Climate bond, stock, gold, and oil markets: Dynamic correlations and hedging analyses during the COVID-19 outbreak

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Abstract

Adverse ecological effects have recently generated several eco-friendly investment opportunities including green and climate bonds. Although climate bonds have emerged as an appealing investment, little is known about their dynamic correlations and market linkages with US equities, crude oil, and gold markets, especially during stress times such as the COVID-19 outbreak, which are essential for asset allocation and hedging effectiveness. In this paper, we report time-varying correlations between climate bonds and each of the markets considered, which intensify during the COVID-19 pandemic. On average, climate bonds are negatively associated with US equities and have a near zero correlation with crude oil, whereas they are positively associated with gold. There is a bidirectional volatility linkage between climate bonds and the three indexes under study, whereas return linkages are marginal. The hedge ratio is positive for bond-gold, whereas it switches between positive and negative states for bond-stock and bond-oil, especially it switches more extremely during the COVID-19 outbreak. Although climate bonds provide the highest risk reduction in a portfolio containing US equities or gold as a part of a hedging strategy, their hedging effectiveness is considerably reduced during the pandemic. The findings have implications for markets participants aiming to green their portfolios and make them robust during stress times, enabling a smooth and speedy transition to a low-carbon economy.

Keywords: Climate bonds; financial markets; ethical investors; time-varying dynamic correlations and hedging effectiveness; decarbonizing portfolio

1. Introduction

Over the last decade or two, growing concern about adverse ecological effects[1] has generated several eco-friendly investment opportunities including green and climate bonds. In March 2017, the Lombard Odier (LO) group launched global climate bonds (LO Funds – Global Climate Bond), as part of a global fixed income strategy focusing on climate bonds. The LO fund invests primarily in a stringent selection of labelled green bonds as well non-labelled climate-aligned bonds. In view of this, climate fixed-income instruments represent a financial innovation intended to finance climate solutions such as investments in emission reduction and/or climate change adjustment[2]. Climate bonds are issued by supranational entities (e.g., the European Investment Bank, the World Bank) and a large variety of private and publicly traded firms, multilateral organizations, municipalities, and governments. Remarkably, climate bonds attract the attention of a particular type of long-term institutional investor, motivated by non-pecuniary motives and strong preferences for supporting a low carbon economy, which means these investors do not easily liquidate their climate bond investments under turbulent market conditions but keep them to maturity. This suggests that climate bonds are quite resilient to adverse market sentiment during periods of high economic uncertainty and market instability such as the COVID-19 outbreak, which in turn may point to the potential role of climate bonds as an effective diversifier and hedge against the downside risk of stock and commodity markets during stressful periods. Interestingly, climate bonds are structured in a similar way to traditional Treasury or corporate-style bonds in terms of proceeds, coupons, maturity, and duration, and thus can be easily incorporated into institutional investment portfolios.

Climate bonds as potential hedging assets encountered a challenge during the COVID-19 outbreak period, especially around March-April 2020[3]. During that unprecedented stress time, financial markets across the globe were subject to enormous chaos such as extreme price instability and market uncertainty. While some investors consider climate bonds to be more sustainable and less

[1] Among a large strand of literature on the adverse ecological effects, some studies point to the negative impacts of climate change on agriculture (Pinkse and Gasbarro, 2019) and the financial performance of industries (Sun et al., 2020).
[2] In this sense, climate bonds differ from green bonds that have an environment and climate friendly use of proceeds.
[3] According to JP Morgan, green and climate bonds offered some reduced volatility during March 2020, compared to their conventional counterparts (https://am.jpmorgan.com/ch/en/asset-management/liq/insights/portfolio-insights/fixed-income/fixed-income-perspectives/how-green-are-green-bonds/).

risky investments than other conventional bonds as well as stock and crude oil investments, the dynamic relationships between climate bonds and US stock, crude oil, and gold markets during the COVID-19 outbreak are understudied. This unaddressed research gap is surprising given that a precise knowledge of such dynamic relationships is crucial for market participants in determining if climate bonds can hedge the downside risk of investment portfolios. Understanding the return and volatility linkages between climate bonds and various financial markets, along with their hedging effectiveness is essential for ethical investors who aim to green their portfolios by holding more assets in climate bonds which focus on sustainable practices.

In this paper, we contribute to the scarce literature by shedding light on the time-varying dynamic correlations and volatility spillovers between climate bonds and leading stocks and commodities. We also study the hedging effectiveness, covering the COVID-19 outbreak period during which uncertainty in the financial markets spiked. Methodologically, we employ VAR asymmetric DCC-GARCH (VAR-ADCC-GARCH) models to study the time-varying dynamic correlations as well as the return and volatility linkages, which represents a nice extension to the symmetric model employed by Kanamura (2020) to study the green bond market. We then examine the hedge ratio and hedging effectiveness of climate bonds for the risk of stock and commodity markets in a time-varying setting (Junttila et al., 2018; Batten et al., 2019). This is important as financial time-series tend to behave differently across time and the hedging ability of assets can be shaped by crisis periods such as the COVID-19 pandemic. For example, the association between climate bonds and financial markets might vary between bearish, normal and bullish markets. This is especially relevant given that, during the COVID-19 outbreak, WTI oil prices moved into negative territory for the first time ever. Hence, understanding the time-dependent correlations and hedging effectiveness among the variables under study could play a pivotal role in estimating the risk linked to climate bonds and its implications for investors and policymakers.

In our empirical analyses, various types of financial and commodity markets are considered including the S&P 500, crude oil (WTI price index) and gold. The financial instrument based on the US equity market is used because the S&P 500 is a key indicator of the global economy. In addition, as crude oil and gold often play a crucial role in hedging the downside risk of financial markets, the information on these commodity prices is considered. For example, Dutta et al. (2020)

argue that gold is always popular as an effective hedging instrument. Overall, assets traded in the commodity markets might offer diversification benefits for ethical investors.

Given that climate bonds refer to a market-based instrument used to raise funds for mitigating the challenges caused by climate change, studying the dynamic correlations, volatility spillovers, and hedging effectiveness between climate bonds and major financial and commodity markets is of supreme significance to ethical and environmental investors who seek to green their portfolios so that there could be a transition to a low-carbon economy. Hence, our findings are of use to those investors who not only aim to decarbonize their portfolios, but also attempt to achieve returns from sustainable investments and consider the added value of climate bonds in risk management inferences. Our findings also matter to policymakers who are concerned with reducing the risks of climate change and the long-term goal of decarbonization.

For rest of the paper, Section 2 reviews the related literature. Section 3 describes the dataset and methods. Section 4 presents and discuses empirical results. Section 5 concludes.

2. Literature review

1.2. Essentials of the climate bond index

Climate bonds have been established with the aim of providing incentives to finance investments in emission reduction and/or climate change adjustment as well as reducing the cost of capital for climate projects in both developed and emerging economies. Notably, climate bonds include a broader universe than green bonds, yet their selection follows a more stringent path. Accordingly, climate bonds can include climate-aligned bonds that are not necessarily covered by the labelled green bond market[4]. Interestingly, the LO Funds – Global Climate Bond covers a flourishing investment space of not only labelled green bonds but non-labelled climate-aligned bonds. According to the LO Group: "*Green Bonds do have some marked currency, country, regional and industrial-sector biases, some of which we believe can be addressed by expanding the investment universe beyond "labelled" Green Bonds to the broader non-labelled climate-bond markets. In our view, investing with integrity in the broader climate-bond market requires sophisticated data and research capabilities and proprietary selection and monitoring criteria – indeed, an investor*

[4] The green bond market can be subject to "greenwashing" most probably due to its high popularity.

with these capabilities soon learns that even "labelled" Green Bonds are not necessarily aligned with its own sustainability or impact criteria". In fact, some climate-aligned bonds might not be labelled "green" although they are issued by corporations that generate more than 95% of their revenues from climate-aligned projects (e.g., solar panel firms, waste-management enterprises, utilities), as evaluated by the Climate Bond Initiative. In this regard, LO look beyond the green label by giving precedence to environmental and social influence over visible "greenness" in a very stringent way. According to LO, around 15% of labelled green bonds are excluded as they do not pass the strict screening process[5].

