The Volatility of Green and Non-green Sovereign Bonds on the Emerging EU Markets

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Abstract:

Green finance is becoming increasingly important today, affecting many areas of the economy. In this regard, the examination of green bond markets is becoming more and more important, as various financial shocks have also led to significant changes in the financial markets and economic policy processes. However, only a few of these new financial assets were issued on the emerging EU market, therefore the side effects of them have not yet been fully explored. In addition, the rise of green finance is only in its infancy in smaller economies, in various financial markets, which may be important to monitor in future investment decisions. The aim of our study was to examine the volatility properties of green sovereign bonds of European small open economies for the period between 2016 and 2021, where we analysed how the differences of these green sovereign bonds to conventional sovereign bonds changed over time. Also, we wanted to test whether there was a possibility of a conditional volatility premium for green government bonds. To answer our research questions, we calculated conditional volatilities, and the green premiums towards their standard forms using GARCH models. Our result suggested that the Polish and Hungarian green sovereign bonds have higher volatility than the traditional ones, which is the opposite of the German experience.

Keywords: GARCH; Green Finance; Sovereign Bond Market.

JEL classification: C58; F30; G10; G15.

1 Introduction

In recent decades, advanced economies have become increasingly asset-centric on their financial habits, and the global warming, climate change and sustainability have been some of the most important challenges over the past few years. These two factors contributed to the emergence of green finance which have become one of the most popular investment opportunities on financial markets. According to Yu et *al.* (2021), the concept of a "low carbon economy" is based on low energy

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consumption and pollution and the so-called green finance was born out of the related financing needs, which have both public finance and capital market motives. Green finance can be briefly defined as a set of steps that mobilize financial resources to finance green investments and in other terms, we can also define it as climate finance based on the views of Khan *et al.* (2022), which requires projects, bond issuance, banks, carbon market instruments, fiscal instruments, monetary policy instruments, fintech, and community-based financing. For all these reasons, it is important to study the strong changes on these markets, their volatility, correlations and to analyse the mechanisms behind them, both in terms of the circumstances of the real sector and the situation of the national economy. Moreover, the study of credit markets is also important, because the changes and trends that can be identified in the bond market also affect the stock market, and some of its phenomena can also provide a forecast for the development of economic crises. However, the conclusions that can be drawn from these observations may be skewed by the fact that, through central bank quantitative easing programs, bonds have become one of the instruments of monetary policy enforcement (Mészáros and Kiss, 2020).

As the market of green bonds tends to expand, the range of studies on the effects and market behaviour about green bonds is growing, but there is no consensus on the size and direction of the green premium. Moreover, we were able to find a literature gap since the emerging EU markets are still at the infant state in case of green bond emissions and we have not found papers dealing with the volatility of sovereign green bonds. For this reason, our analysed sample consists of two CEE countries, Hungary and Poland, and the country of their benchmark sovereign bonds, Germany. The first two countries are European small and open economies with independent national currencies. In addition to the common features of these bonds, they have several differences, for example, in terms of their volatility premia (the green sovereign bonds are slightly more volatile than traditional bonds with similar maturities and EUR denomination). Also, the examination of bond market mechanisms in these countries is important because the initial success of sovereign financing can pave the way for future corporate green bond emissions.

The main goal of our research is to examine the Hungarian and Polish sovereign green bonds compared to their European benchmark. We focus on the following research questions:

- Which correspondence these two types (green and traditional) of sovereign bonds have in terms of their basic features?
- How similar is the volatility of green sovereign bonds to the volatility of standard sovereign bonds with the same maturity and conditions?
- Is there possibility of a conditional volatility premium for green government bonds? – which can show how certain the market was about their pricing.

In the context of the yield volatility differences due to the higher volatility of green bonds, we tried to check and discuss the appearance of "greenium" on the so far less studied sample. To answer our research questions, we examined the time series of weekly sovereign green bond yields where we calculated their green premiums towards their standard forms. Our aim is to present the evolution of green bond premiums in the sample countries for the period 2016–2021, during which several significant shocks affected the economy both regionally and globally. We estimated GARCH(p,q) models for each of the sample bonds by which we tested our pre-constructed empirical model. Our result show that green sovereign bonds (in EUR denomination) have higher volatilities than their traditional peers.

The enhanced importance of green finance contributed to the choice of our research topic, which appears in almost every field of the world economy and financial markets. The structure of the article is as follows: Section 2 summarizes the processes that can be captured in the green bond markets, and the results of prior literature about the main drivers of green bond premia and also contains our theoretical model. In Section 3 we present the examined database and the applied GARCH methodology, while Section 4 contains the empirical results of the model testing. In Section 5, we summarize the main findings of this research and the possible economic policy implications based on the results.

