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Return and volatility spillovers among oil price shocks and international green bond markets

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ABSTRACT

We analyse the spillover effects between oil price shocks and green bonds issued in twelve developed economies. We decompose oil price shocks into demand, risk and supply shocks. We employ daily data from December 2008 to June 2022 enabling us to cover major global crisis episodes such as the global financial crisis, European sovereign debt crisis, Covid-19 pandemic, Russia-Ukraine conflict, and the corresponding boom and bust in energy markets. Our results show the dominance of the US and the European green bond markets as the main contributors to return and volatility spillovers among international green bonds, respectively. The degree of connectedness among markets varies over time with a more pronounced effect on returns during turbulent periods. Oil shocks exhibit a relatively low degree of connectedness with green bonds implying potential diversification attributes. This result is, particularly, supported in the case of green bond markets of USA, Euro, Denmark and Hong-Kong.

1. Introduction

Lately, a significant volume of studies analyzing the patterns of financial linkages and risk transmissions among financial assets have emerged (e.g., [Aloui et al., 2013](#); [Arouri et al., 2012](#); [Belke and Dubova, 2018](#); [Esparcia et al., 2022](#); [Spierdijk and Umar, 2015](#)). Specifically, as financial cycles become a constant feature of the economic landscape, these studies on cross-market linkages are instrumental for investors in terms of risk hedging and portfolio allocation decisions, and for policymakers in terms of formulation of economic predictions. In particular, certain new asset classes and investment themes such as socially and environmentally responsible themed investments have gained a lot of attention (e.g., [Akhtaruzzaman et al., 2022](#); [Umar et al., 2023](#)). In this paper, we study the patterns of return and volatility spillover between green bonds and oil market using a large sample of environmentally friendly (i.e., green) bond markets in order to provide practical investment insights for investors.

A number of earlier studies have investigated the interlinkages between oil and other financial assets (e.g., [Shahzad et al., 2017](#); [Malik and Umar, 2019](#); [Elsayed et al., 2020](#); [Tiwari et al., 2022](#); [Aziz et al., 2022](#); [Naeem et al., 2020](#)). These strands of literature have documented that the connectedness between oil and other markets varies over time (e.g., [Batten et al., 2015](#); [Okorie and Lin, 2020](#);

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Jareno et al., 2021; Mensi et al., 2022; Tiwari et al., 2021; Balcilar et al., 2021). Furthermore, the impact is dependent on whether the shock is induced by a demand – or a supply – side shock in the oil market (e.g., Kilian and Park, 2009; Filis et al., 2011; Cunado and de Garcia, 2014; Degiannakis et al., 2013; Wei and Guo, 2017; Umar et al., 2021a, 2021b). Similarly, a number of empirical studies have explored the interrelationships between crude oil and traditional bonds (e.g., Kang et al., 2014; Gormus et al., 2018; Demirer et al., 2020; Dai and Kang, 2021; Shahzad et al., 2021). For example, Gormus et al. (2018) allude that shocks in oil prices significantly affect, not only corporate energy bonds, but the entire S&P U.S. bond market. Kang et al. (2014) have found that oil price shocks contribute to 30.60% of the variability in the U.S. bond market returns in the long-run. Our study differs from theirs as we separate these shocks into demand – and supply – sides and test for the dynamic bidirectional relationship between oil shocks and green bonds.

Theoretically, oil prices impact fixed-income financial assets (i.e., bonds) through three main channels. The first channel is interest rates. A fall in interest rates could yield to reductions in carrying costs which may lead to funds inflows in the oil market to safeguard against decreasing returns in financial assets (Frankel, 2007). The second channel is the “supply channel” that induces inflationary expectations which may be reflected in financial markets (Demirer et al., 2020). Finally, the long-term connectedness between macroeconomic variables and long-term assets (Hamilton and Kim, 2002) and the resultant effect of these on the exogenous shocks in oil prices could serve as a conduit through which variations in oil prices could affect bonds.

Green bonds have been introduced as novel financial instruments that are conceived to cope with global environmental threats (Coston et al., 2014; Mensi et al., 2022; Umar et al., 2023; Liu and Tang, 2022; Zheng et al., 2023; Boitan and Marchewka-Bartkowiak, 2022). As a result, many investors become interested in this type of assets as it, not only presents an ethical investing tool, but also provides some diversification benefits (e.g., Naeem et al., 2021; Nguyen et al., 2021). Consequently, several researchers have investigated the differences and similarities between conventional and green bonds in terms of financial aspects (e.g., Hachenberg and Schiereck, 2018; Wang et al., 2020; Löffler et al., 2021; Le et al., 2021; Tiwari et al., 2022). Specifically, in addition to the difference in fundamental properties between green bonds and conventional bonds, prior academic literature has found that green bonds are priced with a premium over conventional bonds (Hachenberg and Schiereck, 2018; Nanayakkara and Colombage, 2019; Kapraun et al., 2019; Russo et al., 2021; Sheng et al., 2021), while some other studies demonstrate a lower or insignificant yield of green bonds when compared to conventional bonds (e.g., Karpf and Mandel, 2018; Huynh et al., 2020).

Additionally, to give a better comprehension of the behavior of green bonds, contemporary literature have investigated the connectedness and dependence between green bonds and other financial asset classes, i.e., conventional bond markets (e.g., Pham, 2016; Broadstock and Cheng, 2019; Nanayakkara and Colombage, 2019; Elsayed et al., 2022), stock markets (e.g., Reboredo, 2018; Kanamura, 2020; Nguyen et al., 2021) and energy assets (e.g., Ferrer et al., 2021; Liu et al., 2021; Naeem et al., 2021; Tiwari et al., 2022). Some sizeable diversification benefits have been highlighted when including green bonds into investment portfolios.

A wide range of scholars have explored the connectedness between oil market and green bonds (e.g., Reboredo, 2018; Nguyen et al., 2020; Reboredo et al., 2020; Reboredo and Ugolini, 2020; Mensi et al., 2021; Azhgaliyeva et al., 2022). In the study of Ferrer et al. (2021), authors have discovered a weak relationship between green bonds and crude oil. A study by Lee et al. (2021) shows a bidirectional lower-tail causality from crude oil to the Barclays MSCI green bond index using a quantile causality framework. Kanamura (2020) reports a positive dynamic correlation between crude oil price returns and green bond yields. Dutta et al. (2020) have found that risk in oil price drive green investments more than just the changes in oil price. Our study aims to extend the empirical literature on oil-green bonds connectedness by examining the impact of disentangled oil price shocks (demand, supply and risk) on green bond markets. Given the general inconclusiveness in the literature about the significance and the magnitude of this relation, this study seeks to fill this gap by investigating a large sample of green bonds disaggregated into twelve countries in order to give a more comprehensive feedback. To the best of our knowledge, this is the first such study.

Kilian (2009) has used the seminal structural VAR model to disentangle the sources of oil price fluctuations as induced by demand and supply factors. His model distinguishes between supply and demand shocks in the crude oil market. A stream of literature has used this methodology to explore the differential impact of these oil shock types on stock markets and macroeconomic factors (e.g., Kilian and Park, 2009; Kilian and Murphy, 2012; Lippi and Nobili, 2012; Wang et al., 2013; Kim and Vera, 2019; Herrera and Rangaraju, 2020). Their findings indicate that the reaction depends on the nature of the exogenous shock and that oil supply shocks have a smaller role than oil demand shocks. However, a number of studies point out to the drawbacks of Kilian’s (2009) decomposition method that mainly consist of the higher weight that his methodology gives to oil-specific demand factors as compared to supply-side factors and that it can only be applied to lower frequency (i.e., quarterly and monthly) data (Baumeister and Peersman, 2013; Baumeister and Hamilton, 2019). In this study, we use the technique of Ready (2018) to decompose the different types of oil shocks as per demand – side, supply – side and risk shocks. This method is an improvement of the standard Kilian’s (2009) method and can be applied to higher (i.e., daily) frequency data. It permits us to overcome the drawbacks of the standard Kilian (2009) method. Specifically, using this method, Ready (2018) finds US stock prices to be induced by both oil demand and supply shocks and posited out asymmetry in oil price shocks (demand, supply and risk) effect on the stock market.

This paper makes contribution to the literature in primarily three ways. First, while there are studies on the interrelationship between oil and green bonds at the regional and international levels, there seems to be a dearth in research at the country level. However, since there may be disparities in the extent of financial integration across green bonds, a study employing a wide country-set of green data would be useful for investors seeking to maximize diversification benefits. Our study is the first to use a large set of green bond markets, along with crude oil. Second, given the scarce number of studies devoted to the analysis of connectedness between oil and green bonds, the study aims to extend the existing literature and to provide a more comprehensive feedback that could be insightful for investors in formulating their investment strategies by taking advantage of the information about the dynamic of spillover from oil as induced by risk, demand and supply-side factors. Finally, we rather focus on the post-global financial crisis period that encompasses several global events such as the Covid-19 pandemic and the Russian-Ukrainian war, given the limited empirical

evidence on the interaction issue in this episode.

We document several interesting results in this paper. First, we find that green bond markets are not largely affected by crude oil shocks during the period under study. Second, the dynamic spillover results show that the degree and intensity of dependency varies over time for all the markets under consideration. Thirdly, in terms of magnitude, we find that green bond markets are more affected by return spillovers than volatility spillovers during stressful episodes. Finally, results found also point to the diversification benefits of green bonds, when combined with oil, in both turbulent and normal market conditions.

The remaining sections of the paper are structured as follows. A literature review is presented in [Section 2](#). The methodology is discussed in [Section 3](#). [Section 4](#) contains the data specification and the preliminary analysis with [Section 5](#) reporting the discussion of empirical results. Finally, the conclusion is reported in [Section 6](#).

2. Literature review

The relationship between oil prices and green bonds has been a subject of growing interest among scholars and financial market participants. This interest is fueled by the global shift towards sustainable investing and the urgent need to address climate change challenges. Green bonds, which are debt securities similar to traditional bonds but are specifically issued to finance environmentally friendly projects, have emerged as a popular instrument to channel investment into sustainable projects ([Flammer, 2021](#); [Umar et al., 2023](#)). These projects can include renewable energy, energy efficiency, pollution prevention, and climate change adaptation initiatives. However, being part of the global financial market, their dynamics are influenced by various factors, one of which is oil prices. We present a summary of some relevant studies on the return and volatility connectedness dynamics on Table A-1 of Appendix-A.

Oil is a critical global commodity, and its price has significant implications for the global economy and financial markets ([Kilian, 2008](#)). A vast amount of literature has investigated the impact of oil prices on various financial assets, including stocks, bonds, and currencies. For instance, oil price shocks have been found to affect stock returns negatively ([Billah et al., 2022](#); [Jones and Kaul, 1996](#); [Park and Ratti, 2008](#)), influence exchange rates ([Amano and Van Norden, 1998](#); [Basher et al., 2012](#); [Beckmann et al., 2020](#); [Umar and Bossman, 2023](#); [Umar et al., 2023](#)), and impact the yields of government bonds ([Ciner et al., 2013](#); [Balçilar et al., 2020](#); [Umar et al., 2022](#)).

The relationship between oil prices and green bonds is less extensively studied than the relationships between oil and other financial assets. However, existing literature provides some insights. For example, [Bredin et al. \(2020\)](#) found that green bond returns are negatively correlated with oil returns, suggesting that an increase in oil prices is associated with a decrease in green bond returns. This relationship is consistent with the idea that higher oil prices make fossil fuel investments more attractive, potentially leading to a shift away from green bonds. Furthermore, [Capasso and Monfort \(2020\)](#) analyzed the relationship between oil prices and green bond spreads and found that the green bond market does not react to oil price changes. This is contradictory to the traditional bond market, where bond spreads tend to increase when oil prices rise. The authors suggest that this difference may be due to the specific characteristics of green bonds, such as their dedicated use of proceeds and the generally lower credit risk of their issuers.

In this study, we explore the spillover effects between oil and international green bond markets. Notably, the spillover effects refer to the transmission of shocks or fluctuations from one asset or market to another ([Diebold and Yilmaz, 2009](#)). Although there is a limited literature, specifically, addressing the spillover effects between oil and green bonds, some studies have investigated the spillover effects between oil and other financial assets. For instance, [Arouri \(2011\)](#) found significant spillover effects between oil prices and stock markets in the Gulf Cooperation Council (GCC) countries. [Bouri et al. \(2017\)](#) reported evidence of spillover effects between oil and various asset classes, including stocks, bonds, and commodities. [Kang et al. \(2017\)](#) investigated the spillover effects between oil and financial markets using a time-varying approach and found that the spillover effects vary over time and are influenced by global economic conditions. They also reported that the spillover effects from oil to stock markets are stronger than the spillover effects from stock markets to oil. [Hanif et al. \(2023\)](#) utilized wavelet coherence and frequency connectedness methods to analyze the time-frequency dependency and volatility linkages between oil shocks and green stocks. They find that the relationship is time-varying, and becomes stronger in the medium and long terms, while the lead-lag relationships are inconsistent and fluctuate over time. They found that oil market acts as a significant contributor to risk in the green stock market.

