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Climate Transition Risk and the Impact on Green Bonds

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Abstract: The green bond market develops rapidly and aims to contribute to climate mitigation and adaptation significantly. Green bonds as any asset are subject to transition climate risk, namely, regulatory risk. This paper investigates the impact of unexpected political events on the risk and returns of green bonds and their correlation with other assets. We apply a traditional and regression-based event study and find that events related to climate change policy impact green bonds indices. Green bonds indices anticipated the 2015 Paris Agreement on climate change as a favorable event, whereas the 2016 US Presidential Election had a significant negative impact. The negative impact of the US withdrawal from the Paris agreement is more prominent for municipal but not corporate green bonds. All three events also have a similar effect on green bonds performance in the long term. The results imply that, despite the benefits of issuing green bonds, there are substantial risks that are difficult to hedge. This additional risk to green bonds might cause a time-varying premium for green bonds found in previous literature.

Keywords: green bonds; event study; climate regulatory risk; sustainable investment

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1. Introduction

This paper investigates how green bonds are affected by unexpected political events related to climate change. We find that over the period July 2014 and November 2021, green bonds significantly outperform conventional bonds in terms of returns. We further find that the 2016 US presidential election (USPE) has a significant negative impact on bonds in general and green bonds in particular. Other unexpected political events, such as the 2015 Paris Agreement (PA), have a positive and significant impact on green bonds and no significant impact on conventional bonds.

Green bonds (GB) were introduced by the European Investment Bank in 2007 as an instrument with a purpose to finance projects with an environmentally friendly profile; see, for example, Horsch and Richter (2017), Zhang et al. (2019) and Nguyen et al. (2020). A GB is a fixed-income instrument specifically earmarked to raise money in the debt markets for climate and environmentally friendly projects. These bonds are typically asset-linked and backed by the issuing entity's balance sheet, so they usually carry the same credit rating as their issuers' other debt obligations. GBs are designated bonds intended to encourage sustainability and to support climate adaptation and mitigation.

The green bond market has grown in popularity, and not without reason: according to Chambwera et al. (2014), mitigation and adaptation to climate change require significant investments of $70–100 billion per year to ensure sufficient adaptation in major sectors until 2050. Bonds are suitable financial vehicles for these purposes because they have an inter-temporal basis and let the issuer pay back the raised capital over time. This is one reason why climate finance researchers suggested an introduction of a climate bond in the first place. According to Flaherty et al. (2017), easing the investment burden for the current generation while implementing climate-change policy can be more easily carried out using GB. It means that GB has an important role in the transition to a low-carbon economy.

Long- and short-term climatic trends include changes in the distribution of temperature, precipitation, and cloudiness. Observational studies have found that temperature increases over time, with an increase in all regions on Earth and with an increase in the level, variability, and drivers of the level of temperature; see, for example, Storelvmo et al. (2016), Yuan et al. (2021), and Kotz et al. (2021).

Precipitation, on the other hand, shows more heterogeneous trends, with dry areas getting dryer and wet areas getting wetter; see Gulev et al. (2021) for a thorough treatment of the matter. The change in climatic trends has, in general, a profound impact on economies and financial markets around the world, see Burke et al. (2015), Campiglio et al. (2018), Sarkodie et al. (2020), and Bartram et al. (2021), and on the banking sector in particular, see Duqi et al. (2021). Moreover, Bolton and Kacperczyk (2021) find that investors are already demanding compensation for carbon emissions. Exposure to climate risk restricts access to finance in general (Ginglinger and Moreau 2019). Higher exposure to such risk leads to higher cost of debt (Kling et al. 2021), lower credit ratings, and higher yield spreads (Seltzer et al. 2021) because such companies are perceived as more likely to default (Capasso et al. 2020). In our paper, we investigate how unexpected political events related to transitioning countries and economies towards lower carbon emissions affect the green bond market.

Low-carbon transition is seen as a way to reduce climate change's impact on the economy and planet. This process is expected to induce transition risks in addition to physical ones stemming from the climate change itself. Although both are important, this paper's focus is on the former. The reason is that firms feel less exposed to physical risk, which is expected to materialize in the more distant future (Sakhel 2017). Transition climate risks include a regulatory risk that comes with an introduction of and adjustments to climate policy, either global or local. Companies are more concerned about regulatory risk because its impact could lead to additional expenses or changes in expected growth that should be priced.

With the strong link that GB has to climate and the environment, we hypothesize that GB's price is affected by events related to environmentally sensitive issues, such as climate change and political legislation and regulations on the matter. Mitigation and adaption to climate change have been on the political agenda for a few years, though there are few globally recognized regulations and limitations on, for example, greenhouse gas emissions. Often, regulatory changes are long processes with lengthy negotiations. According to the efficient market hypothesis (see Fama 1970; Tran and Leirvik 2019), any regulations that impact a firm or industry are reflected in the asset prices. For this reason, we investigate how abrupt and *unexpected* political events affect the prices since such events are hard to account for before the event. Building on the previous literature, we focus on three events: the Paris agreement, the 2016 US presidential election, and the US withdrawal from the Paris agreement, and find that all three significantly affect the bond markets.

The green label attracts investors interested in or focused on socially responsible investments (SRI) and investors who want to diversify portfolios, as highlighted in Nguyen et al. (2020). Green bonds widen the choice for SRI investors since they can invest in a project and not in the company itself (Shishlov et al. 2016). The demand for green bonds is high, increases every year, and continues to rise, according to Banga (2019). Thus, green bond investors must understand the risks inherent in the prices.

We argue that green bonds might have an uncompensated advantage since they offer higher returns with lower volatility. However, as we show, there is significant political risk tied up in the prices of GBs, which might be the reason why the premiums found by Zerbib (2019) changes over time.