2 Literature Review

In this section we introduce the key role of sovereign bonds and the drivers of bond yields, highlighting the features and main definitions and prior research results about green bond markets.

Bond yields are determined by macroeconomic factors and specific factors related to these assets. Macroeconomic fundamentals (*e.g.*, interest rates, inflation, economic condition) play a key role in bond yields variances. After the 2008 global financial crisis, central banks' targeted purchases of long-maturity bonds and other long-duration assets (quantitative easing) play a significant role in term premia determination. Central bank asset purchases significantly affect the targeted bond markets by reducing liquidity risk on them. Bond yield also affected by the relative risk, that attributed mainly to credit risk (or default risk) and to liquidity risk (Favero *et al.*, 2010). Credit risk depends on investor assessments of the fiscal position as this affects the sustainability of the debt, that, in the case of a sovereign bond, is influenced by the country's public debt, fiscal policy, and current account. Liquidity risk is affected by the size of the market. In large bond markets, investors face a lower risk that prices will change due to individual transactions and therefore will demand less compensation in terms of the yield (Haugh *et al.*, 2009).

Bond prices reflect not only expectations, but also risks, therefore in addition to the risk-free yield, they should include some form of premium to encourage investment. There are various theories that explain differently what determines the direction and the size of the premium. For example, the liquidity preference theory is based on the fact that, due to the uncertainty of the future, investors prefer to tie up their capital for a shorter length of time, hence longer-term bonds are only purchased at a greater yield and premium. However, according to the preferred habitat theory, risk premium may also fall as maturity grows, because longer-term securities represent a smaller risk for investors with long liabilities – therefore they can also expect a premium for holding shorter-term assets (Veres, 2016).

Overall, the yield premium on bonds can be related to volatility if the investor demands a higher yield for the higher risk associated with greater volatility in the market price of an asset and if the investor does not plan to hold the bond to maturity because it can be sold at par maturity. Yield premium for increased credit risk is frequent in bonds and may be computed using a risk-neutral price and risk-free rate. The higher price and lower required yield of green bonds, which are frequently linked with a negative "greenium", are often justified by a better investor image and tax exemption as compared to a standard non-green bond (see subsection 2.2). In the line of this study, we use different view and we introduce the volatility premium as the difference between the conditional volatility of green and traditional sovereign bonds. Before that, however, we first review the special aspects of green bonds.

2.1 Main features of green bonds

As Deschryver and De Mariz (2020) determined, green bonds can be determined as financial instruments with fixed-income whose goal is to fund projects to the green conversion to a low-carbon economy. Regarding to the reports of ICMA, these are explained by their use of revenue limitation to finance, or refinance classified low-carbon assets and projects in green capital markets. Moreover, these types of bonds do not restrict the usage of proceeds only to green assets, but their conditions vary with pre-defined key performance measures and environmentally sustainable objectives (ICMA, 2021a; ICMA, 2021b; ICMA, 2021c, Deschryver and De Mariz, 2020). However, green bonds do not differ much from conventional bonds in regard to their characteristics. For example, green bonds (as conventional ones) are not revealed to the individual risk of green programs and works but they have appeal to the balance of the issuer and exposed to the same risk which is specified to the firm (Maltais and Nykvist, 2021; Hinsche, 2021). Their main expected benefits are that they provide some security against environmental risks, strengthen the issuer's reputation and social confidence, lower interest rates and higher exchange rates at the time of issuance, and a diversified and strong investor base. In the case of disadvantages, the limited scope of potential projects and the additional costs of qualification should be highlighted. In addition, we may not experience the expected benefits either: in the case of green bonds, the literature on green premiums is not uniform, which is precisely what makes their issuance disadvantageous (Dan and Tiron-Tudor, 2021).

The first green bond was issued by the European Investment Bank (EIB) in 2007, as a Climate Awareness Bond (EIB, 2022). Then, the first labelled green bond was issued by the World Bank in 2008 which was followed later by the first corporate issue in 2013, by the Swedish Vasakronan company and the Scandinavian Individual Bank (Deschryver and De Mariz, 2020). However, green bond market is young and green bonds represent a marginal part of the overall range of bonds, but investors' demand for them is strong and their market is expanding. Mentioning some differences, most green bonds have longer maturity than conventional ones – average of 12 years compared to conventional bond's average maturity of 10 years. This can be explained by the fact that the main goal of green bonds is to finance projects to support environmental sustainability, which usually means long-term investments (Flammer 2020; Hinsche 2021). As Hinsche (2021) listed in her recent study, in terms of denomination, the majority of green bonds are issued in EUR, which is followed by USD and the biggest issuers of these bonds are entities from the public and financial sector, as well as energy providers. She also mentioned that in the case of Europe, group of issuers from the public sector is even more notable – where the leading issuers are sovereigns, and the largest investors are investment funds, insurance companies, credit institutions and pension funds. It is notable that the biggest issuers according to the total outstanding issuance volume are located mostly in France and Germany. Moreover, another important investor is the European Central Bank (ECB) by the green bond purchasing programs called green quantitative easing (QE).

