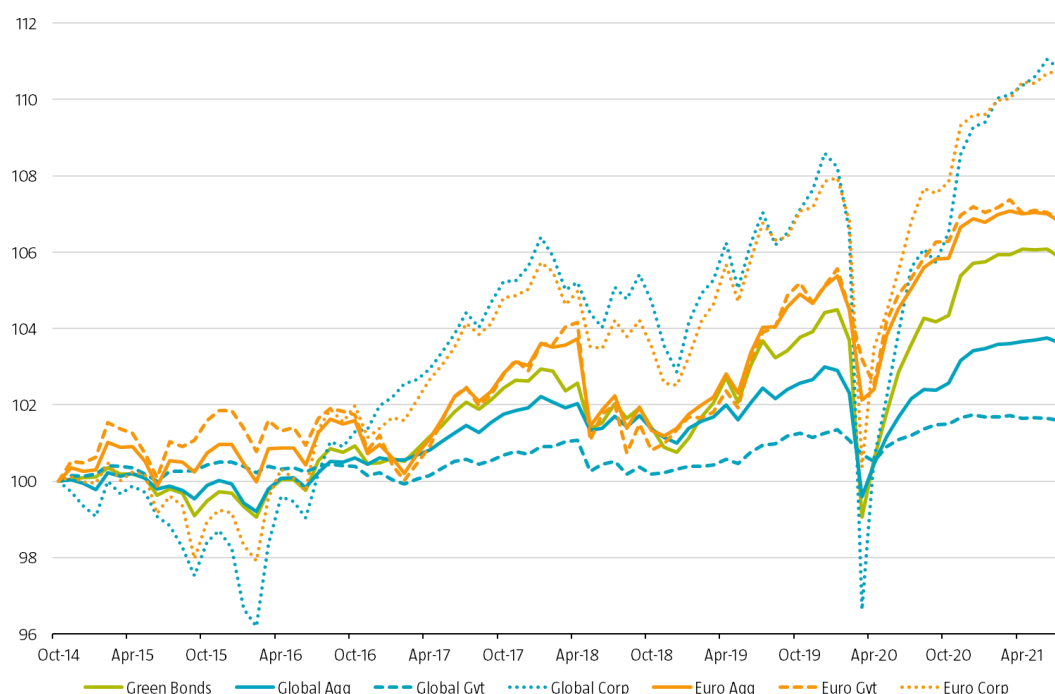
4. Empirical analyses

4.1 Historical returns

In Exhibit 10, the total return index of the green bond market and the other asset classes is displayed over the period 31 October 2014 to 31 July 2021. We show the series hedged to US dollars. Based on the analyses in Section 3, 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 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 difference in the short-term interest

rate in the US and the Eurozone.¹⁵ 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 for the future.

Exhibit 11: Historical excess returns



Excess returns relative to duration-matched government bonds. Sample period: 31 October 2014 to 31 July 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

¹⁵ We only compare green bonds to fixed income asset classes. Reboredo, Ugolini, and Aiube (2020) show that this 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.

of the Eurozone government bond index.¹⁶ Hence, this series also contains a default risk component related to 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 a slightly better than green bonds during this crisis month.

4.2 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 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.¹⁷ 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

¹⁶ See for documentation page 29 of the data manual ICE (7 February 2020) *Bond Index Methodologies*.

¹⁷ 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.

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: Returns-based mimicking portfolios

Sample	Green		Mimicking portfolios											
	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

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

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

4.3 Characteristics-based mimicking portfolio

Instead of using *historical returns* of the relevant assets, an investor can also try to approximate the *current characteristics* as good as possible with the available set of assets. The advantage is that changing index compositions or coincidental past return patterns have no influence on the portfolio construction. The disadvantage is that by matching characteristics, we might restrict the portfolio on dimensions that are irrelevant from a future excess returns and risk perspective. The investor needs to specify which characteristics she finds important to closely match and which characteristics are less important. We examine the mimicking portfolios based on the four characteristic that we discussed in Section 3, and consider several variations of tastes. We do this again for the three global assets, three Eurozone assets, and the combination of both. As 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 market risk of credit portfolios; see Ben Dor et al. (2007). In addition, we include the sector or currency dimension, or both.