So far, the impact of climate risk has been mostly studied on the stock market with an emphasis on carbon risks (Bolton and Kacperczyk 2021; In et al. 2019; Kumar et al. 2019) and attention paid to climate-related policies events (Antoniuk and Leirvik 2021; Birindelli and Chiappini 2021; Diaz-Rainey et al. 2021; Koch et al. 2016; Monasterolo and de Angelis 2020; Ramadorai and Zeni 2019). This paper is among the first to apply an event study on green bonds. This work is complementary to Seltzer et al. (2021), which looked at the effect of climate regulatory risk on conventional corporate bonds, while ours investigates green corporate bonds and extends the analysis to municipal bonds and the secondary bond market.

2. Literature Review

We consider two strands of literature that are related to our research. The first covers green bonds, and the other is related to studies on climate regulation.

2.1. Green Bonds

Earlier studies looked at the definition of green bonds, general market trends (Kochetygova and Jauhari 2014), and barriers for its further development (Clapp 2014). Later research focused on GB performance, how GBs are different from conventional bonds, and how they are related to other assets.

The differences between green and conventional bonds have received much attention. The research interest is a green premium, or *greenium*, a negative yield difference between green and conventional bonds, which causes GBs to have a higher price. Zerbib (2019) finds that GBs have a negative premium compared with conventional synthetic bonds of the same issuer in USD (Euro). This implies that they trade on a discount compared to comparable bonds. This discount, however, is different for bonds with a credit rating lower than AAA. Zerbib (2019) shows that this premium of -2 bp is *neither a risk premium nor a market premium*, and thus it could be related specifically to green bonds. A negative premium was also found by Immel et al. (2021). Partridge and Medda (2020) show that greenium exists for municipal bonds, while Fatica et al. (2021) conclude that financial issuers have a higher GB yield. Larcker and Watts (2020) suggest that green and non-green municipal bonds are seen as substitutes when risk and payoff are held constant. Overall, according to MacAskill et al. (2020), a green premium is found within 56% of primary and 70% of secondary market research papers.

Wulandari et al. (2018) find that GBs are more liquid, and Nanayakkara and Colombage (2019) find that the yield spread is tighter for bonds issued in local currency. Karpf and Mandel (2018) argue that the liquidity premium for green bonds is time-varying and that the premium was negative only until 2015 and positive later. Bachelet et al. (2019) find that the GB premium is positive and about 2.09–5.9 bp but claim that correction for liquidity and issue type solves the premium puzzle. Tsoukala and Tsiotas (2021) find that GBs are riskier than conventional bonds in terms of value-at-risk and conditional value-at-risk.

GBs are correlated with corporate bonds (Horsch and Richter 2017); moreover, this co-movement has a time-varying character: Broadstock and Cheng (2019) find that it was negative before 2014 and became positive after. Green bonds correlate negatively with VIX and the US dollar index (Horsch and Richter 2017; Reboredo and Ugolini 2020), making them a good tool for diversification (Ehlers and Packer 2017), i.e., by reducing the total risk of a portfolio. GB is also connected and dependent on corporate and treasury bonds (Reboredo et al. 2020), commodities (Naeem et al. 2021; and especially oil by Kanamura 2020), clean energy (Nguyen et al. 2020), and carbon futures (Hung 2021; Jin et al. 2020).

Recent studies have looked at the impact of COVID-19 on this connectedness and found that it has become more prominent (Arif et al. 2021; Bouri et al. 2021; Naeem et al. 2021). COVID-19 has also affected bond market efficiency, but the green bond market is more efficient than the conventional one (Naeem et al. 2021).

2.2. Climate Regulation

The impact of the climate-related policies was mostly studied for the stock market. The overall conclusion was that these policies affect market prices. Not only does the introduction of new policy cause reaction on the market, it also affects its timing. Adopting earlier climate policies helps to avoid shocks in asset pricing (Battiston et al. 2017), while introducing policies during low market sentiment or attention can lead to price decrease and volatility increase on the emission market (Deeney et al. 2016).

Some studies look closer at specific events related to climate change. Birindelli and Chiappini (2021) find that only EU high-score firms reacted positively to the Paris agreement, but all companies had an extensive negative wealth effect after it. After this event, the correlation between low-carbon and carbon-intensive indices became lower, and investors started to consider an opportunity to invest in low-carbon assets (Monasterolo and de Angelis 2020).

The 2016 US Presidential election's impact on the stock market was evaluated for fossil and oil companies (Diaz-Rainey et al. 2021), for different types of energy companies (Mukanjari and Sterner 2018), and for other sectors that are climate-sensitive (Antoniuk and Leirvik 2021). All of them found a non-positive reaction to the election results. The only companies with gain in returns are those with large deferred tax liabilities (Wagner et al. 2018).

These events were only touched in few studies on the bond market. Seltzer et al. (2021) studied corporate bonds and found that differences in credit ranking and the yield spread between companies with poor and rich environmental profiles were more prominent after the Paris agreement, with some reversal after the US pullout from the agreement. The Paris agreement also played an important role in the green bond market in general by significantly affecting its growth (Tolliver et al. 2020a) and increasing green bond allocation to renewable energy (Tolliver et al. 2020b).

3. Materials and Method

In this paper, we apply daily prices for July 2014–November 2021 for a sample of green bond indices available from S&P. They include:

GB: S&P Green Bond Index, which tracks the global green bond market and includes only bonds whose proceeds are used to finance environmentally friendly projects.

GB S: S&P Green Bond Select Index, which is a market-value-weighted subset of the GB bonds issued globally, subject to stringent financial and extra-financial eligibility criteria.

Muni GB: S&P Municipal Green Bond Index, which tracks the US green municipal bond market.

Additionally, we consider the S&P International Corporate Bond Index (*Corp B*) and the S&P Municipal Bond Index (*Muni B*) for comparative purposes. The S&P 500 (*SP500*) is used as a reference for the stock market, and the S&P US Treasury Bond Index (***T-BondI***) is a factor that affects the bond market in general.