The existing literature, hereto, that explored the connectedness between oil and green bonds has predominantly examined the connectedness of green bonds with oil by either including green bonds in a broader set of assets (e.g., [Mensi et al., 2022](#); [Dogan et al., 2023](#); [Umar et al., 2022](#); [Banerjee et al., 2024](#)) or by focusing on the global green bond market as a whole, rather than analyzing individual markets separately (e.g., [Lee et al., 2021](#); [Azhgaliyeva et al., 2022](#); [Rehman et al., 2023](#); [Wang et al., 2023](#); [Wei et al., 2023](#); [Banerjee, 2023](#)). Our study differs from theirs in three main ways, which makes our contribution threefold. First, unlike previous studies that investigated the spillover effects between oil and green bonds along with other assets, we focus on the green bond market alone as it could be more insightful for investors interested in this type of assets and for policymakers in designing policies that promote the development of the green bond market. Second, unlike studies that used global or regional green bond indices, we use a large set of international green bond markets. The use of a large sample of green bond markets disaggregated into different regions of the world permits to give a more comprehensive analysis of the relationship between oil and green bond markets, which could be more insightful for international investors by enabling comparison between international sustainable bond markets around the world. Finally, we separate, in our study, the different types of oil prices shocks, *as per* demand, supply and risk shocks, when examining the relationship of oil market and green bond markets. This exercise permits to capture the distinct effects of each type of shock, which enables investors to tailor their investment strategies according to the nature of the shock and develop more effective risk management strategies. This information could also be beneficial for policymakers for making more informed decisions regarding energy policy.

It is also worth mentioning that the topic of cross-market behavior concerning green bonds has been explored in other research

studies with respect to other markets and risk factors. For instance, Long et al. (2022) investigated the spillover effects between the oil market, clean energy stock market, and traditional stock market, focusing on market volatilities rather than price changes. They discovered that spillover effects intensify during periods of market stress and observed a "regional specialization" in green market spillovers, with the US as the primary source and China as the main recipient of spillovers. Duan et al. (2023) examined the time-varying spillover effects between China's conventional energy and nascent green markets, as well as the influence of the COVID-19 pandemic on these spillover effects. They found that the pandemic onset significantly impacted the volatility of the various spillover effects in the markets under study, and green bonds were the primary net recipients of volatility spillovers in the entire system, followed by crude oil, while new energy was the major net contributor of volatility spillovers, followed by clean energy. Dai et al. (2023) reported asymmetric spillover effects between green bonds, brown stocks, and the oil market during bullish and bearish periods. Lastly, Khalfoui et al. (2023) diverted the focus away from the oil market, revealing that during the COVID-19 pandemic bear markets, misinformation about the virus and cryptocurrencies were significant sources of spillovers, while green bonds were the primary recipients. Top of Form.

3. Methodology

Our estimation approach involves two steps. Following Ready (2018), we first decompose the sources of shocks of oil prices. Second, we calculate the general prediction error variance's network connectedness index decomposition using Diebold and Yilmaz's generalized VAR framework (2009, 2012, 2014).

3.1. Decomposition of oil price shocks

Ready (2018) posit that enterprises that produce oil do not only profit from increase in demand but can also profit from contraction in supply by operating defensive measures against shock to oil supply. That is, even if they sell less owing to a shrinking in supply, this decrease in sell will be associated to increased prices which may reduce losses. Based on the logic of Ready (2018), we decompose the shock by selecting the possible sources of shocks in the oil market: those related to supply, risk, and demand. First, we use an ARMA (1, 1) approach to detect the innovations in VIX movements (unexpected movements), called the Risk Shocks (SSHK), in order to breakdown these components. We employ the returns of the production index of oil enterprises as the dependent variable in a contemporaneous regression that uses these three innovations as the explanatory variables. This method confirms that the orthogonal residuals (innovations) in the contemporaneous regression are identified as orthogonal demand shocks (DSHK). We follow the same approach to obtain the supply shocks (SSHK) by taking the orthogonal residuals from contemporaneous regression. We use the World Integrated Oil and Gas Producer Index (WIOGPI). This index is made up of oil-producing firms, and the returns of the one-month crude oil futures on the second-nearest maturity for the New York Mercantile Exchange (NYMEX). We employ this index to capture changes in oil prices as obtained by following the above procedure in the manner described by Ready (2018). The CBOE's proxy of volatility, VIX, is a volatility indicator representing the risk in oil prices. According to Ready (2018), the term "DSHK" refers to the proportion of returns of a worldwide index of oil-producing businesses (the WIOGPI, in our example) that are orthogonal to the unanticipated logarithm of the fluctuations or innovations in the VIX index (RSHK), perhaps resulting from shifting risk aversion. In contrast, SSHK is defined as the component of oil price movements orthogonal to DSHK and RSHK (in our example, returns of the one-month crude oil futures on the second closest maturity for the NYMEX). Additionally, in line with Ready (2018), we show that demand – and supply – side shocks account for, virtually, all of the volatility, which is supported by the poor connection between the VIX and oil prices throughout the study period.

The following three elements can be categorized as risk shocks to oil prices:

$$X_t \equiv \begin{bmatrix} \Delta p_t \\ R_t \\ \xi_{VIX,t} \end{bmatrix}, Z_t \equiv \begin{bmatrix} SSHK \\ DSHK \\ RSHK \end{bmatrix}, A \equiv \begin{bmatrix} 1 & 1 & 1 \\ 0 & \alpha_{22} & \alpha_{23} \\ 0 & 0 & \alpha_{33} \end{bmatrix} \quad (1)$$

Where Δp_t refers to the log changes in oil prices at time t , R_t stands for the index return matching to those changes at time t for oil businesses, and $\xi_{VIX,t}$ refers to the unanticipated changes in VIX as derived from the ARMA (1,1) process (VIX innovation). The DSHK, SSHK, and RSHK denote the terms demand, supply, and risk shocks, respectively. The coefficient matrix A is 3×3 .

The shocks are translated into detectable variables in the A matrix in Eq. (1) using a matrix form as follows:

$$X_t = AZ_t \quad (2)$$

In line with Ready (2018), we additionally satisfy Eq. (3)'s prerequisites to establish orthogonality:

$$A^{-1} \sum_X (A^{-1})^T = \begin{bmatrix} \sigma_{SSHK}^2 & 0 & 0 \\ 0 & \sigma_{DSHK}^2 & \alpha_{23} \\ 0 & \sigma_{RSHK}^2 & \alpha_{33} \end{bmatrix} \quad (3)$$

Where, \sum_X represents the covariance matrix of the observable variables in X_t , and σ_{DSHK}^2 , σ_{SSHK}^2 , and σ_{RSHK}^2 represent the volatility of the demand, supply, and risk shock variables, respectively. The imposition in Eq. (3) renormalizes the conventional orthogonalization, which is used to define structural shocks in SVAR models. Notably, rather than being limited to the value of 1, the

cumulative aggregate of all shocks must match the whole fluctuation in oil prices.

3.2. Diebold and Yilmaz's connectedness index

Diebold and Yilmaz (2012); (2014) developed a time-domain spillover based on Generalized forecast error variance decomposition (GFEVD) by Koop et al. (1996) and Pesaran and Shin (1998). Among others, a critical attraction of this model has to do with its dynamic composition which enables it to flexibly cater for time variation in its spillover results, unlike the static spillover models. For specification, we first illustrate a VAR(p) process and its FEVD. Given time, $t = 1, \dots, T$, the VAR(p) model expresses the n-variate order, $x_{t,1}, \dots, x_{t,n}$ as follows:

$$\phi(L)x_t = \varepsilon_t \tag{4}$$

where $\phi(L) = \sum_h \phi_h L^h$ denotes an $n \times n$ order of coefficient matrix t whose lag polynomial is infinite. Then, the FEVD is given as (Diebold and Yilmaz, 2012):

$$(\theta_H)_{j,k} = \frac{\sigma_{kk}^{-1} \sum_{h=0}^H (\Psi_h \Sigma)_{j,k}^2}{\sum_{h=0}^H (\Psi_h \Sigma)_{j,j}} \tag{5}$$

where $\sigma_{kk} = (\Sigma)_{k,k}$, and Ψ_h are $n \times n$ order of coefficient matrices with the lag of h . The shocks contributed to the forecast error variance of another variable j by a k -th variable is explained by $(\theta_H)_{j,k}$. Meanwhile, since all the rows of $(\theta_H)_{j,k}$ do not sum up to one, the resulting value after summation is used as a divider of each constituent of the decomposition matrix normalization. The expression is as follows:

$$(\bar{\theta}_H)_{j,k} = \frac{(\theta_H)_{j,k}}{\sum_{k=1}^n (\theta_H)_{j,k}} \tag{6}$$

with $\sum_{j,k=1}^n (\bar{\theta}_H)_{j,k} = N$ and $\sum_{k=1}^n (\bar{\theta}_H)_{j,k} = 1$.

The overall spillover index can be computed as the mean contribution of one variable to others in the system, and is specified as:

$$C_H = \frac{\sum_{j \neq k} (\bar{\theta}_H)_{j,k}}{\sum (\bar{\theta}_H)_{j,k}} \times \left(1 - \frac{Tr\{\bar{\theta}_H\}}{\sum (\bar{\theta}_H)_{j,k}} \right) 100 \tag{7}$$

where C_H is the overall spillover index and $Tr\{\bullet\}$ is the trace operator.

The directional spillovers are also computed. In this case, the specific spillovers from and to a particular variable is calculated so that the level of influence of a variable on the entire system, and how much it is influenced by the system is gauged. Eqs. (5) and (6) express the transmitted $((C_H)_{j \rightarrow})$ and received $((C_H)_{j \leftarrow})$ spillovers respectively:

$$(C_H)_{j \rightarrow} = 100 \times \frac{1}{n} \sum_{j \neq k, k} (\bar{\theta}_H)_{j,k} \tag{8}$$

$$(C_H)_{j \leftarrow} = 100 \times \frac{1}{n} \sum_{j \neq k, k} (\bar{\theta}_H)_{j,k} \tag{9}$$

Whether a variable, that is a net contributor to or recipient of spillover, is finally determined by deducting the amount of spillover

Table 1
Descriptive statistics.

	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	Observations
Australia	0.0068	0.0032	3.4599	-3.2858	0.5672	0.0750	5.6412	3542
Canada	0.0094	0.0126	5.0426	-3.6381	0.5429	0.1810	7.9294	3542
Denmark	0.0137	0.0191	2.7910	-2.8953	0.3701	-0.1771	10.0402	3542
Euro	0.0137	0.0175	2.7972	-2.8991	0.3711	-0.1765	10.0107	3542
Hong Kong	0.0087	0.0123	6.8156	-3.7672	0.5843	0.6725	15.2746	3542
Japan	0.0186	0.0296	5.3506	-4.5534	0.7226	-0.0365	9.1774	3542
New Zealand	0.0048	0.0042	3.9627	-3.4471	0.6053	0.1860	6.1294	3542
Norway	0.0180	0.0095	4.5565	-3.2939	0.5590	0.3816	7.6406	3542
Sweden	0.0149	0.0130	2.2010	-2.2883	0.3928	-0.0632	5.4545	3542
Switzerland	0.0015	0.0039	8.4831	-12.0651	0.5678	-2.0800	84.7299	3542
UK	0.0150	0.0051	7.1648	-3.5074	0.5784	0.9007	16.7339	3542
USA	0.0083	0.0104	6.8246%	-3.7730	0.5889	0.6537	15.0993	3542
Demand shock	0.0000	-0.0212	14.0472	-14.3970	1.1713	-0.4113	24.0693	3542
Risk shock	-0.0211	-0.7070	78.5853	-31.7466	7.5974	1.3206	10.1438	3542
Supply shock	0.0000	0.0180	24.7538	-38.7649	2.2997	-1.3426	44.8229	3542

Notes: This table shows the sample statistics of the green bond returns for each country and the disentangled oil shocks.

received from the amount of spillover transmitted, i.e.

$$(C_H)_{j,net} = (C_H)_{j\rightarrow} - (C_H)_{j\leftarrow} \tag{10}$$

If $(C_H)_{j,net}$ is greater (lower) than zero, then the variable in question is a net transmitter (recipient) of shocks.

