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Market volatilities vs oil shocks: which dominate the relative performance of green bonds?

Abstract

The market performance of green bonds determines whether they will make a significant contribution to future financial markets and sustainable investment. It is therefore important to conduct a thorough study of the dominant factors affecting the market performance of green bonds, particularly their performance relative to conventional bonds. Thus, the main objective of this paper is to investigate and compare the impact of market volatilities (mainly VIX, OVX, and MOVE) and oil shocks (including supply shock, demand shock, and speculative demand shock) on the relative performance of green bonds. The main findings indicate that when volatilities coincide with oil shocks, the former consistently exert a more pronounced influence on the relative performance of green bonds. This phenomenon is particularly evident in the post-COVID-19 period. Concerning crude oil shocks, oil supply and demand shocks have opposite effects on the relative performance of green bonds, with the supply shock having a negative impact and the demand shock having a positive impact. Furthermore, our analysis shows that volatilities and oil shocks tend to have significant effects on the relative performance of green bonds during periods of heightened market risk aversion, while their impact remains negligible in a stable market environment. The empirical results may provide novel insights and significant implications for the further development of the green bond market.

Keywords: Green bond; Relative performance; Uncertainty; Market volatilities; Crude oil shocks

JEL classification: C32; C58; Q40; G11

1. Introduction

As a sustainable investment tool, green bonds have become increasingly prominent in financing frameworks for sustainable development (Tolliver et al., 2019) and have attracted widespread attention from investors, particularly socially responsible investors (Flammer, 2021). Since its first issuance in 2007, the green bond market has continued to expand, with cumulative global issuance reaching approximately US\$3.0tn by the end of 2023, according to data published by the Climate Bonds Initiative (CBI)¹. In addition to their key financing role in addressing climate issues and the low-carbon transition, green bonds have proven to be an effective tool not only for improving a company's environmental footprint (Fatica and Panzica, 2021; Flammer, 2021) but also for improving intergenerational environmental well-being (Flaherty et al., 2017).

Meanwhile, after more than a decade of development, the green bond market is gradually maturing and becoming more active and is often seen as an asset class that plays an important role in portfolios and risk management (Reboredo, 2018; Reboredo and Ugolini, 2020). However, the market performance of green bonds is one of the key determinants of whether they can compete with, or even substitute, conventional bonds in asset allocation and, more importantly, whether they can become a major

¹ <https://www.climatebonds.net/>

contributor to financial markets and sustainable investment in the future ([Hachenberg and Schiereck, 2018](#)). It is therefore important to conduct an in-depth study of the market performance of green bonds, in particular their relative performance to conventional bonds, and the key factors behind their relative performance.

To examine the relative performance of green bonds and the underlying factors, it is first necessary to explore the key differences between the two types of bonds that may lead investors to make allocation trade-offs between the two. Currently, the main differences between the two bond markets are the smaller size (i.e., higher liquidity risk) and environmental attributes of green bonds ([Boutabba and Rannou, 2022](#)). The former is a relative disadvantage for green bonds, while the latter is an attractiveness, especially for socially responsible investors. If certain factors increase investors' attention to these differences and affect investors' allocation trade-offs between green and conventional bonds, then the performance differential (i.e. relative performance) between the two bonds may change. Specifically, if some factors exacerbate investors' liquidity concerns, investors may prefer conventional bonds to green bonds due to a flight to liquidity, while if some factors increase the attractiveness of green bonds, investors may prefer green bonds to conventional bonds. Therefore, this paper analyzes the potentially important factors affecting the relative performance of green bonds from the two dimensions mentioned above.

In terms of the factors that exacerbate market liquidity risk and investors' liquidity concerns, uncertainties are one of the most important and widely studied ([Bams and Honarvar, 2021](#); [Chung and Chuwonganant, 2014](#); [Debata and Mahakud, 2018](#); [Easley and O'Hara, 2010](#); [Fengrong et al., 2022](#); [Fiorillo et al., 2023](#); [Lyu et al., 2021](#); [Ozsoylev and Werner, 2011](#); [Rehse et al., 2019](#)). Among various uncertainties, stock market uncertainty and crude oil market uncertainty are the most important

influences on the green bond market (Long et al., 2022). In addition, as a type of bond, green bonds are theoretically directly affected by bond market uncertainty. Therefore, this paper mainly focuses on the impact of three types of market uncertainty, namely stock market uncertainty, crude oil market uncertainty, and bond market uncertainty, on the relative performance of green bonds. These three types of uncertainties are represented by the Chicago Board Options Exchange Volatility Index (VIX), the Chicago Board Options Exchange Crude Oil ETF Volatility Index (OVX), and the Intercontinental Exchange BofAML U.S. Bond Market Option Volatility Estimate Index (MOVE), respectively, which we refer to as market volatilities.

Concerning factors affecting the attractiveness of green bonds, we focus mainly on oil shocks. As a sustainable investment tool, green bonds inherently possess an environmental dimension, commonly referred to as "greenness" (Kanamura, 2020), which potentially exposes them to shocks stemming from the energy sector, especially price shocks from the crude oil market (Azhgaliyeva et al., 2022; Rehman et al., 2023). Crude oil price shocks not only affect investors' enthusiasm to participate in green investments (Bondia et al., 2016; Taghizadeh-Hesary et al., 2021; Xia et al., 2019) but also affect corporate social responsibility engagement (Hasan et al., 2022) and the probability of corporate green bond issuance (Azhgaliyeva et al., 2022). In this paper, we mainly focus on three types of oil price shocks, namely supply shock (S_shock), demand shock (D_shock), and speculative demand shock (Spe_shock). Although the OVX is already included in the market volatilities, we believe it is still necessary to consider the influence of oil price shocks from different sources on the relative performance of green bonds. On the one hand, OVX and oil price shocks have different effects on green assets (Dutta et al., 2020). On the other hand, oil price shocks from different sources have significantly different and unique implications

(Chen et al., 2020; Kilian, 2009; Lyu et al., 2024; Ready, 2018; Wong and Hasan, 2021).

The question then naturally arises as to which of the two types of factors mentioned above dominates the relative performance of the green bond market. The clarification holds significant importance, particularly in the aftermath of the COVID-19 outbreak, when market volatilities and crude oil shocks overlap. Identifying the different effects of these variables can, to some extent, provide valuable insights into how investors trade off the liquidity disadvantage of green bonds against their environmental attributes. This understanding, in turn, can aid policymakers in formulating effective strategies to attract investor participation in the green bond market. Simultaneously, at a micro level, a comparative analysis of the impacts of these two types of variables offers intricate insights into the main drivers behind the performance disparity between green and conventional bonds. This can enable investors to better balance the allocation between green and conventional bonds in different situations. To this end, we undertake a thorough assessment of the influence of market volatilities and crude oil shocks on the relative performance of green bonds. To the best of the authors' knowledge, this paper is the first to examine the factors affecting the relative performance of green bonds from a comparative perspective.

In this paper, we use the difference in returns between green bonds and conventional bonds, always referred to as excess returns (ER), as a proxy for the relative performance of green bonds. To further examine the state-dependent characteristics of the impact of these two types of factors on green bonds ER, we conduct the following two works. Firstly, we opt to partition our sample into two distinct segments: the pre-COVID-19 period and the post-COVID-19 period, utilizing January 2020 as the demarcation point. The advent of the COVID-19 pandemic has

left an indelible imprint on the global economy and financial markets, as underscored by numerous studies (Bai et al., 2021; Chen et al., 2023; Li et al., 2021; Liu et al., 2022; Naeem et al., 2021; Shahzad et al., 2021; Wang et al., 2023b; Wei et al., 2022b; Wei et al., 2022c). Among these financial markets, the green bond market stands out as the most affected by the COVID-19 pandemic (Cui et al., 2022). The epidemic not only significantly affects the market efficiency of green bonds (Naeem et al., 2021), but also greatly increases the cumulative abnormal return of green bonds (Yi et al., 2021). Moreover, the epidemic has also led to structural breaks in crucial variables such as the VIX and OVX, as discussed by Pham and Nguyen (2022), which are relevant to this article. Therefore, it is necessary to separately examine the impact of different factors on green bond ER before and after COVID-19 to determine whether these factors have different influences.

