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KAROLINA DASZYŃSKA-ŻYGADŁO

karolina.zygadlo@ue.wroc.pl
Wrocław University of Economics and Business. Faculty of Economics and Finance
118/120 Komandorska St., 53-345 Wrocław, Poland
ORCID ID: https://orcid.org/0000-0003-4710-0220

JAKUB MARSZAŁEK

jakub.marszalek@uni.lodz.pl
University of Łódź. Faculty of Management
22/26 Jana Matejki St., 90-237 Łódź, Poland
ORCID ID: https://orcid.org/0000-0002-7665-1497

KRZYSZTOF PIONTEK

krzysztof.piontek@ue.wroc.pl
Wrocław University of Economics and Business. Faculty of Economics and Finance
118/120 Komandorska St., 53-345 Wrocław, Poland
ORCID ID: https://orcid.org/0000-0001-9197-561X

ILZE ZUMENTE

ilze.zumente@rtu.lv
Riga Technical University. Faculty of Engineering Economics and Management
6 Kalnciema St., Riga, Latvia
ORCID ID: https://orcid.org/0000-0002-9129-458X

Are Green Bonds a Good Investment Opportunity for Turbulent Times?

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Abstract

Theoretical background: The green bonds market is growing rapidly and serving as a source of financing for energy transition, social impact investments, green economy transition, and climate change mitigation projects. It is also an interesting alternative investment opportunity for increasingly conscious investors. Researchers are studying the green bonds market from several perspectives, among others they search for premiums for being green – greenium; they analyse the interconnectedness of conventional and green bonds markets in the search for portfolio diversification opportunities and they consider the usefulness of green bonds in the times of market crisis or turbulences as hedging strategies instruments.
Purpose of the article: The purpose of this article is to verify the nature and direction of the relationship between green bonds markets and conventional bonds markets, as well as its permanence during market shocks.
Research methods: Our analysis is based on rates of returns from green bonds indices and their respective counterparts in the period between January 2015 and April 2021, we used conditional volatility and dynamic conditional correlation with multivariate Gaussian and *T*-Student distributions.
Main findings: We found similar patterns of behaviour between green and conventional bonds markets, but the green bonds market is riskier than the non-green one and the risk relationship of both bond markets is changing. Our research results lead to the conclusion that investors are more prone to flee from the green bond market and stay in the conventional bond market in times of market shocks such as the outburst of the COVID-19 pandemic.

Introduction

The significance and size of the green bonds market is growing, the analysis of Climate Bonds Market Intelligence has revealed that GSS+ (Green, Social, Sustainability, Sustainability-Linked and Transition) themed debt rose to almost USD 1.1 trillion in 2021, which is 57% higher than 2020 volumes (www1). As of 2021, the green bonds market constituted around 6% of the global corporate bond market with the figure raising over the years (Caramichael & Rapp, 2022). This happens in times of greater efforts to mitigate climate change, introduce green economy and energy transformation, and act towards reducing the effects of climate crises. Capital markets have a key role to play in providing financing for huge investments necessary to reach climate goals set by the Paris Agreement. Both companies and investors are becoming more aware of sustainability and using sustainable finance instruments such as green debt, especially green bonds. Although the sustainability awareness and sustainable finance market values are growing, the needs are way more significant. According to OECD, to reach climate goals annual investment of USD 6.9 trillion is needed.

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The motivation for this study was to get a better understanding of the performance of green bonds and patterns of investors' behaviours, especially in comparison to conventional bonds markets. The objective was to verify the nature and direction of the relationship between green bonds markets and conventional bonds markets, as well as its permanence. With the recent COVID-19 pandemic spread and its impact on financial markets we have chosen an additional objective to identify the spillover effects between those two markets, the risk, and resistance to market shocks. Therefore, our research questions are the following:

RQ1: Is there a connection between the green and non-green bond markets?

RQ2: Is the risk of the green bond market and non-green bond market the same? If so, is this relationship permanent?

RQ3: What is the resistance of green bonds to market shocks?

RQ4: To what extent can green bonds be considered a more attractive investment opportunity during high turmoil market situations?

In order to answer those research questions, we have chosen to investigate bonds' indices as proxies for portfolios made up of bonds in the period of January 2015 and April 2021, while the first green bonds indices were launched in 2014, our study covers the same period for four indices equalized according to the inception of the latest one from the sample. We applied the GARCH methodology in order to capture the degree of volatility and correlation changes between both bond markets. We used conditional volatility and dynamic conditional correlation with multivariate Gaussian and *T*-Student distributions (Engle, 2000, further cf. Tsay, 2014).

While there is existing literature on the performance of green bonds in various market conditions, there is still a rather limited amount of research specifically examining their behaviour during periods of market instability or crisis. In addition, with the raise of the importance of the green bond market, the differences between the conventional and green bond markets become more relevant for investors and policymakers seeking to make informed decisions about sustainable investing in volatile markets. We contributed to the research gap and discussion about differences in rates of returns and risk between conventional market and green bonds market, so-called *greenium* following Hyun et al. (2020), Nanayakkara and Colombage (2019), Partridge and Medda (2018) and Kapraun and Scheins (2019) among others. We studied interrelatedness of the two markets referring to the results of Pham (2016) and Reboredo (2018). Finally, we looked into the opportunity of using green bonds as alternative investments for hedging during the market turmoil joining the discussion with Pham and Nguyen (2021), Ferrer et al. (2021) and Arif et al. (2021). By providing insights into the risk and return profiles of the two markets the analysis is relevant to Modern Portfolio Theory as it supplies essential inputs for portfolio optimization.