Previous research finds a connection between green bonds and other assets; therefore, we also include data on:

Dollar: US dollar index is obtained from the St. Louis Federal Reserve.[1]

Commodity: S&P GSCI Index, which is a benchmark for investment in the commodity markets and a measure of commodity performance over time.

Brent: daily Brent Crude Oil price.

Clean energy: S&P Global Clean Energy Index, tracks the performance of companies in global clean energy-related businesses from both developed and emerging markets.

CO2: CO_2 European Emission Allowance, which prices climate credits used in the EU Emission Trading Scheme.

VIX: CBOE Market Volatility Index, measures 30-day expected volatility of the stock market.

Our sample starts in July 2014, although a more extended time series for the S&P green bond indices is available. Since most of the green bond indices from S&P were launched in 2014, we argue that only after that would index prices reflect the event's impact. Table 1 shows the summary statistics of the assets we investigate in this study. The *GB* has the lowest mean return at 0.42 bp (0.0042%), and *Muni B* had the lowest risk, as measured by the standard deviation of the returns.

Table 1. Summary statistics. The numbers in this table are given in percentages using daily data over the period we investigate. The Green Bond Index (GB) has the lowest mean daily return at 0.42 bp (0.0042%), and the Municipal Bond Index (Muni B) has the lowest daily volatility at 0.191% among bond indices.

	Mean	Std. Dev	Min	Median	Max	Skewness	Kurtosis	N.Valid
GB	0.0042	0.312	−2.386	0.003	2.033	−0.526	5.794	1825
GB S	0.0047	0.355	−2.913	0.008	2.292	−0.523	6.004	1825
Corp B	0.0043	0.495	−4.547	0.010	2.990	−0.858	9.661	1825
Muni GB	0.0153	0.267	−3.330	0.019	4.221	−0.899	86.031	1825
Muni B	0.0143	0.191	−2.592	0.019	3.394	−0.379	124.893	1825
T-BondI	0.0095	0.216	−1.674	0.012	1.805	0.239	8.160	1825
SP500	0.0466	1.124	−12.765	0.066	8.968	−1.039	21.247	1825
Brent	−0.0144	2.647	−27.976	0.040	27.419	−0.521	21.982	1825
Clean Energy	0.0484	1.456	−11.748	0.083	11.666	−0.480	10.315	1825
CO2	0.1230	2.773	−18.969	0.132	12.497	−0.438	4.497	1825
Dollar	0.0111	0.317	−2.089	−0.004	1.925	0.165	3.949	1825
Commodity	0.0074	1.404	−11.770	0.074	7.986	−0.629	7.914	1825
VIX	−0.0034	8.348	−29.983	−0.723	76.825	1.261	6.897	1825

We apply a standard event study methodology, which has been widely applied in financial research to investigate how significant news (the event) affects stock prices and returns; see, for example, Bessembinder and Zhang (2013), Duarte-Silva and Tripolski Kimel (2014), Buigut and Kapar (2019), Heyden and Heyden (2020). We have identified three events relevant for our study: the Paris agreement (*PA*), the 2016 US presidential election (*USPE*), and the announcement of the US pullout from PA (*USPO*; Table 2). PA and USPE are of particular interest, as both were highly unanticipated political events with significant consequences for climate-relevant policies. PA initiated the adoption and gradual implementation of national plans about coping with climate change, in which investment instruments such as green bonds played a significant role. Two other events were seen as an inhibitors to climate adaptation and mitigation. We hypothesize that PA will benefit green bonds, whereas other events will affect it negatively. Our results largely confirm these hypotheses.

Table 2. Set of the events for analysis.

	Date	Event	Description
PA	12 December 2015	Paris agreement	UN Climate Change Conference, which adopted the Paris Agreement that governs climate change reduction measures from 2020.
USPE	8 November 2016	US election	The 58th quadrennial US presidential election had an outcome that differed from the results of the poll.
USPO	1 June 2017	US pull out	US President announced that the US would cease all participation in the 2015 Paris Agreement on climate change mitigation.
COVID	13 November 2020	COVID-19 Lockdown	A national emergency was declared in the US in order to reduce the spread of SARS-CoV-2.

The underlying idea is to test whether realized returns around the event dates are different from the expected ones derived from the model. For each model, the estimation is done based on 200 observations 10 days before the event, meaning that if the event day is denoted as $t = 0$, the estimation of the relevant parameters is based on observations $t \in [-210, -11]$. Suppose the event does not carry new information for the market. In that case, there will be no surprise, and thus excess (abnormal) return, which is the difference between realized and expected returns, for the event should be zero.

We calculate abnormal returns (AR) based on three expected returns models (Warner and Brown 1985):

- Mean adjusted model: the expected return is equal to the mean return in the estimation period;
- Market adjusted model: the expected return is equal to the [stock] market return;
- Market model: the expected returns follow a one-factor [stock] market model.

The event window is then defined to include the three trading days before and three days after the event, or $t \in [-3;3]$. For this window, both abnormal and cumulative abnormal returns (CAR) are calculated.

$$CAR_{iT_0,T_1} = \sum_{t=T_0}^{T} AR_{it}, \tag{1}$$

where T_0 indicates the number of days before the event included in the computation, and T_1 indicates how many days after the event are included. We tested $CAR_{-3,-1}$, $CAR_{-1,1}$, and $CAR_{1,3}$, which means that we tested event windows of three days, though with a varying number of days before and after the event.