Secondly, we decompose ER into an upward component, the upward ER (up-ER), and a downward component, the downward ER (down-ER). The terms "up" and "down" here refer to the benchmark (conventional bonds in this paper), with up-ER measuring the ER of green bonds when the conventional bond market rises and down-ER measuring the ER of green bonds when the conventional bond market falls. Given that the rise and fall of bond prices are often closely related to market stability and risk aversion (Adrian et al., 2019; Bansal and Stivers, 2022; Wei et al., 2019), an increase in bond prices often indicates an increase in market instability and risk aversion, and conversely, a decrease in bond prices may indicate a decrease in risk aversion. Therefore, we use up-ER and down-ER to proxy the relative performance of green bonds in environments where risk aversion increases and decreases, respectively.

The reason for doing this is inspired by Barclays (2015), which finds that green bonds have a lower beta than conventional bonds and a lower magnitude of returns in

both positive and negative return years. In other words, when the conventional bond market rises, green bonds perform relatively worse; when the conventional bond market falls, green bonds perform relatively better. We conjecture that this may be because investors assign different weights to the liquidity and environmental attributes of green bonds in different market environments. Empirical research shows that in a normal market, bond investors care about both the quality and liquidity of bonds, especially quality. However, in a stressed market, investors chase liquidity rather than quality ([Beber et al., 2009](#)), which is known as the "fight to liquidity". Similarly, when investors make trade-offs between green bonds and conventional bonds, liquidity and greenness may matter differently in different market conditions. Specifically, in a market environment with heightened risk aversion, investors are concerned more about liquidity and allocate less to green bonds, leading to underperformance of green bonds; in an environment with high market stability, the green attributes of green bonds may be more attractive, which may lead to outperformance of green bonds.

The above perspective is also supported by [Broadstock and Cheng \(2019\)](#), who find that investors may have an incentive to focus on conventional bonds when financial markets are in a period of heightened instability. Therefore, it is imperative to distinguish between market conditions and assess the influence of variables on the green bond ER under different conditions.

The contributions of this paper are twofold. Firstly, this paper extends the research on the green bond market by examining the impact of market volatilities and crude oil shocks on the relative performance of the green bond market. What sets our work apart from previous studies is our focal point on the relative performance of the green bond market, rather than its absolute performance. In doing so, we furnish

market participants with fresh insights into the performance disparities between green and conventional bonds, their evolution, and the pivotal role played by pertinent variables in steering these differentials.

Second, we comprehensively compare the impact of market volatility and crude oil shocks on the relative performance of green bonds across two dimensions: different market states and different sub-sample periods. The comparative analysis provides market participants with a deeper understanding of the characteristics of the impact of these two types of factors, which vary depending on the situation. On the one hand, it helps policymakers to formulate more effective strategies to attract green bond issuers and investors. On the other hand, it also helps investors to construct optimal portfolios and formulate effective risk management strategies based on the impact of different factors.

The main conclusions of this paper are as follows: i) volatilities, as the dominant drivers of all variables considered in this paper, always negatively impact the ER of green bonds; ii) oil demand and supply shocks have opposite effects on the ER of green bonds, with the former having a positive and larger effect, and the latter having a negative and relatively small effect; iii) these variables are more likely to have a significant impact in an environment of heightened risk aversion or market instability.

The organization of this study is outlined as follows. The subsequent section offers a brief review of the related literature. Section 3 describes the data used in this current study. The methodologies are outlined in Section 4. Section 5 presents the empirical results and analysis. An extended analysis is performed in Section 6. Section 7 concludes the paper and draws some implications.

2. Literature review

2.1 Investigations of greenium

The current study is closely related to the literature on greenium, an important branch that focuses on the pricing of green bonds, i.e., whether there is a green premium (greenium) for green bonds relative to conventional bonds. Although green bonds are not fundamentally different from traditional bonds in terms of asset structure such as maturity and yield, empirical studies often find differences in pricing or market performance between the two, the so-called greenium. For example, [Baker et al. \(2022\)](#), [Nanayakkara and Colombage \(2019\)](#), [Zerbib \(2019\)](#), [Hachenberg and Schiereck \(2018\)](#), and [Löffler et al. \(2021\)](#) all support the existence of a positive greenium for green bonds. [Xu et al. \(2022\)](#) find that Chinese green bonds have a negative green premium due to greenwashing.

Although the existing literature examines the differences in pricing or market performance between green bonds and conventional bonds from different perspectives, these pieces of literature mainly focus on the endogenous variables that lead to such differences between the two, such as the industry in which the issuer operates, credit ratings, disclosure of information and the size of bond issuance, etc., and less literature pays attention to the impact of exogenous variables, such as market volatilities, oil shocks and other factors on the relative performance of green bonds.

2.2 Market volatilities and green bonds

Despite the rapid development of the green bond market, it is still in its infancy. The small size and low liquidity of the green bond market often makes it vulnerable to various uncertainties or fluctuations in the broader capital markets ([Adekoya et al.](#),

2023; Elsayed et al., 2022; Gao et al., 2021; Long et al., 2022; Pham and Nguyen, 2022; Reboredo and Ugolini, 2020; Wei et al., 2022a). For example, Pham and Nguyen (2022) study the impact of VIX, OVX, and economic policy uncertainty (EPU) on green bond returns and conclude that the impact of these variables is time-varying and state-dependent. Specifically, these variables have a stronger impact on green bonds during periods of high uncertainty and the opposite is true during periods of low uncertainty. Long et al. (2022) suggest that VIX and OVX have a stronger impact on green bonds, especially in extremely bullish markets, and that the impact is time-varying, asymmetric, and heterogeneous. Tian et al. (2022) examine the impact of OVX and other uncertainties on green bond prices in the US, Europe, and China, and find that these uncertainties have a heterogeneous impact on the green bond market across countries, and the impact is asymmetric.

Within the broader framework of financial markets, the green bond market is closely linked to other markets and is highly susceptible to influences from other financial markets. Adekoya et al. (2023) examine the predictive power of commodity and financial asset prices, as well as speculative factors (EPU, VIX, and investor sentiment) on green bond returns, and find that most factors are significant predictors of green bond returns. This suggests that the green bond market is not only sensitive to risks transmitted from other financial and commodity markets but also to general market-based uncertainties such as EPU and VIX. Reboredo and Ugolini (2020) study price spillovers between green bonds and financial markets and find that the green bond market receives substantial price spillovers from fixed-income and currency markets and transmits negligible backward effects. Elsayed et al. (2022) examine the time-frequency interdependence between green bonds and financial markets and find that the green bond market receives more volatility but transmits less.

The above literature focuses on the impact of various uncertainties on the green bond market, providing valuable information for investors and policymakers. However, from a comparative perspective, green bonds and conventional bonds have different characteristics, especially in terms of liquidity, which makes them react differently to these uncertainties. Therefore, it is necessary to pay attention to the impact of different uncertainties on the relative performance of green bonds, which can help investors make the optimal trade-off between green bonds and conventional bonds, and help policymakers determine the best policy to pursue.