4. Data and summary statistics

We use daily green bond market price indices of twelve developed economies including Australia, Canada, Denmark, Euro, Hong Kong, Japan, New Zealand, Norway, Switzerland, Sweden, USA and UK. Additionally, we employ the decomposed oil price shocks as

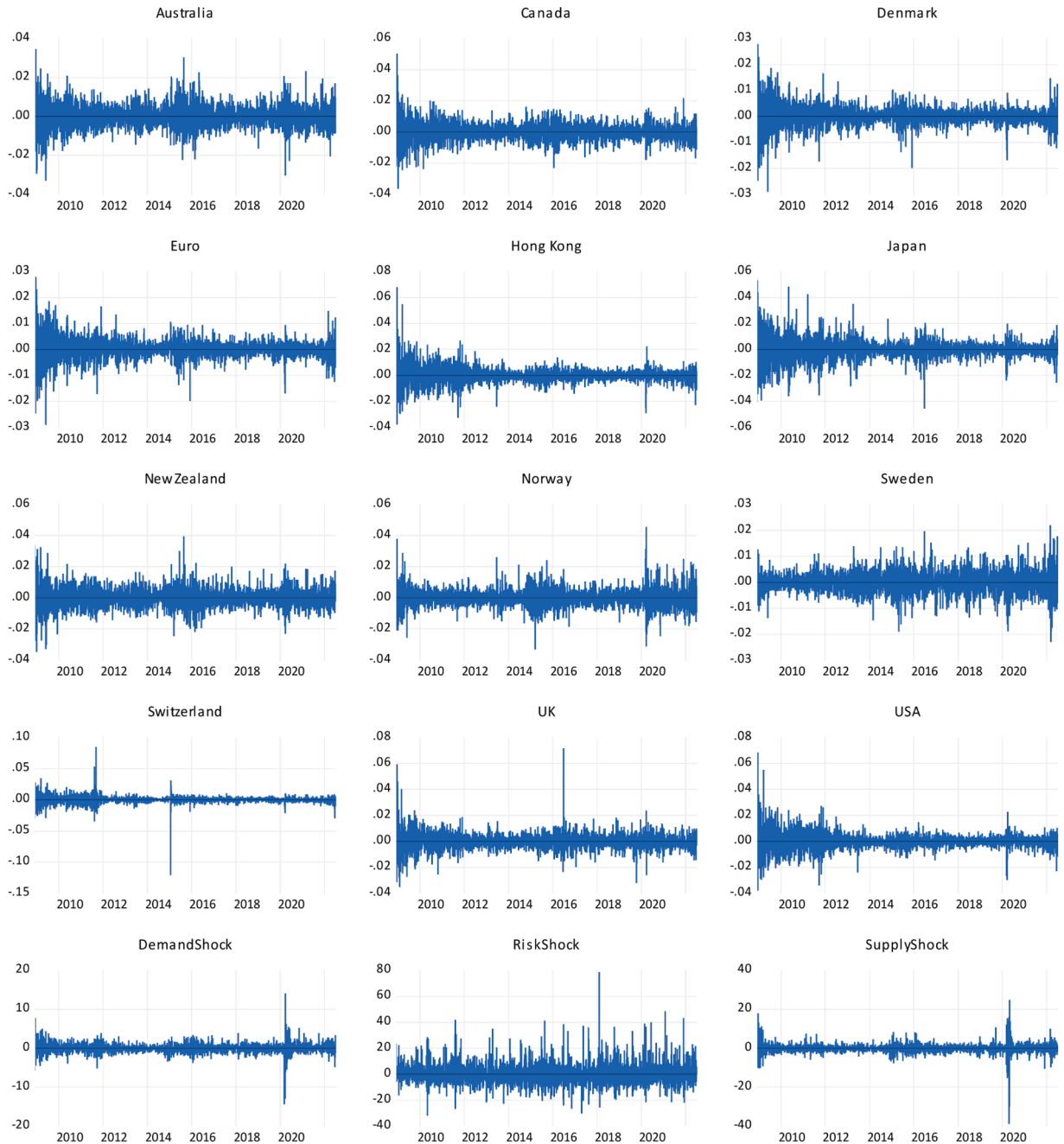


Fig. 1. Time series of oil price shocks and returns of green bond markets. Notes: This figure shows the time series of the green bond markets' returns and the disentangled oil price shocks.

Table 2
Static directional return spillovers and connectedness results.

	RiskShock	DemandShock	SupplyShock	Australia	Canada	Switzerland	Denmark	Euro	UK	HongKong	Japan	Norway	NewZealand	Sweden	USA	FROM
Risk Shock	80.32	0	0.03	2.11	0.78	1.68	0.32	0.3	0.11	1.05	5.61	3.27	1.07	2.2	1.15	19.68
Demand Shock	0.67	60.56	0.08	2.46	0.45	1.58	0.63	0.63	0.06	7.93	7.95	5.3	1.15	2.35	8.19	39.44
Supply Shock	0.44	0.53	94.94	0.11	1.3	0.06	0.01	0.01	0.04	0.65	0.25	0.93	0.06	0	0.67	5.06
Australia	1.71	1.57	0.03	39.72	13.12	1.05	1.76	1.76	5.52	2.56	0.65	6.37	20.2	1.57	2.41	60.28
Canada	0.55	0.32	0.55	11.84	35.9	2.17	3	2.99	7.26	10.61	2.22	4.11	7.48	0.51	10.48	64.1
Switzerland	1.01	1.06	0.02	0.97	2.57	41.98	12.58	12.48	3.86	6.14	8.47	1.41	1.08	0.16	6.22	58.02
Denmark	0.24	0.32	0	1.31	2.54	9.11	30.36	30.31	5.61	4.21	3.77	4.14	1.14	2.72	4.22	69.64
Euro	0.24	0.32	0	1.31	2.53	9.06	30.38	30.43	5.61	4.19	3.75	4.13	1.14	2.72	4.19	69.57
UK	0.05	0.06	0.04	5.47	8.04	3.57	7.27	7.25	39.61	8.35	3.31	3.47	4.38	0.81	8.32	60.39
Hong. Kong	0.51	3.69	0.15	1.76	8.3	4.14	3.91	3.87	5.9	28.07	10.3	0.08	0.97	0.36	27.98	71.93
Japan	3.17	5.07	0.06	0.47	2.32	7.83	4.79	4.76	3.12	14.08	38.52	0	0.69	0.92	14.22	61.48
Norway	2.14	4.05	0.44	7.39	5.34	1.42	6.22	6.18	4	0.13	0.01	45.8	5.06	11.7	0.11	54.2
New. Zealand	0.97	0.89	0.01	23.06	9.52	1.3	1.75	1.74	5.03	1.75	0.97	5.03	45.53	0.8	1.64	54.47
Sweden	1.69	2.38	0	2.4	0.82	0.22	5.45	5.43	1.21	0.77	1.46	15.53	1.08	60.74	0.82	39.26
USA	0.57	3.81	0.16	1.65	8.19	4.19	3.91	3.88	5.87	27.97	10.39	0.06	0.9	0.39	28.06	71.94
TO Others	13.97	24.08	1.59	62.31	65.81	47.39	81.97	81.58	53.19	90.38	59.1	53.81	46.42	27.22	90.62	799.45
NET	-5.71	-15.36	-3.47	2.04	1.71	-10.64	12.33	12.02	-7.2	18.46	-2.38	-0.39	-8.05	-12.04	18.68	CTCI/ TCI= 56.41/53.38

Notes: This table shows the average connectedness of returns of green bonds and oil price shocks over the sample period. TCI denoted total connectedness index.

the second variable of interest. The decomposed oil price shocks include Demand shock (DSHK), Risk shock (RSHK), Supply shock (SSHK). We use daily data on the WIOGPI Index for the supply shocks, the VIX (CBOE's volatility index) for the risk shocks and the one-month crude oil futures' returns on the second nearest maturity for the demand shocks. We obtain data for prices and volatility spanning from December 2008 to June 2022 sourced from DataStream.

The mean, median, skewness, kurtosis and standard deviation of returns of the green bond markets of all countries, as well as decomposed oil price shocks are shown in Table 1. Focusing on green bond markets, we observe that Switzerland (0.015) has the lowest mean return followed by New Zealand (0.0048) and Australia (0.068). On the other hand, Japan (0.0186) has recorded the highest mean value followed by UK (0.0150). The skewness value shows that green bond market's return distributions of Australia, Canada, Hong Kong, New Zealand, Norway, UK and USA are positively skewed whilst the other markets exhibit negatively skewed return distributions. For all the series under consideration, the kurtosis statistic demonstrates that the series of observations are fat-tailed. In the case of standard deviation, we observe marginal variability in green bond markets' returns. Denmark shows the least standard deviation estimate (0.3710) with Japan obtaining the largest standard deviation (0.7226). Concerning the shocks of oil prices, the risk shocks have the highest mean value among the three decomposed types of shocks. The standard deviation figure shows that risk shocks (7.5974) are the most volatile type of shocks, while demand shocks (1.1713) have the lowest volatility.

Fig. 1 reports the plot of daily returns for all series under examination. According to Fig. 1, the log-return graphs display also enormous fluctuations with peaks and valleys at different time periods including the start of our sample and towards its end that coincides with the COVID-19 crisis period. Thus, these results justify the use of time-varying methods in modelling the connection between oil price shocks and green bond markets. The correlation matrix between returns of green bonds and oil price shocks is reported in Table A-2, in the appendix, depicting varying values for correlation for the different pairs, thus underscoring the desirability of a detailed spillover analysis. Lastly, the time series of green bond prices is presented in Figure A-1, in the appendix, to give the reader a depiction of evolution of bond prices over the sample period.

5. Empirical discussion of results

In this section, we discuss the relationship between oil price shocks and green bond markets using the DY approach to capture the return and volatility transmissions and the level of connectedness between oil and green bond markets. The decomposed shocks in the oil price and the countries' green bond markets modelled in one network system for the assessment.

5.1. Static based directional return spillover and connectedness

Table 2 shows the return spillovers and connectedness results from the Diebold approach for 15 variables in the network system. In general, we observe heterogeneity in the return spillover across green bond markets. We find that the own variable spillover (idiosyncratic shock) is higher for oil price shocks than for green bond markets, as evidenced by the figures in the diagonal. In the case of Sweden, 60.74% of the price movement is associated with the market own shocks/behavior, with only 39.26% of the green bond market shocks attributable to markets' connections in the network. It is important to mention that, except for Sweden, the price movement in the green bond markets of the remaining countries is mainly driven by the network connections evidenced by the diagonal element. For example, 39.61% of UK green bond market's price evolution, 39.72% of Australia green bond market's price evolution, 35.9% of Canada green bond price's evolution and 28.06% of US green bond price's evolution are driven by own-market shocks which implies that a significant portion of price movement is instigated by the network connections. We find that the green bond markets of Canada, Australia, Denmark, Switzerland, UK, Euro, Hong Kong, Norway, Japan, USA and New Zealand have more than 50% of their shocks driven by spillovers in the market network connections. This finding is contrary to the finding of Mensi et al. (2022) who show that green bonds price variation is heavily influenced by its own shocks. Regarding the decomposed oil price shocks, we find that the price movement is mainly driven by own-market shocks. For example, 80.32% and 94.94% of the index movement in risk shocks and supply shocks is driven by own-market shocks. Finding from the diagonal element suggests that green bond market price movement can be linked to oil price shocks movement. Concerning the bidirectional return spillovers between oil price shocks and the green bond markets, we find a higher spillover from green bond markets to oil demand shocks compared to risk shocks and supply shocks which is not surprising given that, about 39.4% of demand shock evolution is driven by network interaction in the system. In general, we find that Japan (3.17%; 5.07%) and Norway (2.14%; 4.05%) receive most return spillovers from risk shocks and demand shocks, respectively.

Concerning the return spillover from a specific market to the other markets in the network system ("TO OTHERS"), the demand shock component records the greatest transmission of return shocks (24.08%) to other markets, followed by Risk shocks (13.97%), and Supply shocks (1.59%). Our results align with extant studies such as Yaya et al. (2022), who posits that oil consumption demand shocks reduce volatility of green assets while oil consumption supply shocks increase volatility in green investment. On the other hand, the US green bond market transmits the highest return shocks (90.62%) to other markets, followed by Hong Kong (90.38%), Denmark (81.97%), Euro (81.58%) with Sweden contributing the least to the shocks in the system with a transmission rate of 27.22%. Comparatively, the green bond markets of USA, Hong Kong, UK, and Euro have significant impact on other markets in the network system. This is not surprising given that the green bond markets of these countries are more developed compared to those of the other used countries (GSIA report, 2020). We report the dominance of oil demand shocks and the US green bond market as main contributors to return shocks in the system. In particular, we observe heterogeneity in return spillovers between green bonds and oil price shocks which aligns with the findings of Salisu and Gupta (2021) and Guo and Zhou (2021).