Because events tend to affect not only returns but also volatility, we check for this simultaneously by applying [omment = Added a better explanation of the used models]exponential generalized autoregressive conditional heteroscedasticity model, EGARCH(m, s), which also includes S&P 500 as an external regressor that affects returns model with an autoregressive moving average process ARMA(p, q):generalized autoregressive conditional heteroscedasticity model, GARCH(1,1), which also includes S&P 500 as an external regressor that affects returns:

$$\begin{aligned} R_t &= \mu + cX_t + \textstyle\sum_{i=1}^{p} \phi_i R_{t-i} + a_t - \sum_{j=1}^{q} \theta_j a_{t-j}, \quad a_t = \sigma_t \epsilon_t \\ ln(\sigma_t^2) &= \omega + \textstyle\sum_{i=1}^{s} \alpha_i \frac{|a_{t-i}| + \gamma_i a_{t-i}}{\sigma_{t-i}} + \sum_{j=1}^{m} \beta_j \, ln(\sigma_{t-j}^2) \end{aligned} \tag{2}$$

where R is daily index return, X is an explanatory variable, ϵ is an iid standard normal error, and a is an innovation. σ^2 is a volatility of the returns. A set of dummy variables D_i is introduced in the mean and variance models to capture the event effect. D_i equals one if t corresponds to event day and zero otherwise. A detailed specification of distribution and order for ARMA and EGARCH models is given in Appendix A.

The advantage of this model is two-fold: firstly, we can additionally account for event-induced changes in volatility, and secondly, we do not need to divide our sample into testing and event window because events enter the model as dummy variables (Pynnönen 2005).

We also calculate correlation and different performance measures (risk, return, value-at-risk, and Sharpe (1994) ratio) for bond indices to assess a longer-term impact of four events: the Paris Agreement, the 2016 US presidential election, the announcement of the US pullout from PA, and US lockdown in 2020. Recent research shows that the COVID-19 pandemic and lockdown impact the financial markets and thus should also be considered.

4. Empirical Results

As discussed previously, this study aims to investigate the impact of unexpected political events related to environmentally sensitive issues on the returns of assets related to the green bond market. The reason we choose political events, and not physical events such as a natural disasters creating destruction to plants and infrastructure, is that political events, in contrast to physical events, do not carry a direct cost for which it is possible to compute changes in cash flows to the firm.

The indices history shows that some of the selected events are associated with changes in returns, and others not so much; see Figure 1 for an illustration. Note that the green bond indices are highly correlated with corresponding conventional bond indices. However, for both municipal and corporate bonds, green bonds slightly outperform conventional ones: for both groups, darker lines for conventional bond indices in Figure 1 are mostly visible below. The municipal bond indices do not seem to be affected by the events, whereas corporate bonds, to a higher extent, increase or decrease after the events. The lockdown is associated with a bond market decline, during which corporate green bonds outperformed the conventional ones until late 2020, when this relationship reversed. In contrast, municipal green bonds also continued to outperform conventional municipal bonds after the US lockdown. We test the impact of the events on the returns statistically and find their significant effect on both green and conventional bonds (Table 3).

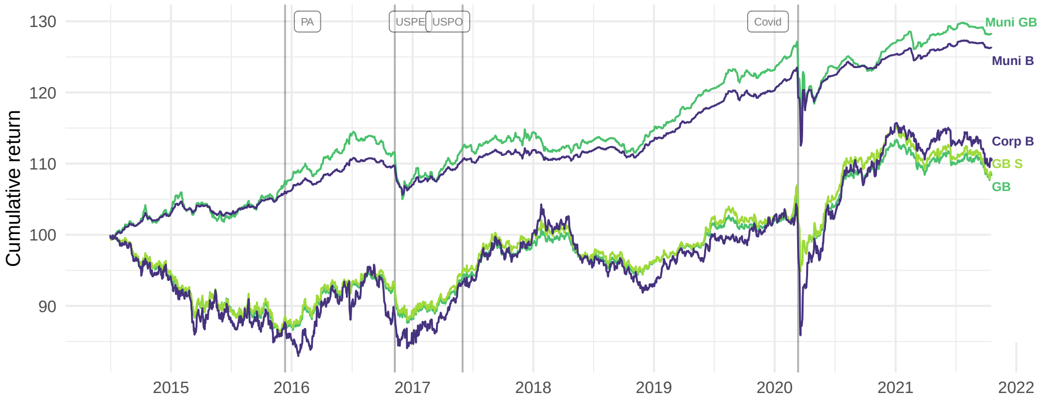

Figure 1. Historical prices of the green bond indices.

Table 3. Estimated reaction on the events. This table shows estimated abnormal returns in percentages obtained based on the mean adjusted, market, and market adjusted models [(1), (2), and (3) respectively]. It also presents estimated abnormal returns [(4) ret.] and abnormal volatility [(4) vol.], obtained by ARMA-EGARCH with S&P500 or T-Bond index as an external regressor to mean model and event dummy variables added to mean and variance modeling. For each event, we look at the abnormal outcomes on the event day (event) and the cumulative abnormal returns three days prior to the event (−3;−1) and after the event (1;3). Additionally, we report cumulative abnormal returns for one day before and after the event (−1;1). Asterisks indicate the significance of the coefficients: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