2.3 The crude oil market and green bonds

As an environmentally friendly investment vehicle, green bonds are sensitive to shocks from the energy sector, mainly those emanating from crude oil markets ([Azhgaliyeva et al., 2022](#); [Rehman et al., 2023](#); [Wei et al., 2019](#)). Oil price shocks not only stimulate investor interest but also affect the ability and willingness of firms to engage in green activities. Some literature argues that the increase (decrease) in oil prices stimulates (reduces) green investment ([Bondia et al., 2016](#); [Dutta et al., 2020](#); [Taghizadeh-Hesary et al., 2021](#); [Xia et al., 2019](#)), suggesting a positive relationship between oil prices and green bond prices or a substitution effect between the green bond market and the crude oil market. [Tian et al. \(2022\)](#) provide evidence that the OVX has a significant positive impact on green bond prices in the US, Europe, and China, suggesting a substitution effect between the green bond market and the crude oil market. Some other literature also supports this point by showing a positive correlation between crude oil prices and green bond prices ([Kanamura, 2020](#)), suggesting that an increase in oil prices will lead to an increase in green bond prices as investors will be more inclined to turn to the green bond market. On the other hand,

the impact of oil price shocks can also affect corporate green activities, for example, [Azhgaliyeva et al. \(2022\)](#) investigate oil shocks on green bonds and find that both the oil supply and demand shock have a significant positive effect on the probability of corporate green bond issuance. [Hasan et al. \(2022\)](#) provide evidence that the oil demand shock has a significant positive impact on corporate social responsibility (CSR) behavior, while the oil supply shock has a significant negative impact.

However, some papers present different views. [Huang et al. \(2022\)](#) argue that green bonds are negatively correlated with crude oil prices during the COVID-19 pandemic and the outbreak of the Russia-Ukraine conflict. [Lee et al. \(2021\)](#) find that the oil price and the green bond market have significant bidirectional causality in a bearish state, but the predictability of oil for green bonds is limited in a bullish market. [Li et al. \(2022\)](#) suggest that the oil price negatively impacts the green bond index in the short and medium term. [Rehman et al. \(2023\)](#) examine the predictive power of oil shocks for the green bond market and document that three oil shocks can robustly predict green bond returns, but the signs (directions) of the coefficients tell different stories across countries. [Su et al. \(2023\)](#) find an ambiguous relationship between oil prices and green bond prices, i.e. positive in the short run but negative in the medium to long run due to oversupply in the oil market and increased profits in the green energy industry. [Wang et al. \(2023a\)](#) examine the relationship between crude oil prices and green bonds using a rolling window Granger causality test. They find positive, negative, and uncorrelated effects of oil prices on green bonds using the same sample. [Lee et al. \(2022\)](#) find that the aggregate demand shock negatively affects green bond returns.

Although the above literature unanimously suggests that crude oil price fluctuations have a significant impact on the green bond market, there is no consensus

on the direction of the impact and few studies focus on and compare the impact of these variables on the relative performance of green bonds.

3. Data

There are three sets of original variables in this paper. The first dataset consists of the green bond index, the conventional bond index, and three relative performance measures of green bonds (i.e., ER, up-ER, and down-ER). Following [Nguyen et al. \(2021\)](#), we use the S&P Green Bond Index as a proxy for the green bond market, and the Barclays Bloomberg Global Treasury Index as a proxy for the conventional bond market. The details of how to calculate ER, up-ER, and down-ER are presented in Section 4. As the S&P Green Bond Index was launched on 31 July 2014, the data points of all variables in this study start from August 2014 and end in October 2023, for a total sample period of 111 months. We conduct the empirical analysis based on monthly data, while we use daily data with the same period as the monthly data when calculating the up-ER and down-ER of green bonds. The monthly and daily data for the green and conventional bond indices are obtained from Bloomberg Terminal. The second dataset is the three market volatilities, consisting of VIX, OVX, and MOVE, which are obtained from the Bloomberg terminal.

The third dataset is used to generate oil shocks. Following [Azhgaliyeva et al. \(2022\)](#), we use the structural VAR model, a workhorse model for oil market analysis ([Zhou, 2020](#)), proposed by [Kilian and Murphy \(2014\)](#) (hereafter KM14), with sign restrictions and price elasticity bounds to generate the oil shocks used in this paper. Since a sufficiently long time series is required to estimate a structural model of the oil market ([Kilian and Zhou, 2020](#)), we use monthly data from January 1974 to October 2023, based on the maximum availability of data. The KM14 model requires

four series: the percent changes in global oil production, the Kilian index, the detrend log real oil prices, and the changes in global oil stocks. The global oil production is obtained from the Energy Information Agency's (EIA) Monthly Energy Review. The Kilian index is taken from the Federal Reserve Bank of Dallas database. The real oil price, a deflated series of the US refiner's acquisition cost of imported crude oil, is reported by the EIA and can be accessed directly from the EIA website.

Data on global oil stocks are not available. Following [Kilian and Murphy \(2014\)](#), we use the scaled series of US crude oil inventories provided by the EIA as a proxy for global oil inventories. The scaling ratio is the ratio of OECD petroleum stocks to US petroleum stocks. Note that the series for OECD oil stocks is not available for the period 1974:1 to 1987:12. Following [Kilian and Murphy \(2014\)](#), we extrapolate the percentage change in OECD stocks backward using the growth rate of U.S. petroleum stocks.

[Insert Table 1 about here]

[Table 1](#) **Table 1** displays the descriptive statistics for the variables used in this paper. We can see from [Table 1](#) that nearly all the series exhibit stationarity, as evidenced by the unit root tests (ADF and PP). Additionally, most time series do not follow a normal distribution, as indicated by the outcomes of the Jarque-Bera (JB) test. It's interesting to note that the mean of the up-ER is negative and left-skewed, while the mean of the down-ER is positive and right-skewed. This suggests that green bonds underperform conventional bonds when the bond market is rising and outperform when the bond market is falling. This finding is similar to that of [Barclays \(2015\)](#). As we can see from the standard deviation, the up-ER is more volatile than the down-ER. The correlation coefficients of the six variables that may affect the ER of green bonds

are shown in Fig. 1. The correlation coefficients between the three volatilities and the three oil shocks.. As shown in Fig. 1. The correlation coefficients between the three volatilities and the three oil shocks., the correlation coefficients between these variables range from -0.420 to 0.536, indicating that there is not excessive information overlap among the variables. Therefore, multicollinearity is not a major concern in the multivariate regression models used in the empirical part of this paper².

[Insert Fig. 1 about here]

A more comprehensive and intuitive depiction of the evolutions of green bond ER, up-ER, and down-ER is presented in Fig. 2. Firstly, we can see from Panel A of Fig. 2 that there is no pronounced trend in green bond ER. However, there are notable declines in the first half of 2016 and early 2020. These declines are attributed to significant events such as the Chinese stock market crash, the Brexit episode in 2016, and the outbreak of the COVID-19 pandemic in early 2020. These events caused significant volatility in the global capital market.

[Insert Fig. 2 about here]

Secondly, as depicted in Panel B of Fig. 2, it is apparent that the up-ER of green bonds predominantly lies below the zero axis. This observation suggests that green

² In addition, to further test for possible multicollinearity among the six independent variables, we calculate the variance inflation factors (VIFs) of them, and find no multicollinearity among them. All empirical results are available upon request.

bonds tend to underperform during periods of ascent in conventional bond values. Conversely, Panel C of [Fig. 2](#) illustrates the converse pattern. This phenomenon could imply that in times of heightened risk aversion, characterized by a surge in bond market prices, investors might cut off their allocation to green bonds due to their elevated liquidity risk. On the contrary, as market risk appetite grows, the appealing environmentally friendly attributes of green bonds might come to the fore, rendering them more attractive to investors.

Thirdly, the trend in the change in the down-ER of green bonds has been declining since 2016, which may indicate that the difference between the two bond markets is becoming smaller as the overall size of the green bond market expands. For this downtrend alone, we agree with the findings of [Kanamura \(2020\)](#), who finds that green bonds outperform conventional bonds and the superiority diminishes over time.