Concerning the return spillovers from the system to a specific market, we observe significant spillovers from the system to other

markets. The shocks in the system range from 5.06% to 71.94%. The US green bond market (71.94%) receives the greatest shocks from other markets, followed by Hong Kong (71.93%), whilst oil supply shocks (5.06%) receive the least shocks from the system, advanced by Risk shocks (19.68%). These results imply that oil supply shocks are marginally impacted by shocks from other markets. The US green bond market, on the other hand, is seen to be significantly affected by shocks from other markets. Comparatively, green bond markets receive higher shocks from the system than oil price shocks. That is, except for the Swedish green bond market, over half of the shocks in all green bond markets are attributable to spillovers from the system. Our findings on green bond markets being major receivers of return shocks suggest the high level of financial integration among them. This finding supports those of Kang et al. (2014) who document that oil supply and demand shocks jointly account for 30% of the return shocks in the US green bond market. Specifically, our results show that about 37% of price variation of international green bond markets are attributable to oil shocks.

We focus on the net return spillover calculated as the difference between spillover “TO OTHERS” and spillovers “FROM OTHERS”. A negative net spillover figure denotes a net recipient of return shocks and a net positive spillover figure denotes a net transmitter of shocks. We find that risk shocks, demand shocks, supply shocks, as well as the green bond markets of Switzerland, UK, Japan, Norway, New Zealand, and Sweden have negative net spillover estimates of -5.71 , -15.36% , -3.47% , -10.64% , -7.2% , -2.38% , -0.39% , -8.05% , and -12.04% , respectively. These results indicate that these markets are net receivers of return spillover. Oil demand shocks is the greatest recipient of shocks, followed by the Swedish green bond market. Our results mildly contradict those of prior studies such as Lee et al. (2022) who find a significant impact of the oil-specific demand shocks on green bond dynamics. Within the green bond markets, we observe that the US market (18.68%) is the greatest net transmitter of return shocks, followed by Hong Kong (18.46%), Denmark (12.33%), Euro (12.02%), Australia (2.04%) and Canada (1.71%). Our result about disaggregated oil price shocks (i.e., risk, demand and supply shocks) being net recipients of shocks in the entire spillover system is in accordance with the results of Le et al. (2021) who also find weak spillovers from oil price shocks to green bonds.

Overall, the total return connectedness index (TCI) of 53.3% shows a moderate return spillover among oil price shocks and green bond markets, which is unsurprising given that the index movement of the examined series is marginally driven by other markets shown in the non-diagonal element. We discover the dominance of green bonds over oil price shocks. We conjecture that an increase in green investments in recent years may have contributed to this dominance of green bond markets. The implication of the afore results is that there are diversification benefits of holding of green bonds against oil, and vice versa.

For a more comprehensive analysis of the interlinkage between the two assets, we examine the volatility spillovers and connectedness between the studied markets. Table 3 presents the static directional volatility spillover results. Contrary to what is observed in Table 2, green bond markets of Australia and Canada are net receivers of volatility spillover. Risk shocks as well as the Japanese green bond index also appear to rather be net transmitters of volatility spillover. Our results show that only risk shocks transmit significant volatility shocks to green bond markets. This finding supports those of Dutta et al. (2020) who also find some level (marginal) effect of oil price shocks on green assets. Euro green bond market (22.08%) appears as the greatest net transmitter of volatility spillover in the system followed by Denmark (21.06), USA (16.44%) and Hong Kong (15.92%). The emergence of the Euro green bond market as the lead transmitter of volatility shocks in the system is not surprising. This may be due to the fact that European countries have widely embraced sustainable investment which is broadly practiced in the European markets as compared to other regions (Global Sustainable Investment Review report, 2018). Thus, to say, compared to other regions around the world, the green development and green markets are more advanced in Europe. The USA lost its dominance as the largest transmitter of return shocks in Table 2 to Euro in Table 3, when we consider volatility shocks. According to Reboredo et al. (2020), green bond markets of USA and EU are the most active green bond markets in the world, which confirms their dominance as transmitters of shocks in the entire system. Another significant observation in Table 3 is that the net volatility estimates for demand and supply shocks has been reduced together with most of the green bond markets which suggests that return spillovers are more intense than volatility spillovers among the studied markets. This initial assertion is confirmed by the TCI of 43.04% recorded in Table 3 which is below the TCI of 53.3% recorded in Table 2. Regarding the contribution to the system by individual markets, we again observe the dominance of green bond markets of Euro, USA, Denmark and Hong Kong since these markets transmit more shocks than they receive from other markets in the system. In terms of similarity, we observe that index movement of used green bond markets is driven by market interactions evidenced by the diagonal element while oil price shocks' movement are driven by own-market shocks, similar to what we observe in Table 2.

5.2. Time-Varying return and volatility total connectedness

In this section, we further examine the evolution of the total connectedness index (TCI) for both return and volatility spillovers as shown in Fig. 2. A high TCI suggests a strong connectedness across markets in the network system. Our sample period from December 2008 to June 2022 gives a true picture of the patterns of the total connectedness between used markets since it encompasses important financial events in the global market (i.e., the 2009 global financial crisis; 2014 Europe's debt crisis, 2016–2020 Brexit, the Covid-19 pandemic and the Russia-Ukraine in 2022). In addition, the period contains the Russia-Saudi Arabia oil price war during which oil price declines by more than 50%.

We observe a time-varying connectedness between markets. The results show that the total connectedness index swings with a range from 45% to 72%. This suggests that the level of connectedness between oil and green bond markets is precarious on global events. The highest total connectedness between used markets for both return and volatility spillovers is observed in 2009, whilst the lowest connectedness is seen in 2018. Bring the financial crisis periods into the picture, the connectedness between the markets appears to be moderate during the period of the 2014 European debt crisis, especially for return spillover. The connectedness is higher in the voting period of Brexit and COVID-19 as compared to the exit period. The connectedness is seen to be relatively high in 2020 and 2022, the periods of COVID-19 and Russian-Ukraine war. A closer look shows that the TCI spiked (72%) in 2009 during the late period

Table 3
Static directional volatility spillovers and connectedness results.

	RiskShock	DemandShock	SupplyShock	Australia	Canada	Switzerland	Denmark	Euro	UK	HongKong	Japan	Norway	NewZealand	Sweden	USA	FROM
Risk Shock	97.92	0	0.03	0.23	0.24	0.01	0.12	0.11	0.15	0.2	0.21	0.28	0.25	0.04	0.19	2.08
Demand Shock	1.12	97.93	0.14	0.02	0.05	0.11	0.01	0.01	0.11	0.02	0.08	0.2	0.12	0.06	0.02	2.07
Supply Shock	0.5	0.61	96.35	0.05	0.01	0.33	0.36	0.36	0.2	0.41	0.28	0.08	0.08	0	0.37	3.65
Australia	0.21	0.02	0.02	44.22	7.84	0.91	4.75	4.72	3.83	2.38	2.46	6.54	17.69	2.11	2.31	55.78
Canada	0.16	0.01	0.03	9.84	42.54	1.3	4.99	5.04	6.01	9.37	2.8	3.27	4.61	0.73	9.3	57.46
Switzerland	0.08	0.09	0.05	1.01	0.79	69.86	6.24	6.61	1.05	3.44	4.19	1.16	1.79	0.1	3.56	30.14
Denmark	0.14	0	0.1	2.23	1.64	5.26	31.11	31.19	2.8	7.05	5.95	2.11	2.09	1.24	7.08	68.89
Euro	0.14	0	0.1	2.22	1.63	5.24	30.97	31.22	2.84	7.06	6.02	2.12	2.12	1.23	7.1	68.78
UK	0.03	0.06	0.12	2.78	3.12	0.72	7.51	7.68	52.65	6.39	6.73	2.55	2.06	1.24	6.36	47.35
Hong. Kong	0.14	0.02	0.16	1.05	3.15	2.54	7.47	7.49	4.77	30.88	9.18	0.79	1.2	0.23	30.93	69.12
Japan	0.32	0.05	0.2	1.08	1.4	3.2	7.15	7.21	4.65	12.06	48.24	0.41	1.38	0.52	12.13	51.76
Norway	0.24	0.02	0.4	5.38	2.47	0.83	4.37	4.39	2.63	2.88	1.24	58.33	5.39	8.47	2.97	41.67
New. Zealand	0.27	0.04	0.04	16.93	5.37	1.35	4.66	4.58	2.31	1.82	2.46	5.45	51.52	1.39	1.8	48.48
Sweden	0.07	0.02	0.01	2.37	0.51	0.54	3.9	3.99	1.12	1.19	1.42	12.26	0.91	70.51	1.19	29.49
USA	0.14	0.03	0.15	1	3.08	2.6	7.45	7.47	4.7	30.78	9.3	0.78	1.16	0.23	31.14	68.86
TO Others	3.54	0.98	1.54	46.2	31.28	24.96	89.95	90.86	37.17	85.04	52.32	38.01	40.85	17.58	85.31	645.57
NET	1.46	-1.1	-2.11	-9.58	-26.18	-5.19	21.06	22.08	-10.18	15.92	0.57	-3.66	-7.64	-11.9	16.44	CTI/TCI= 47.1/43.04

Notes: This table shows the average connectedness of volatility of green bonds and oil price shocks over the sample period. TCI denoted total connectedness index.

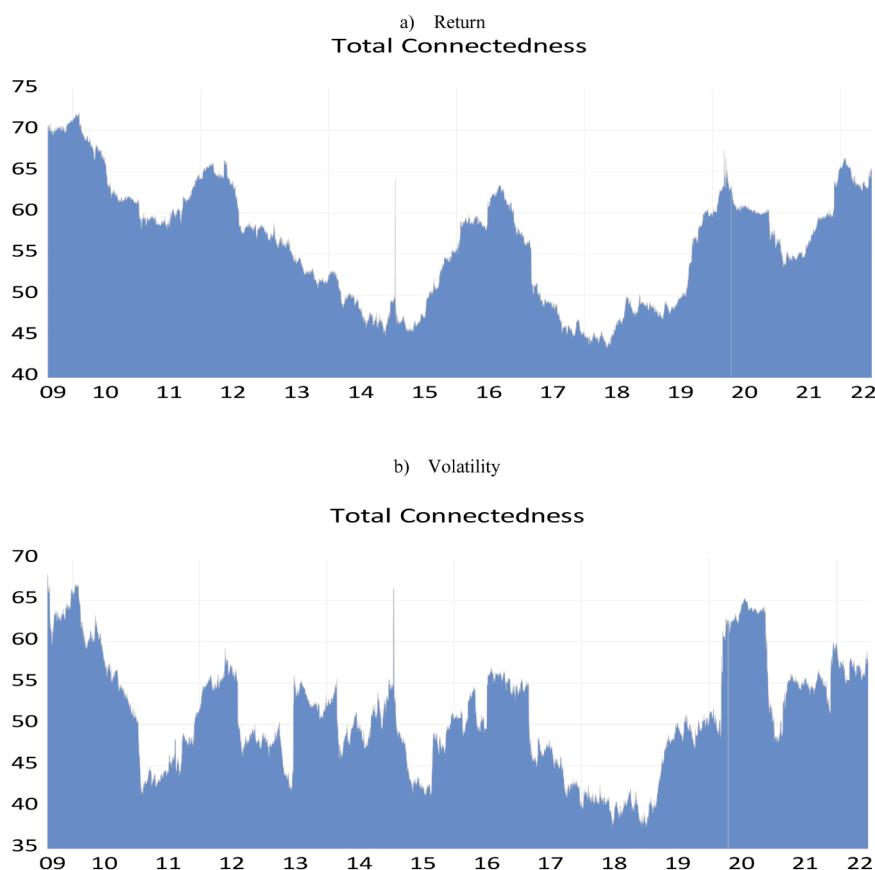


Fig. 2. Time-Varying total connectedness in returns and volatility. Notes: This figure shows the total connectedness of the return and volatility of green bonds and oil price shocks over the sample period.

of the global financial and had its lowest value (45%) in 2018. Overall, the observation shows that the connectedness spiked during turbulent periods. These findings are in concordance with [Shahzad et al. \(2017\)](#), [Bouri et al. \(2020\)](#) and [Mensi et al. \(2021\)](#) who posit that market interconnectedness vary over time and that the level of interdependence is ascribed to market conditions.