Furthermore, investors switching a part of their investment in conventional investment-grade bonds to a green bond portfolio may encounter the risk associated with managing tracking error against a comprehensive fixed-income benchmark. Accordingly, it is relevant to realign the academic literature from a strict focus on green bonds to a wider focus on climate-aligned bonds which helps manage benchmark tracking error risk[6].

2.2. Related studies involving green bonds

Early studies consider the significant presence of a green premium, or "greenium", in green bonds relative to conventional bonds (Ehlers and Packer, 2017). Later studies examine the relationship between green bonds and financial markets to make inferences regarding portfolio and hedging abilities. However, given that climate bonds have emerged as an investment tool appreciated by investors who care about our planet's sustainability, there is room for improvements in the growing but incomplete academic literature on the relationship between climate bond and financial markets. Reboredo (2018) uses copula functions and conditional diversification measures to show that green bonds have strong linkages with government and corporate bonds, whereas they exhibit very weak linkages with stock and energy markets. Furthermore, they indicate strong diversification abilities for stock and energy markets, but trivial diversification benefits from combining green bonds with government bonds. Reboredo and Ugolini (2020) use various methods based on the structural

[5] For example, "*a EUR 1.2 billion Green Bond from French renewable energy and power company Engie, which finances renewable-energy and smart-meter projects with annual reporting on installed renewable capacity and energy-consumption reduction, is excluded because one of its projects was halted in 2016 by Brazil's environmental protection agency over fears for the local freshwater ecology and indigenous communities*".

[6] More details about the tracking error risk can be found at: https://am.lombardodier.com/files/live/sites/am/files/images/AssetManagement/Investment%20strategies/Climate%20Bonds/Climate%20Bond%20White%20Paper_EN_28Feb17.pdf

vector autoregressive (VAR) model and report that the green bond market is strongly connected to fixed-income and currency markets and plays the role of a receiver of price shocks from these markets. Conversely, green bonds' connection with equity and energy markets is negligible. Reboredo et al. (2020) examine the spillovers between green bonds and the US and EU financial markets over various time scales. Using a wavelet-based method to decompose the series and then a VAR approach to study connectedness measures, they find that green bonds and treasury and corporate bonds are interconnected in the short- and long-run and in both US and EU markets. Furthermore, they show that green bonds are weakly interconnected with high-yield corporate bond, stock and energy markets regardless of the time scales. Hammoudeh et al. (2020) study the relationship between green bonds and three assets covering the US 10-year Treasury bond index, clean energy stock index, and CO2 Emission Allowance prices. Their results show mixed evidence of unidirectional Granger causality running from each of the three assets to green bonds over various time periods, suggesting the inability of green bonds to predict the price changes of the three asset indices under study. Saeed et al. (2020) use a quantile-based approach and reveal evidence that return spillovers between green and non-green investments are stronger during stressful periods and are driven by macroeconomic conditions.

The above-mentioned studies seem to focus on green bond indices to the detriment of climate bonds. Furthermore, previous studies generally consider price spillovers only, ignoring spillovers in the second moment (i.e., volatility) of the return distribution even though stylized features of financial markets such as clustering, and asymmetries/leverage effects are associated with return volatility. Importantly, these stylized features cannot be depicted or investigated via a wavelet analysis, quantile approach or VAR model, but requires asymmetric GARCH-based models. In addition to this important research gap in the nexus between climate bonds and financial markets, most previous studies use an aggregate index for the energy market, ignoring the gold market, and time-varying hedging analysis. Notably, the sample period applied does not include the COVID-19 outbreak which represents an unprecedented severe challenge that potentially shapes the relationship between green bonds and financial markets. This is an important issue to address for the sake of investors and policymakers, especially in light of recent debate that climate and COVID-19 issues represent intertwined and timely challenges to policymakers in 2021[7].

Accordingly, our current study addresses these shortcomings by considering dynamic conditional correlations as well as return and volatility linkages between climate bonds and the markets of US equities, crude oil, and gold commodities using VAR-ADCC-GARCH models. Furthermore, we model the volatility of climate bonds and each of the financial market indices using univariate asymmetric GARCH processes. Secondly, we study the hedge ratio and hedging effectiveness of climate bonds against the risk of US equity, oil, and gold markets in a time-varying setting. This allows us to capture market linkages among the indices examined and the hedging role of climate bonds during normal periods and the unprecedented stress period of the COVID-19 outbreak, an unexplored research area in the academic literature on climate bonds.

3. Data and method

3.1. Data

The data on LO Funds – Global Climate Bond is available from March, 2017. Therefore, our sample period begins on 1 March 2017 and ends on 30 June 2020, covering 818 daily observations. All the data is extracted from DataStream and priced in USD. For the US stock market, we use the S&P 500 composite index. Crude oil and gold prices are represented by the spot prices of WTI and London bullion markets, respectively.

Fig. 1 shows the level series of the climate bond index and the three other indices under study. We observe an upward trend in the climate bond index, especially from Q3 2018, which is comparable to that of gold. While there is a large price fall around the COVID-19 pandemic outbreak in March 2020, especially in the S&P 500 index and oil price[8], a much smaller and less substantial price drop appears in the climate bond and gold markets. Fig. 2 plots the natural logarithmic return series, showing the large price movements experienced during the COVID-19 outbreak, especially for the US stock market index and WTI oil index.

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[7] https://www.climatebonds.net/2020/12/climate-covid-recovery-%E2%80%93-intertwined-challenge-policy-makers-2021

[8] The WTI market experienced negative prices for the first time ever, driven by the COVID-19 outbreak and the price war between Saudi Arabia and Russia.

Table 1 gives the descriptive statistics of the natural logarithmic returns for climate bonds and the three other indexes. The mean return of all indexes is positive. As expected, the climate bond index has a lower volatility than the leading financial markets, while the WTI oil market has higher volatility than the stock and gold markets. This is not surprising given the extreme price movements experienced by WTI prices, especially during April 2020 when WTI prices declined to negative levels. None of the return series obey the normality law as shown by the Jarque-Bera test results. The results the augmented Dickey and Fuller (ADF) test show that all return series are stationary at the 1% level of significance. All return series exhibit evidence of heteroscedasticity up to 10 lags, which suggests the appropriateness of applying GARCH-based models to deal with the presence of heteroscedasticity.

3.2. The VAR-ADCC-GARCH approach

The DCC-GARCH model of Engle (2002) has gained popularity among the researchers over the past years due to its computational advantages and power over BEKK, CCC, or VAR-GARCH models (Lin et al., 2014; Basher and Sadorsky, 2016; Singhal and Ghosh, 2016). Notably, its asymmetric version, the so called asymmetric DCC-GARCH (ADCC-GARCH) model of Cappiello et al. (2006) accounts for the potential asymmetric effects that often characterize financial series (Dutta et al., 2019)[9]. However, given that the climate bond index and financial markets may interact not only in their volatility but in their returns, we apply the VAR-ADCC-GARCH model. We also conduct a robustness analysis involving other multivariate models such as the corrected DCC-GARCH model of Aielli (2013).

The mean equation in our VAR-ADCC-GARCH process is modelled as:

$$R_t = L + \tau R_{t-1} + \varepsilon_t \tag{1}$$

$$\varepsilon_t = H_t^{1/2} \xi_t \tag{2}$$

where R_t represent the vector of returns of the climate bond index and each of the other financial assets, L denotes the intercepts vector, τ captures the impact of lagged returns, ε_t corresponds to the error terms vector, ξ_t, denotes the innovations matrix, and $H_t^{1/2}$ represents the conditional volatility that can be decomposed as:

[9] As Dutta et al. (2020) note: '*This notable process is suitable for studying time-varying correlations and making inferences regarding the hedging effectiveness*'.

$$H_t = D_t R_t D_t \quad (3)$$

$$D_t = diag\left(\sqrt{h_t^b}, \sqrt{h_t^o}\right) \quad (4)$$

$$R_t = diag(Q_t)^{-1/2} Q_t diag(Q_t)^{-1/2} \quad (5)$$

$$Q_t = (1 - \theta_1 - \theta_2)\bar{Q} - \theta_3 \bar{Z} + \theta_1 \xi_{t-1}\xi'_{t-1} + \theta_2 Q_{t-1} + \theta_3 z_{t-1}z'_{t-1} \quad (6)$$

where, in Equation (5), R_t denotes the conditional correlation matrix of the standardized returns ε_t with Q_t representing the time-varying conditional dependence, b denotes climate bond returns, and o denotes the returns of S&P 500, gold, or WTI oil. In Equation (6), θ_3 captures the asymmetric effect, i.e., positive and negative shocks induce different correlations among indexes; θ_1 and θ_2 are non-negative scalars $s.t. \theta_1 + \theta_2 < 1$ for stationary of the underlying framework; $\overline{Z} = [z_t z'_t]$[10].