Exhibit 13 shows also that an Eurozone aggregate portfolio (59% weight) supplemented with a global corporate bond portfolio (35% weight) leads to good matching of bond characteristics with green bonds. When sector composition is deemed irrelevant, we see that suddenly the global and Eurozone government bond portfolios 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 very similar rating distribution as the aggregate portfolio, but its maturity profile does not fit well.

Exhibit 13: Characteristics-based mimicking portfolios

<i>Rating</i>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
<i>Currency</i>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<i>Sector</i>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
<i>Maturity</i>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
<i>Global agg</i>	6	0	0	62	58	56	0	0	0
<i>Global gov</i>	0	0	11	0	0	0	0	0	0
<i>Global corp</i>	35	22	0	38	42	44	0	0	0
<i>Euro agg</i>	59	65	0	0	0	0	66	66	35
<i>Euro gov</i>	0	0	63	0	0	0	0	0	44
<i>Euro corp</i>	1	13	26	0	0	0	34	34	21

Data from 31 July 2021.

This 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.

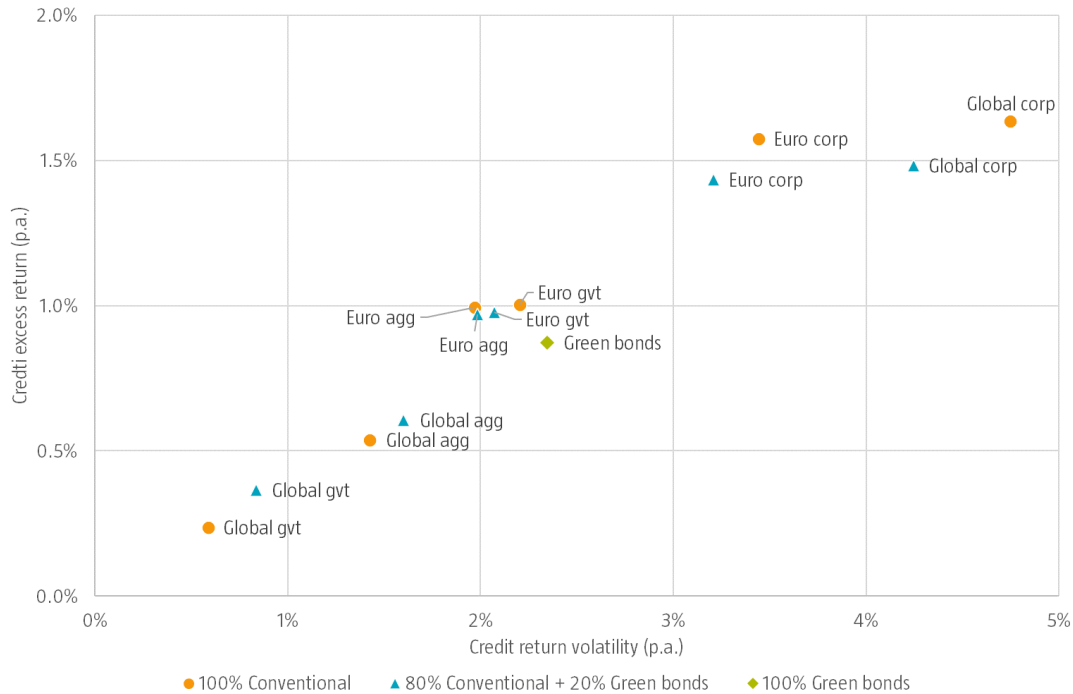
4.4 Implications for fixed income portfolio risk

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 is ranges from November 2014 to July 2021, but the results over the last three years of our sample are similar.¹⁸ The green bond index

¹⁸ See Appendix Exhibits A5 and A6 that correspond to Exhibits 14 and 15 in the main text.

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.