Considering the behavior of the volatility spillover index in Panel B, we observed that the total connectedness index is marginally lower than the index of the total return connectedness (Panel A) and ranges from 37% to 69%. This joins the findings from [Table 3](#) which show marginal connectedness in the case of volatility spillover as compared to return spillover in [Table 2](#). The highest TCI (69%) is recorded in 2009, the period that coincides with the global financial crisis. We also find that the total connectedness is not constant and increases in the episodes of critical global events, i.e., global financial crisis in 2009, European debt crisis in 2014, Brexit in 2016, the COVID-19 pandemic in 2020 and outbreak of the Russia-Ukraine conflict in February 2022. This suggests that the studied markets are more mildly interconnected during the periods of low or normal market volatility than during highly volatile market states. This analysis of the evolution of TCI over time provides an information for the assessment of the effects of different crisis episodes on the degree of connectedness between markets. Our findings show higher levels of TCI during GFC than other crisis episodes and, more notably, the Covid-19 crisis period. A comparison between these two episodes of the two most severe crises in recent time suggest that the level of return and volatility connections among oil and green bond markets is higher during GFC than during Covid-19. This result is contrary to the findings of previous studies that have recorded higher levels of spillovers between energy and stock markets during the pandemic than during the GFC episode (e.g., [Jebabli et al., 2022](#)). Our findings rather suggest that spillover between green bonds and oil is higher during endogenous (financial) crisis periods than during exogenous (Covid-19; Russo-Ukrainian induced) crisis periods. These results could be attributed to the green bond market maturity. As reported by previous studies (e.g., [Taghizadeh-Hesary and Yoshino, 2019](#); [Le et al., 2020](#); [Elsayed et al., 2022](#)), green bonds have experienced an increasing growth rate from 2014 onwards given their crucial role in achieving sustainable development goals.

5.3. Net total directional connectedness

In this section, we discuss the dynamics of the net return and volatility spillovers for each market in the network system. A negative net spillover figure, appearing at the lower part of the chart, denotes a market that is a net recipient of return or volatility shocks, and a net positive spillover value, appearing at the upper part of the chart, denotes that the market is a net transmitter of shocks.

Fig. 3 shows the behavior of the net return spillovers. We observe that, for most the sample period, green bond markets of Denmark, Euro, Hong Kong, and USA appear to be net transmitters of shocks, while UK, as well as Supply shocks appear to be net receivers of return shocks throughout the period. A closer look reveals that the net spillover sign for the other remaining markets switches at a point in time. For instance, Australia's green bond market is a net receiver of shocks during normal market periods from 2010 to 2014. Then, the market experiences a short period as a net transmitter of shocks in the late part of 2012 and between 2016 and 2018, before switching to its former position. During turbulent market periods such as the Brexit period, the COVID-19 period and the Russia-Ukraine war period, the Australian green bond market is seen as the greatest transmitter of return shocks to the other markets. The other green bond markets, i.e., Canada, Japan, New Zealand and Switzerland together with risk shocks appear as net receivers of shocks during the COVID-19 pandemic. However, this position has changed during the latter part of 2020. During the outbreak of the

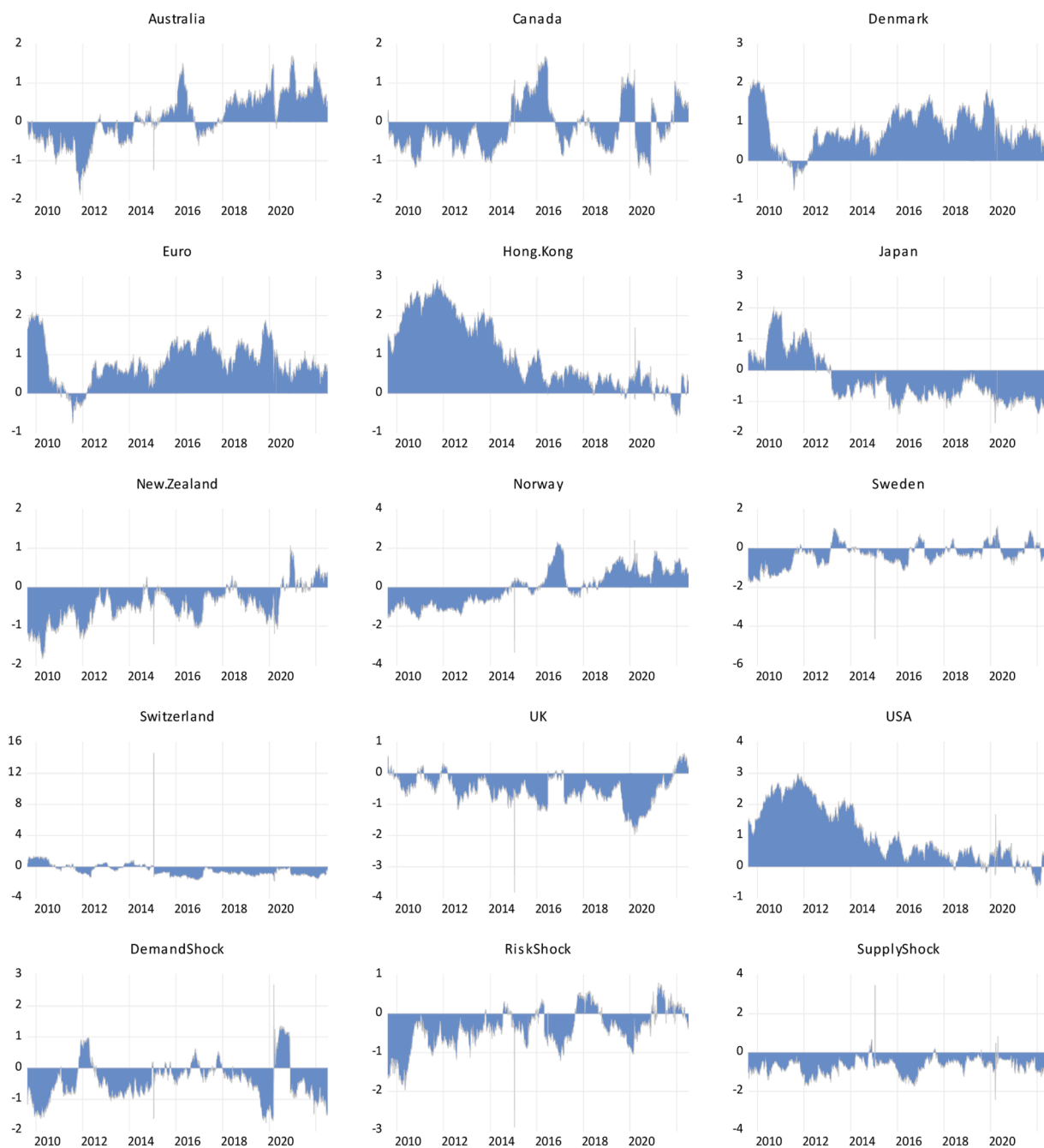


Fig. 3. Net directional connectedness – returns. Notes: This figure shows the net directional connectedness of returns of green bond markets and oil price shocks over the sample period.

Russia-Ukraine crisis, Risk shocks and green bond markets of Australia, Canada, Denmark, Euro, Norway, and UK emerge as net transmitters of shocks, whilst green bond markets of USA, Sweden, Japan, Switzerland emerge as net receivers of shocks. A comparison of the net spillover positions of the series under examination during the outbreak of COVID-19 and Russia-Ukraine war as well as other global events reveals the dominance of the Euro, Hong Kong, Danish and US green bond markets. Thus, we report the diversification benefits of these markets during turbulent market conditions.

Concerning the net volatility spillovers (in Fig. 4), we observe a reciprocity in terms of net spillover positions throughout the sample period for all markets. Specifically, contrary to the net return spillover positions that appear to be more stable for most markets during the sample period, the net volatility spillover positions appear to interchange throughout the studied period. For example, Euro green bond market appears to be a net transmitter of return shocks for most of the sample period, as depicted in Fig. 3. However, the position

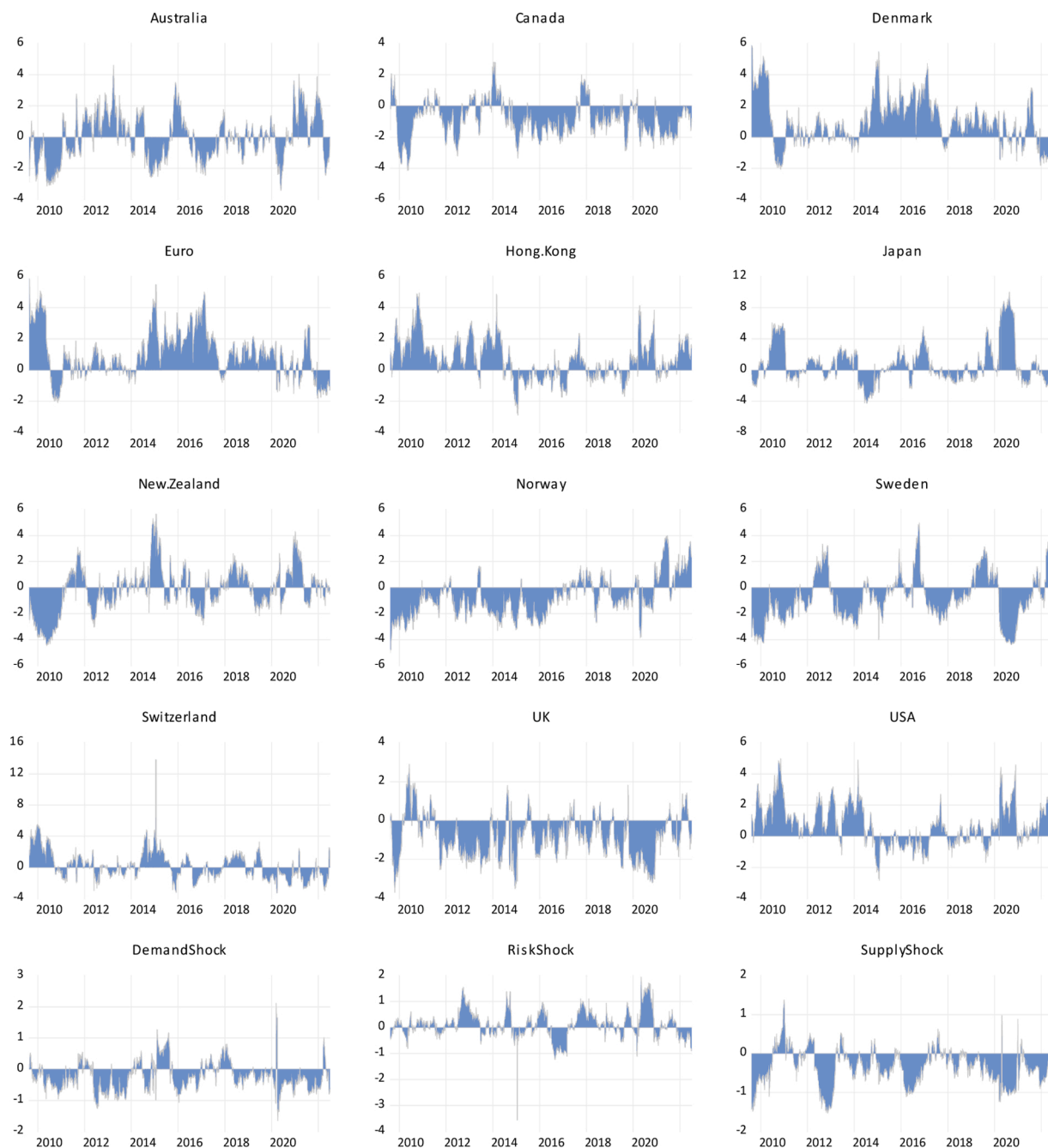


Fig. 4. Net directional connectedness – volatility. Notes: This figure shows the net directional connectedness of volatilities of green bond markets and oil price shocks over the sample period.

of the market switches between a net receiver and transmitter of volatility shocks in Fig. 4 during this same period. Similarly, all the other markets under examination followed the same pattern. The variability of the net spillover positions signifies the evolution of the behavior of markets. Nevertheless, we note the same results, as for return spillover, of the dominance of the Euro, Hong Kong, Danish and US green bond markets during turbulent episodes.

5.4. Net pairwise network analysis

Fig. 5 shows the pairwise network plot for both return and volatility spillovers in Panel A and Panel B, respectively. The nodes represent the information sharing between the markets. The direction of the arrows shows the transmitter (source of the arrow) and the recipient (edge) of spillover. The width of the arrow indicates the strength of the spillover between the pairs. The source of red color arrows shows the markets with the highest contribution to shocks, whereas, the blue color arrows edge shows the markets with the highest values as net recipients of spillover in Tables 2 and 3.

In Panel A, we observe the dominance of the US green bond market, evidenced by the higher number of red arrows sourced. This connotes that the US green bond market is the most connected with the other markets in the network system. This dominance of the US green bond market is followed by Hong Kong, Euro and Denmark green bond markets, being the most influential markets in terms of return spillover, while Sweden, New Zealand, Norway, and Switzerland appear to be the recipients of these return shocks, as depicted by blue color arrows. For the oil price shocks, Demand shocks are the greatest recipient of shocks from other markets in the network system, followed by Risk shocks and Supply shocks.