4. Methodology

4.1 SVAR model for generating oil shocks

The SVAR model is defined as follows:

$$A_0 Z_t = \sum_{i=1}^{24} A_i Z_{t-i} + \varepsilon_t, \quad (1)$$

where Z_t is a vector of four variables used to generate oil shocks, they are global oil production (in percent changes), Kilian index, detrended log real price of oil, and changes in global oil inventories. A_i , $i = 0, \dots, 24$ denotes the coefficient matrices. ε_t is a vector of orthogonal structural innovations and is composed of four shocks, namely: the flow supply shock, which captures disruptions in oil production caused by exogenous events in oil-producing countries or OPEC members; the flow demand shock, which captures demand disruptions associated with unexpected changes in real

economic activity; the speculative demand shock, which captures shifts in demand for above-ground inventories due to forward-looking behaviors; and the residual shock, which is not accounted for by the other three shocks.

Following [Kilian and Murphy \(2014\)](#), we set sign restrictions on the SVAR model and bounds on the price elasticities of oil demand and oil supply. The bounds of oil supply elasticity and oil demand elasticity are 0.025 and -0.8, respectively. Sign restrictions are set as follows:

$$A_0^{-1} = \begin{bmatrix} - & + & + \\ - & + & - \\ + & + & + \\ & & + \end{bmatrix}, \quad (2)$$

where missing places mean there are no sign restrictions. To rule out structural models that are at odds with conventional views of the effects of unanticipated oil supply disruptions, an additional restriction is to limit the response of the real oil price to a negative oil supply shock to be non-negative for 12 months as well as the response of oil production and global real economic activity to the same shock to be non-positive for 12 months. The construction of the set of admissible models follows the standard approach of the VAR model based on sign restrictions in the literature, and the detailed process can be referred to [Canova and Nicoló \(2002\)](#), [Uhlig \(2005\)](#), and [Kilian and Murphy \(2014\)](#).

Following [Kilian and Murphy \(2014\)](#), and [Azhgaliyeva et al. \(2022\)](#), we focus only on three types of crude oil shocks, namely supply shock, demand shock, and speculative demand shock. These three types of oil shocks from January 1976 to October 2023 are shown in [Fig. 3](#). The values shown in the graph represent the average monthly impact per year.

[Insert Fig. 3 about here]

4.2 Models for calculating the ER, up-ER, and down-ER

To determine whether the impact of the variables included in this study on green bond ER varies under different market conditions, we divide the ER into up-ER and down-ER and examine the impact of the variables on up-ER and down-ER separately. The ER, up-ER, and down-ER are specified as follows:

$$ER_{\tau} = R(GB, \tau) - R(CB, \tau), \quad (3)$$

$$up_ER_{\tau} = \sum R(GB, t) - \sum R(CB, t) \quad \text{if } R(CB, t) \geq 0, \quad (4)$$

$$down_ER_{\tau} = \sum R(GB, t) - \sum R(CB, t) \quad \text{if } R(CB, t) < 0, \quad (5)$$

where ER_{τ} , up_ER_{τ} and $down_ER_{\tau}$ denote the monthly excess returns, upward excess returns, and downward excess returns of green bonds in month τ , respectively. $R(GB, \tau)$ and $R(CB, \tau)$ are monthly returns of the green and the conventional bond market at month τ , respectively. $R(GB, t)$ and $R(CB, t)$ are daily returns of the green bond and the conventional bond market at time t in month τ , respectively.

4.3 Regression models

To analyze the impact of different variables on the ER, up-ER, and down-ER of green bonds, we run univariate regressions on each variable individually, as well as a multivariate regression on all variables. To clarify the differences in the effects between the two sets of variables, namely market volatilities and oil shocks, we again run multivariate regressions on each of these two sets of variables. The univariate and multivariate regression models are specified as follows:

$$Y_{\tau} = \alpha_i + \beta_i x_{\tau,i} + \varepsilon_{\tau}, \quad (6)$$

$$Y_{\tau} = \alpha_i + \sum_{i=1}^6 \beta_i x_{\tau,i} + \varepsilon_{\tau}, \quad (7)$$

where Y_{τ} represents the monthly ER, up-ER, or down-ER. x_i represents one of VIX,

OVX, MOVE, S_shock, D_shock, and Spe_shock. The two grouped multivariate regressions are specified as follows:

$$Y_t = \alpha + \beta_1 VIX_t + \beta_2 OVX_t + \beta_3 MOVE_t + \varepsilon_t, \quad (8)$$

$$Y_t = \alpha + \beta_1 S_shock_t + \beta_2 D_shock_t + \beta_3 Spe_shock_t + \varepsilon_t. \quad (9)$$

5. Empirical results and analysis

In this section, we perform univariate regressions and multivariate regressions to analyze the impact of the independent variables on green bond ER, up-ER, and down-ER. To gain a deeper insight into the dynamics and differences in the impact of the independent variables, we also conduct the same regression analysis on the two subsamples: one pre-COVID-19 and one post-COVID-19. The detailed empirical results are presented in the following subsections.

5.1 The empirical results based on the full sample

In this part, we exhibit the regression results of the green bond ER over the full sample period through [Table 2](#) and draw the following conclusions. First, in the univariate regression part, the regression coefficients of all independent variables except Spe_shock are statistically significant, indicating that most of these variables have a significant impact on green bond ER. In terms of the level of significance, all three volatilities are significant at the 1% level, while among the three oil shocks, only the demand shock is significant at the 1% level.

Secondly, from the R^2 , we can assess the extent to which various variables influence green bond ER. Specifically, the R^2 for VIX, OVX, and MOVE are 0.207, 0.232, and 0.089 respectively, while those for S_shock, D_shock, and Spe_shock are 0.055, 0.133, and 0.001 respectively. Higher R^2 signifies greater explanatory power

of independent variables on changes in the dependent variable. The R^2 values suggest that the three volatilities, particularly VIX and OVX, exhibit substantial explanatory power for changes in green bond ER, thus exerting significant impact. This reaffirms the pronounced influence of VIX and OVX on the green bond market (Long et al., 2022), while also underscoring the comparatively larger impact of OVX over crude oil price shocks on green bonds (Dutta et al., 2020). The R^2 of the multivariate regression based on the volatility group is 0.304, which is higher than that of the oil shock group of 0.171. This also suggests that the overall impact of the three volatilities on green bond ER is greater than that of oil shocks.

Thirdly, looking only at the impact of oil shocks, Table 2 (ninth column) shows that the coefficients of both oil supply and demand shocks are significant. However, the significance level of the latter is higher, suggesting that the demand shock has a more significant impact on green bond ER than the supply shock. These findings are supported by previous studies that show that demand shock always dominates (Baumeister and Hamilton, 2020; Kilian, 2009; Kilian and Murphy, 2014; Kim and Vera, 2019; Lee et al., 2022; Zhou, 2020).

[Insert Table 2 about here]

There are several key points worth noting and exploring further in the empirical findings of this section. The first point is that volatilities, as dominant drivers, have a significant negative impact on green bond ER. Since the higher the volatility, the more investors are concerned about the liquidity risk (Bams and Honarvar, 2021; Chung and Chuwonganant, 2014; Copeland and Galai, 1983) and thus reduce the allocation to green bonds, a negative relationship between volatilities and green bond ER is not surprising. Meanwhile, the dominant role of volatilities on green bond ER may

indicate that the low liquidity of green bonds is a major constraint on their performance relative to conventional bonds. Therefore, some researchers are concerned that liquidity problems would undermine the further expansion of the green bond market (Boutabba and Rannou, 2022). Since the global financial crisis (GFC) of 2008, the cumulative effects of strict regulation and the market environment have perpetuated a negative influence on bond market liquidity (European Commission, 2017). Given this backdrop, the liquidity challenge faced by green bonds is particularly conspicuous. From this perspective, regulators need to strongly encourage corporations to actively issue green bonds and provide more liquidity to the green bond market.