Moreover, h_t^b and h_t^o correspond to conditional volatilities for climate bond and other financial markets, which are defined as:

$$h_t^b = d_b^2 + b_{11}^2 h_{t-1}^b + b_{21}^2 h_{t-1}^o + a_{11}^2 \varepsilon_{b,t-1}^2 + a_{21}^2 \varepsilon_{o,t-1}^2 \quad (7)$$

$$h_t^o = d_o^2 + b_{12}^2 h_{t-1}^b + b_{22}^2 h_{t-1}^o + a_{12}^2 \varepsilon_{b,t-1}^2 + a_{22}^2 \varepsilon_{o,t-1}^2 \quad (8)$$

The pairwise asymmetric dynamic conditional correlation between the climate bond index b and the other index o is given by:

$$\rho_t = \frac{h_t^{bo}}{\left(\sqrt{h_t^b}\sqrt{h_t^o}\right)} \quad (9)$$

4. Empirical results

4.1. Estimated results of the VAR-ADCC-GARCH model

The results of the return and volatility linkages between climate bond and other financial markets are reported in Tables 2-4. Most of the estimated coefficients are significant at conventional levels and there is no more evidence of significant heteroskedasticity, which suggests the appropriateness

[10] More details of the ADCC-GARCH model are given in Cappiello et al. (2006).

of the models applied. Starting with the model involving climate bond and stock indices, Table 2 indicates evidence of a return spillover from the US stock market to the climate bond market and vice versa. Looking at the variance equation, the volatility of the S&P 500 index is substantially influenced by its own lagged news and past volatility shocks as indicated by the significant coefficients for h_{t-1}^{s} and $\varepsilon_{s,t-1}^{2}$. There is evidence that news and volatility shocks transmit from one market to another. We note that the climate bond market is affected by its own lagged news and past volatility shocks. It is also worth mentioning that the Lagrange multiplier (ARCH-LM) test suggests that no ARCH effects exist.

For the model involving climate bond and gold indices, Table 3 reveals some interesting findings. The return equations show that gold returns are significantly influenced by climate bond returns, while the latter do not react to the former. Therefore, climate bond returns have predictive power for gold returns. Further results indicate that both the gold and climate bond markets are influenced by their own one-period lagged news/shocks and past volatilities. There is a bilateral volatility connection in this case. News shocks emanating from these two markets impact each other. Hence, investors can predict one market using information from the other.

For the model involving climate bond and crude oil indices, Table 4 shows very similar results to those of the stock-bond model. Accordingly, the climate bond and oil markets are influenced by their own past shocks and lagged volatility. While no return spillovers exist between the climate bond and crude oil markets, there is strong evidence of bidirectional volatility transmission between these two markets. Notably, news shocks stemming from the climate bond market affect the oil volatility, but not the other way around.

Overall, there are a number of interesting findings regarding the volatility transmission relationship between climate bond and leading financial markets. Firstly, we find a bidirectional volatility linkage between the climate bond and stock/commodity markets. Therefore, the information on stock/gold/oil (bond) can be used to predict the bond (stock/gold/oil) market. Secondly, for the gold-bond model, we find evidence that the lagged returns of climate bonds have predictive power for future gold returns. Thirdly, compared to the influences of own one-period lagged shocks and volatilities, the magnitude levels of cross-market news shocks and volatilities are found to be much smaller. These results indicate that for all these markets, own past news and volatility shocks are more crucial in predicting market movements.

4.2. Time-varying conditional correlations

The statistics of the time-varying conditional correlations are reported in Table 5, and the plots of the conditional correlations are shown in Fig. 3.

Table 5 shows that the mean of the correlations is positive for both bond-gold and bond-oil. Therefore, an increase in gold or crude oil prices is associated with an increase in climate bond prices. For the WTI oil market, such a finding is not surprising given that climate bonds are brought to the market to fund eco-friendly projects such as clean energy projects. Given that the objective of renewable energy companies is to provide a substitute for crude oil, an upsurge in crude oil prices would encourage economic agents to swap to alternative energy sources. Consequently, due to demand-side pressures, one might expect that clean energy prices would experience a rise following an increase in crude oil prices. Therefore, a positive linkage between oil and climate bond markets could be anticipated. It is also noteworthy that the correlation between WTI and climate bonds is somewhat close to zero, suggesting potential hedging opportunities for oil market participants. The gold market, on the other hand, appears to have the highest correlation with climate bonds implying that gold is not a good hedge for ethical investments. One possible explanation for this finding is that both gold and climate bonds can be used as safe haven assets during periods of economic downturn, which introduces a positive relationship between these asset classes. Baur and Lucey (2010) show that gold does not act as a hedging instrument for the US or UK bond markets.

The results indicate that climate bonds are negatively associated with the S&P 500 index, which is somewhat unexpected given that the existing literature points to a positive association between stock and conventional bond markets. Andersson et al. (2008), for example, document that stock and bond markets are mostly positively correlated and argue that only during periods of equity market turmoil do investors shift towards safe fixed-income investments such corporate investment-yield and treasury bonds[11]. Dungey et al. (2009) conclude the same. Our findings, however, show that the climate bond and S&P 500 indexes do not move in the same direction revealing that climate bonds could be used to hedge the downside risk of the S&P 500 index.

[11] This action is widely known as flight-to-quality.

Therefore, our findings have important implications for ethical investors who want to diversify the potential risk linked to their equity portfolios.

Fig. 3 indicates that the DCC correlations tend to be time-varying. The correlations are seen to swing between positive and negative regions for all the pairs considered in our analysis. For the bond-oil pair, our results are comparable to Kanamura (2020), although they cover a longer sample period which includes the COVID-19 outbreak. Notably, a spike in the correlation between climate bonds and each stock and oil market is seen during the COVID-19 outbreak, which is in line with previous findings showing stronger associations during stress periods. However, the correlation between the climate bond and gold markets eases during the pandemic, declining from over 0.40 to around 0. Overall, the results indicate time-dependent relationships between climate bonds and each of these financial markets. Such time-dependent relationships have several implications for policy making, forecasting, and risk management. Hence, taking these dynamic relationships into account is crucial when modelling the volatility of climate bonds (Lu et al., 2017).

4.3. Portfolio implications and hedging effectiveness

4.3.1. Optimal hedge ratio

Following Junttila et al. (2018) and Jalkh et al. (2020), we calculate the risk-minimizing optimal hedge ratio (β_t) in a time-varying setting:

$$\beta_t = \frac{h_t^{bo}}{h_t^{o}} \qquad (10)$$

where h_t^{bo} denotes the conditional covariance between the climate bond index and each of stock, gold, and WTI oil indexes at time *t*; h_t^{o} is the conditional variance of the other index (i.e., S&P 50, gold, or WTI oil) at time *t*. Notably, the variances and covariances are based on the time-varying variance-covariance matrix of the VAR-ADCC-GARCH model.