Shifting to Panel B, Euro green bond market is seen as the most influential market and the most connected market to the other markets in the system. Canada is seen as the major recipient of volatility shocks. The dominance of the US green bond market disappears in Panel B. Thus, examining only return shocks may not give a vivid picture of the extent of spillovers between the examined markets. Interestingly, the decomposed oil price shock components emerge as major recipients of volatility spillover from green bond markets, which suggests the emergence of green bonds as a viable asset class with significant diversification potential. Our findings on the dominance of green bond prices over oil price shocks differ from the conclusion of Kanamura (2020) that finds that oil prices significantly impact green bond prices.

Lastly, we conducted robustness analysis of our estimates by segregating our sample period into various subperiods and analyzed the pairwise connectedness during each subperiod as each subperiod has its own underlying market dynamics (Banerjee, 2021, 2022, 2023). Figure A-2 depicts the pairwise connectedness during global financial crisis, Figure A-3 during European sovereign debt crisis and Figure A-4 during the COVID-19 pandemic.¹ We notice that during the first two sub-periods Norway is the highest recipient of spillover, however, during the COVID-19 pandemic Japan became the highest recipient of spillover, thus underscoring our earlier finding of time varying nature of spillover.

As another robustness measure, we employed the TVP-VAR based connectedness approach of Antonakakis et al., (2023). The total connectedness results are reported in Figure A-5 and the net directional connectedness results are reported in Figure A-6 and Figure A-7. Qualitatively, our results show similar patterns to those discussed above and as such underscores the robustness of the employed methodology.

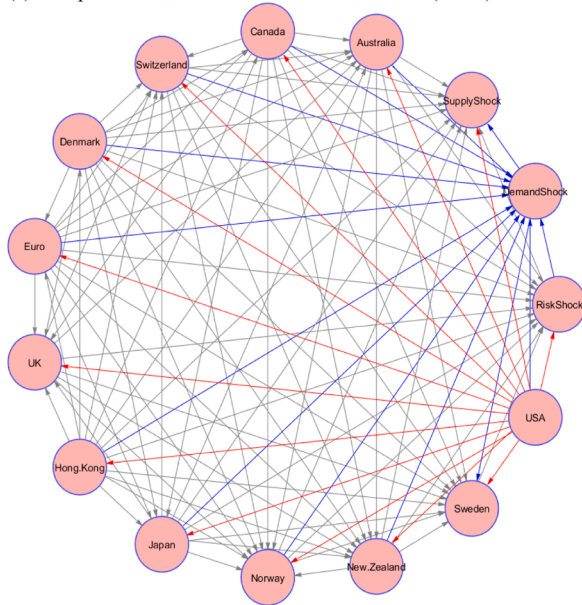
6. Conclusion

This paper examines the return and volatility spillover effects between oil price shocks and green bond market indices of 12 developed economies, namely Australia, Canada, Denmark, Euro, Hong Kong, Japan, New Zealand, Norway, Switzerland, Sweden, USA and the UK. We use the decomposed oil price shocks including Demand shock (DSHK), Risk shock (RSHK), Supply shock (SSHK) with data running from December 2008 to June 2022. Using the Diebold and Yilmaz's generalized VAR framework model (2009; 2012; 2014), we document several interesting findings. First, the results of the static directional spillover show that, in the case of all green bond markets, except for Sweden, price shocks are mainly driven by more than 50% by spillovers in the market network connections. Second, static spillover analysis also shows that, although, demand – side shocks have a higher effect on green bonds than supply – side shocks, the effect remains marginal for the three decomposed oil price shock sources. Third, the results of the dynamic spillover analysis indicate that the degree of dependency between markets varies over time. Fourth, with regards to global crisis events, findings suggest that both return and volatility spillovers become higher during crisis episodes such as the global Covid-19 pandemic, Brexit, the European debt crisis and the Russian-Ukrainian war. Finally, we document the dominance of green bond markets over oil price shocks.

The findings of the study have several policy implications based on the results. First, during market downturns, policymakers should emphasize the importance of risk management strategies. The significant return and volatility spillovers between green bonds and oil price during volatile market states suggest the importance of preparedness and risk mitigation measures. Second, our findings emphasize the significance of comprehending the dynamics of spillovers during times of crises such as COVID-19 and the Russia-Ukraine war. To assess the potential impact of extreme events on the green bond and oil price association, policymakers and market participants should focus on strengthening crisis preparedness and risk management measures to appropriate risk mitigation strategies and ensure the energy sector's stability and resilience. Third, our findings show green bond market of developed economies

¹ We thank anonymous referees for insightful suggestions.

(a) Net pairwise network directional connectedness (return)



(b) Net pairwise directional connectedness (volatility)

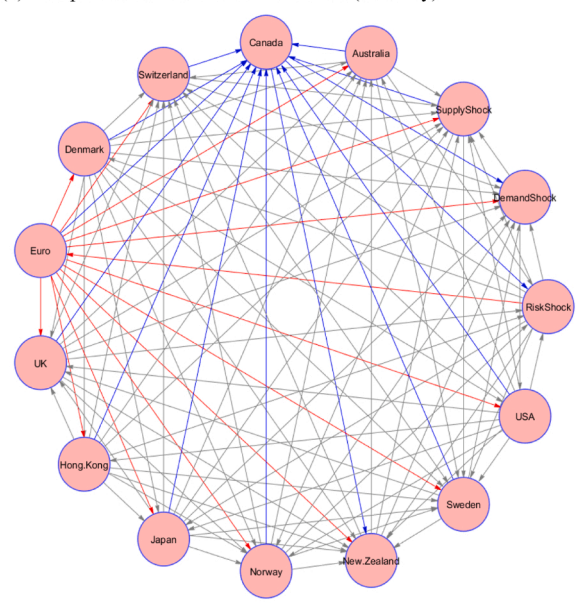


Fig. 5. Net pairwise network plot. Notes: This figure shows the pairwise connectedness of returns and volatility of green bond markets and oil price shock.

have the potential to play a significant role in mitigating the spillovers associated with green bond markets during crisis periods. Thus, green bond markets should be developed and adopted by policymakers by creating a favorable regulatory environment and promoting innovative financial instruments. This can encourage investment in the green markets sector, while also improving market efficiency and stability. Investors and portfolio managers may adopt dynamic portfolio strategies that adjust based on the changing interconnectedness patterns induced by market states. This can help investors align their portfolios with evolving market conditions and optimize risk-return trade-offs. Future extension of our work can study the connectedness using high frequency data-based volatility measures and higher order moments.²

CRediT authorship contribution statement

Umar Muhammad: Formal analysis, Validation, Writing – review & editing. **Hadhri Sinda:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Umar Zaghum:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Usman Muhammad:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization. **Abakah Emmanuel Joel Aikins:** Writing – review & editing, Writing – original draft, Visualization, Validation, Conceptualization.

Data availability

Data will be made available on request.

Appendix

² We acknowledge an anonymous referee for highlighting this.

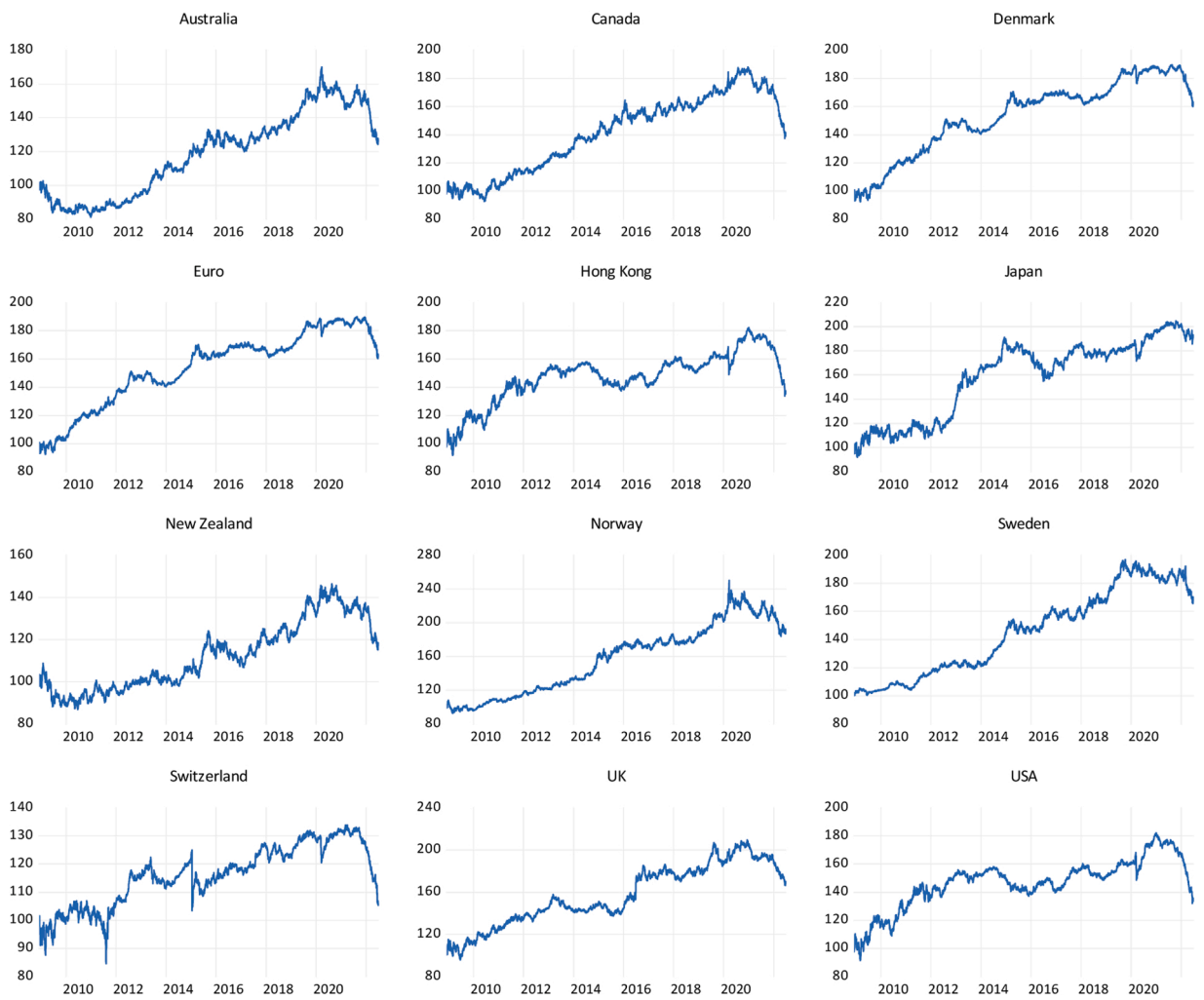


Fig. A-1. Time series of Green Bond prices. Notes: This figure shows the time-varying green bond prices.