Another point worth exploring further is that oil demand and supply shocks have opposite effects on green bonds ER, with the former being positive and the latter negative. According to the sign restriction of the KM14 model, all three oil shocks lead to an increase in oil prices, and there should be a positive correlation between oil shocks and green bond returns and thus their ER. Due to the substitution relationship between the crude oil market and the renewable energy market, higher oil prices may increase the motivation and interest in green investments, thereby increasing the price of green bonds (Bondia et al., 2016; Dutta et al., 2020; Kanamura, 2020; Taghizadeh-Hesary et al., 2021; Xia et al., 2019), and then potentially positively affect green bond ER. On the other hand, oil demand shocks are often associated with positive prospects such as economic growth, more investment opportunities, and sales growth (Peersman and Robays, 2012; Ready, 2018; Wong and Hasan, 2021), which helps to stabilize capital market expectations and increase investors' risk appetite. At this point, the illiquidity disadvantage of green bonds is less pronounced, their green attractiveness increases, and investors prefer green bonds more. Therefore, it is easy to understand

the positive impact of the oil demand shock on green bond ER.

However, the impact of the oil supply shock on green bond ER is negative. The rationale is based on the evidence that oil supply shocks often induce uncertainty about future prospects, such as slowing economic growth (Hamilton, 1983, 2009; Kilian and Murphy, 2014) and increasing the volatility of asset returns and cash flows (Wong and Hasan, 2021). In an uncertain environment, investors prefer more conventional bonds (Broadstock and Cheng, 2019). This is similar to the impact of volatilities on the green bond ER.

5.2 The empirical results of Up-ER and Down-ER

In this part, we perform regression analysis on up-ER and down-ER as the same in the former section. The regression results are presented in Table 3 and Table 4, respectively. From Table 3, we can draw similar conclusions to those in Table 2. Specifically, 1) in the univariate regression, three volatilities and the oil demand shock continue to exert a significant impact on the up-ER of green bonds, and the direction of this impact is fully consistent with that presented in Table 2; 2) when only three volatilities are considered, the VIX and OVX still have a negative and significant impact on the up-ER; 3) when only three oil shocks are considered, the coefficient of the oil demand shock remains positive and significant; and 4) when all variables are considered, the impact of oil shocks becomes insignificant, while the VIX and OVX still have a significant negative impact. These findings suggest that when market risk aversion is high, volatilities are the main drivers of the performance differential between the two bond markets.

[Insert Tables 3 and 4 about here]

Table 4 shows significant contrasts, with all variables being insignificant in both univariate and multivariate regressions. Comparing Table 3 and Table 4, we can see that the variables mentioned in this paper are more likely to exert significant effects when risk aversion increases (bond market rises), while their impact becomes insignificant when risk appetite increases (bond market falls). This may be because, with the increase in market risk appetite, the lower liquidity of green bonds is no longer a significant constraint on investors' allocation decisions. At this point, investors perceive green bonds as investment instruments that are substitutable for conventional bonds. In particular, as the size of the green bond market increases (see Fig. 1), its performance gradually converges with that of the conventional bond market.

5.3 The empirical results before and after COVID-19

To test whether the impact of volatilities and oil shocks on green bond ER changes due to the epidemic of COVID-19, we divide the total sample into two parts: pre-COVID-19 and post-COVID-19 and conduct univariate and multivariate regression analysis on green bond ER of each sub-sample. The regression results based on the pre-COVID-19 and post-COVID-19 subsamples are detailed in Table 5 and Table 6. In terms of the univariate regression results, the conclusions from Table 5 are almost the same as those from Table 2. Specifically, the three volatilities and the oil supply shock still have a significant negative impact on green bond ER, and the coefficient of the oil demand shock remains significant and positive. Regarding the outcomes of the multivariate regression analysis, Table 5 reveals noteworthy disparities when compared to Table 2. Notably, when exclusively focusing on the three volatility measures, MOVE emerges as the sole significant predictor during the

pre-COVID-19 epoch. When all variables are taken into account, the oil demand shock has the largest impact among all variables. This finding suggests that in non-crisis periods, the environmental attributes embedded in green bonds significantly drive their ER.

[Insert Tables 5 and 6 about here]

Comparing [Table 6](#) with [Table 5](#), the differences are striking. Specifically, in the multivariate regression with all variables in [Table 6](#), VIX and OVX are the only two significant variables, suggesting the dominance of the volatilities in driving the performance gap between the two bond markets. It is also worth noting that the R^2 of VIX and OVX in univariate regression is 0.328 and 0.549 respectively, while the R^2 of the entire volatility group is 0.590. This indicates that the volatility group has a powerful explanation for the changes in green bond ER after the COVID-19 outbreak. These findings suggest that after the outbreak of COVID-19, market volatilities have a dominant impact on the green bond market. This is consistent with the observations of [Pham and Nguyen \(2022\)](#), who find that green bonds are significantly affected by VIX and OVX at the beginning of COVID-19, while they are weakly affected in non-crisis periods. This may also explain the findings of [Rehman et al. \(2023\)](#), who document a decline in the predictive power of oil shocks during the crisis period.

By comparing [Table 5](#) and [Table 6](#), we can infer that during non-crisis periods, investors prioritize the environmentally friendly features of green bonds and are willing to accept their low liquidity drawbacks. However, during crisis periods, investors place a higher value on the liquidity of their investment vehicles and are unwilling to sacrifice investment returns to pay for a "green" label ([Larcker and Watts, 2020](#)). This interesting finding provides a somewhat unique insight into how investors

trade off investment returns and environmental preferences in different market conditions.

In summary, we can draw the following conclusions in this section. i) Overall, three volatilities and the oil supply and demand shocks all have a significant impact on green bond ER. Among them, volatilities and the oil supply shock have negative effects, while the oil demand shock has positive effects. ii) When only three volatilities are considered, VIX and OVX are often dominant. When only the three oil shocks are considered, the oil demand shock always stands out. iii) When volatilities and oil shocks coexist, volatilities are often dominant factors. iv) When analyzed over different periods, the oil demand shock is the dominant driver of green bond ER in the pre-COVID-19 period, while volatilities (especially VIX and OVX) dominate in the post-COVID-19 period. v) When analyzed based on market conditions, the impact of the variables covered in this paper is most pronounced in an environment of heightened market risk aversion, but as market risk appetite increases, the impact of these variables becomes insignificant³.

³ We also utilize several univariate and multivariate regressions including interest rate as an additional explanatory variable to test its impact on the ER, Up-ER, Down-ER, and IR in the full sample and before/after the COVID-19 pandemic. The empirical results show no qualitative changes found in these new regressions, indicating the negligible effect of the interest rate on the relative performance of green bonds. Full results are available upon request.

6. Extended analysis

In the real world of investment, investors are not only concerned with returns but also with risks. To this end, we further analyze the impact of market volatilities and oil shocks on the risk-adjusted ER of green bonds, i.e. the information ratio. The information ratio and the Sharpe ratio are similar in that they both measure the risk-adjusted return of a security or portfolio. However, while the information ratio evaluates risk-adjusted returns relative to a specific benchmark, the Sharpe ratio compares risk-adjusted returns to the risk-free rate (Bertrand and Protopopescu, 2010; Goodwin, 1998). Since the primary objective of this paper is to examine the relative performance of green bonds compared to conventional bonds, the risk-adjusted returns in this study are measured against the benchmark, i.e. conventional bonds, rather than against the risk-free rate. In this context, the information ratio emerges as a more appropriate measure of the performance matrix for this paper, which is also used as a measure of risk-adjusted returns in some research examining the performance of green bonds relative to conventional bonds (Kanamura, 2020).

The information ratio is expressed as follows:

$$IR_{\tau} = \frac{ER_{\tau}}{\sqrt{\text{Variance}(ER_{\tau})}}, \quad (10)$$

where the IR_{τ} represents the information ratio of green bonds, and the denominator denotes the standard deviation of green bond ER in month τ . We run univariate and multivariate regressions on green bond IR using the same methodology as before, and the empirical results are shown in Table 7.