Several recent studies have dealt with different aspects of these bonds, for example Pham and Nguyen (2021) analysed the impacts of stock market and oil volatility, and economic policy uncertainty on green bond returns, on a sample of four leading green bond indices. Their model contained the VIX, OVX and EPU indices as uncertainty indices and their outcomes showed that the linkage between green bonds and market uncertainty is time-varying and state-dependent. Their main finding was that green bonds can be used to hedge against uncertainty during low uncertainty periods because in this case the connection between these types of bonds and uncertainty is low. Hung (2021) also investigated the links between green bond and conventional asset classes (namely Bitcoin price, main stock market indices and 10-year US bonds) for the interval from May 2013 to December 2019. His findings proved that there is a conditional time-varying dependence between them, and this reliance is relatively small. In a study of Bremus *et al.* (2021) the ECB's green asset purchasing program (APP) and the pandemic emergency purchasing program (PEPP) were analysed and their results showed that these programs affected green corporate bond's financing conditions in a significant positive way. Their research also showed that the corporate sector purchasing program (CSPP) decreased the examined green bond yields more than the ineligible green bonds, which demonstrates the strong effect of ECB's green QE.

The rapid growth of the green bond market has been mainly the result of macroeconomic growth and development of institutional environments and unique factors in the green bond market. The government's sovereign green bond issuance plays a key role in this growth as stated in the following features listed by the Climate Bonds Initiative (2018): (i) Finance: the main reason for green sovereign bond issuing is the ability to finance projects with positive environmental impact, such as renewable energy and green infrastructure. (ii) Signalling: a sovereign green bond can signal the country's commitment to its sustainable growth strategies, which would have a positive impact on the private sector investment case for green sectors. The government can use the green bond issuance as a promotional tool, to reinforce its sustainability agenda or to announce policy shift to sustainable economy. (iii) Tracking spending: Issuing a green bond can improve government tracking of climate-related and sustainable expenditure. (iv) New and diverse investors: the issuance helps the diversification and attracts new, socially and environmentally responsible investors. For emerging economies, increasing and diversifying the investor base could be a key benefit. (v) Price advantages: high demand for green bonds and increasing investor base may result in a reduction in the risk premium. (vi) Market creation: government bonds have a benchmark role in the domestic debt markets, sovereign green bonds can support the market's further development. Issuing sovereign green bonds can provide liquidity for a new green bond market. Sovereign issuers can serve as role models for other types of issuers. (vii) Capital mobilization: government participation in the green bond market can catalyse private sector funds into low-carbon and climate-resilient investments (Climate Bonds Initiative, 2018).

The causes of the climate crisis are rooted in our global socio-political-economic system, so actual solutions need to consider all three aspects. Thus, central bank can also play a role in developing an appropriate green sustainability strategy. One of the reasons why it has become important to integrate environmental protection into economic policy is that climate change may have a serious impact on the future stability of the financial system, which Dafermos *et al.* (2018), Aglietta and Espagne (2016) or Scott et *al.* (2017) highlighted. Using an ecological macroeconomic model related to stock flows, Dafermos *et al.* (2018) also analysed the effects of green quantitative easing on financial and global warming, identifying two significant financial risks. The first type, the so-called temporary risks, are associated with the revaluation of carbon-intensive assets because of the shocks associated with the transition to a low-carbon economy. The second type is physical risks related to the economic damage caused by climate-related events. Their estimates for the period 2016–2020 provide several important findings with the conclusion that implementing a green corporate QE program can significantly reduce financial instability caused by climate change, which can be supported by a strong green sovereign bond market.