	Paris Agreement (PA)				**US Presidential Election (USPE)**				**US Pullout from the PA (USPO)**				**COVID-19 Lockdown**			
Model	**event**	**−1;1**	**−3;−1**	**1;3**	**event**	**−1;1**	**−3;−1**	**1;3**	**event**	**−1;1**	**−3;−1**	**1;3**	**event**	**−1;1**	**−3;−1**	**1;3**
GB																
(1)	−0.13	−0.31	0.95 *	−0.86	−0.05	−1.45 ***	−0.48	−2.73 ***	−0.13	0.62	0.41	0.52	−0.89 ***	−3.81 ***	−3.88 ***	−4.56 ***
(2)	−0.10	−0.34	0.79	−0.80	−0.05	−1.52 ***	−0.51	−2.75 ***	−0.10	0.66	0.40	0.51	−0.17	−4.93 ***	−4.70 ***	−5.55 ***
(3)	−0.64	0.02	3.37 **	−1.94	−0.39	−5.04 ***	−1.99 *	−3.78 ***	−0.88 *	−0.46	0.55	0.55	−9.74 ***	10.14 ***	6.37 ***	7.77 ***
(4) ret.	−0.13 *				0.23 *				−0.18 *				0.58 *			
(4) vol.	−1.16 *				2.74 *				−1.16 *				3.34 *			
GB S																
(1)	−0.14	−0.28	1.12 *	−0.93	−0.03	−1.51 ***	−0.55	−2.74 ***	−0.16	0.62	0.39	0.53	−1.09 ***	−4.45 ***	−4.31 ***	−5.58 ***
(2)	−0.10	−0.31	0.90	−0.85	−0.03	−1.58 ***	−0.58	−2.76 ***	−0.12	0.67	0.37	0.52	−0.16	−5.90 ***	−5.38 ***	−6.86 ***
(3)	−0.65	0.06	3.53 **	−2.01	−0.37	−5.10 ***	−2.05 *	−3.80 ***	−0.91 *	−0.45	0.53	0.57	−9.94 ***	9.51 ***	5.94 ***	6.76 ***
(4) ret.	−0.13 ***				−0.01 *				−0.20 ***				−0.24 *			
(4) vol.	−0.80 *				1.96 ***				−0.90 *				3.12 ***			
Corp B																
(1)	−0.30	−1.05	1.07	−1.81 **	−0.06	−1.82 **	−0.29	−3.11 ***	−0.22	0.38	−0.01	0.56	−1.69 ***	−6.81 ***	−5.53 ***	−9.58 ***
(2)	−0.26	−1.09	0.87	−1.74 **	−0.12	−2.46 ***	−0.55	−3.29 ***	−0.20	0.42	−0.02	0.56	−1.25 ***	−7.50 ***	−6.04 ***	−10.19 ***
(3)	−0.81	−0.73	3.48 **	−2.90 *	−0.42	−5.43 ***	−1.81	−4.19 ***	−0.98	−0.69	0.13	0.60	−10.55 ***	7.14 ***	4.73 ***	2.76 *
(4) ret.	−0.31 *				−0.02 *				−0.12 *				−2.22 *			
(4) vol.	−0.55 *				1.39 **				0.17 *				3.24 ***			
Muni B																
(1)	−0.12	−0.11	0.29 **	−0.06	−0.06	−0.65 ***	0.00	−2.14 ***	−0.03	0.30	0.34	0.34	0.07	−2.61 ***	−4.35 ***	−1.80 ***
(2)	−0.11	−0.12	0.24 *	−0.04	−0.04	−0.50 ***	0.06	−2.10 ***	−0.03	0.30	0.34	0.34	0.49 ***	−3.26 ***	−4.83 ***	−2.37 ***
(3)	−0.58	0.34	2.82 **	−1.02	−0.42	−4.29 ***	−1.55	−3.25 **	−0.79 *	−0.79	0.46	0.36	−8.78 ***	11.36 ***	5.92 ***	10.56 ***
(4) ret.	−0.03 **				0.14 **				−0.13 ***				1.51 ***			
(4) vol.	0.01 *				4.31 ***				−0.62 ***				4.93 ***			

Table 3. *Cont.*

	Paris Agreement (PA)				US Presidential Election (USPE)				US Pullout from the PA (USPO)				COVID-19 Lockdown			
Model	**event**	**−1;1**	**−3;−1**	**1;3**	**event**	**−1;1**	**−3;−1**	**1;3**	**event**	**−1;1**	**−3;−1**	**1;3**	**event**	**−1;1**	**−3;−1**	**1;3**
Muni GB																
(1)	−0.22	−0.17	0.56 **	0.00	−0.10	−1.22 ***	0.01	−3.63 ***	−0.05	0.53	0.56	0.62 *	0.04	−3.10 ***	−5.25 ***	−2.24 ***
(2)	−0.20	−0.19	0.47 *	0.04	−0.08	−0.94 ***	0.12	−3.55 ***	−0.05	0.53	0.56	0.62 *	0.56 ***	−3.93 ***	−5.86 ***	−2.97 ***
(3)	−0.68	0.29	3.11 **	−0.95	−0.47	−4.86 ***	−1.54	−4.74 ***	−0.82 *	−0.60	0.65	0.61	−8.81 ***	10.88 ***	5.04 ***	10.13 ***
(4) ret.	−0.09 ***				0.33 **				−0.22 ***				1.86 *			
(4) vol.	0.06 *				4.11 ***				−0.47 **				4.30 ***			

4.1. The Paris Agreement

According to traditional event study methodology results, bonds do not significantly react to the news on the event day itself. However, all bond indices have positive cumulative returns three days prior to the event. According to the mean adjusted model, *GB* and *GB S* gain 95 and 112 bp (basis points) before the event (significant at the 10% level). Municipal bond return increased by 29 bp, and municipal green bond gained twice more, 56 bp.

Only conventional corporate bonds adjusted prices after the announcement of the Paris agreement. Depending on the model applied, they lost 1.7–2.9% of the value three days after the event. Regression-based analysis shows that PA was associated with negative shock to return for all bond types. *GB* and *GB S* lost 13 bp on the event day; *Muni GB* and *Muni B* lost 3–9 bps, while *Corp B*'s return dropped by 31 bp.

The marginally significant effect of the PA event on volatility depends on the type of bond: corporate bonds experienced a decrease in volatility, which varies from 0.55 pp (percentage point) for conventional ones to 0.8–1.16 pp for green bonds. On the other hand, municipal green bond volatility slightly increased by 0.01–0.06 pp.

4.2. The US Presidential Election

Similarly, a traditional event study estimated the reaction on USPE to be negative, albeit insignificant. Regression-based results suggest that corporate bonds of both types had some reaction to the change in returns that was economically significant, but statistical significance was only at the 10% level.

Results suggest that all bonds adjusted their prices significantly three days after the event. These changes are up to −3% for *GB*, *GB S*, and *Muni B*. *Corp B* and *Muni GB* returns dropped by 3.2–4.7%, depending on the model.