Table 6 presents the average values of the hedge ratio and hedging effectiveness. The average value of the hedge ratio is negative for climate bonds and US equities (crude oil), which suggests that a $1 long position in US equities (crude oil) can be hedged for $1.9310 ($0.4281) with a long position in climate bonds. However, it is positive for climate bonds and gold, implying that a $1 long position in gold can be hedged for $1.6792 with a short position in climate bonds. Regarding the hedging effectiveness, on average the percentage of the variance reduced by hedging the S&P 500 with climate bonds is highest, followed by gold, whereas marginal risk reduction is seen for the crude oil market. Fig. 4 shows that the optimal hedge ratio varies over time for these cases. Notably, the optimal hedge ratio for climate bonds and crude oil exhibits the largest time-variation, stemming from the instability of the oil market and its high price sensitivity to various economic and non-economic variables and events. This is especially the case during the COVID-19 outbreak period, when the hedge ratio experiences tremendous variability and thus costly dynamic adjustment of the hedging position. Relatively less variability is shown for the bond-stock index, although it is higher than for the more stable hedge ratio of the bond-gold case. This is not surprising given that gold is known for its low return volatility, especially during stress periods (e.g., Baur, 2012). While the hedge ratio involving gold is mostly positive, implying that a short position in climate bonds is required to reduce the risk of a long position in gold, in the cases of bond-stock and bond-oil, the hedge ratio switches between negative and positive values and turns negative around the COVID-19 outbreak, especially for the US stock market index, reflecting the negative performance of the S&P 500 index. Accordingly, there is a need around the pandemic period for a temporary long position in the climate bond index to reduce the risk of US equities. Overall, the results indicate that market participants should rebalance their positions in the climate bond market more frequently during stress periods to maintain a risk minimizing position in US stock and oil markets, which induces a high cost of hedging. These findings add to the existing literature on green bonds and financial markets (e.g., Hammoudeh et al., 2020; Kanamura, 2020; Saeed et al., 2020; Reboredo and Ugolini, 2020; Reboredo et al., 2020) by showing the time-variation in the hedge ratio and the effect of the COVID-19 outbreak while considering the climate bond index and its particularity against the risk of financial markets.

4.3.2. Hedging effectiveness

Following Batten et al. (2019) and Jalkh et al. (2020), we calculate the time-varying hedge effectiveness (TVHE), which gives an indication of the percentage of the variance eliminated by the hedge:

$$TVHE_t = \beta_t^2 \frac{h_t^b}{h_t^o} \tag{11}$$

If $TVHE_t$ is equal to 1, a perfect hedge situation emerges, whereas if it is equal to 0, there is a lack of hedging effectiveness.

Figure 5 shows a time-variation in the hedging effectiveness of climate bonds for the three assets under study. Notably, the percentage of the variance reduced by hedging the S&P 500 with climate bonds is highest, implying that the climate bond index is the best hedge for US equities. For example, at the end of 2019, around 50% of the bond-stock portfolio's variance is reduced by the hedge. However, the hedging effectiveness of climate bonds for the three assets declines significantly during the months of March and April of 2020, which coincides with the peak of the COVID-19 outbreak, before rebounding around May and June 2020 for the cases involving US equity and gold markets. For the case involving the oil market, the percentage of the variance reduced by hedging the oil market with climate bonds remain marginal.
Our above findings are generally in line with recent evidence suggesting that hedge ratios and hedging effectiveness are not stable over time (e.g., Junttila et al., 2018; Batten et al., 2019; Jalkh et al., 2020). However, we provide the first evidence of time-variation in the hedging role of climate bonds for stock, gold, and oil markets and the effect of the COVID-19 outbreak on that role.

4.4. Robustness analysis

We assess the robustness of our above analysis to the choice of DCC model. Using a symmetric DCC-GARCH model, the results for return and volatility spillovers are qualitatively unchanged. Similarly, the dynamics of the conditional correlations between climate bonds and each of the S&P 500, gold, and oil markets are comparable to those reported by the asymmetric model[12]. However, given that the implications of our analysis revolve around hedge ratios and hedging effectiveness, we estimate these based on the symmetric model and report the results in the Appendix. In addition, we report the time-varying correlations obtained from the symmetric DCC-GARCH approach. Table A1 shows the summary statistics of these correlations, illustrated in Fig. A1. Overall, the results are mostly in line with those given in Table 5 and Fig. 3. Moreover, as shown in Fig. A2, the dynamics of the hedge ratio for the three cases exhibit time-variation quite similar to that reported in Fig. 4, especially around the pandemic period. Furthermore, Fig. A3 indicates that the

[12] The results are available from the authors upon request.

hedging effectiveness is highest for bond-stock and is shaped by the outbreak of COVID-19. We also re-conduct the analysis based on the corrected DCC model of Aielli (2013), which considers potential bias in the estimator of the covariance matrix. Unreported results show that implementing the corrected DCC approach does not alter our main results regarding the hedge ratios and hedging effectiveness. Taken together, the results from this robustness analysis indicate that our reported findings are robust to the choice of model and the specification of the DCC process.

5. Conclusions and policy implications

This paper examines the interactions between climate bonds and leading stock and commodity markets such as S&P 500, crude oil and gold. Using the bivariate VAR-ADCC-GARCH model, the results indicate time-varying correlations between climate bonds and each of the major financial and commodity markets under study, which are shaped by the COVID-019 outbreak. Climate bond prices have a negative association with the S&P 500 for most of the sample period, while positive correlations are observed with both commodity markets under investigation. These findings are generally consistent with previous studies (Gormus et al., 2018; Reboredo, 2018; Kanamura, 2020), implying that although climate bonds are introduced to fund eco-friendly projects, they share some features with conventional bonds regarding their relationship with financial markets. We show evidence of significant volatility linkages between climate bonds and financial markets, whereas the return linkages are marginal. The results of the hedging effectiveness analysis show that climate bonds are effectives hedges, especially against the risk of US equities and gold. The hedge ratios vary with time, especially during the COVID-19 outbreak, suggesting the necessity of regular monitoring and adjustment of hedged positions, especially those for oil and stock. The hedge effectiveness of the climate bonds for US equities is highest but reduces substantially during the peak of the COVID-19 outbreak around March and April 2020. Overall, the hedging effectiveness during the COVID-19 outbreak is hindered by a relatively higher cost, especially for the hedging strategy of oil and to some extent US equities.

Understanding the interactions and dynamic relationships between climate bond and leading financial markets is of paramount importance to ethical investors, as this information is essential for gaining superior risk-adjusted returns through proper allocation of climate bonds to a portfolio and for managing risk. Such knowledge helps identify whether and to what extent climate bonds are sensitive to return and volatility shocks emanating from stock and commodity markets. Accordingly, our findings have several implications for market participants. Firstly, climate bonds have the ability to induce significant hedging benefits for US stock and gold investors, as we find a strong negative relationship between these climate bonds and these two asset classes. Secondly, oil prices have a weak relation with the climate bond market and some marginal hedging benefits can emerge if climate bonds are used as a hedge. Thirdly, the relationship between climate bonds and each of the three indexes is altered by the market turbulence during the COVID-19 outbreak, which leads to a large reduction in the hedging ability of climate bonds. It is worth mentioning that although environmentally friendly investors aim to decarbonize their portfolios, the main purpose is still receiving healthy returns on their investment (Hoti et al., 2005). If decarbonizing portfolios did not provide incentives to switch to ethical investments, investors would be reluctant to green their portfolios which would hamper the migration towards a low-carbon economy. Therefore, our findings are of particular interest to those market participants who want to invest in socially responsible firms. Moreover, our findings have implications for climate bond issuers. Given that climate bonds appear to be a sound financial instrument for environmentally friendly investors, issuers can employ this device to diversify their investor base and improve their environmental, social and governance (ESG) scores (Reboredo, and Ugolini, 2020). However, they should be aware of the adverse effect of health crisis periods such as the COVID-19 outbreak on the stability of the hedging strategy and the resulting benefits.

Future research could explore how climate bonds react to changes in the implied volatility indexes of stock and commodity markets. It is important to examine whether climate bonds can be used as a hedging instrument for socially responsible investments such as ESG and clean energy stock indices. Finally, our reliance on a stricter index representing an interesting range of climate bonds ultimately opens a wide path for new research covering the extremely understudied climate-aligned bonds, their stylized facts, price and volatility dynamics, and their interdependence with various asset classes and uncertainty measures, and possible hedging ability.