2.2 Green bond premium – "greenium"

The principles and standards of green bond principles are important mechanisms for advertising green finance. Since the introduction of the Green Bond Principles by the ICMA in 2014, labelled green bonds have become popular fast. Various green bond indices have also been offered to take more diversified position in green bonds for a large range of investors. The practice proposes that investors place value on the green label at the time of their first appear on the market, despite the post-issuance financial performance of green bonds is worthy to comparison with that of conventional bonds (Ehlers and Packer, 2017). Since the first green bonds appeared in 2007, their market has globally expanded and nowadays these are popular investment opportunities to fund environmentally friendly companies and projects. The fundamental risk factors of traditional and green bonds are similar for the same issuers (*e.g.*, default risk and liquidity risk). This is reinforced by the results of Wulandari *et al.* (2018) who found that liquidity risk is negligible in the case of green bonds. Most of the empirical studies have found that there is a difference between the conventional and green bonds yields. In that case, if this premium (the difference between conventional bond yield and green bond yield) is negative, it has been labelled as a "greenium" in the literature (Löffler *et al.*, 2021). The existence of greenium means that the green bonds are traded at a lower yield/higher price compared to similar conventional bonds (*e.g.*, Baker *et al.*, 2018).

There are two theoretical explanations that the yield on green bonds may be lower than that on traditional bonds. First, investors accept lower yields due to the bond's green nature. For example, this behaviour may stem from social or environmental commitments toward green goals or the green responsibility of public relations. These instruments are relevant to finance green projects, investors' portfolio diversification and companies' more socially responsible image (Wadhwa, 2020). The second paradigm is based on asset pricing theory. For instance, the regular monitoring of green bond issuance may also decrease the default risk compared to traditional bonds and the fact that traditional bonds have long-term climate change risks (*e.g.*, carbon tax or effects from environmental damage) explain the greenium. These calculations are supported by the findings of Löffler *et al.* (2021) showing that green bond yields are 15–20 bps smaller but more volatile than comparable conventional ones. They found two possible explanations for the question why green bonds have a lower yield than their counterparts. One of them is that the lower yields of green bonds can be clarified by their less underlying risks. The second reason which is proposed in the literature is that institutional investors are ready to pay a premium price for the bond's green mark because of their environmentally-safe attitude. Given that green bond issuers are less likely to have a credit rating and that green bonds are more likely to be senior unsecured debt, the second hypothesis appears to be more reasonable due to their opinion.

In this context, as the Liaw (2020) introduced green bond premium as the premium on green rated bonds, which is likely to stem from demand anomalies (or higher risk expectations). Compensating for a reduction in the green premiums offset by credit ratings, tax benefits and a green investor focus. In this respect, the literature also suggests differences between sovereign, financial and corporate issuers. Especially because of the size of the issue and the presence of ETFs, the interest rate environment and the legal framework also add to the change in the bond market (Dan and Tiron-Tudor, 2021). Liaw (2020) analysed the literature separately and found completely contradictory results. Several authors completely rule out or minimize the potential for a green premium, while a much larger portion found significant spreads when looking at average time, liquidity premium, or bid-ask spread. In addition, there were negative premiums for sovereign and financial issuers. From this, he concluded that any green surcharges revealed so far in the literature could be attributed to the sampling period, issuer, and test procedure, respectively. Different results show that there is no consensus in the empirical research about the size and the direction of the green bond premium. In an earlier study, Preclaw and Bakshi (2015) justified a significant average green bond premium around –17 bps and they showed that the greenium rises over time. According to Larcker and Watts (2020) who compared green US municipal bonds to nearly identical conventional ones, the greenium is essentially zero. In contrast, Partridge and Medda (2020) identified a green premium in the US secondary market, but no significant premia in the primary market. Even beyond the US municipal bond market, several authors find no significant greenium. For instance, Hachenberg and Schiereck (2018) find no significant greenium, even though they detect a tendency for green bonds to trade tighter. Hyun *et al.* (2020) also could not find green bond premium, unless the green bond was certified. Meanwhile, Karpf and Mandel (2018) found positive premium up to 7.8 bps. Wadhwa (2020) suggests that green bonds had an investor premium and issuer discount historically. Zerbib (2019) investigated the yield differential between a green bond and an otherwise identical synthetic conventional bond for the period July 2013 to December 2017. By using matching method and a two-step regression he proved a small negative premium, as the green bond yield was lower than the yield of a conventional bond.

According to Baker *et al.* (2018), the size of the greenium ranged from –5,7 bps to –8,2 bps. Germany issued traditional and green sovereign bonds (twin bonds) with the same maturity and coupon rate in September 2020 and according to Löffler *et al.* (2021) the green version of the bond was trading at a 2 bps lower yield to maturity in the secondary market. It is indicating that investors accept a lower yield because of the green label. Agliardi and Agliardi (2019) argue that the size of the greenium in the secondary market is positively affected by the volatility of asset prices, bond financed green technology effectiveness and negatively affected by lower corporate tax rates. Bachelet *et al.* (2019) proved the existence of greenium for institutional issuers, but positive premium for private bonds. Hinsche (2021) also found the existence of the greenium in the public green bond market and her results justified that this varies with issuer sector and credit rating, but the asset type, issue size, and duration have not influenced them significantly (like the previously mentioned papers of Kapraun *et al.*, 2021; Zerbib, 2019; or Hachenberg and Schiereck, 2018).