[Insert Table 7 about here]

The results extracted from Table 7 are very similar to those presented in Table 2.

First, in the univariate regressions, all three volatilities show a statistically significant negative correlation with the IR of green bonds. In contrast, the oil demand shock has a significantly positive correlation with the IR, while the oil supply shock has a negative correlation with the IR. Second, in the grouped multivariate regressions, three volatilities remain significant when only volatilities are considered, while the oil supply shock and the oil demand shock are significant when only the three oil shocks are considered. Third, when all variables are considered, the three market volatilities and the oil demand shock are significant. In terms of R^2 , the R^2 for the volatility group and the oil shock group are 0.316 and 0.113 respectively. These values imply that the risk-adjusted ER of green bonds continues to be more sensitive to market volatilities. As a result, the results presented in this paper retain their consistency, regardless of whether ER or risk-adjusted ER of green bonds are considered.

7. Conclusions and implications

With the growing emphasis on environmental risk among investors, a thorough understanding of the performance, especially the relative performance, of the green bond market and the factors driving it has become imperative. This understanding is important not only for investors' asset allocation and risk management decisions but also for the expansion of the green bond market. We therefore analyze how market volatilities and oil shocks affect the relative performance of the green bond market. Of particular importance, we examine the differences between these two sets of variables in terms of their impact over different t periods and under different market conditions. Our conclusions are presented below.

Firstly, it is consistently observed that both volatilities and the oil supply shock exert a negative influence on green bond relative performance, whereas the oil

demand shock often yields positive effects. Secondly, VIX and OVX consistently emerge as dominant factors among the three volatilities, and the oil demand shock consistently stands out among the three oil shocks. Thirdly, when volatilities coincide with oil shocks, the former consistently exhibits a more pronounced impact on green bond relative performance. Fourthly, the oil demand shock dominates the impact of all variables on the relative performance of green bonds before COVID-19, while volatilities (mainly VIX and OVX) take the lead after COVID-19. Fifthly and finally, the impact of volatilities and oil shocks on green bond relative performance tends to be more noticeable during periods of heightened market risk aversion. Conversely, in a stable market environment, their impact is almost negligible.

The empirical research provides new insights for investors and policymakers to better understand the differences in market performance between green bonds and conventional bonds, and to take optimal actions based on different scenarios. On the one hand, green bonds have become increasingly popular among investors in recent years, making the question of whether and when to allocate more green bonds of paramount importance. Our empirical findings can guide investors in optimal trade-offs between green and conventional bonds under different scenarios. Specifically, when considering bond positions in asset allocation, investors should consider not only factors affecting the bond market itself but also adverse impacts from other markets and sectors. They should evaluate the relative performance of green and conventional bonds based on the prevailing market conditions and dominant drivers to select bonds with relatively superior performance. In particular, during turbulent markets or periods of heightened risk aversion, green bonds may underperform conventional bonds, leading investors to allocate more to conventional bonds; conversely, during an oil demand shock, green bonds may outperform conventional

bonds, justifying an increased allocation to green bonds in the investment portfolio.

On the other hand, since the relative performance of green bonds is positively correlated with the oil demand shock, policymakers can strongly encourage investors and issuers to actively participate in the green bond market when an oil demand shock occurs, to provide more liquidity. However, during significant market fluctuations or in the event of an oil supply shock, regulatory authorities must devise more effective measures to mitigate and shield against the adverse effects of these factors.

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Figures

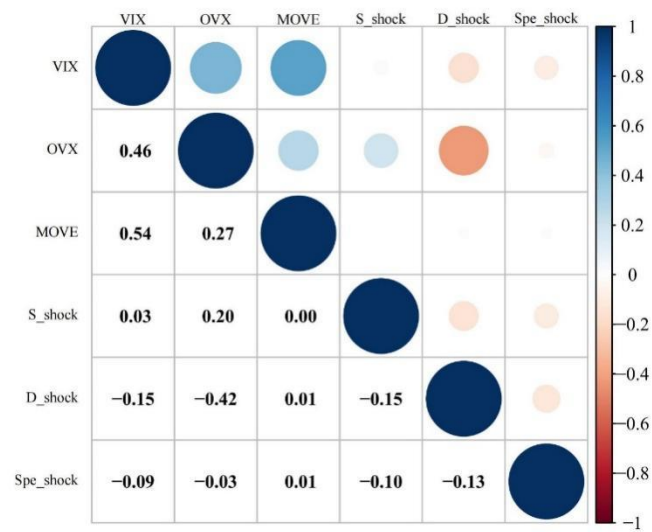


Fig. 1. The correlation coefficients between the three volatilities and the three oil shocks. "S_shock", "D_shock", and "Spe_shock" represent oil supply, demand, and speculative demand shocks, respectively.

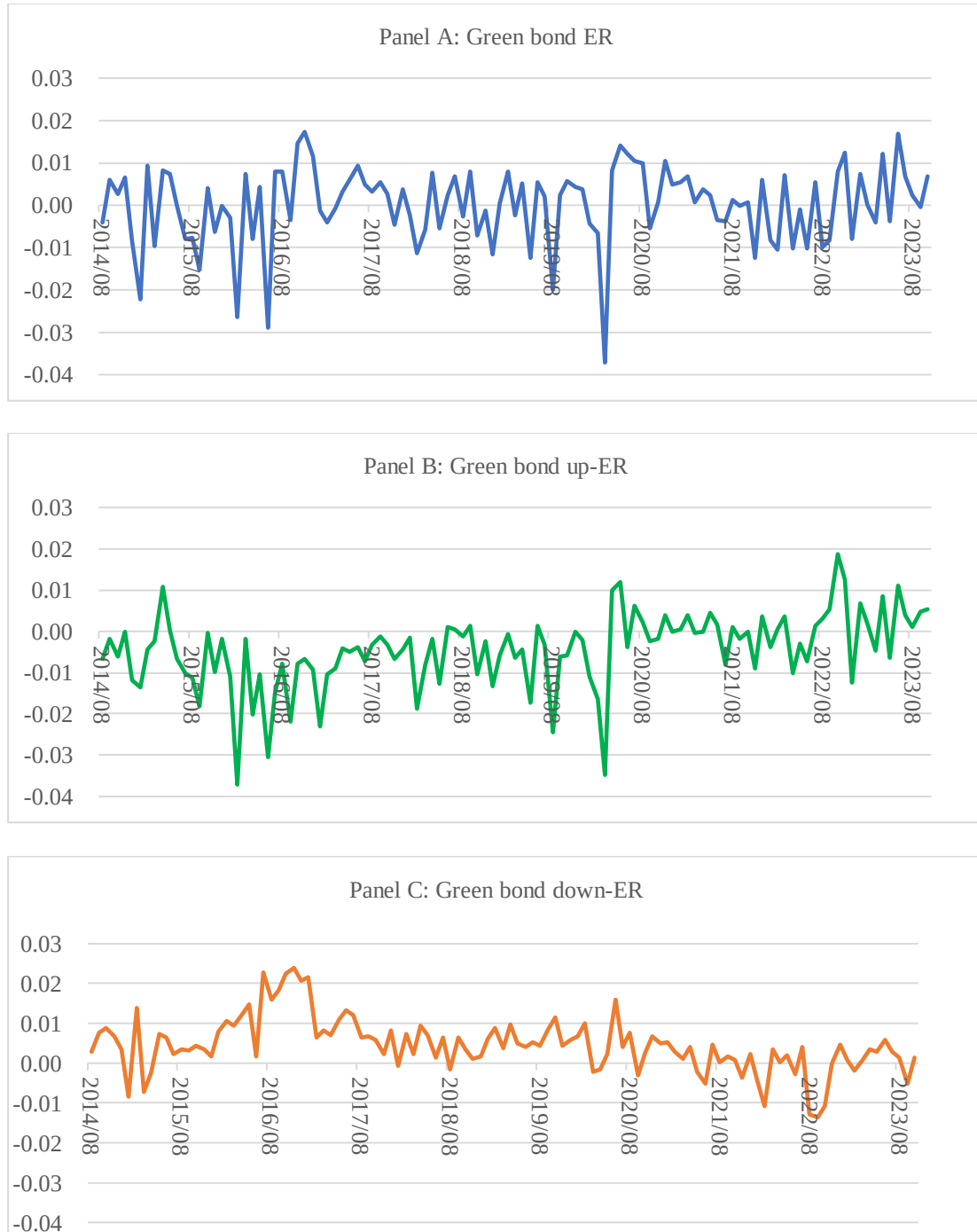


Fig. 2. The dynamics of green bonds excess return (ER), upward (up-ER), and downward excess returns (down-ER).