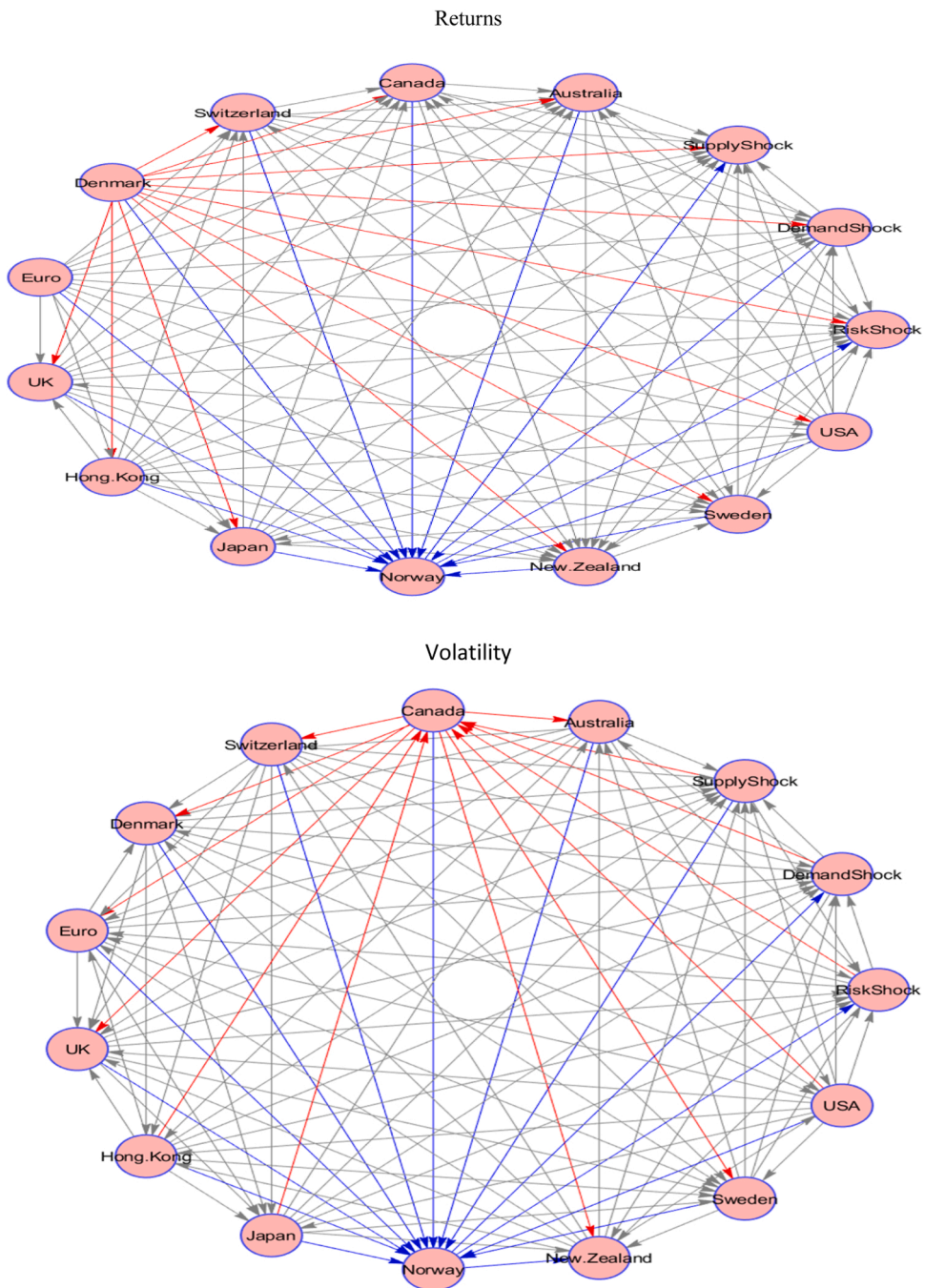


Fig. A-2. : Pairwise connectedness of green bond returns and volatility and oil price shocks during the global financial crisis.

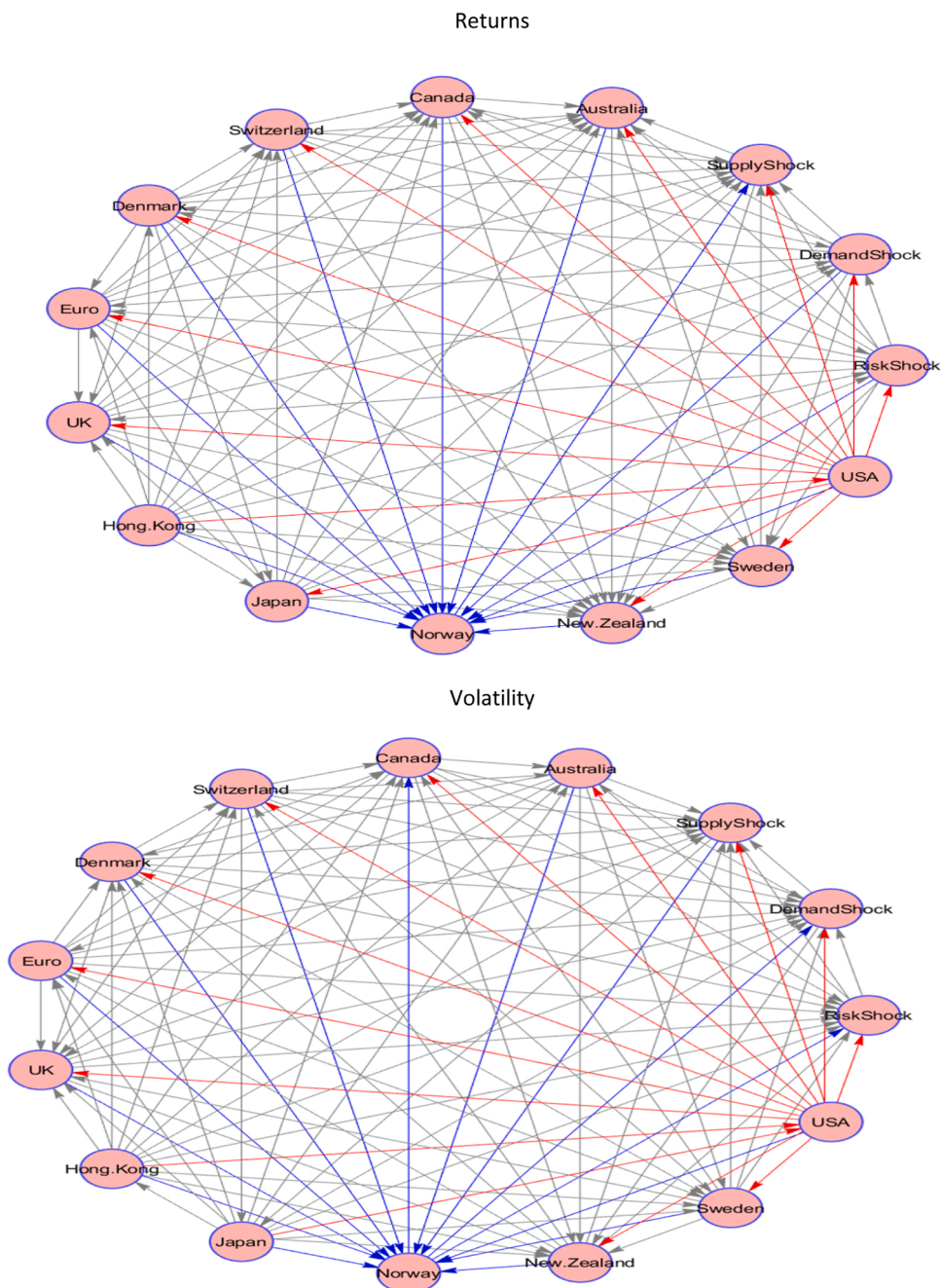


Fig. A-3. Pairwise connectedness of green bond returns and volatility and oil price shocks during European sovereign debt crisis.

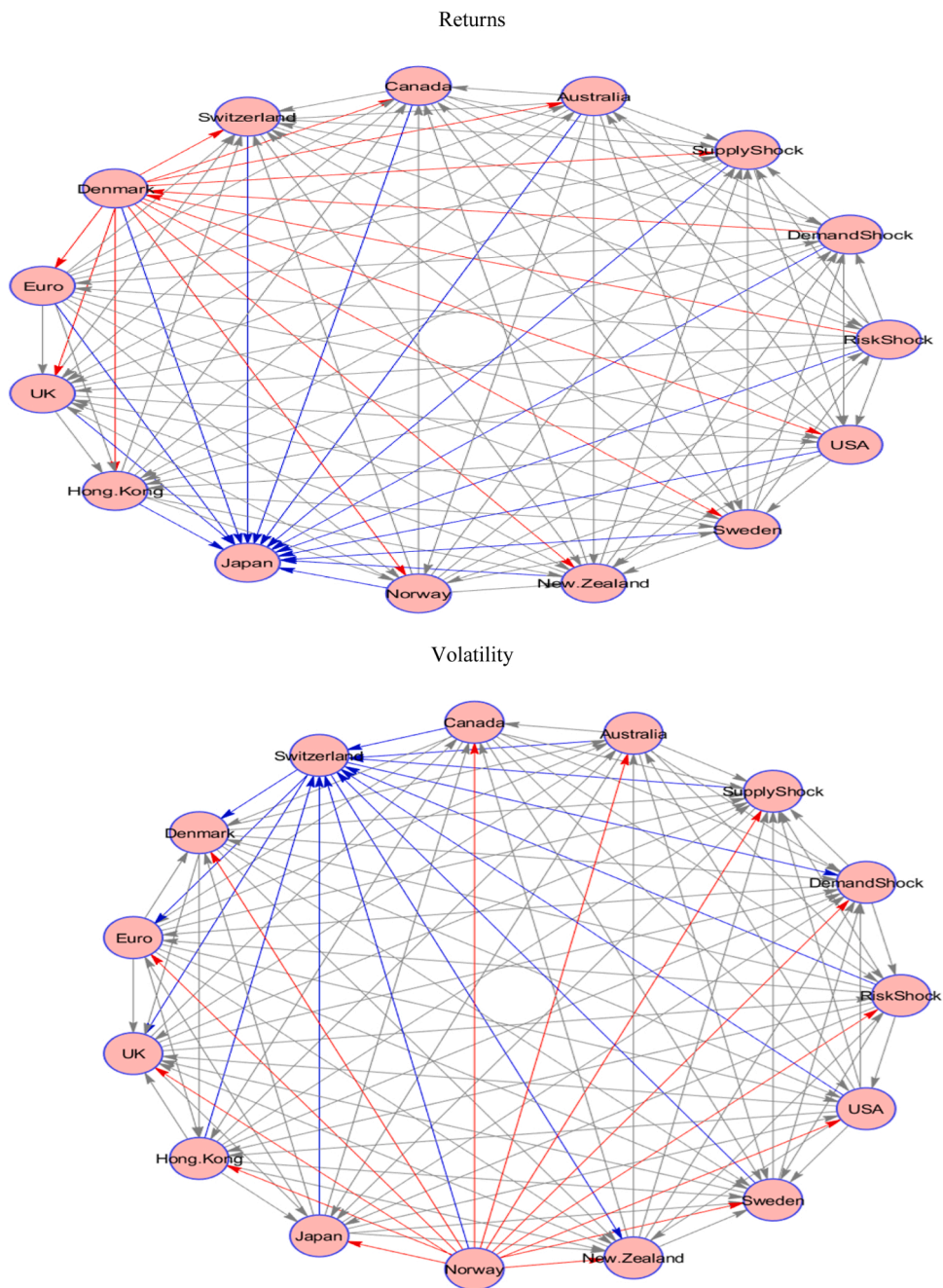


Fig. A-4. : Pairwise connectedness of green bond returns and volatility and oil price shocks during the COVID-19 pandemic.

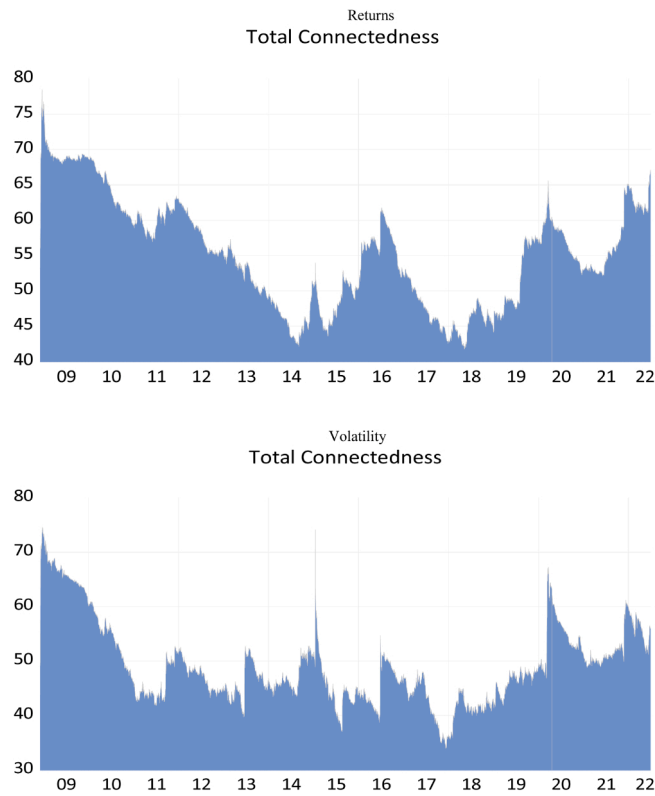


Fig. A-5. : Time-Varying total connectedness in returns and volatility of green bonds and oil price shocks using the TVP-VAR approach of Antonakakis et al. (2023). Notes: This figure shows the total connectedness of the returns and volatility of green bond markets and oil price shocks over the sample period.