Overall, the results and insights generated by this research can be applied by investors seeking socially responsible alternative investment opportunities, issuers considering green bond emission as well as policymakers driving regulation.

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The structure of the remaining part of the paper is the following. In the second part, we introduced existing literature analysis, third part covered research methods and hypotheses development. We presented the results of our research in the fourth part, which is followed by the discussion in the fifth part and conclusions including limitations of the study and future potential research in the last part.

Literature review

Is there a difference in price?

A significant part of the academic literature on green bonds consists of studies searching for differences between conventional bonds and their green counterparts. Most commonly, the theoretical assumption is that there shall be no significant rational differences in the price of both bond types, given the same issuer, similar maturity, coupon, and currency. Nevertheless, given the rising demand for sustainable financial instruments in the investment market and the growing amounts of funds available for such investments, several studies discuss the premium that investors are ready to pay for green bonds, also called in the literature – the greenium – confirmed by multiple academic studies.

Zerbib (2019) found on average 2 bp yield difference between the green and their matching synthetic conventional counterparts of the same issuer and closest maturity. Bachelet et al. (2019) similarly adopted the matching methodology allowing identification of a premium between 2.06 and 5.9 bp conditional on external verification of the green bond. In addition, authors found that green bonds were around 5 bp more liquid than their conventional counterparts and exhibited lower volatility. Kapraun and Scheins (2019) examined the differences in the yields at issue without creating synthetic bond comparisons, thus allowing to significantly increase the sample. The results on the primary market data showed a significant greenium of 20 to 30 bp for green bonds with a varying magnitude across issuer types and currencies, while the secondary market data revealed a contrasting result of green bonds trading at higher yields. A small, but growing premium has been documented also by Partridge and Medda (2018).

The aforementioned method of the spread yield differential comparison has been recently critically debated in the literature due to the difficulty to find exact matching counterparts in terms of generated cash flows and maturities. A different approach of option-adjusted spreads was used by Nanayakkara and Colombage (2019) resulting in a concluded premium of 63 bp in favour of the green bonds confirming the growing demand for this type of sustainable investment.

The evidence on the greenium, however, is not conclusive. Hyun et al. (2020) found no robust evidence that there is a green bond premium or discount relative to their conventional counterparts. Contrary, however, the results showed that exter-

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nally assured green bonds with the Climate Bonds Initiative (CBI) certificate traded at discount of around 6 to 15 bp in comparison to their non-rated peers. Also recent paper by Larcker and Watts (2019) showed similar of a very low yield difference of 0.45 bp concluding that almost no greenium exists for this asset class.

The results of the research about the existence and size of the greenium are still inconclusive. The mixed results are argued to most likely come from the differences in applied methodologies, sample selection techniques, and matching processes. From a theoretical perspective, there is no clear conclusion on the reason for the existence of the greenium – while some studies suggest that the greenium could come from the increased sustainability focus of the respective financial assets (Orlitzky et al., 2003), others explain it with investors preference for certain assets impacting the equilibrium of the asset pricing as suggested by Fama and French (2007). Finally, heterogeneity concerning the existence of a greenium in the green bond universe has been modelled by Agliardi and Agliardi (2021) based on the cash flows of the firm and the effectiveness of the financed green projects.

How is green bond market connected?

Another strand of green bond research examines the interrelation between green bonds and other financial markets. If green bonds were to provide an opportunity to diversify their portfolios, financial investors should be more interested in using this alternative asset class as an effective hedging instrument, thus, a dedicated research part is devoted to measuring the connectedness between green bonds and other financial assets markets.

Pham (2016) started the research stream on the volatility behaviour of the green bond market. By building a univariate and multivariate GARCH framework to study the volatility of the green bond in relation to the conventional S&P Aggregate Bond Index, the results suggested individual volatility clustering in each of the indices, in addition to volatility spillover from the conventional bond market into the green bond market. Broadstock and Cheng (2019) based on Pham's (2016) methodology additionally found that the green and black bond correlation is sensitive to financial market conditions such as volatility, economic policy uncertainty, daily economic activity, oil prices, and perceived sentiment regarding green bonds, especially after the mid of 2016. Also Park et al. (2020) exploring the volatility spillover between the equity and green bond markets found volatility clusters in both time series. In addition, a unique type of asymmetric volatility sensitive to the positive shocks was found to be present in the data unlike the evidence found for other types of financial instruments. In addition, to evaluate the volatility transfers, authors applied a bivariate GARCH model to show that green bond and equity markets have volatility spillovers, however, neither is significantly affected by the negative shocks in the other. Large volatility clustering across the returns of green bond indices has been previously concluded also by Daszyńska-Żygadło et al. (2017).

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Motivated by the need to establish an insight into the application of green bond instruments as having portfolio risk hedging properties and potential diversification benefits Reboredo (2018) used bivariate copula functions to examine the price connectedness between the green bond and financial markets. He used 2014 to 2017 data on four green bond indices – Barclays MSCI GB Index, S&P Dow Jones GB Index, Solactive GB Index, and Bank of America Merill Lynch GB Index and compared the movements of the index data with corresponding global financial market benchmarks. The results revealed that green bond prices move in line with the treasury and corporate markets, however, are independent of the stock market and energy price movements. A follow up paper by Reboredo and Ugolini (2020) found the closest integration of the Barclays MSCI GB Index to the treasury bond market. In addition, they also confirmed that the green bond market is weakly tied to the stock, energy, and high-yield corporate bond markets while linking closer to the dollar currency market as well as the corporate debt market.