The volatility of municipal bonds increased by than 4 pp. Green corporate bonds' volatility increased by 2–2.74 pp, while *Corp B* got only 1.39 pp. USPE-induced volatility is statistically significant at the 1% level for municipal conventional, green corporate, and conventional bonds.

4.3. The US Pullout from the Paris Agreement

Mean adjusted and market models suggest that there was no reaction on the event day. The only exception is the negative reaction to the US pullout from the Paris agreement, estimated by the market adjusted model. According to it, all but *Corp B* lost 79–91 bp on the day of USPO. However, this decline is significant only at the 10% level. According to the market model, *Muni GB*'s returns increased by 62 bp after the USPO.

In contrast, regression-based analysis shows that USPO was associated with negative shock to return for all bond types: smaller for conventional bonds (around 13 bp) and greater for green bonds (18–22 bp). In terms of volatility, USPO decreased the volatility of *Muni B* and *Muni GB* by 0.62 and 0.47 pp, respectively, which are significant at the 1% level. Corporate conventional bonds' volatility increased by 0.17 pp, but corporate green bonds became less volatile by 0.9–1.16 pp. These changes in the volatility of corporate bonds are significant only at the 10% level.

4.4. COVID-19 Lockdown

Although COVID-19 is not related to the climate regulatory risk, the pandemic is a source of big market uncertainty, affecting bond index performance. Anecdotal evidence of the lockdown effect on the bond indices in Figure 1 is also supported by empirical results. According to traditional event study methodology, lockdown brings a negative shock to both types of corporate bonds. Their reaction is present before and after the announcement about the national emergency. The same is true for municipal bonds; however, results vary between models.

All indices but *GB* got a volatility increase on the day of the lockdown announcement in the 3.12–4.93 pp range, significant at the 1% level. Municipal bonds experienced a greater volatility shock.

4.5. Bond Indices' Performance

We further analyze the correlation between the various indices in our study, both the correlation over the entire period and for sub-periods defined by studied events. We find that the overall correlation for the same bond type is high; namely, correlation within corporate bonds sample and correlation between *Muni B* and *Muni GB* is above 0.9. There is also co-movement of corporate and municipal bonds, but it is weaker: correlation is within the 0.25–0.39 range. Figure 2 shows that corporate and municipal bond correlation was the lowest after PA and highest after USPE.

Municipal bonds co-move with *VIX* and T-Bond index, and the correlation with the latter is much stronger. In addition, the correlation between *VIX* and *Muni B* and *Muni GB* is positive but becomes weaker after USPE and forward. On average, correlation with other indices, such as S&P 500, *Dollar, Commodity,* CO_2, *Clean Energy*, and *Brent*, for municipal bonds, is negative and below 0.5. These relationships are statistically significant and persist over time (Figure 2). Only after USPE did these correlations change direction, but these estimates are not statistically different from zero.

Figure 2. Correlation between green bonds and other assets, by periods. Black frame shows cases when estimated Pearson's correlation is not significantly different from zero.

Corporate bonds are highly negatively correlated with the *Dollar* index. They also have weak positive relationships with the T-bond index and *Clean Energy*, which are statistically significant at the 5% level. Correlation with S&P 500, *Commodity,* CO_2, and *Brent* are positive but rather low for corporate bonds so that they are not statistically different from zero in most sub-periods.

The correlation between studied bonds and *S&P 500,* CO_2, and *Clean Energy* changed to significant and positive during the lockdown. Corporate conventional and green bonds also gained a statistically significant correlation with T-bond and commodity indices. In contrast, the relationship between municipal bonds and the T-bond index was insignificant during the COVID-19.

Table 4 presents different performance measures for bond indices. These measures are also calculated for sub-periods. We also test changes in average returns and standard deviations between periods and find that differences in returns are not statistically significant.

Only *GB* and *GB S* had a significant change in long-term mean return after PA—others are not significantly different from zero, even at 10% level.

Table 4. Performance measures for the bond indices, by periods. This table reports performance measures such as annualized average return (*Return*), standard deviation (*Std.Dev*), and Sharpe ratio (*Sharpe*); daily expected shortfall (*ES*) and value-at-risk (*VaR*) are given in percentages. Asterisks indicate the test significance for difference in measures: * $p < 0.1$; ** $p < 0.05$; and *** $p < 0.01$. Red color shows significant negative, and green color shows significant positive change in measure, compared with the previous period.

Index	Measure	Before	After PA		After USPE		After USPO		COVID-19	
Corp B	Return	−0.1004	0.0199		0.0705		0.0131		0.0759	
	Std.Dev	0.0812	0.0960	***	0.0915		0.0592	***	0.0889	***
	VaR	−0.0089	−0.0098	↘	−0.0100	↘	−0.0065	↗	−0.0092	↘
	Sharpe	−1.2376	0.2069	↗	0.7700	↗	0.2204	↘	0.8530	↗
GB	Return	−0.0908	0.0572	*	0.0308		0.0277		0.0401	
	Std.Dev	0.0581	0.0481	***	0.0563	*	0.0394	***	0.0546	***
	VaR	−0.0066	−0.0040	↗	−0.0061	↘	−0.0042	↗	−0.0055	↘
	Sharpe	−1.5635	1.1885	↗	0.5480	↘	0.7041	↗	0.7350	↗
GB S	Return	−0.0870	0.0589	*	0.0369		0.0273		0.0376	
	Std.Dev	0.0623	0.0539	**	0.0608		0.0469	***	0.0649	***
	VaR	−0.0070	−0.0046	↗	−0.0065	↘	−0.0050	↗	−0.0066	↘
	Sharpe	−1.3958	1.0936	↗	0.6081	↘	0.5834	↘	0.5792	↘
Muni B	Return	0.0422	0.0411		0.0132		0.0318		0.0434	
	Std.Dev	0.0163	0.0151		0.0286	***	0.0229	***	0.0512	***
	VaR	−0.0016	−0.0009	↗	−0.0033	↘	−0.0003	↗	−0.0003	↘
	Sharpe	2.5813	2.7288	↗	0.4634	↘	1.3874	↗	0.8465	↘
Muni GB	Return	0.0521	0.0452		0.0093		0.0355		0.0370	
	Std.Dev	0.0305	0.0274	*	0.0493	***	0.0305	***	0.0666	***
	VaR	−0.0031	−0.0020	↗	−0.0056	↘	−0.0020	↗	−0.0020	↗
	Sharpe	1.7076	1.6504	↘	0.1887	↘	1.1647	↗	0.5554	↘