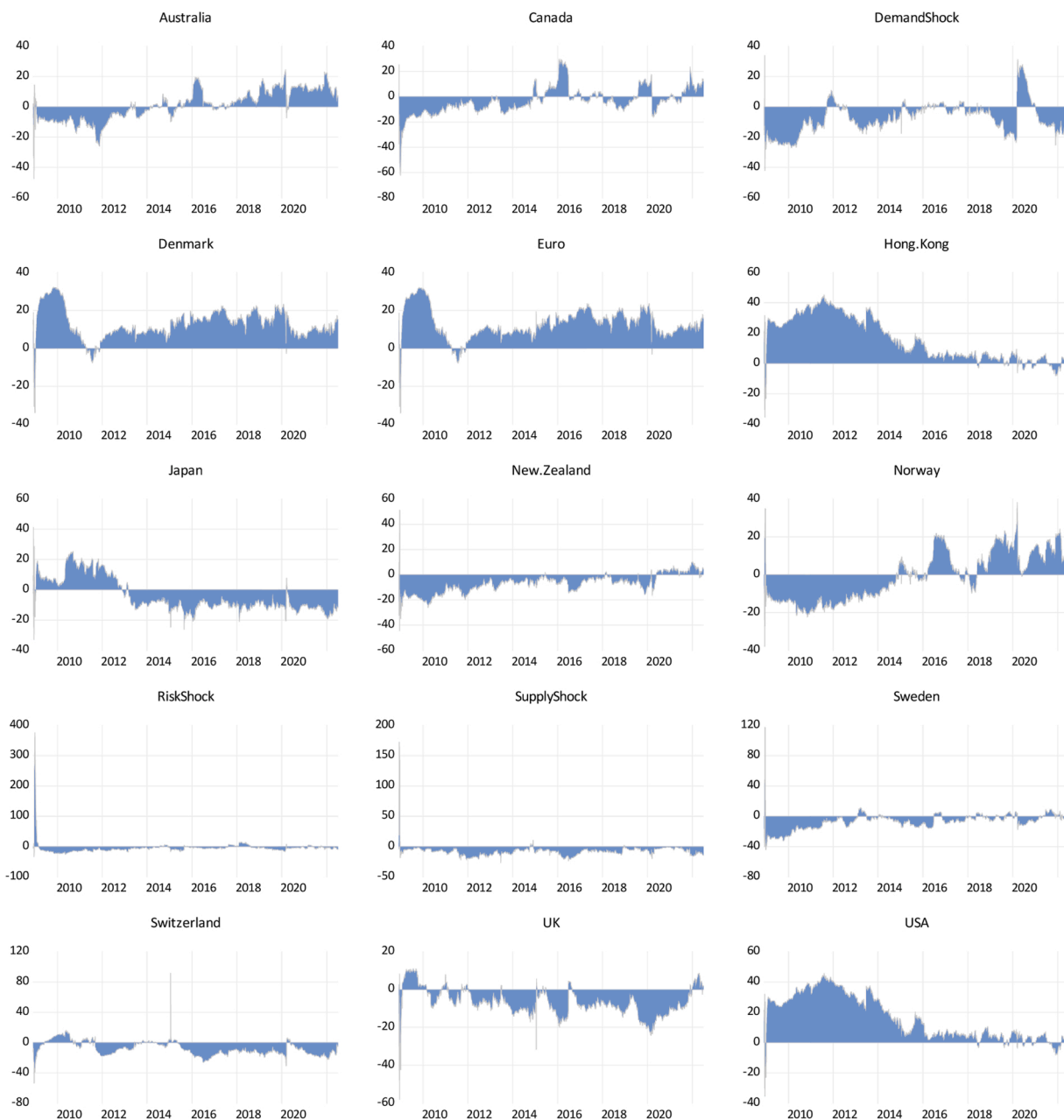


Fig. A-6. : Net directional connectedness – returns using the TVP-VAR approach of Antonakakis et al. (2023). Notes: This figure shows the net directional connectedness of returns of green bond markets and oil price shocks over the sample period.

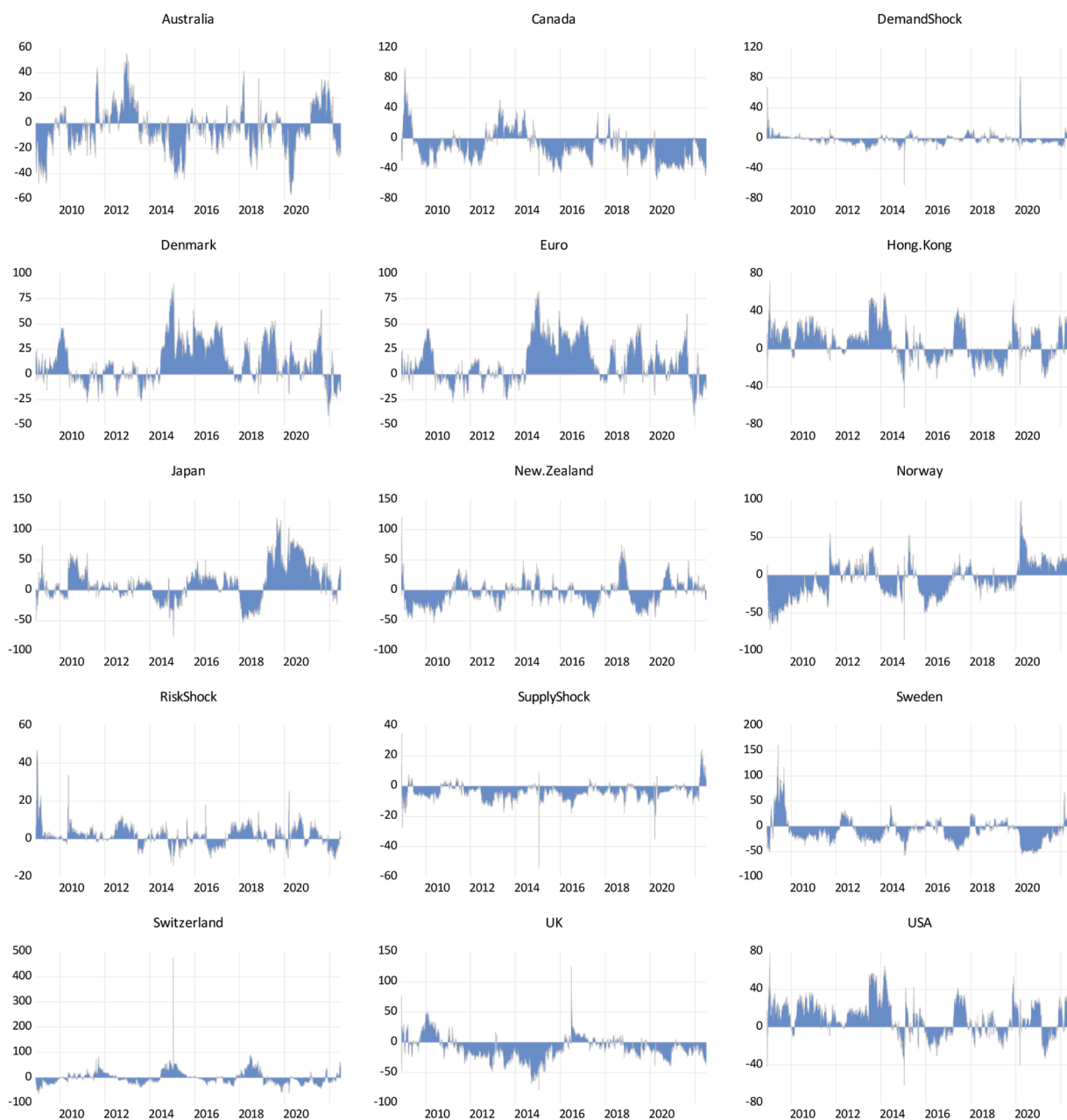


Fig. A-7. : Net directional connectedness – volatility using the TVP-VAR approach of Antonakakis et al. (2023). Notes: This figure shows the net directional connectedness of volatilities of green bond and oil price shocks over the sample period.

Table A-1
Summary of literature review on return and spillover connectedness studies.

Authors	Research Question	Methods	Findings
Arnell et al. (2023)	To investigate the interaction of technology subsector stocks with financial assets given economic and financial uncertainty.	Dynamic conditional correlation	Structural breaks have diverse effects on financial asset connectedness

(continued on next page)

Table A-1 (continued)

Authors	Research Question	Methods	Findings
Choi et al. (2021)	To identify the dynamic volatility spillovers and connectedness network across 11 Australian Securities Exchange.	Diebold and Yilmaz (2014) approach	Support the contagion hypothesis in the wake of the recent financial crises.
Mensi et al. (2021a)	investigates the frequency dynamics of volatility spillovers among oil and equities in the US, Europe and Asia	Diebold and Yilmaz (2012); Baruník and Křehlík (2018)	Spillovers exhibit time varying with increase in intensity during crisis and in short term.
Mensi et al. (2021b)	Examines the connectedness among 28 commodity futures markets covering precious metals, industrial metals, energy, agriculture, and livestock	Baruník and Křehlík (2018) and wavelet method.	total spillover is greater in the short term.
Mensi et al. (2021c)	Investigates the connectedness between oil and European fixed income securities	Diebold and Yilmaz (, 2012, 2014)	spillovers between oil and bonds are dynamical and excessive with magnitude of risk transmission relatively lesser during pre-crisis and economic recovery phases.
Mensi et al. (2021d)	Investigates the volatility spillover between precious metals, oil, and ASEAN equities	Quantile cross-spectral approach and DECO-FIAPARCH model.	Commodities such as precious metals and oil offer better hedging effectiveness during periods of crises.
Mensi et al. (2022b)	investigates the time-frequency connectedness between U.S. sectoral equities, oil and gold.	Diebold and Yilmaz (2012) and Baruník and Křehlík (2018)	short-term spillovers are greater than the long-term with heterogenous effects.
Mensi et al. (2022c)	Study the spillovers and portfolio dynamics of oil and US sectoral Islamic equities	Baba-Engle-Kraft-Kroner (BEKK)-GARCH model and Baruník and Křehlík (2018)	significant time-varying spillovers between oil and Islamic equities with short term connectedness more pronounced.
Mensi et al. (2023)	Investigate the diversification and safe hedge dynamics in time-frequency between gold, palladium, platinum, and silver, oil, US equities, Treasury Bond, and the US dollar	Baruník and Křehlík's (2018)	US dollar and metals exhibit hedge in short and long term. Oil and bonds are not a safe haven for US equities.
Mensi et al. (2023a)	Investigate the quantile return spillover between oil and Chinese sectoral equities.	Ando et al. (2022)	Spillovers are more pronounced during bearish markets than bullish markets.
Mensi et al. (2023b)	Investigates the return and volatility spillovers in frequency domain along with the hedging capacity for Green Bonds, gold, silver, oil, the US dollar.	Diebold and Yilmaz (2014) Baruník and Křehlík (2018) Quantile-on-Quantile regression	short-term volatility spillovers stand out relative to long-term with different spillover dynamics for various asset classes.
Raham (2021)	Investigate the quantile dependence between Islamic and non-Islamic stocks	the cross-quantilogram approach.	Document independence between Islamic and non-Islamic stocks markets during normal and bullish states and dependent during bearish states.
Mensi et al. (2023c)	Investigates connectedness between oil and the African stock markets various market conditions.	Ando et al. (2022)	Spillover intensifies during bearish market condition relative to normal and bullish market conditions.
Mensi et al. (2022d)	Investigates connectedness between oil and Vietnamese stocks various market conditions.	Ando et al. (2022)	Spillover intensifies during bearish market condition relative to normal and bullish market conditions.
Rehman et al. (2023)	study the impact of oil shocks on equity returns.	Baruník and Křehlík (2019); Ando et al. (2022)	Oil demand shocks show stark coherence relative to supply and risk shocks in the short-term.
Rehman et al. (2023a)	study the static and dynamic connectedness between Chinese equities and commodities.	Ando et al. (2022)	Steel and gold are net receivers of spillover. Zinc and copper are net transmitter of spillover.

Table A-2

Correlation between green bond returns and oil price shocks.

	Australia	Canada	Demand shock	Denmark	Euro	Hongkong	Japan	New Zealand	Norway	Risk shock	Supply shock	Sweden	Switzerland	UK
Canada	0.58													
Demand shock	-0.20	-0.09												
Denmark	0.20	0.28	0.12											
Euro	0.20	0.28	0.12	1.00										
Hongkong	0.24	0.53	0.37	0.38	0.38									
Japan	0.10	0.24	0.38	0.36	0.36	0.61								
New Zealand	0.72	0.46	-0.14	0.18	0.18	0.18	0.12							
Norway	0.41	0.34	-0.30	0.36	0.36	0.05	-0.01	0.34						
Risks hock	0.16	0.09	0.00	-0.06	-0.06	-0.11	-0.26	0.12	0.20					
Supply shock	-0.01	-0.11	0.00	0.00	-0.01	-0.08	-0.05	0.00	-0.07	0.00				
Sweden	0.20	0.12	-0.20	0.29	0.29	-0.11	-0.16	0.13	0.50	0.16	0.00			
Switzerland	0.14	0.23	0.17	0.55	0.55	0.39	0.46	0.15	0.17	-0.15	-0.02	0.05		
UK	0.37	0.45	0.03	0.43	0.43	0.46	0.28	0.33	0.29	0.03	-0.02	0.14	0.30	
USA	0.23	0.53	0.38	0.38	0.38	1.00	0.62	0.17	0.04	-0.12	-0.08	-0.12	0.39	0.45

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