The interrelatedness between green bonds and other financial markets provides a basis for the exploration of the question of whether green bonds can be a reasonable alternative for investments during financial turmoil, especially in the light of presenting reasonable hedging opportunities. During times of high financial market volatility, investors tend to turn to alternative investments hoping for higher resilience. Most recently, with the start of the COVID-19 pandemic, the global economy and society has been faced with the question of how to combine the general growth of sustainability efforts with maintained financial results. Arguably, sustainable investment products provide such a factor combination. According to Morningstar data, the flows into sustainable fixed income funds have significantly grown since the Q2 of 2020 (Reuters, 2021a) signalling the rising demand and investor confidence in the socially responsible market. A similar increase has been witnessed also by the green bonds market. According to Moody, the issuance of sustainable and green bonds globally reached a record of USD 99.9 billion in the second quarter of 2020, in addition, sustainable bond issuance was 65% higher between April and June than between January and March, with social bonds and sustainability bonds leading the trend (Edie Newsroom, 2020). Academically, this evidence is confirmed by Ferriani and Natoli (2020) documenting higher fund inflow for lower ESG risk funds. The trend has continued also in 2021 reaching a new record volume of issuance of USD 777.6 billion in the first nine months of 2021 (Reuters, 2021b). On the supply side, the drivers of the green market growth have been identified among Nationally Determined Contributions to the Paris Agreement, institutional effects as well as macroeconomic factors (Tolliver et al., 2020). In addition, also factors such as fiscal balance, inflation rate, and population have a significant impact and lead to a higher volume of green bond issuances (Dan & Tiron-Tudor, 2021).

Historic evidence suggests that sustainable investments could indeed be a reasonable alternative for times of financial downturns – Weber et al. (2010) have concluded such higher return benefits for socially responsible fund portfolios, while Nofsinger

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and Varma (2013) showed that investors preferred sustainable assets even during the financial crisis of 2009 when the sustainable investment trend was still significantly less developed. With respect to the financial turmoil caused by the COVID-19 pandemic and the green bonds market behaviour, the evidence is still emerging, and the studies already completed do not show unified results. Ramel and Michaelsen (2020) found that there was a sharp decrease in the difference between green and non-green spreads as the risk sentiment increased at the start of the COVID-19 crisis, indicating a substantial outperformance of the green bonds. Furthermore, an additional period of a risk-off period in Q1 2016 was examined by comparing the green and traditional bonds of the same issuers, concluding that green bonds outperformed non-green bonds, on a relative basis, during the risk-off period in 2016, by about 15 bps. With respect to the diversification benefits of green bonds to corporate and treasury bonds, as well as energy and stock markets Pham and Nguyen (2021) find different outcomes of volatility spillovers depending on the market conditions. In addition, the correlation between green bonds and other assets is found to weaken for a longer horizon indicating rather longer-term diversification benefits of green bonds over other asset classes. This result is confirmed by Ferrer et al. (2021), who find higher short-period connectedness between the global green bond market and the conventional financial and energy markets. Also, Arif et al. (2021), when examining COVID-19 period data, reach similar results for the green bonds being a better medium and long-term diversifier. Finally, the study of Haq et al. (2021) revealed additionally that green bonds have diversifying properties with clean energy stocks and rare earth elements during the COVID-19 pandemic.

Research methods

Our aim is to capture the degree of volatility and correlation changes for green and conventional bonds. For this purpose, we have selected the following pairs of green and conventional bonds indices indicated in Table 1.

Table 1. Pairs of bonds indices used for analysis

Green Bonds Index	Conventional Bonds Index
Bloomberg Barclays MSCI Global Green Bond Index Total Return Index Value Unhedged USD (GBGLTRUU)	Bloomberg Barclays US AGG TOTAL RETURN VALUE UNHEDGED USD (LBUSTRUU)
ICE BofAM GREEN BOND INDEX (GREN)	Bloomberg Barclays US AGG TOTAL RETURN VALUE UNHEDGED USD (LBUSTRUU)
ICE BofAM GREEN BOND INDEX (GREN)	S&P AGGREGATE BOND INDEX TOTAL RETURN (SPUSBMIT)
S&P GREEN BOND INDEX TOTAL RETURN (SPUSGRN)	S&P AGGREGATE BOND INDEX TOTAL RETURN (SPUSBMIT)
Solactive Green Bonds Index (SOLGREEN)	S&P AGGREGATE BOND INDEX TOTAL RETURN (SPUSBMIT)

Source: Authors' own study.

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Since the inception of green bonds and the development of the first green bonds indices, the family of various green bonds indices has grown to over 200 indices at the time of conducting this research. Therefore, we decided to choose the exact same indices as investigated in earlier studies (Daszyńska-Żygadło et al., 2017; Reboredo, 2018) and match them with respective aggregate conventional bond indices from two of the families that green bonds indices were from, i.e. Bloomberg Barclays and S&P. Matching for GREN index was inconclusive, therefore, initially we decided to test it in two pairs for the sake of robustness. For the analysis, we use daily return data retrieved from the Bloomberg database for the period of January 2015 to April 2021. Missing observations were filled in by the average of the two last observable prices. We calculated the logarithmic rate of returns.