Exhibit 14: Impact on credit risk-return profile of adding 20% green bonds



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. *This figure has been changed in June 2023, when a mistake was discovered.*

During this period, corporate bond excess returns were relatively high with 1.6% per annum for both the global and Eurozone index.¹⁹ The global government bond index had a low excess return, as only small part of those returns is due to credit spreads relative to risk-free government bonds. The reason that excess returns for Eurozone government bonds is higher, is 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 substantial variation of realized credit returns over such short periods. The goal of this analysis is to compare

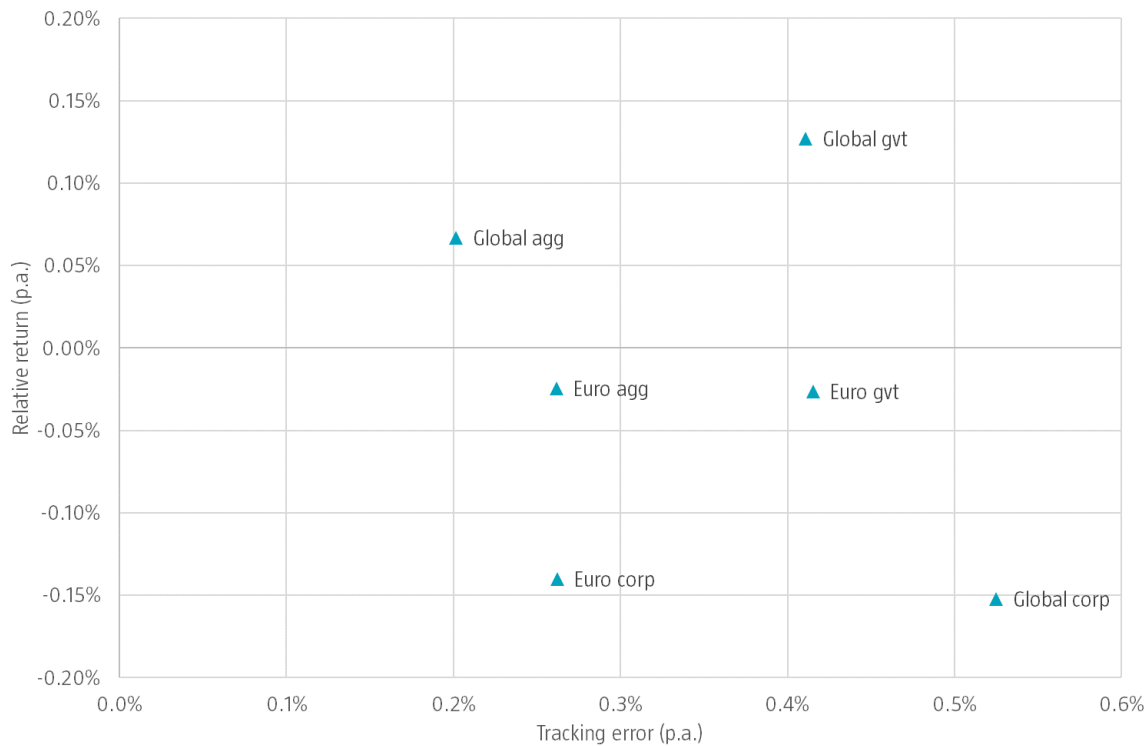
¹⁹ Relatively high compared to investment grade credit premium estimates of 0.42% per annum by Ng and Phelps (2011) over the period 1990-2009 and the 0.80% per annum by Giesecke et al. (2011) over the period 1866-2008.

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 sub-sections: 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 take into account 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, which represent the 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 is about double 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.

Exhibit 15: Impact on the tracking error of adding 20% green bonds



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.