Based on the literature presented in this section, although the number of studies examining green bond premiums is growing, small European countries have not yet been analysed in this regard, while also empirical research on the volatility is missing. Therefore, it is worth examining the green sovereign bond differences of our chosen CEE countries.

3 Data and Methodology

In this section we introduce what motivated the calibration of the theoretical model, list the examined bond and the dataset, and enclose the chosen method.

3.1 Theoretical model

For the model building process, we started from that climate risks can have two kinds of influence on the financial assets. First, the increase of harmful events can increase risk levels. Second, adaptation to the changing environment (both literally and institutionally) can have a transitional effect, which can also increase pricing uncertainties. Therefore, this article analyses the conditional volatility of green sovereign bonds and their traditional counterparties on a sample of emerging EU member states to see how market accepted the first issuance of these financial assets. In case of both the risk premia and the conditional volatility is higher, we can expect that the green bond market is still in the state of its infancy and if there are more uncertainties for a country to tap these financing sources, companies will be even more cautious.

3.2 Data

The analysis focuses on the sovereign green bonds from the Visegrad countries. Since only Hungary and Poland issued such assets and provided weekly data through the Eikon database, we analysed these markets with their German counterparts. We paired each individual sovereign green bond with its traditional pair, with similar maturities and EUR denomination (Tab. 1).

Tab. 1 Individual bonds with different maturities and trading weeks (EUR denomination)

Country	Sovereign (S) bonds		Sovereign Green (SG) bonds	
Poland	5Y (*N* = 251)	10Y (*N* = 208)	5Y (*N* = 261)	8Y (*N* = 208)
	10Y (*N* = 151)	30Y (*N* = 151)	10Y (*N* = 151)	
Hungary	12Y (*N* = 86)		15Y (*N* = 86)	
Germany	5Y (*N* = 30)	10Y (*N* = 73)	5Y (*N* = 30)	10Y (*N* = 73)
	10Y (*N* = 30)	30Y (*N* = 30)	10Y (*N* = 30)	30Y (*N* = 30)

Source: Authorial computation based on data from Refinitiv EIKON.

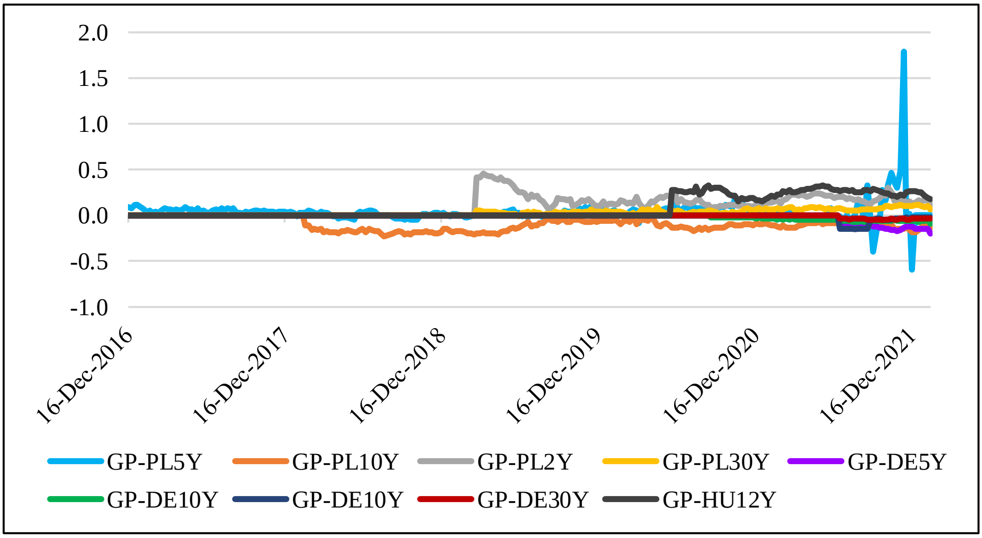
The Polish and the German market had bonds with 5, 10 and 30 years of maturities, but the Hungarian had only one, with 12 years of maturity (there were two other in HUF denomination and three in JPY denomination, but they were excluded later due to their missing counterparts in the rest of the countries). There were only several corporate green bond data available from these countries, but only two in EUR denomination from Poland and none from Hungary, therefore they were excluded as well.