Based on the literature review and our research questions we tested the following hypotheses:

H1: The green and non-green bond markets are positively related.

H2: The green bonds market is riskier than the non-green bond market.

H3: The risk relationship of both bond markets is changing.

H4: The green bonds market is a better investment opportunity than the conventional bonds market in times of market turmoil.

In our investigation, we used one of the most complex and flexible approaches to model time-varying covariance between two instruments (bond indices). It allowed us for the analysis of the conditional volatility (on the diagonal of the variance-covariance matrix) and dynamic conditional correlation (based additionally on covariances) with multivariate Gaussian and *T*-Student distributions (Engle, 2000, further cf. Tsay, 2014). This approach is one of the most cited works in parametric modelling of time-varying correlations of multivariate portfolios. We used the R programming language with the rmg arch package for statistical computing.

Based on analysis of conditional volatility we draw conclusions about risk and sensitivity to shocks on the market of both types of instruments. Based on these results we calculated the risk relationship between green and conventional bonds to identify different market behaviours of those instruments.

This approach is represented by the Dynamic Conditional Correlation (DCC) model is a generalization of the Constant Conditional Correlation (CCC) model (Bollerslev, 1990), where all standard deviations are time-varying, but conditional correlations are assumed to be constant over time. The advantages of the DCC model are that it provides a positive-definite time-varying conditional covariance matrix and allows for flexibility in describing time-varying conditional correlations between assets' returns. The parameters of the DCC model can be estimated in three steps, which makes this approach relatively simple. The present study uses that procedure.

By definition (two bond markets) we estimate a bivariate version of the model. Similarly to the univariate version, we decompose a multivariate time series r_t. We consider the stochastic vector of two random processes:

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$\mathbf{Y_t} = \boldsymbol{\mu}_\mathbf{t} + \boldsymbol{\eta}_\mathbf{t}$,

where:

$\mathbf{Y_t} = [y_{1t}, y_{2t}]^T$ – two-dimensional process of rates of return for both bond indices,

$\boldsymbol{\mu}_\mathbf{t} = E[\mathbf{Y_t}|F_{t-1}]$– vector of conditional expectations of bond returns (on available previous information F) based on the ARMA models, predictable component of $Y_\mathbf{t}$,

$\boldsymbol{\eta}_\mathbf{t} = [\eta_{1t}, \eta_{2t}]^T$ – two-dimensional column set of innovations for 2 financial assets' (bonds) returns.

Dimensions of all major elements of the model $\{\mathbf{Y_t}, \boldsymbol{\eta}_\mathbf{t}\}$ are $(2 \times T)$, where T is equal to the number of observations. The main idea is to describe the conditional relations between elements as the variance-covariance matrix of innovations:

$\boldsymbol{\eta}_\mathbf{t} = \mathbf{H}_\mathbf{t}^{0.5} \boldsymbol{\varepsilon}_\mathbf{t}$,

where: $\{\boldsymbol{\varepsilon}_\mathbf{t}\}$ is a sequence of independent and identically distributed (multivariate Gaussian or T-Student) two random vectors such that: $E[\boldsymbol{\varepsilon}_\mathbf{t}] = \mathbf{0}$, $cov[\boldsymbol{\varepsilon}_\mathbf{t}] = \mathbf{I}_2$

$\mathbf{I}_2$ – identity matrix of order 2 (with ones on the main diagonal and zeros elsewhere),

$\mathbf{H}_\mathbf{t}^{0.5}$ – denotes the positive-definite square-root matrix of $\mathbf{H_t}$.

Based on the model of conditional variance-covariance model we are able to do the decomposition of the $\mathbf{H_t}$ matrix

$$\mathbf{H_t} = \begin{bmatrix} H_{1,t} & \\ cov_{12,t} & H_{2,t} \end{bmatrix} = \mathbf{V_{t\text{-}1}}(\boldsymbol{\eta}_\mathbf{t}),$$

into two conditional standard deviation processes and one which describe time-varying conditional correlation,

$\mathbf{H_t} = \mathbf{D_t R_t D_t}$,

where:

$\mathbf{V_{t\text{-}1}}(\boldsymbol{\eta}_\mathbf{t})$ is the conditional covariance matrix of the residuals $\boldsymbol{\eta}_\mathbf{t}$ based on the past information set,

$\mathbf{R_t}$ – matrix of time varying conditional correlation (2×2),

$\mathbf{D_t}$ – diagonal matrix with conditional standard deviations, $\mathbf{D_t} = diag\left(\sqrt{H_{1,t}}, \sqrt{H_{2,t}}\right)$ or equivalently $\mathbf{D}_\mathbf{t}^2 = diag(\mathbf{H_t})$.