4.5 Asset pricing tests

We can also statistically test whether green bonds expand the mean-variance frontier for a fixed income investor. De Roan 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 U.S. term factor and the U.S. default factor as the two relevant pricing factors. We proxy the term factor by the return on the Bloomberg Barclays U.S. Treasury Index minus the Bloomberg Barclays U.S. 1-3 Month Treasury Bill Index, and the credit factor by the excess return of the Bloomberg Barclays U.S. Corporate Investment Grade Index relative to duration-matched U.S. 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’, i.e. 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. The former is the Bloomberg Barclays U.S. Treasury Inflation-Protected Securities Index minus the Bloomberg Barclays U.S. 1-3 Month Treasury Bill Index, and the latter the U.S. equity market excess return factor from Kenneth French’s online data library.

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
R2 (adj)	0.22	-	0.19	-	0.75	-	0.74	-	0.75	-

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 U.S. 1-3 Month Treasury Bill Index). Alpha is the intercept in the regression, annualized in percentages. Included are the return factors ‘term’ (Bloomberg Barclays U.S. Treasury Index minus the Bloomberg Barclays U.S. 1-3 Month Treasury Bill Index), ‘default’ (excess return of the Bloomberg Barclays U.S. Corporate Investment Grade Index relative to duration-matched U.S. Treasuries, ‘inflation’ (Bloomberg Barclays U.S. Treasury Inflation-Protected Securities Index minus the Bloomberg Barclays U.S. 1-3 Month Treasury Bill Index), and equities (Fama-French U.S. equity market excess return).

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-square 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, exposure to term and default risks have been the main determinants of the returns on the green bond market.

5. Conclusion

This paper 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 year 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 that 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.

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Appendix A

Exhibit A1: Green bond index comparison - Number of bonds and market value

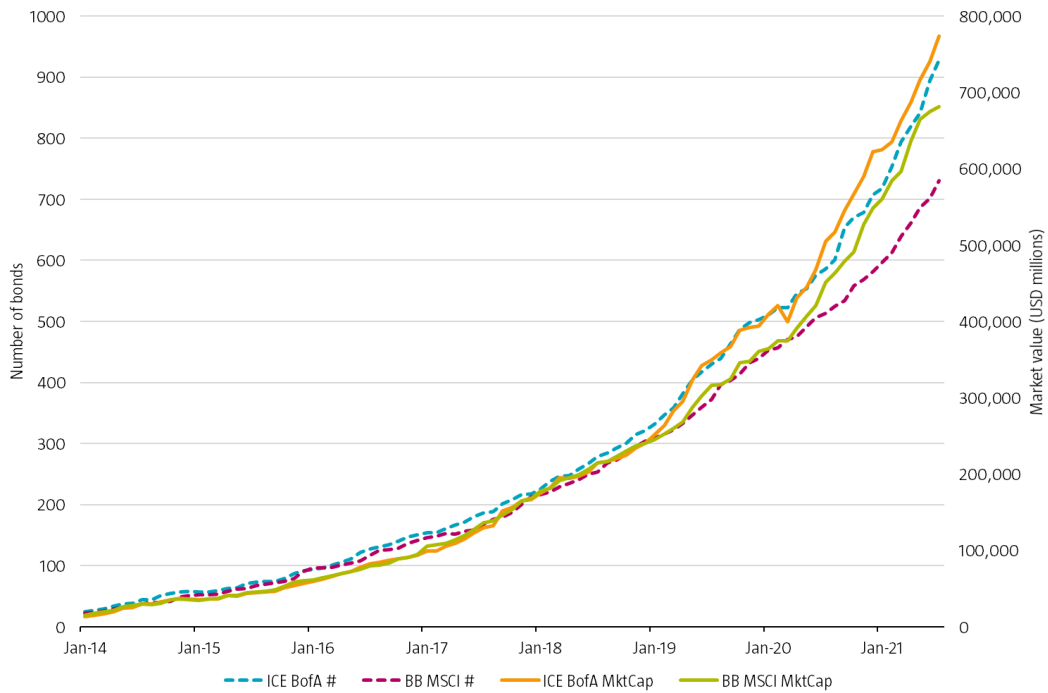


Exhibit A2: Green bond index comparison - Total return index (USD hedged)