Fig. 1 shows the sovereign green premia (GP), that is the difference between the yields of green bonds and the yields of conventional bonds. Green bonds had a positive premium mostly, except in the case of the 10Y Polish and the long-term German bonds, highlighting that market still considers them to be riskier assets and does not recognize their long term positive transitional influence; or maybe they were too unique on the market and their depth is still weak.

3.3 Methodology

Volatility is time variant what represented by the heteroscedasticity as high and low volatile periods. Such persistence can be captured by different GARCH models, since they can be fitted to estimate conditional (time-variant) standard deviations (Cappeiello *et al.*, 2006; Kiss and Schuszter, 2014). This article uses GARCH (*p*,*q*) models to analyse the differences among the conditional volatilities among the green and traditional sovereign bonds. Student-*t* distributed residuals were used to manage the apparently higher kurtosis of the sample (which can be the result of both the

Fig. 1 Sovereign green premia (in %)



Source: Authorial computation based on data from Refinitiv EIKON.
Note: DE – Germany, HU – Hungary, PL – Poland.

novelty and the short lifetime of the asset class). Using weekly data still provided enough heteroskedasticity in the dataset but simplified database synchronisation. Since conditional volatility can be affected by the increase or decrease of the yields (if this happens, they are asymmetric), the model included not just the traditional GARCH(*p*,*q*) but the asymmetric GJR-GARCH(*p*,*o*,*q*) and the TARCH(*p*,*o*,*q*) models under *p* = 1:2, *o* = 0:1, *p*1:2 constraints, as well as an APARCH (1,1,1) model; formulas (1) through (4). The best fitting model was selected if its standardized residuals were homoscedastic and provided the lowest BIC values. The following GARCH(*p*,*q*), GJR GARCH(*p*,*o*,*q*), TARCH(*p*,*o*,*q*) and APARCH(*p*,*o*,*q*) models can be useful to capture volatility developments and their clustering in time (heteroscedasticity).

$$\sigma_t^2 = \omega + \sum_{i=1}^{p} \alpha_i \, \varepsilon_{t-i}^2 + \sum_{j=1}^{q} \beta_i \, \sigma_{t-j}^2 \tag{1}$$

where σ_t^2 represents present variance, ω is a constant term, p denotes the lag number of squared ε_{t-i}^2 past innovations with α_i parameters, while q denotes the lag number of past σ_{t-j}^2 variances with β_i parameters to represent volatility persistence.

Asymmetric GARCH models can be introduced via

$\begin{cases} S_{t-i}^{-} = 1, if\ \varepsilon_{t-i} < 0 \\ S_{t-i}^{-} = 0, if\ \varepsilon_{t-i} \geq 0 \end{cases}$, as a sign asymmetric reaction to decreasing returns (volatility increases if the return is positive or negative).

GJR GARCH (*p*,*o*,*q*):

$$\sigma_t^2 = \omega + \sum_{i=1}^{p} \alpha_i\ \varepsilon_{t-i}^2 + \sum_{i=1}^{o} \gamma_i\, S_{t-i}^{-} \varepsilon_{t-i}^2 + \sum_{i=1}^{q} \beta_i\, \sigma_{t-i}^2 \qquad (2)$$

TARCH (*p*,*o*,*q*):

$$\sigma_t = \omega + \sum_{i=1}^{p} \alpha_i |\varepsilon_{t-i}| + \sum_{i=1}^{o} \gamma_i S_{t-i}^{-} |\varepsilon_{t-i}| + \sum_{i=1}^{q} \beta_i\, \sigma_{t-i} \qquad (3)$$

The Asymmetric Power Arch applies a δ index parameter that can be between 1 and 2 and this model represents other, more regular models according to Ding *et al.* (1993), but it is able to calibrate the power-parameter and the asymmetric tendencies in the volatility as well.:

APARCH (*p*,*o*,*q*):

$$\sigma_t^{\delta} = \omega + \sum\nolimits_{i=1}^{p} \alpha_i (|\varepsilon_{t-i}| - \gamma_i \varepsilon_{t-i})^{\delta} + \sum\nolimits_{j=1}^{q} \beta_j \sigma_{t-j}^{\delta} \qquad (4)$$

where $\alpha_i > 0$ $(i=1,\dots,p)$, $\gamma_i + \alpha_i > 0$ $(i=1,\dots,o)$, $\beta_i \geq 0$ $(i=1,\dots,q)$, $\alpha_i + 0{,}5\ \gamma_j + \beta_k + < 1$ $(i=1,\dots,p,\ j=1,\dots,o,\ k=1,\dots,q)$.