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Table 1: Descriptive statistics of daily returns

Index ↓	Mean	Standard Deviation	Skewness	Kurtosis	Jarque-Bera test	ADF	ARCH-LM
Climate bond	0.0076	0.1384	-1.1104	10.125	1893.481***	-24.041***	39.245***
S&P 500	0.0376	1.3563	-1.1837	24.299	15614.842***	-8.378***	1595.729***
Gold	0.0442	0.7988	0.0207	9.717	1533.810***	-28.233***	22.372***
WTI	0.0493	3.8695	-0.4251	33.923	32537.027***	-8.571***	20.098***

Notes: In this table, natural logarithmic returns are used for the indexes. The sample is 1 March, 2017 to 30 June, 2020. Jarque-Bera statistics are used to test the null hypothesis that the return series are normally distributed. ADF is the augmented Dickey Fuller statistics used to test the null hypothesis that the return series contains a unit root, which is conducted with an intercept. ARCH-LM statistics are used to test the null hypothesis that the return series exhibit heteroscedasticity at lag 10. *** $p<0.01$.

Table 2: VAR-ADCC-GARCH analysis of climate bond and stock markets

Variables ↓	Climate bond	S&P 500
r_{t-1}^{b}	0.1345 (.00)***	-0.0824 (.00)***
r_{t-1}^{s}	0.0081 (.00)***	- 0.0811 (.00)***
$\varepsilon_{b,t-1}^{2}$	0.1085 (.00)***	-0.0499 (.00)***
$\varepsilon_{s,t-1}^{2}$	0.0010 (.00)***	0.2850 (.00)***
h_{t-1}^{b}	0.6189 (.00)***	0.0525 (.00)***
h_{t-1}^{s}	-0.0006 (.00)***	0. 7218 (.00)***
θ_1	0.1332 (.00)***	
θ_2	0.7614 (.00)***	
θ_3	0.0006 (.00)***	
Log Likelihood	-397.61	
ARCH-LM	0.62 (.81)	

Notes: This table reports the outcomes for the VAR-ADCC-GARCH model for the bond-stock combination. r_{t-1}^{s} refers to the return on the S&P 500 index at time *t*-1 and r_{t-1}^{b} denotes the same for the climate bond market. In addition, h_{t-1}^{b} measures the conditional variance of the bond price returns at time *t*-1 and h_{t-1}^{s} indicates the conditional variance of stock market returns at time *t*-1. The squared error terms $\varepsilon_{s,t-1}^{2}$ and $\varepsilon_{b,t-1}^{2}$ measure the effects of unexpected news or shocks in stock and bond markets, respectively. ARCH-LM statistics are used to test the null hypothesis that the return series exhibit heteroscedasticity at lag 10. ***, ** and * indicate statistical significance at 1%, 5% and 10% levels, respectively. Values in parentheses indicate *p*-values.

Table 3: VAR-ADCC-GARCH analysis of climate bond and gold markets

Variables ↓	Climate bond	Gold
r_{t-1}^{b}	0.0947 (.00)***	0.1053 (.00)***
r_{t-1}^{g}	-0.0082 (.11)	0.0074 (.73)
$\varepsilon_{b,t-1}^{2}$	0.0402 (.00)***	1.4286 (.00)***
$\varepsilon_{g,t-1}^{2}$	0.0015 (.00)***	0.0527 (.00)***
h_{t-1}^{b}	0.9389 (.00)***	-2.0853 (.00)***
h_{t-1}^{g}	-0.0024 (.00)***	0. 9225 (.00)***
θ_1	0.0091 (.00)***	
θ_2	0.2464 (.00)***	
θ_3	0.0037 (.00)***	
Log Likelihood	-286.15	
ARCH-LM	0.88 (.59)	

Notes: This table reports the outcomes for the VAR-ADCC-GARCH model for the bond-gold combination. r_{t-1}^{g} refers to the return on the gold index at time *t*-1 and r_{t-1}^{b} denotes the same for the climate bond index. In addition, h_{t-1}^{b} measures the conditional variance of the bond price returns at time *t*-1 and h_{t-1}^{g} indicates the conditional variance of gold market returns at time *t*-1. The squared error terms $\varepsilon_{g,t-1}^{2}$ and $\varepsilon_{b,t-1}^{2}$ measure the effects of unexpected news or shocks in gold and bond markets, respectively. ARCH-LM statistics are used to test the null hypothesis that the return series exhibit heteroscedasticity at lag 10. ***, ** and * indicate statistical significance at 1%, 5% and 10% levels, respectively. Values in parentheses indicate *p*-values.

Table 4: VAR-ADCC-GARCH analysis of climate bond and WTI markets

Variables ↓	Climate bond	WTI
r_{t-1}^{b}	0.0135 (.02)**	- 0.2281 (.72)
r_{t-1}^{o}	0.0022 (.11)	- 0.0990 (.00)***
$\varepsilon_{b,t-1}^{2}$	0.1031 (.00)***	44.8426 (.00)***
$\varepsilon_{o,t-1}^{2}$	0.00001 (.16)	0.0908 (.00)***
h_{t-1}^{b}	0.8145 (.00)***	-12.5619 (.00)***
h_{t-1}^{o}	-0.00001 (.02)**	0. 8808 (.00)***
θ_1	0.2703 (.00)***	
θ_2	0.0034 (.04)***	
θ_3	0.0044 (.00)***	
Log Likelihood	-1403.28	
ARCH-LM	0.76 (.67)	

Notes: This table reports the outcomes for the VAR-ADCC-GARCH model for the bond-oil combination. r_{t-1}^{o} refers to the return on WTI oil index at time *t*-1 and r_{t-1}^{b} denotes the same for the climate bond index. In addition, h_{t-1}^{b} measures the conditional variance of the bond price returns at time *t*-1 and h_{t-1}^{s} indicates the conditional variance of oil market returns at time *t*-1. The squared error terms $\varepsilon_{o,t-1}^{2}$ and $\varepsilon_{b,t-1}^{2}$ measure the effects of unexpected news or shocks in oil and bond markets, respectively. ARCH-LM statistics are used to test the null hypothesis that the return series exhibit heteroscedasticity at lag 10. ***, ** and * indicate statistical significance at 1%, 5% and 10% levels, respectively. Values in parentheses indicate *p*-values.

Table 5: Summary statistics of dynamic time-varying correlations

	Mean	Standard Deviation	Maximum	Minimum
Climate Bond/S&P 500	-0.2648	0.2276	0.6717	-0.7370
Climate Bond/Gold	0.2943	0.1538	0.6652	-0.1035
Climate Bond/WTI	0.0273	0.1726	0.6913	-0.6267

Notes: This table reports the summary statistics of time-varying correlations obtained from the asymmetric DCC-GARCH process.

Table 6: Average values of hedge ratio and hedging effectiveness

	Hedge ratio	Hedging effectiveness
Climate bond-stocks	-1.9310	12.19%
Climate bond-gold	1.6792	11.02%
Climate bond-oil	-0.4281	3.05%

Notes: In this table, we provide the average of the hedge ratio and hedging effectiveness between climate bonds and each of the three indexes under study. The sample includes 817 daily observations.