The DCC model (Engle, 2002, further cf. Tsay, 2014) takes advantage of the fact that correlation matrices are easier to handle than covariance matrices. Finally, we used popular in financial econometrics DCC model:

$\mathbf{Y_t} = \boldsymbol{\mu}_\mathbf{t} + \boldsymbol{\eta}_\mathbf{t}$ (returns = predictable part of the model plus innovations),

$\boldsymbol{\eta}_\mathbf{t}|F_{\text{t-1}} \sim (\mathbf{0}, \mathbf{H_t}) = (\mathbf{0}, \mathbf{D_t R_t D_t})$ (decomposition of variance-covariance matrix of innovations),

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$H_{i,t} = \omega_i + \alpha_i \eta_{i,t-1}^2 + \beta_i H_{i,t-1}$ (standard GARCH (1,1) models with Gaussian distribution for every instrument),

$\boldsymbol{\varepsilon}_\mathbf{t} = \mathbf{D}_\mathbf{t}^{-1} \boldsymbol{\eta}_\mathbf{t}$ (standardized residuals from univariate GARCH models),

$\mathbf{Q}_t = \bar{\mathbf{Q}}(1 - \alpha - \beta) + \alpha \boldsymbol{\varepsilon}_\mathbf{t-1} \boldsymbol{\varepsilon}_\mathbf{t-1}^{'} + \beta \mathbf{Q}_\mathbf{t-1}$ (process of quasi conditional correlation to normalization),

$\mathbf{R}_\mathbf{t} = diag\{\mathbf{Q}_\mathbf{t}\}^{-0.5} \mathbf{Q}_\mathbf{t} diag\{\mathbf{Q}_\mathbf{t}\}^{-0.5}$ (time varying conditional correlation as a final result),

where:

$\mathbf{Q}_\mathbf{t}$ – a positive-definite quasi correlation matrix (need to be normalized),

$\omega, \ \alpha_i, \ \beta_i$ – the parameters of the univariate conditional variance equations (standard GARCH models) for every single instrument, i={1,2},

$\alpha, \ \beta$ – the parameters of the conditional correlation equation,

$\bar{\mathbf{Q}}$ – the unconditional covariance matrix[1] of the epsilons which is estimated simply as $E[\boldsymbol{\varepsilon}_\mathbf{t} \boldsymbol{\varepsilon}_t^{'}]$.

A procedure for estimating parameters of the ARMA-DCC model and the conditional correlation is given in three steps.

a) We fit the univariate ARMA model to every instrument. We used the AIC criterion to choose one-dimensional ARMA models to every time series of the returns (y_{it}) which gave us the best fit for models nested in (1,1) parametrization. During this procedure we also estimated parameters ϕ_i of the conditional mean ARMA model $\mu_i(\phi_i)$. Knowing parameters of the conditional mean model and previous observations we calculate two series of residuals η_{it}.

b) Based on each series of ARMA residuals we model separately the conditional variances $H_{1,t}$ and $H_{2,t}$ with the standard univariate GARCH(1,1) models.

c) Residuals ($\hat{\eta}_{it}$) standardized with the estimated standard deviations ($\widehat{H}_{i,t}^{0.5}$) are used to calculate standardized innovations $\hat{\varepsilon}_{i,t}$ and then to estimate $\bar{Q}$ and finally – the parameters of the conditional correlation (α and β). The time varying conditional correlation coefficient (in the case of two instruments) is given in the R_t vector.

Results

The analysis of conditional variance dynamics of individual indices (Figure 1) shows multiple similarities. All indices sharply changed their values in early 2020, when uncertainty about COVID-19 and related lockdowns invaded the financial markets. It was an unprecedented situation. Stopping the economy directly causes difficulties in the implementation of operating activities, which has a significant impact on the company's liquidity. This, in turn, is crucial for the solvency of the

[1] In our analysis for two instruments it is simply the long-term correlation coefficient.

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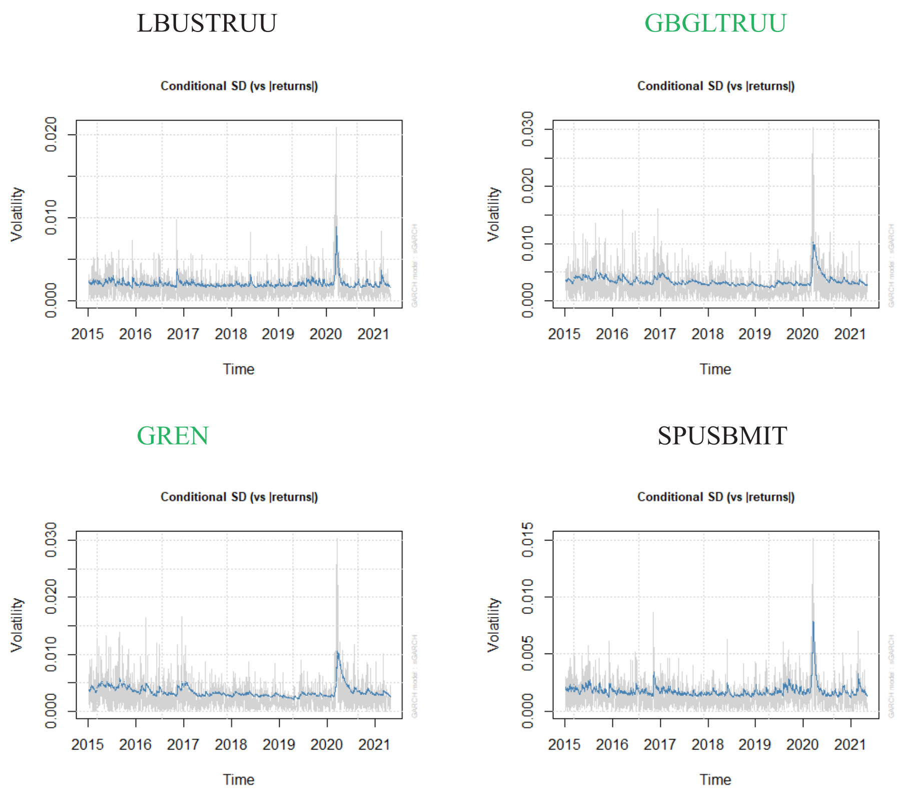
bond issuer. However, it can be observed that there are no significant differences in the value of conditional variance dynamics in this period, both in the case of green and non-green bond indices. The sharp rise in risk peaks in the first quarter of 2020 is followed by a relatively rapid decline in this parameter. LBUSTRUU stands out from the analysed bond indices, with the decline occurring the fastest. In other cases, the changes are similar. This indicates that both markets have a common risk factor as they react at the same moment and in the same direction.