Where $\delta > 0$ coefficient balances between TARCH and GJR GARCH specifications, $-1 < \gamma_i < 1$ coefficient and *o* parameter represents negative news impact on volatility, p parameter represents the lags of news and q parameters volatility persistence.

This analysis focuses on the model selection (GARCH model seems to be less risky), the level of the beta (volatility persistence) and the relative levels of the conditional volatility between the green and traditional bond. Higher volatility can adversely affect green assets' demand due to their higher option fees or biased value-at-risk thresholds.

4 Results and Discussion

Both the green and the traditional sovereign bonds showed the usual characteristics of the financial time series: their first differentials had zero mean and no unit root

Tab. 2 Basic statistics of the time series

Bond	Mean	Std	Skewness	Kurtosis	Jarque-Bera (*p*)	Ljung-Box (*p*)	ARCH-LM (*p*)	ADF (*p*)
SG-PL5Y	0.00	0.15	–4.36	99.93	0.00	0.00	0.36	0.00
SG-PL8Y	0.00	0.05	2.54	24.15	0.00	0.00	0.00	0.00
SG-PL10Y	0.00	0.06	1.59	11.77	0.00	0.00	0.01	0.00
SG-PL30Y	–0.01	0.04	0.45	8.33	0.00	0.00	0.00	0.00
SG-DE5Y	0.00	0.06	–1.43	7.28	0.00	0.82	0.93	0.00
SG-DE10Y	0.00	0.06	–0.44	3.88	0.13	0.19	0.37	0.00
SG-DE10Y2	0.01	0.07	–0.29	3.27	0.84	0.03	0.05	0.04
SG-DE30Y	0.00	0.07	0.35	2.29	0.51	0.01	0.01	0.04
SG-HU15Y	0.00	0.06	–1.07	6.39	0.00	0.01	0.03	0.00
S-PL5Y	0.00	0.06	2.88	32.35	0.00	0.31	0.64	0.00
S-PL10Y	0.00	0.05	2.09	16.21	0.00	0.00	0.00	0.00
S-PL10Y2	0.00	0.05	3.06	25.34	0.00	0.00	0.01	0.00
S-PL30Y	–0.01	0.04	0.30	6.36	0.00	0.00	0.00	0.00
S-DE5Y	0.01	0.06	–1.39	6.96	0.00	0.83	0.91	0.00
S-DE10Y	0.00	0.06	–0.47	4.21	0.05	0.16	0.35	0.00
S-DE10Y2	0.01	0.06	–0.59	3.95	0.36	0.13	0.20	0.02
S-DE30Y	0.00	0.07	0.35	2.31	0.51	0.01	0.00	0.05
S-HU12Y	0.00	0.05	–0.79	6.46	0.00	0.00	0.00	0.00

Source: Authorial computation, using Matlab 2021b.

(ADF-test $p < 0.05$), but they were asymmetric and showed fat-tailness with a plenty of autocorrelation (Ljung-Box test $p < 0.05$) and heteroscedasticity (ARCH-LM test $p < 0.05$). Therefore, the estimation of GARCH-models are justified and the more frequent appearance of extreme fluctuations (kurtosis > 3) underlines the usage of Student-*t* residuals (Tab. 2).

After the estimation process following Cappeiello *et al.* (2006), only the GARCH(p,q) model was selected,[1] mainly with the simple $p = 1$, $q = 1$ configuration (only the 5Y German green bond had better fit with a $t = 2$ alpha shock parameter). Despite the traditionally expectable high beta values (which would be the sign of the volatility persistence), green bonds had lower betas in 4, similar in 3 and higher in 2 cases. It suggests that their volatility can be more the subject of the underlying fat-tailed data generating process (the shocks or innovations, represented by the alpha coefficient) than their previous value, which make them less likely to "stuck" in a "high" or "low" volatility state. This persistence is still there, just the tendency seems to be smaller.