We see that *Corp B* had a significantly higher risk at 0.09%, while the risk of *GB* became significantly lower (0.5%). After PA, corporate green bonds and *Muni B* became less risky based on the value-at-risk measure (VaR, calculated with 95% probability) and offered a higher reward per unit of risk. *Corp B* became riskier, but a positive average return helped one to obtain a meaningful (not-negative) Sharpe ratio of 0.2%. The outcome was the opposite for *Muni GB*: despite lower risk by VaR, the Sharpe ratio changed from 1.7 to 1.65%.

After USPE, all bonds but *Corp B* became riskier and, thus, offered lower return per unit of risk. Despite higher risk by VaR measure, *Corp B* improved their Sharpe ratio from 0.2 to 0.77%. After USPO, all bonds became less risky; however, only *Corp B* started to offer less return per unit of risk: its Sharpe ratio was reduced to 0.22%. During the lockdown, all bonds became riskier in terms of volatility. However, corporate green and conventional bonds also improved their Sharpe ratio, the former ones from 0.22 to 0.85%.

5. Discussion

Our findings show that municipal and selected green bond indices react to political events associated with climate change policy. Their response to the arrival of the news is generally negative: most estimates of abnormal returns on the event day are negative and significant at the 1% level. The decline of the bond index prices suggests that investors associate studied events with increased uncertainty about market developments. This uncertainty leads to an increase in bond price volatility, meaning that the events studied in this paper initiate significant price adjustment, thus impacting the trading in the market. This finding supports Pham and Luu Duc Huynh's (2020) results on the significant effect of investor attention on bond market performance.

However, bond index reaction to an event depends on its features: whether an issuer is a corporation or municipality and whether bonds are conventional or green. In addition, bond indices need time to fully incorporate information into prices, as significant cumulative abnormal returns after events suggest.

A closer look at each event reveals that the Paris agreement boosted the development of green bonds. The results show that the market anticipated this event because most bond indices had a significant positive cumulative return before the announcement about the reached agreement. However, we also admit that the Paris Green Bond Statement could have shaped this reaction from the global institutional investors in support of policies related to climate finance. This statement was media-released three days before the PA agreement, and, thus, our cumulative returns also capture bond indices' reaction to this statement.[2]

The Paris agreement contributed to corporate green bonds' increase in reward per unit of risk until the US presidential election. It had a reciprocal effect because green bonds contributed significantly to achieving climate goals (Tolliver et al. 2020b). The Paris agreement's positive effect did not extend to conventional corporate bonds: on this event and during days after it, corporate bonds' returns declined and offset positive anticipation.

Unlike the Paris agreement, the US presidential election had a significant effect on the volatility on the event day, which is in line with the unexpected nature of the election results. All bond indices experienced a negative cumulative abnormal return after the election. Interestingly, municipal bonds faced greater event-induced volatility. Municipal green bonds lost most in returns, suggesting that this sector is more vulnerable to climate regulatory risks. Although green bonds returns decreased less or even gained compared with conventional ones, the former were subject to higher volatility shock on the event days. After USPE, all but conventional corporate bonds performed more poorly, as the Sharpe ratio shows.

The US pullout from the Paris agreement caused a negative return shock to green and municipal bonds. Only some models showed a positive return shock in the days after USPO for the municipal green bonds. Because our sample contains only US municipal bonds, such a specific reaction to USPE and USPO is justified. Both events brought uncertainty about the development of the US climate policy that is expected to affect municipal green bonds, not corporate bonds.

Similar to Monasterolo and de Angelis's (2020) findings for stocks, we document a lower correlation between green and conventional bonds after the Paris agreement. Starting from the Paris agreement, corporate green bonds became positively correlated with clean energy prices. In contrast, their correlation with commodity and stock market almost disappeared (was statistically insignificant). In addition, our results corroborate the work of Pham (2016), suggesting a time-varying correlation between green and conventional bonds and extending this finding also up to 2020 and for the municipal bond universe. According to our findings, the COVID-19 pandemic is associated with a tighter relationship between bonds and other assets. Most of these relationships became statistically significant during 2020–2021, especially in the case of green bonds. This impact was also sited in Bouri et al. (2021) based on the observed higher connectedness between asset classes in the period.

Although, according to our results, conventional corporate bonds offer a better rewards-per-unit-risk recently, they might be subject to market inefficiency (Naeem et al. 2021). During the pandemic, corporate conventional and corporate green bonds' changes followed the same direction (higher VaR risk and Sharpe ratio), but not the selected green bonds. This difference in performance might have been influenced by the credit ranking because the selected green bonds have a minimum BBB- one; thus, they have lower risk. Corporate green bonds are found to be less risky in terms of volatility and value-at-risk. Given positive changes in the Sharpe ratio after the Paris agreement, it is reasonable to expect a similar reaction to a new climate policy introduction. Their insignificant correlation with the crude oil index is also favorable in the long run during the transition to a low-carbon economy.