The period of 2015–2017 is also a period with noticeably higher values of conditional variance. Similarly, it is difficult to notice significant differences between the analysed green and non-green bond indices. Again, compared to the bond indices studied, LBUSTRUU stands out, for which the volatility is slightly lower, but it cannot be considered a significant difference. The 2017–2019 period is characterized by similar volatility of conditional variance value, regardless of the type of the bond index under study. During this time, the observed values are the lowest for the entire test period.

After the market calmed down in the second quarter of 2020, the volatility of the indices decreased significantly, however, they did not reach the levels observed before the pandemic. Similarly, it is difficult to notice significant differences between the examined indices of green and non-green bonds.



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SPUSGRN SOLGREEN

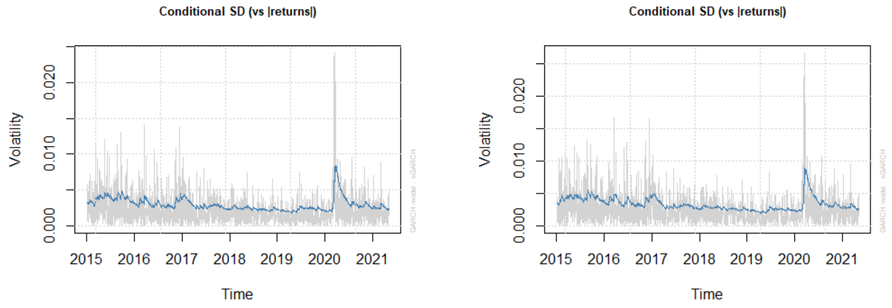

Figure 1. Conditional Variance Dynamics for analysed indices

Source: Authors' own study.

The analysis of the conditional correlation between the rates of returns of green and non-green bond indices (Figure 2) provides a lot of valuable information about the relationships between these segments of the public debt market. The correlation value is moderate and oscillates around 0.4 on average. The highest average value was obtained by the pair LBUSTRUU and GBGLTRUU (correlation 0.4581), while the pair SPUSBMIT and SOLGREEN (correlation 0.3672) turned out to be the least correlated. However, it should be noted that there is a significant variation in the correlation in the analysed period. The highest levels of correlation of the studied indices are observed in the first quarter of 2020, i.e. at the beginning of the COVID-19 pandemic. The strength of the relationship then exceeds the level of 0.6. It should be noted that the studied pairs of bond indices showed increasing correlation much earlier. The upward trend in correlation has been observed since mid-2018 when their values reached local lows. The changes in the correlation strength appear to be very similar.

A high level of correlation is also observed in the fourth quarter of 2016. For pair SPUSBMIT and SPUSGREEN, it is almost equal to the maximum from the time of the beginning of the pandemic, i.e. the first quarter of 2020. For other pairs, it is slightly lower. The fourth quarter of 2016 also started a long-term downward trend in correlation that stopped in mid-2018. The lowest correlation values were recorded in mid-2016. They dropped quite sharply to around 0.1 and almost no correlation was observed for the pair SPUSBMIT and SPUSGREEN. A similar dynamic of the decrease in correlation is observed in the first half of 2020, just after the tested correlation values reached their maximums. This was the strongest in the SPUSBMIT and SPUSGREEN pair. In other pairs, no significant differences in the decline in the dynamics of the conditional correlation were noticed. In general, the variability of the correlation should be considered high. In the analysed period, both one-year trends were observed as well as sudden breakdowns.