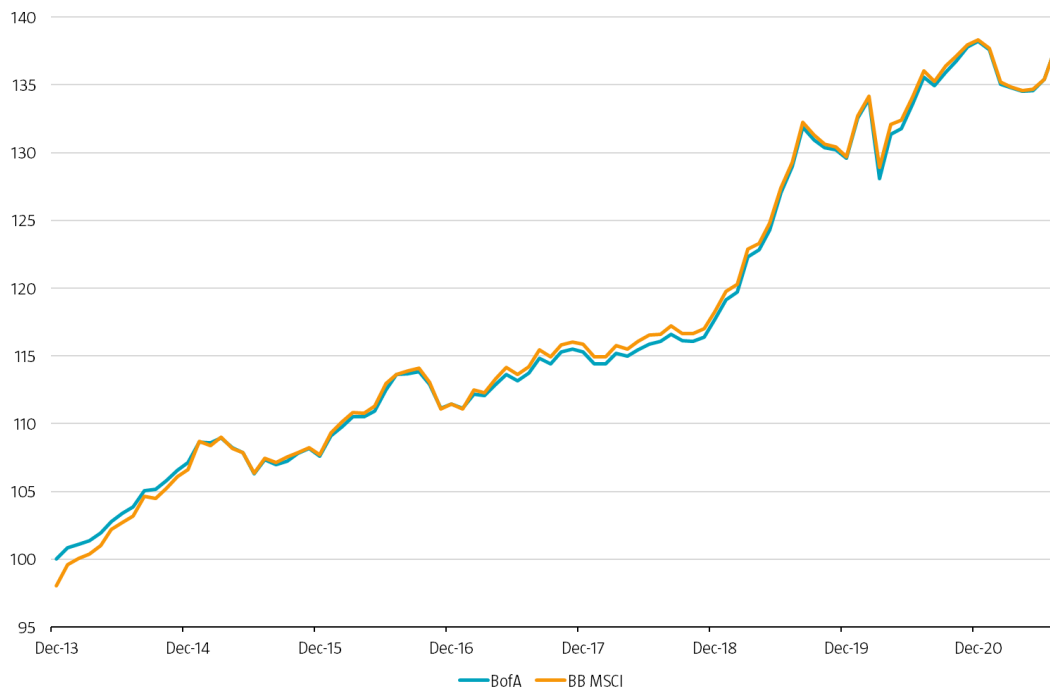


Exhibit A3: Green bond index from December 2010