Fig. 1: Level series from March 2017 to June 2020

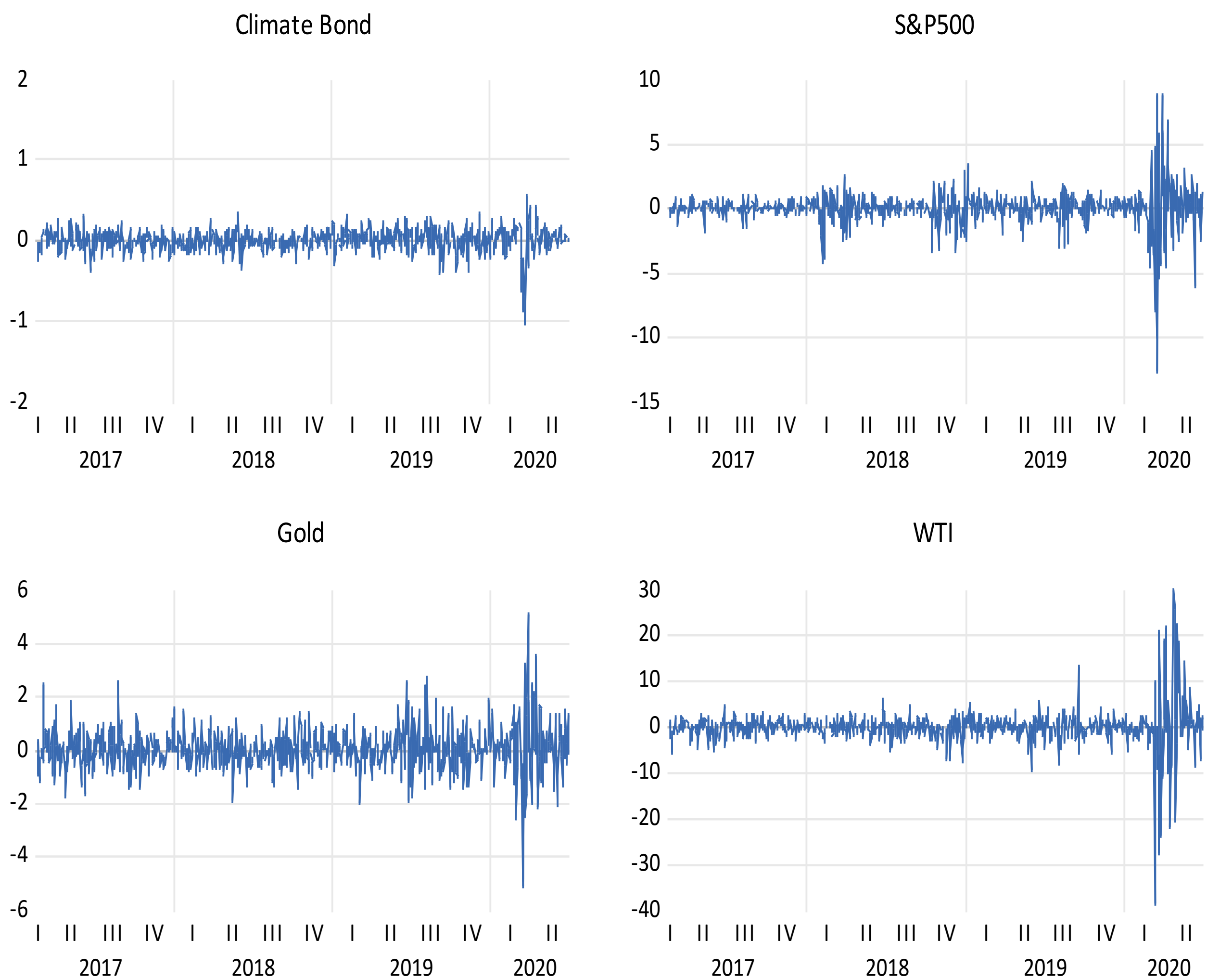

Fig. 2: Return series from March 2017 to June 2020

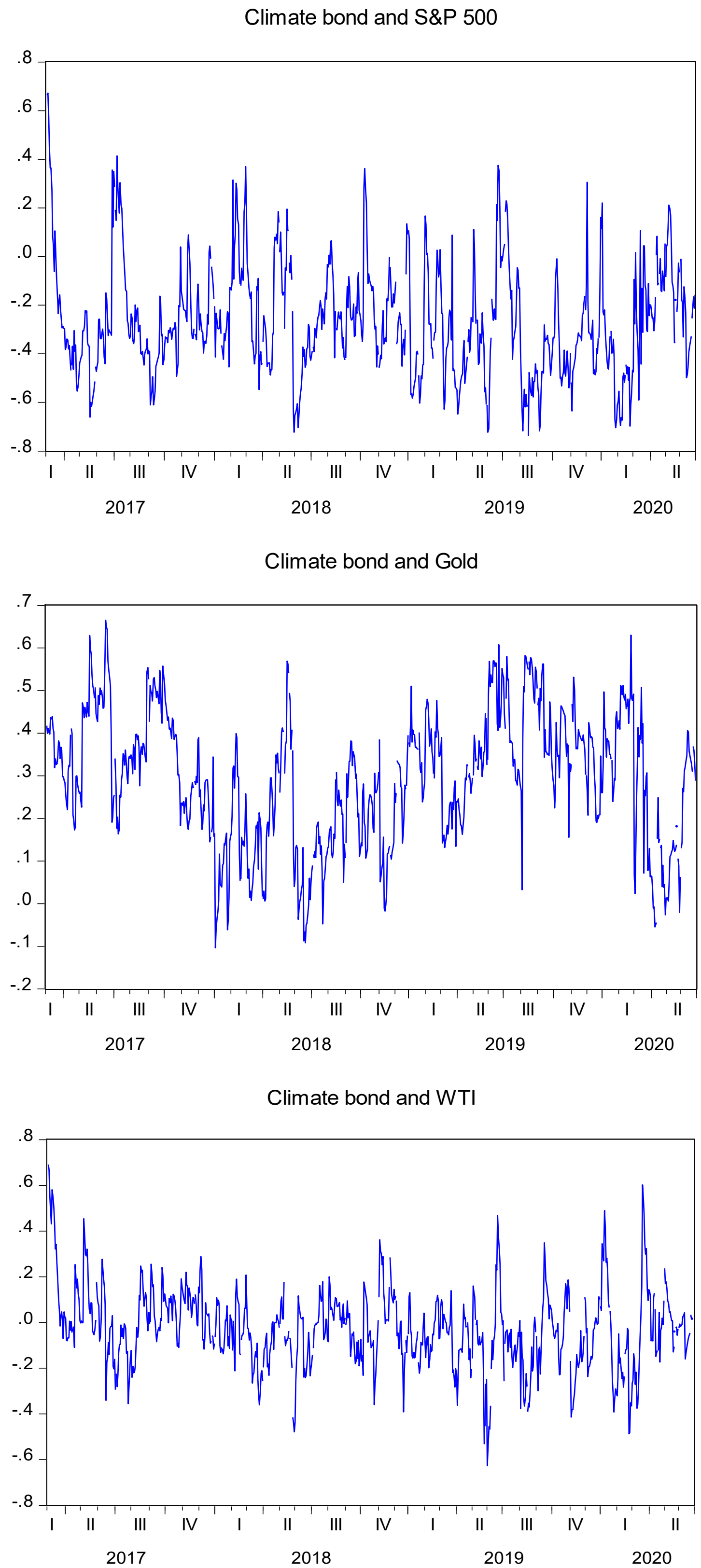

Fig. 3: Pairwise dynamic conditional correlations based on the ADCC-GARCH process