The sample period for these three excess return series runs from August 2014 to October 2023. "ER", "up-ER", and "down-ER" represent the excess return and its two components of green bonds, respectively.

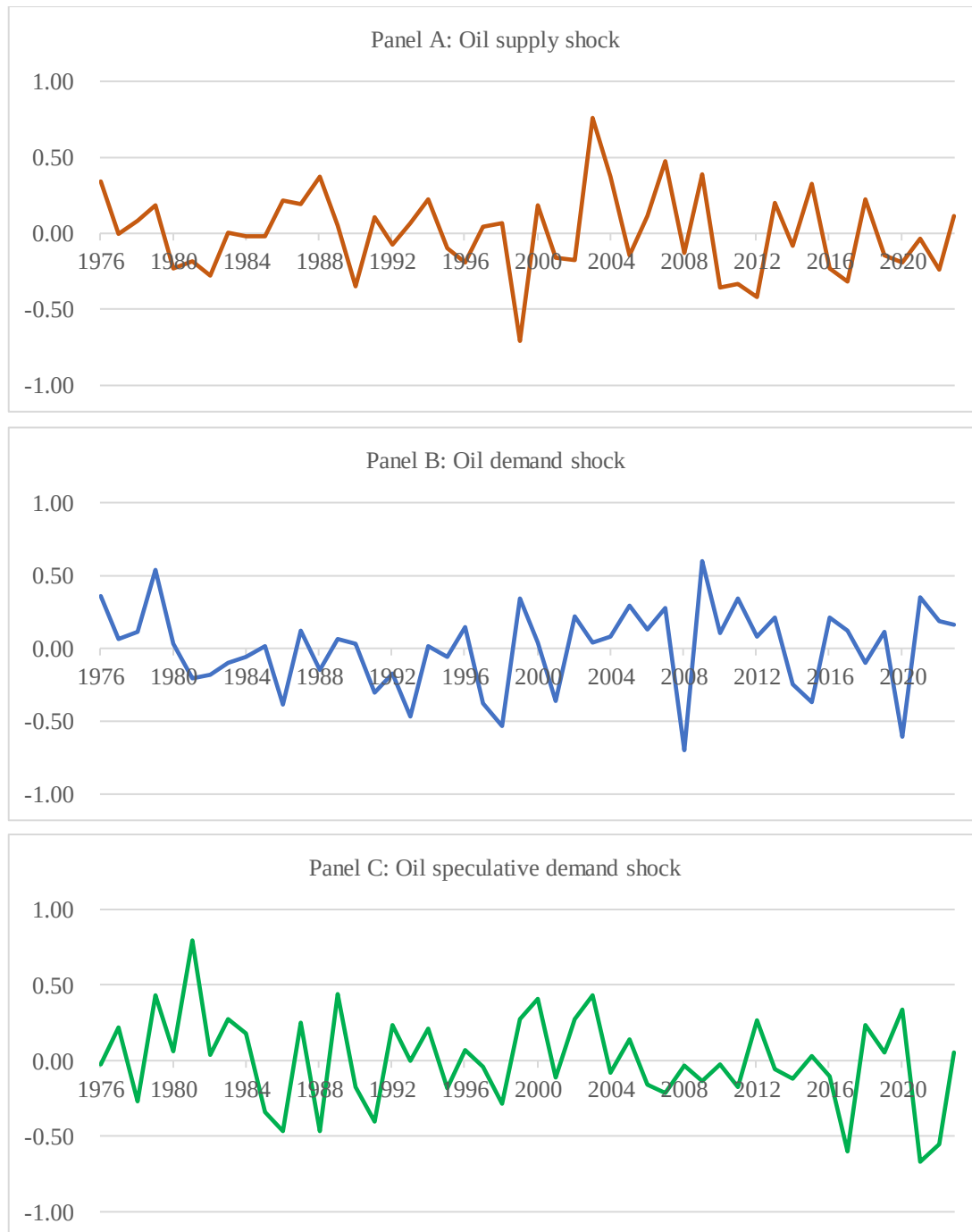


Fig. 3. Three types of structure shocks in the crude oil market.
The sample period for these three shocks runs from January 1976 to October 2023. The values shown in the graph represent the average monthly impact of oil shocks per year.

Tables

Table 1
Summary statistics.

Variable	Obs	Mean	Std.	Skewness	Kurtosis	Min	Max	ADF	PP	JB
GB	111	-0.001	0.020	-0.523	1.387	-0.070	0.059	-3.400*	-109.325***	15.158***
CB	111	-0.001	0.019	-0.427	0.656	-0.060	0.047	-3.863**	-101.535***	5.891*
ER	111	0.000	0.009	-1.104	2.087	-0.037	0.017	-4.713***	-114.442***	45.146***
up-ER	111	-0.004	0.009	-0.861	1.887	-0.037	0.019	-3.854**	-103.790***	32.153***
down-ER	111	0.005	0.007	0.281	1.112	-0.014	0.024	-2.776	-72.236***	8.019**
IR	111	0.122	1.105	-0.207	-0.193	-2.739	3.413	-4.237***	-123.455***	0.911
VIX	111	0.001	0.258	0.416	0.620	-0.614	0.853	-6.078***	-128.280***	5.460*
OVX	111	0.007	0.238	1.273	5.155	-0.568	1.202	-7.271***	-91.204***	160.920***
MOVE	111	0.007	0.170	0.300	0.464	-0.448	0.467	-5.293***	-122.972***	2.998
S_shock	111	-0.024	1.255	-1.069	6.786	-6.875	3.176	-5.006***	-122.410***	246.090***
D_shock	111	-0.021	1.121	-0.637	1.369	-4.105	3.079	-4.859***	-84.635***	17.424***
Spe_shock	111	-0.123	0.915	0.392	0.148	-2.324	2.486	-4.243***	-104.744***	3.119
Oil production	598	0.081	1.563	-2.233	16.274	-13.559	6.714	-3.977**	-105.709***	88.418***
Kilian index	598	-0.122	54.416	0.842	1.172	-161.350	189.400	-3.150*	-32.994***	72.818***
Real oil price	598	-0.015	47.679	-0.143	-0.806	-129.027	100.556	-13.137***	-2419.414***	2213.558***
Oil inventory	598	2.282	25.318	0.134	0.187	-83.205	98.665	-13.378***	-2341.437***	1133.993***

Notes: This table presents the descriptive statistics of the variables used in this paper. "Obs" is the number of observations. "Std." denotes the standard deviation; "ADF" and "PP" denote the Augmented Dickey-Fuller and Phillips-Perron unit root tests, respectively; "JB" denotes the Jarque-Bera statistic for the null hypothesis of normal distribution of return series; "GB" and "CB" are return series of the green and conventional bonds, respectively. "ER", "up-ER", and "down-ER" are excess return and its two components, respectively. "IR" is the information ratio. "S_shock", "D_shock", and "Spe_shock" represent oil supply, demand, and speculative demand shocks, respectively. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 2
Regression results for green bond ER: full sample.