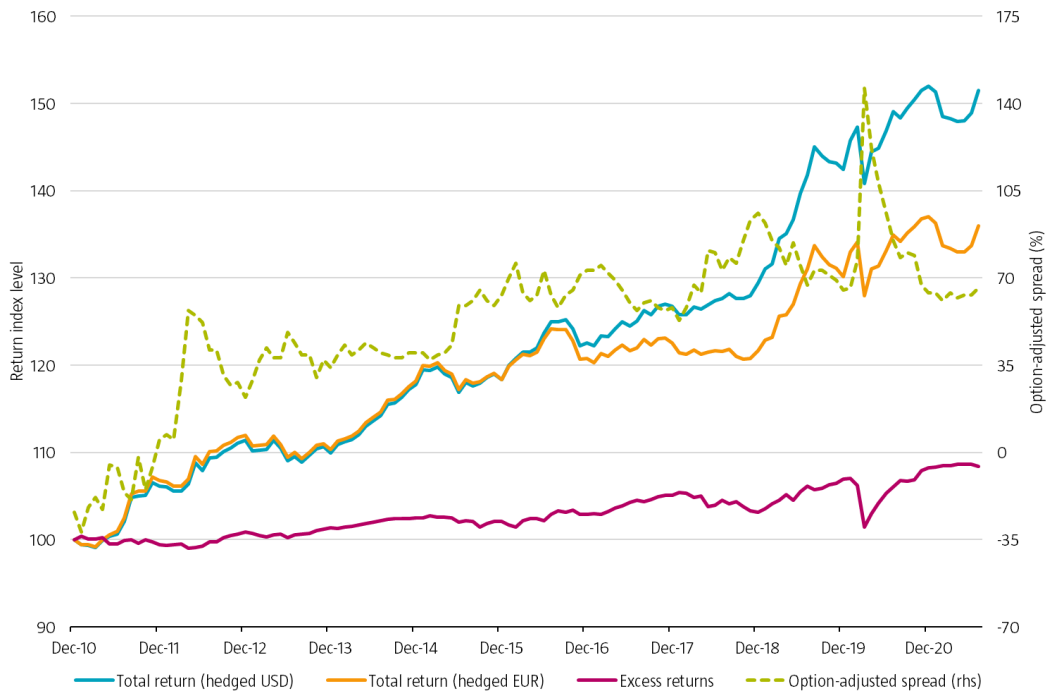
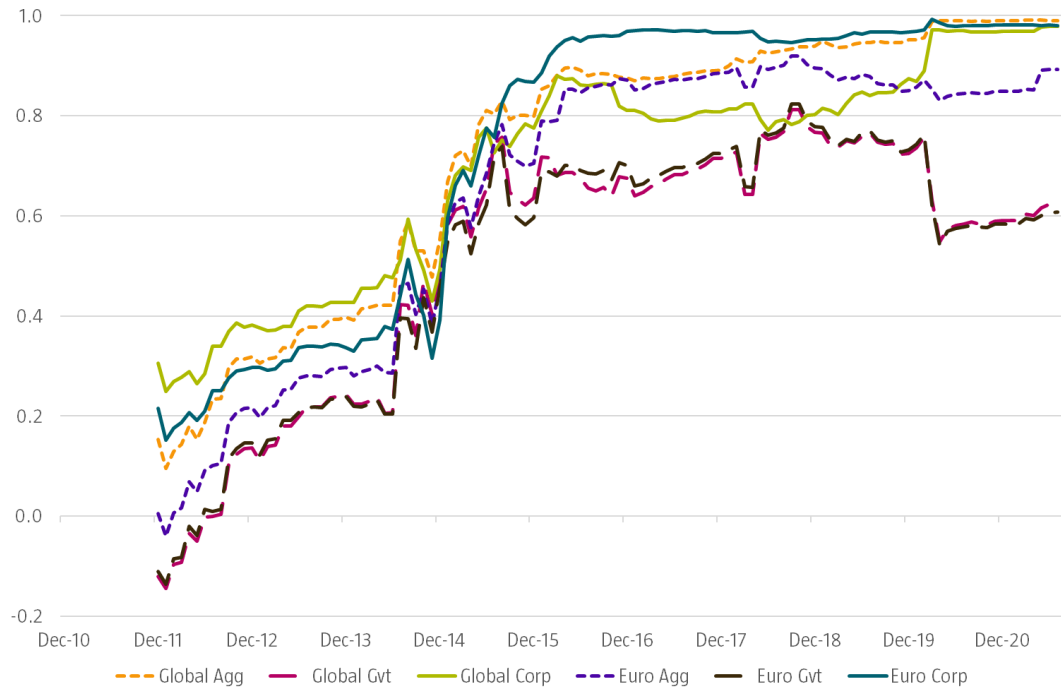
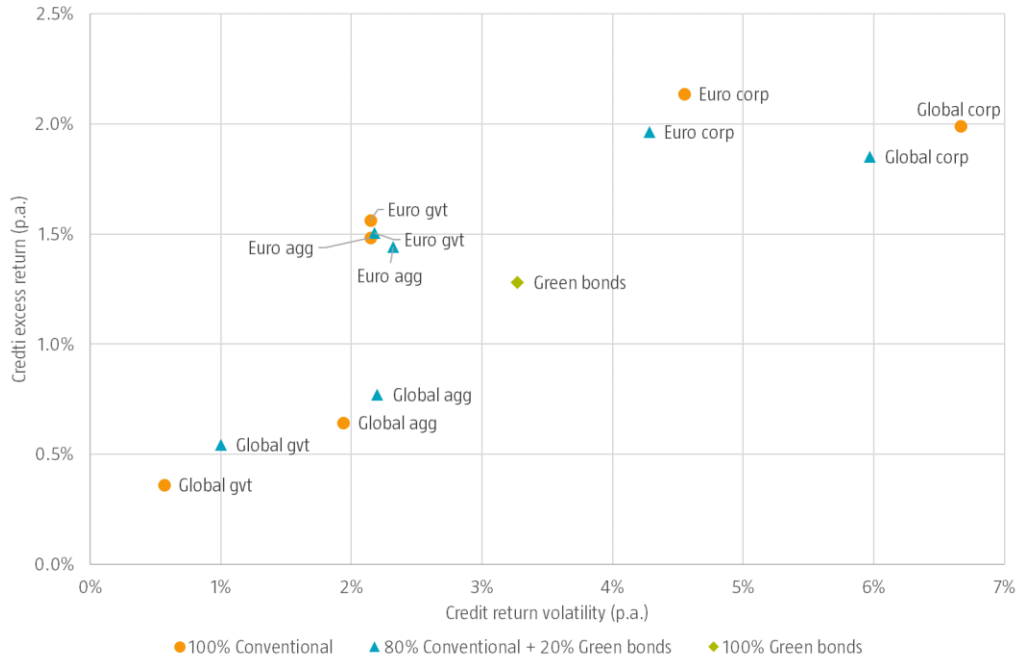