Tab. 3 GARCH(*p,q*) parameters

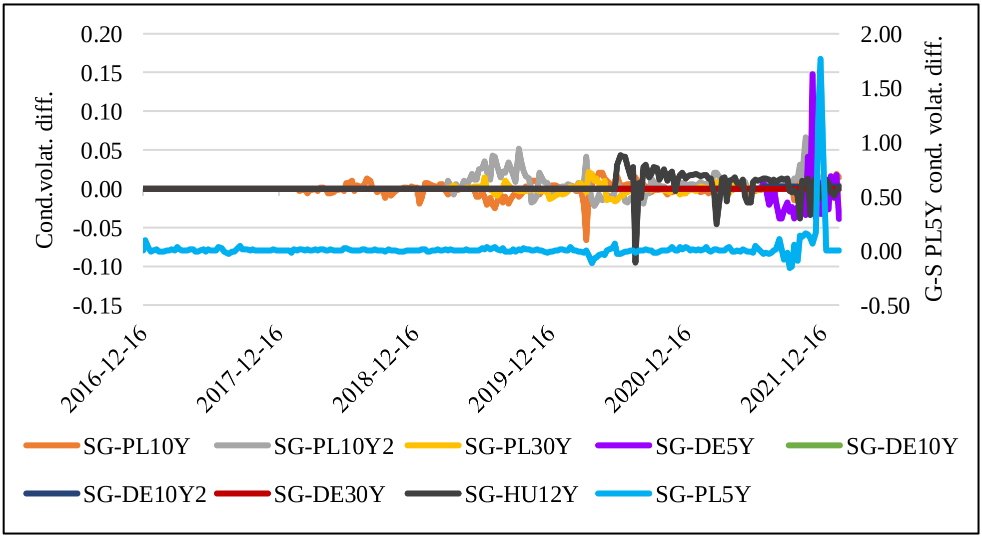
Bond	Const.	Alpha *t*-1	Alpha *t*-2	Beta *t*-1	nu
SG-PL5Y	0.00	0.86		0.14	3.26
SG-PL8Y	0.00	0.35		0.65	3.14
SG-PL10Y	0.00	0.44		0.56	4.41
SG-PL30Y	0.00	0.34		0.66	4.09
SG-DE5Y	0.00	0.00	1.00	0.00	3,858.70
SG-DE10Y	0.00	0.00		1.00	37.72
SG-DE10Y2	0.00	0.00		0.00	23.10
SG-DE30Y	0.00	0.00		0.00	10,002.00
SG-HU15Y	0.00	0.00		0.93	3.61
S-PL5Y	0.00	0.58		0.42	4.17
S-PL10Y	0.00	0.44		0.56	3.69
S-PL10Y2	0.00	0.32		0.68	3.59
S-PL30Y	0.00	0.30		0.70	4.40
S-DE5Y	0.00	0.00		0.49	2.92
S-DE10Y	0.00	0.00		1.00	15.29
S-DE10Y2	0.00	0.00		0.00	9.31
S-DE30Y	0.00	0.00		0.00	3,855.95
S-HU12Y	0.00	0.50		0.04	4.56

Source: Authorial computation, using Matlab 2021b.

[1] Based on the lowest BIC value of the selected model and the homoscedasticity of the standardized residuals.

Our third research question focused on the possible presence of differences between conditional volatilities (meaning that the market is less sure about their pricing) for the green sovereign bonds. While in the Polish (5Y: 73%, 8Y: 47%, 10Y: 79%, 30Y: 43%) and Hungarian (10Y: 76%) cases it was quite clear, it was completely the opposite in Germany (5Y: 27%, 10Y: 15%, 10Y: 100%, 30Y: 0%) (Fig. 2). The market reacted similarly to the bad news of rising inflation at the end of 2021, meaning that the green bonds are also the subjects of such effects.

Fig. 2 Difference between the cond. volat. of green and traditional sovereign bonds



Source: Authorial computation, using Matlab 2021b.

5 Conclusion

Climate change will challenge both the economy and the society in the next decades; therefore, no government can assume its independence from these adverse effects. This transition can introduce both negative and positive effects on the climate shock – economic innovation scale. This procedure can be accelerated from green financial sources through targeted institutional changes. Many new green financial instruments are appearing on different markets and it is interesting to compare how different these are from traditional financial assets in addition to their green characteristics. Following this line, our study analysed the market acceptance of the first green sovereign bonds in two emerging EU member states, Poland and Hungary. These were compared with the more mature German market, as their benchmark green market. Our investigation focused on the difference between the yields of green bonds and the yields of conventional bonds – as a green premium. In order to reveal the specifics of these markets, we examined the time series of weekly sovereign green bond yields where we calculated the green premiums towards their standard forms, and we also checked the volatilities of the sample bonds by applying GARCH(p,q) models. Our results showed that green sovereign bonds have higher volatilities than their traditional ones which indicates that the market is still suspicious at this infant state and these assets reacted more on the shocks (this can mean that the market has not recognized the long term positive transitional influence yet). However, these differences were not that high, meaning that a deeper green bond market can have similar (although possibly not better) statistical characteristics like to the traditional one. Unfortunately, the regional corporate bond market was too narrow already, so it was not possible to make similar comparisons among the sample markets. As a future research direction, it would be interesting to further analyse the investigated green bond markets, including the factors that can drive the changes of green bond prices and yields.

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