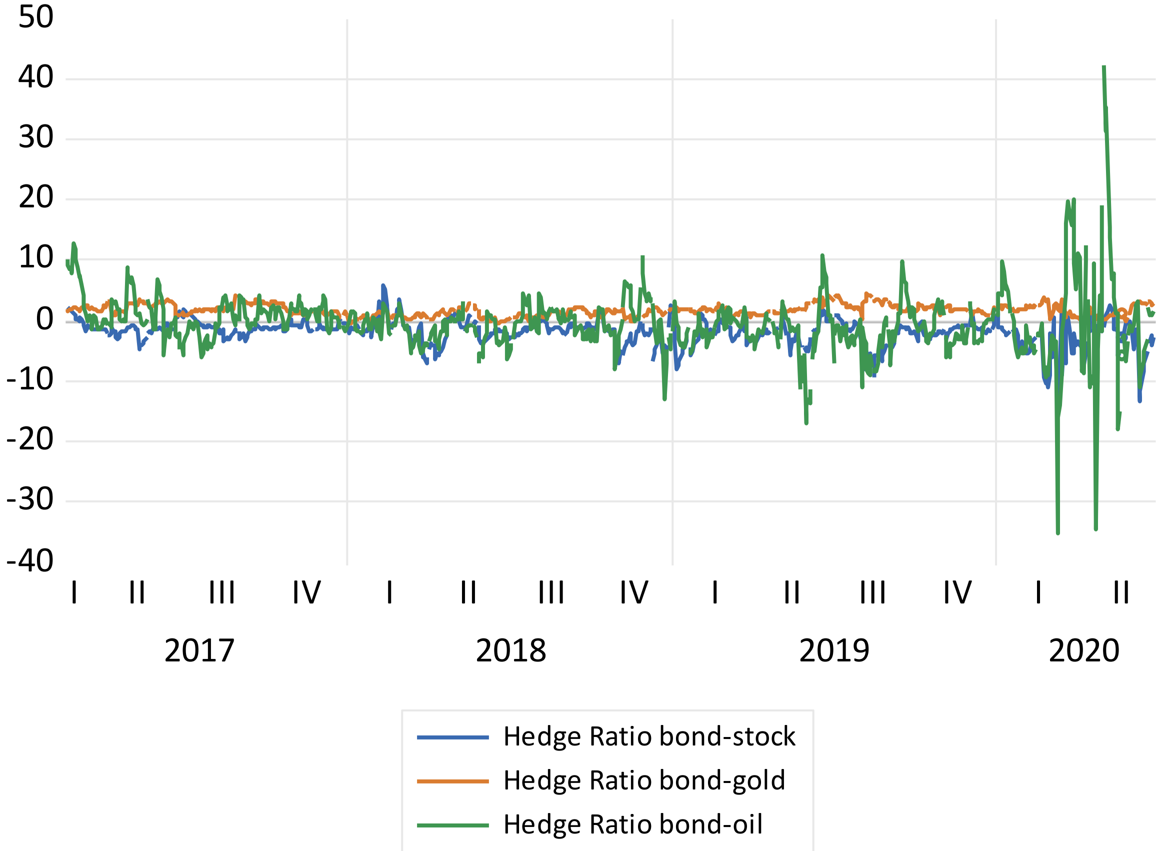

Fig. 4: Hedge ratio between the climate bond index and each of the three assets

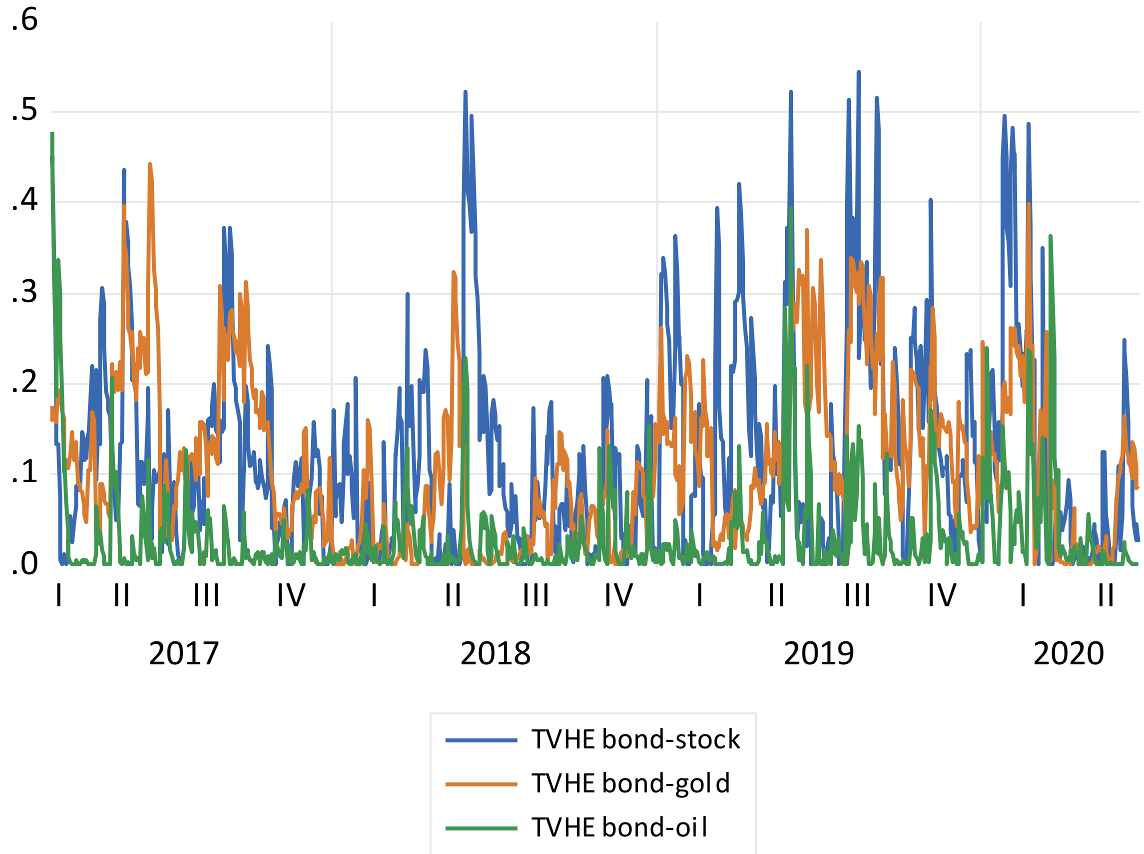

Fig. 5: Hedge effectiveness between climate bonds and each of the three assets

APPENDIX

Table A1: Summary statistics of dynamic time-varying correlations

Index ↓	Mean	Standard Deviation	Maximum	Minimum
Climate Bond/S&P 500	-0.2490	0.1787	0.6452	-0.5602
Climate Bond/Gold	0.2996	0.0961	0.5174	0.0668
Climate Bond/WTI	0.0069	0.1003	0.5800	-0.4063

Notes: This table reports the summary statistics of time-varying correlations obtained from the DCC-GARCH model.