Our findings suggest that the green bond market accounts for the regulatory risk of unexpected events and related to climate change. The results show that climate policy events have short- and long-term effects on green bond pricing and performance on the secondary market. Changes in climate policy also affect relationships between green bonds and other assets. This indicates that despite the many benefits of issuing green bonds to firms and investors, political risks to these assets are challenging to account for. Previous research has shown that these relationships can be utilized in portfolio diversification (Horsch and Richter 2017; Nguyen et al. 2020; Reboredo 2018) and as a hedging instrument (Jin et al. 2020). Indeed, corporate green bonds come with lower idiosyncratic risk and less correlation with more conventional financial assets and, as such, carry great diversification benefits to a portfolio of assets. Our study highlights the necessity of portfolio readjustment after changes of regulatory risk to obtain all benefits from such diversification.

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Abbreviations

The following abbreviations are used in this manuscript:

GB	green bond
PA	the Paris agreement
USPE	the US Presidential election
USPO	the US pullout from the Paris agreement

Appendix A

The estimation of the ARMA-GARCH models is made with the `rugarch` package (Ghalanos 2020). In order to identify suitable ARMA specifications, all combinations of ARMA-orders up to the fourth lag were tested for the bond indices with the following distributions:

- *norm*: the normal distribution
- *snorm*: the skew-normal distribution
- *std*: the Student *t*-distribution
- *sstd*: the skew-Student *t*-distribution
- *ged*: the generalized error distribution
- *sged*: the skew-generalized error distribution
- *nig*: the normal inverse Gaussian distribution
- *jsu*: Johnson's S_U distribution
- *ghyp*: the generalized hyperbolic distribution

The S&P 500 was introduced as an external regressor to all models. The choice of the initial ARMA specification is based on the Akaike Information Criteria (AIC). Table A1 shows the top-three specifications with the lowest AIC.

Table A1. The top-three selected ARMA specifications by the lowest Akaike Information Criteria (AIC). Asterisks denote specifications used in the first run of ARMA-EGARCH models.

Bond index	Distribution	AR (p)	MA (q)	Mean	AIC	Used
Corp B	std	4	2	0	1.2491	*
	std	4	2	1	1.2496	
	sstd	4	2	0	1.2497	
GB	std	2	4	0	0.3832	*
	std	2	4	1	0.3834	
	sstd	2	4	0	0.3835	
GB S	ghyp	4	3	1	0.6534	*
	std	2	4	0	0.6539	
	std	2	4	1	0.6543	
Muni B	sstd	2	4	1	−1.9055	*
	sstd	1	0	1	−1.9043	
	sstd	1	1	1	−1.9040	
Muni GB	jsu	4	3	1	−0.9201	*
	jsu	1	0	1	−0.9200	
	jsu	1	1	1	−0.9194	

The starred ARMA specification was used in the ARMA(p, q)-EGARCH(2, 4) model. After eliminating insignificant ARMA-orders and remaining serial autocorrelation in residuals and squared residuals, the final specifications have changed (Table A2).

Moreover, the serial autocorrelation in residuals of the municipal bond indices with the S&P 500 index as a regressor remained significant at high lags order. Thus, the S&P 500 was replaced with the T-Bond index for the municipal bond indices, and dummy variables for Mondays (which impacts bond indices, see Berument and Kiymaz 2001) and January were introduced. The models are tested for serial autocorrelation in residuals and squared residuals, so that final models do not have significant serial autocorrelation present. These models also have no uncaptured asymmetry present in the residuals. Estimated coefficients of the models are given in Table A3, where their significance is derived based on the robust standard errors.

Table A2. The final specifications for the ARMA models with associated Akaike Information Criteria (AIC).

Bond Index	Distribution	AR (p)	MA (q)	s	m	AIC
Corp B	std	4	2	2	2	1.1779
GB	std	2	4	2	3	0.3183
GB S	ghyp	4	2	2	2	0.6014
Muni B	snorm	4	4	2	2	−1.3531
Muni GB	snorm	2	2	2	2	−2.3481

Table A3. Estimation results for the ARMA-EGARCH models.Asterisks indicate the significance of the coefficients: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

	GB		GB S		Corp B		Muni B		Muni GB	
Mean model										
μ			0.007	*			0.010	***	0.016	***
ϕ_1	−0.187	***	−0.162	***	−1.622	***	−0.336	***	0.073	**
ϕ_2	−0.991	***	−0.941	***	−0.595	***	−0.386	***	0.354	***
ϕ_3			0.034	***	0.018	***	0.368	***		
ϕ_4			0.045	***	−0.009	***	0.158	***		
θ_1	0.237	***	0.183	***	1.647	***	0.710	***	0.275	***
θ_2	1.047	***	0.982	***	0.646	***	0.705	***	−0.206	***
θ_3	0.066	*					−0.021	**		
θ_4	0.055						−0.094	***		
c	−0.016	*	−0.024	***	0.008	*	0.225	***	0.336	***
Mon							0.010	***	0.006	*
Jan							0.043	***	0.047	***
Variance model										
ω	−0.100	*	−0.107	**	−0.073	*	−0.279	***	−0.183	***
α_1	0.008	*	0.019	*	−0.009	*	−0.084	*	−0.063	*
α_2	0.017	*	0.019	*	0.014	*	0.077	*	0.076	*
β_1	0.182	*	0.321	***	0.440	*	1.000	***	1.000	***
β_2	0.333	*	0.632	***	0.516	*	−0.056	**	−0.047	
β_3	0.446	*								
γ_1	0.050	*	−0.013	*	0.023	*	0.407	***	0.402	***
γ_2	0.185	*	0.193	***	0.192	**	−0.130	*	−0.110	*
Distribution										
skew			−0.604	*			0.968	***	0.984	***
shape	7.287	*	0.250	*	6.552	***				
λ_{gh}			−3.790	***						

Notes

1 St. Louis Federal Reserve: stlouisfed.org. Accessed on 23 November 2021.

2 We checked the bond indices' reaction to the Paris Green Bond Statement and found a positive abnormal return for corporate and negative abnormal return for municipal bonds, significant at 1% level in both cases.

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