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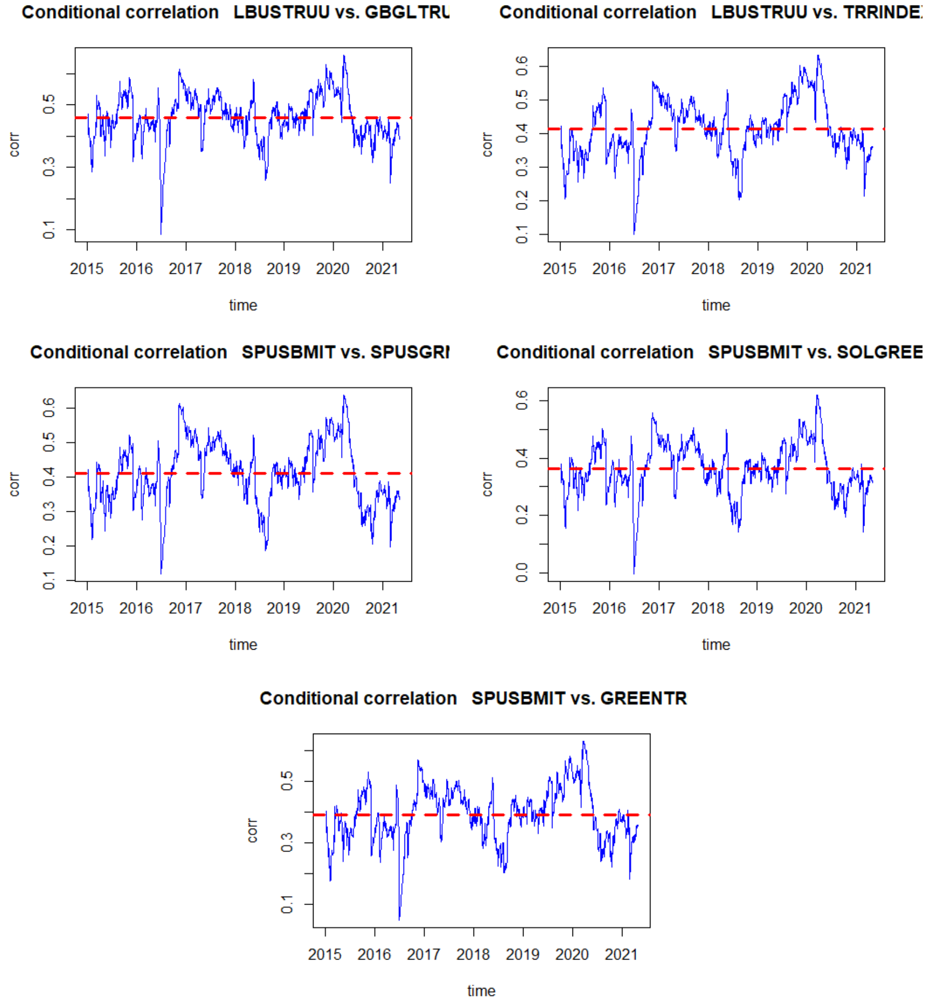

Figure 2. Conditional correlation between pairs of indices

Source: Authors' own study.

Based on the results of conditional volatility we calculated the risk relationship between green and conventional bonds to identify the different market behaviors of those instruments. It was the third area of the research. Results are presented in Figure 3.

The research of the analysed index pairs shows a long-term decline in the risk of green bonds' indices in comparison to the risk of conventional bonds' indices. This trend is disturbed in shorter periods, nevertheless, the tendency is quite clear. The risk relationships of individual pairs are similar, although there are several differences. The lowest risk variability occurs in the SPUSBMIT and SPUSGREEN pair. The risk relationship between the indices ranges from less than 1 (0.7465) to less than 3

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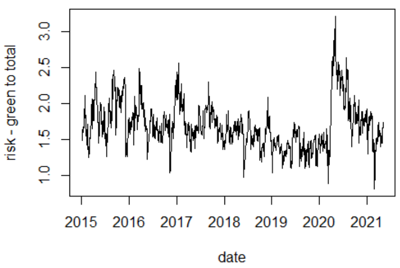
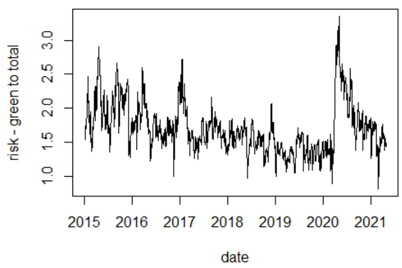
(2.9720). In the case of other pairs of indices, the risk relationship is also lower than 1, but significantly exceeds 3 (3.07). However, taking into account the frequency of risk changes, the least turbulent pair is LBUSTRUU and GBGLTRUU, which does not show significant variability in 2015–2017, in contrast to other analysed index pairs. This period is characterized by the greatest turbulence in the risk of green bonds versus conventional bonds. There is a slight downward trend in a few cases, but rather the change in risk over time is of a horizontal nature. A significant decrease in risk is observed from mid-2017 to the first quarter of 2020. At the end of this period, the risk value of green bonds was approaching 1, so the volatility of both groups of analysed indices was almost the same, although the indices of green bonds were characterized by slightly higher volatility compared to their conventional counterparts.

The real shock came at the onset of the COVID-19 pandemic, when green bonds' risk tripled against conventional bonds' risk, reaching or near highs. The scale of the increase in risk is unprecedented compared to the rest of the period studied. A similar dynamic of changes is observed only at the end of 2016. Interestingly, the risk relationship quickly returned to the level observed before the pandemic, setting new minimum values. For example, two indices' pairs LBUSTRUU/GBGLTRUU and LBUSTRUU/GREN recorded risk relationship levels below 1 in the first quarter of 2021, which means lower volatility of the green vs. conventional bond index. For these two pairs, the decrease in risk relationship was smoother than in other pairs.

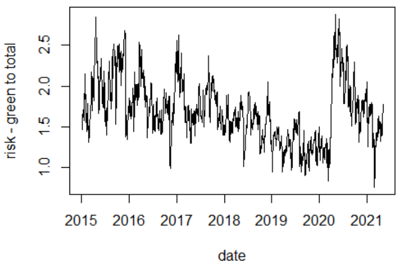
LBUSTRUU and GBGLTRUU



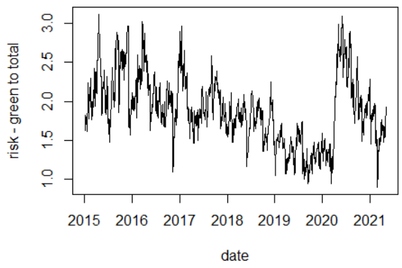
LBUSTRUU and GREN



SPUSBMIT and SPUSGRN



SPUSBMIT and SOLGREEN



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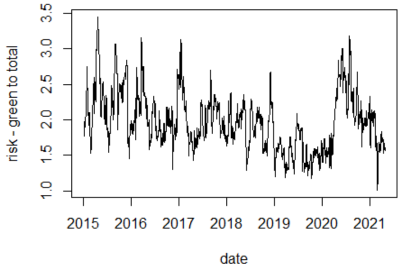

SPUSBMIT and GREN

Figure 3. Risk relationship between green bonds indices and their corresponding counterparts

Source: Authors' own study.