Exhibit A4: Rolling correlation of green bonds with other fixed income assets



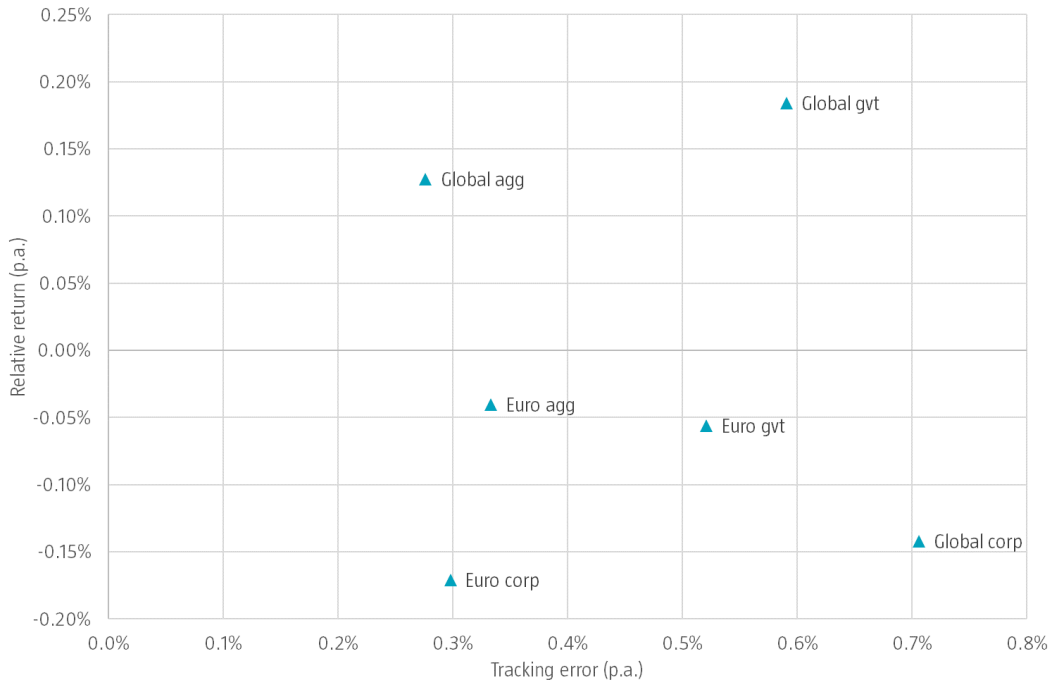
First observation uses the first 12 monthly observations, then expanding window to 36 monthly observations. Thereafter a 36 month rolling window.

Exhibit A5: Impact on credit risk-return profile of adding 20% green bonds: last 3 years



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



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.