Variable	Univariate regression						Multivariate regression		
	Coefficient						Coefficient		
							3 volatilities	3 shocks	All variables
Intercept	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)
VIX	-0.016*** (0.003)						-0.010** (0.004)		-0.010*** (0.004)
OVX		-0.019*** (0.003)					-0.013*** (0.004)		-0.008** (0.004)
MOVE			-0.016*** (0.005)				-0.003 (0.005)		-0.006 (0.005)
S_shock				-0.002** (0.001)				-0.001** (0.001)	-0.001* (0.001)
D_shock					0.003*** (0.001)			0.003*** (0.001)	0.002** (0.001)
Spe_shock						0.000 (0.001)		0.001 (0.001)	0.000 (0.001)
<i>R</i> ²	0.207	0.232	0.089	0.055	0.133	0.001	0.304	0.171	0.368

Notes: The table reports the regression coefficients of green bond excess returns (ER) over the full sample period, with statistically significant regression coefficients in bold. The numbers in parentheses are **standard errors**. "S_shock", "D_shock", and "Spe_shock" represent oil supply, demand, and speculative demand shocks, respectively. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 3
Regression results for the green bond up-ER.

Variable	Univariate regression						Multivariate regression		
	Coefficient						Coefficient		
							3 volatilities	3 shocks	All variables
Intercept	-0.004*** (0.001)	-0.004*** (0.001)	-0.004*** (0.001)	-0.005*** (0.001)	-0.004*** (0.001)	-0.005*** (0.001)	-0.004*** (0.001)	-0.005*** (0.001)	-0.005*** (0.001)
VIX	-0.013*** (0.003)						-0.007* (0.004)		-0.007* (0.004)
OVX		-0.015*** (0.003)					-0.011*** (0.004)		-0.008* (0.004)
MOVE			-0.013** (0.005)				-0.003 (0.006)		-0.004 (0.006)
S_shock				-0.001 (0.001)				-0.001 (0.001)	-0.001 (0.001)
D_shock					0.002*** (0.001)			0.002*** (0.001)	0.001 (0.001)
Spe_shock						-0.001 (0.001)		-0.001 (0.001)	-0.001 (0.001)
<i>R</i> ²	0.126	0.154	0.056	0.022	0.087	0.006	0.195	0.101	0.234

Notes: The table reports the regression coefficients of the green bond upward excess returns (up-ER) over the full sample period, with statistically significant regression coefficients in bold. The numbers in parentheses are **standard errors**. "S_shock", "D_shock", and "Spe_shock" represent oil supply, demand, and speculative demand shocks, respectively. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 4
Regression results for the green bond down-ER.

Variable	Univariate regression						Multivariate regression		
	Coefficient						Coefficient		
							3 volatilities	3 shocks	All variables
Intercept	0.005*** (0.001)	0.005*** (0.001)	0.005*** (0.001)	0.005*** (0.001)	0.005*** (0.001)	0.005*** (0.001)	0.005*** (0.001)	0.005*** (0.001)	0.005*** (0.001)
VIX	-0.004 (0.003)						-0.003 (0.003)		-0.002 (0.003)
OVX		-0.004 (0.003)					-0.002 (0.003)		-0.001 (0.003)
MOVE			-0.004 (0.004)				0.000 (0.005)		-0.002 (0.005)
S-shock				-0.001 (0.001)				-0.000 (0.001)	-0.000 (0.001)
D-shock					0.001 (0.001)			0.001 (0.001)	0.001 (0.001)
Spe-shock						0.001 (0.001)		0.001 (0.001)	0.001 (0.001)
<i>R</i> ²	0.021	0.017	0.008	0.014	0.010	0.023	0.026	0.046	0.060

Notes: The table reports the regression coefficients of the green bond downward excess returns (down-ER:) over the full sample period, with statistically significant regression coefficients in bold. "S_shock", "D_shock", and "Spe_shock" represent oil supply, demand, and speculative demand shocks, respectively. The numbers in parentheses are **standard errors**. *** $p < 0.01$.

Table 5
Regression results for green bond ER: before COVID-19.

Variable	Univariate regression						Multivariate regression		
	Coefficient						Coefficient		
							3 volatilities	3 shocks	All variables
Intercept	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)
VIX	-0.014*** (0.005)						-0.008 (0.005)		-0.009 (0.006)
OVX		-0.010* (0.006)					-0.004 (0.006)		0.003 (0.007)
MOVE			-0.025*** (0.007)				-0.017** (0.008)		-0.012 (0.009)
S_shock				-0.002** (0.001)				-0.002* (0.001)	-0.001 (0.001)
D_shock					0.003** (0.001)			0.003** (0.001)	0.002* (0.001)
Spe_shock						-0.000 (0.001)		-0.000 (0.001)	-0.000 (0.001)
<i>R</i> ²	0.129	0.045	0.155	0.059	0.088	0.000	0.194	0.129	0.249

Notes: The table reports the regression coefficients of green bond excess returns before COVID-19, with statistically significant regression coefficients in bold. VIF represents the variance inflation factor. "S_shock", "D_shock", and "Spe_shock" represent oil supply, demand, and speculative demand shocks, respectively. The numbers in parentheses are **standard errors**. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 6
Regression results for green bond ER: after COVID-19.

Variable	Univariate regression						Multivariate regression		
	Coefficient						Coefficient		
							3 volatilities	3 shocks	All variables
Intercept	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)
VIX	-0.019*** (0.004)						-0.009** (0.005)		-0.009* (0.005)
OVX		-0.024*** (0.003)					-0.019*** (0.004)		-0.016*** (0.004)
MOVE			-0.010 (0.007)				0.005 (0.006)		0.001 (0.006)
S_shock				-0.001 (0.001)				-0.001 (0.001)	-0.001 (0.001)
D_shock					0.003*** (0.001)			0.003*** (0.001)	0.001 (0.001)
Spe_shock						0.001 (0.001)		0.002 (0.001)	0.000 (0.001)
<i>R</i> ²	0.328	0.549	0.046	0.054	0.193	0.015	0.590	0.249	0.631

Notes: The table reports the regression coefficients of green bond excess returns after COVID-19, with statistically significant regression coefficients in bold. The numbers in parentheses are **standard errors**. "S_shock", "D_shock", and "Spe_shock" represent oil supply, demand, and speculative demand shocks, respectively. *** p < 0.01, ** p < 0.05, * p < 0.1.

Table 7
Regression results for green bond IR.

Variable	Univariate regression						Multivariate regression		
	Coefficient						3 volatilities	3 shocks	All variables
Intercept	0.124 (0.092)	0.137 (0.095)	0.141 (0.097)	0.118 (0.103)	0.128 (0.101)	0.128 (0.106)	0.140 (0.088)	0.133 (0.101)	0.141 (0.088)
VIX	-2.069*** (0.359)						-1.146** (0.438)		-1.153*** (0.436)
OVX		-2.062*** (0.399)					-1.278*** (0.418)		-0.792* (0.457)
MOVE			-2.518*** (0.576)				-1.090* (0.618)		-1.288** (0.617)
S_shock				-0.175** (0.083)				-0.135* (0.082)	-0.116 (0.072)
D_shock					0.287*** (0.090)			0.272*** (0.092)	0.162* (0.088)
Spe_shock						0.042 (0.116)		0.066 (0.112)	0.018 (0.098)
<i>R</i> ²	0.234	0.197	0.149	0.040	0.085	0.001	0.316	0.113	0.357

Notes: The table reports the regression coefficients of the green bond information ratios (IR) over the full sample period, with statistically significant regression coefficients in bold. The numbers in parentheses are **standard errors**. "S_shock", "D_shock", and "Spe_shock" represent oil supply, demand, and speculative demand shocks, respectively. *** p < 0.01, ** p < 0.05, * p < 0.1.