Discussion

The research of relationships between the values of green and conventional bonds' indices allows for the formulation of several generalizations. Are both markets related? It seems so, although the relationship appears to be quite casual. This is evidenced by the study of the conditional correlation, which may not reach very high values, but levels around 0.4 are observed. It can, therefore, be considered as a moderate degree of correlation. The study of the volatility of green bond indices against the volatility of conventional bonds leads to similar conclusions. The risk of green bonds is initially higher but tends to decrease to around 1 at the end of the analysed period. Finally, the analysis of the conditional variance dynamics of individual indexes shows a number of similarities. Therefore, we can accept the H1 hypothesis and conclude that the green and non-green bond markets are positively related. Our findings stay in line with Reboredo (2018) and Reboredo and Ugolini (2020). The observable volatility clustering and converging behaviour of pair of indices over time indicate similarities in research results with Pham (2016), Broadstock and Cheng, (2019) and Park et al. (2020).

It should be emphasized that all the tested parameters showed high variability in the analysed period. It is particularly visible in the study of conditional correlation and the values of conditional variance dynamics. This is important for the answer to the second research question regarding the similarity of risks in both markets and the stability of the relationships between them. The conducted research shows a clearly higher volatility of green bond indices. The risk of green bonds' indices is initially twice as high, although it decreases over time. Nevertheless, except for a few cases, it is generally higher than 1, which does not allow the recognition of the identity of the risk of both groups of instruments. This is also confirmed by the analysis of the conditional correlation. The level of correlation of the indices is moderate, but it is subject to strong fluctuations. On this basis, it can also be concluded that there is no

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stable risk relationship between these two markets. Rather, there is a convergence of the risk of green bonds with conventional bonds over time. The above observations allow us to accept hypotheses H2 and H3 and conclude that the green bonds market is riskier than the non-green one and that the risk relationship of both bond markets is changing. This indirectly might lead to the conclusion about greenium existence, which stays in line with previous findings of Partridge and Medda (2018) among others

The study of the volatility of green bond indices also shows that investors' activities in this market are more divergent. It is more difficult for them to interpret the information received and they make various investment decisions, some buy, some sell, which in turn is causing higher volatility. It might also indicate that they are more prone to flee from the green bond market and stay in the conventional bond market in times of market shocks. The observed risk changes in the face of the COVID-19 pandemic indicate limited investors' confidence in these instruments compared to conventional bonds. However, the volatility of indices of both types of bonds increases significantly in the first quarter of 2020, the comparison of volatility shows that the increase in volatility is significantly greater for green bonds. This could also be explained by the nature of green bond projects and their use of proceeds. They are largely financed by public entities, and these, in the face of high expenses supporting the economy struggling with a pandemic, may postpone investments, including environmental ones, which undermines the legitimacy of issuing green bonds. Of course, this does not mean a collapse in the solvency of issuers or public guarantors, but it may mean their reluctance to increase the attractiveness of the financing process. It should also be remembered that many green bonds obtain greenium due to the social importance of the implemented investments. In the event of turbulence in the financial market, especially as serious as related to COVID-19, the premium becomes less important as investors try to protect the value of their assets. If green bonds were bought with greenium, they will be subject to greater volatility in times of the bond market turbulences. On the other hand, green bonds funds are used to finance innovations, therefore the imbedded risk of their issuers is higher.

Based on the risk analysis only we can state that green bonds would be a better investment opportunity in times of market turmoil than conventional bonds for investors with lower risk aversion. As we can assume that together with increased risk the rates of return would be higher. Therefore, we accept H4.

Conclusions

Based on our findings we can conclude that the green bonds market differs from the conventional bonds market, but these differences tend to fade in the most recent period. The risk of both markets seems to converge over time, especially in the post-pandemic times. Similarly to other authors the results of our research show that spillover effects of both markets exists; and that the volatility is clustering, although

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higher volatility of green bonds is indicating a bigger risk of these instruments and ultimately potentially greenium existence.

The conducted research may contribute to the development of research on the principles of managing a portfolio of securities. It indicates the relationships that occur between different types of the same class of assets which can be relevant for the investors seeking alternative sustainable investment opportunities. Our findings can also be useful for financial managers of companies issuing green bonds. This is because that they show that greenium is highly sensitive to disturbances in the financial market, which may be important for the issue-planning process. Results are also relevant in the context of Modern Portfolio Theory proving inputs for portfolio optimization by potentially including green bond indices in the portfolio structure as instruments with different risk characteristics, especially during market turmoil.

The limitations of the study result from investigating aggregated and limited data, representatives of green bonds indices. The future research could be focused on analysis of individual issuers and the effectiveness of the projects using green bonds as the source of financing. Future studies could also focus on investors' preferences for choosing green bonds indices or individual instruments. Another stream of research could be dedicated to testing diversification features and optimization possibilities by constructing a portfolio in the market turmoil and in stable times including green bonds indices.

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