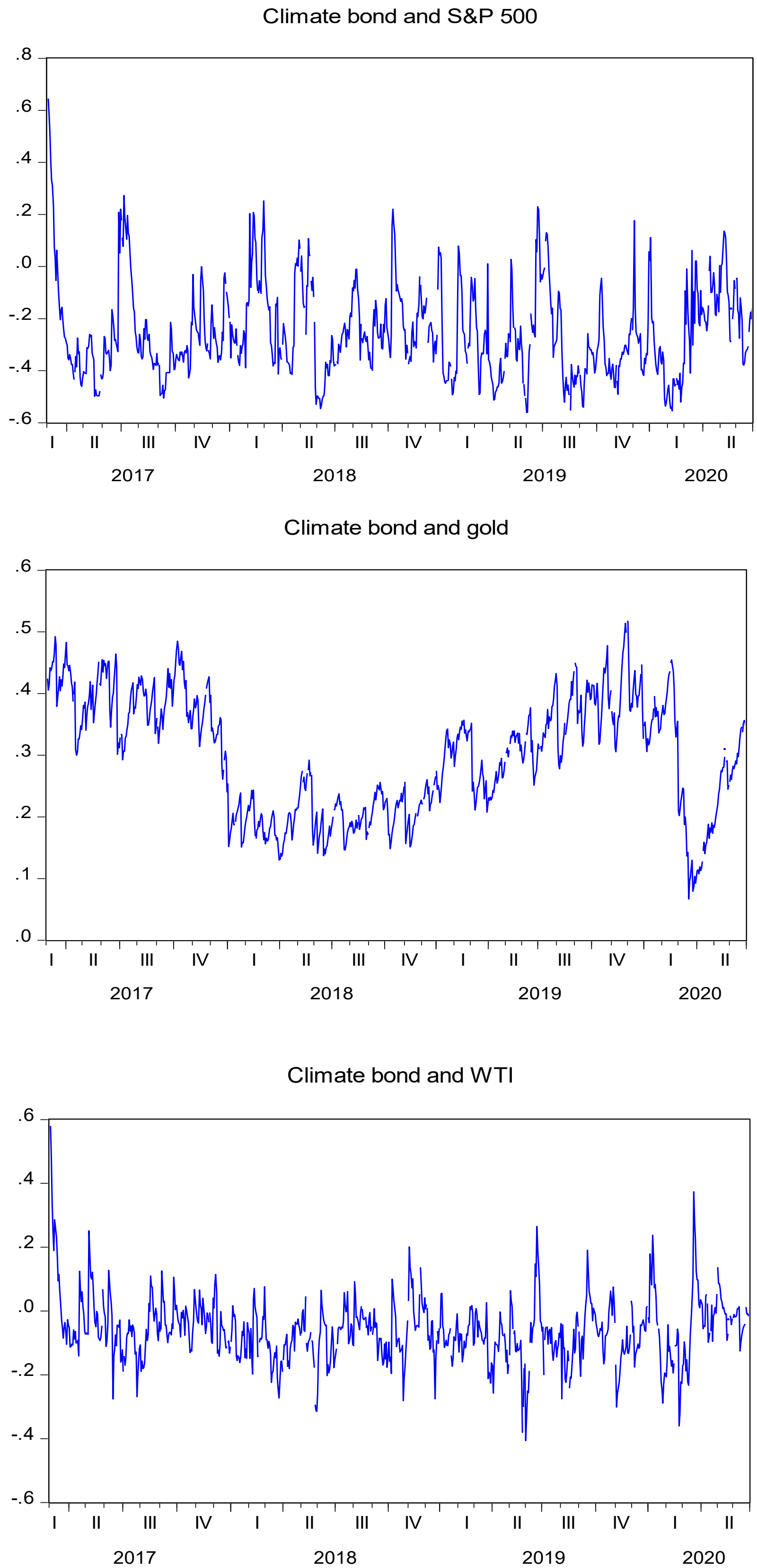

Fig. A1: Pairwise dynamic conditional correlations based on the DCC-GARCH process

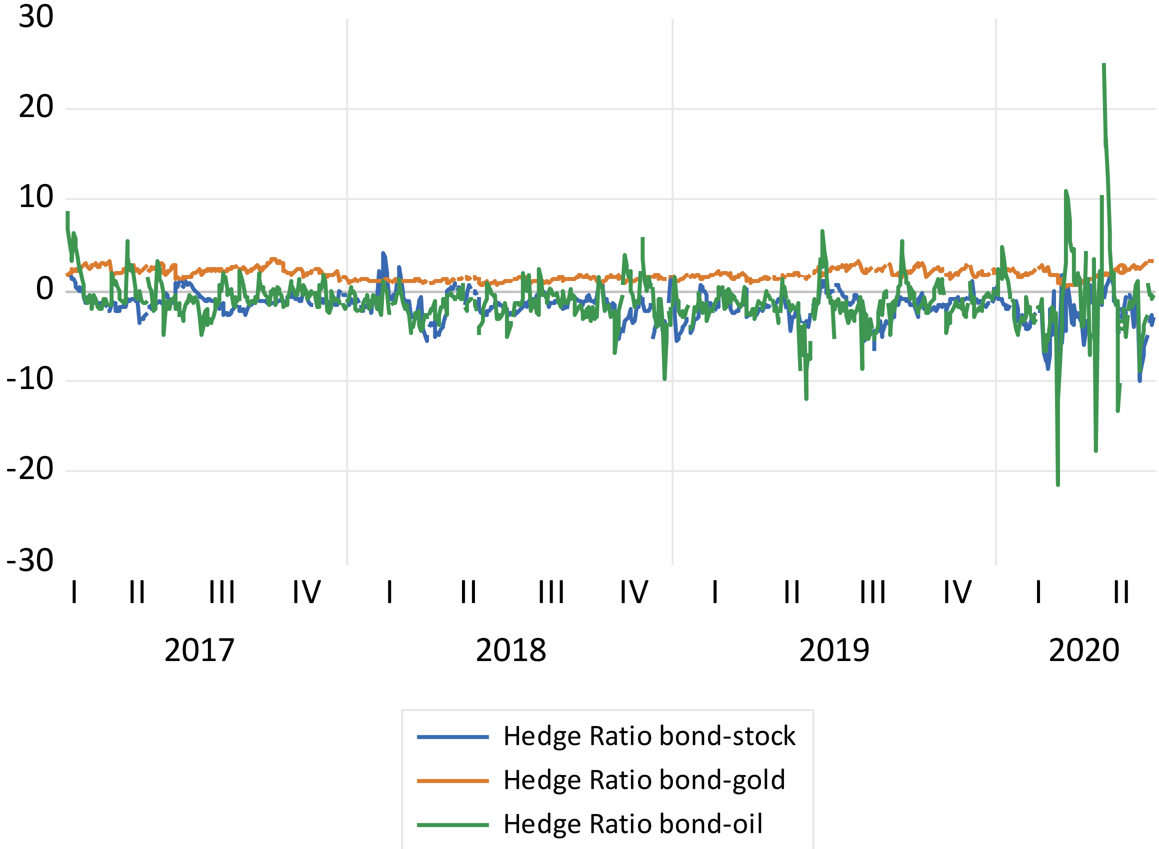

Fig. A2: Hedge ratio between the climate bond index and each of the three assets based on the DCC-GARCH process

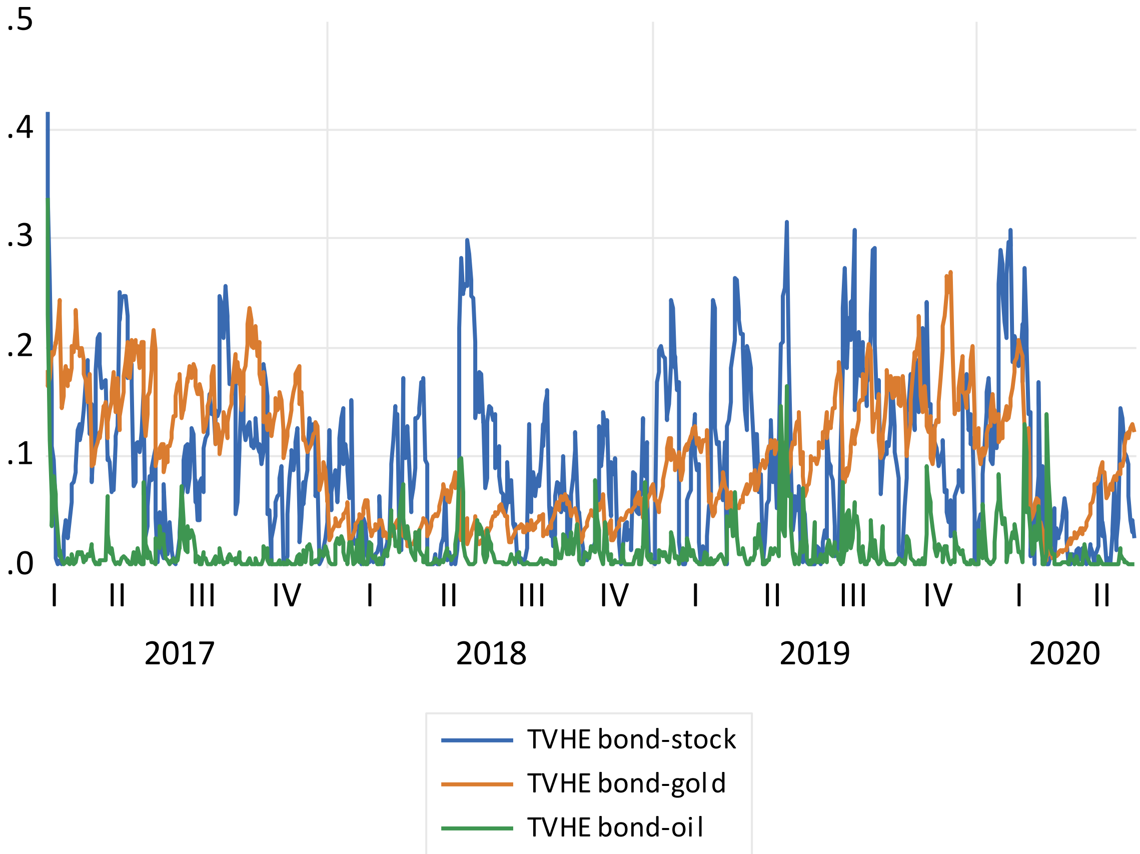

Fig. A3: Hedge effectiveness between climate bonds and each of the three assets using the DCC-GARCH process