Environmental and Managerial Impacts of Crude Oil Volatility on QUAD Financial Markets: Insights into Dynamic Connectedness

Abstract

The QUAD nations' (United States, India, Japan, and Australia) financial markets are deeply integrated with global markets. The burgeoning surge of risk in global markets requires caution, which can be possible by determining the connectedness. This study elucidates the dynamic connectedness between crude oil and the financial markets of QUAD nations, aiming to enhance understanding of its environmental and managerial implications.This study uses Diebold & Yilmaz (2012) model for the empirical investigation. After investigation, the connectedness, portfolio weight, and hedge ratio are determined to know the hedge ratio. It is found that the Japanese market and crude oil emerge as the least transmitter and least receiver of the shock, respectively. Additionally, the result reveals that hedging is most expensive in the US market while cheapest in the Australian market. This study contributes to understanding the influence of energy market fluctuations on financial markets amidst recent global crises, such as the COVID-19 pandemic and the Russia-Ukraine conflict, with implications for both environmental and economic resilience.

Keywords: Crude Oil; QUAD; Portfolio hedge ratio; Environmental management; Dynamic connectedness; Portfolio diversification

Table 1: List of Acronyms

Abbreviation	Meaning
GFC	Global Financial Crisis
QUAD	Quadrilateral Security Dialogue
BMCMC	Bayesian Markov Chain Monte Carlo
TVP-VAR	Time-varying parameter vector autoregression
CCC	Constant conditional correlation
BEKK	Baba, Engle, Kraft, and Kroner
DCC	Dynamic Conditional Correlation
GARCH	Generalized autoregressive conditionally heteroskedasticity
VAR	Vector autoregression
JB	Jarque-Bera
ADF	Augmented Dickey-Fuller
TCI	Total connectedness index
NFTs	Non-fungible tokens
DeFi	Decentralized finance
RVP	R Studio Vine Copula
HARRV	Heterogeneous Autoregressive Realized Volatility
QQR	Quantile-on-Quantile Regression model
ARMA	Autoregressive-moving average
TGARCH	Threshold generalized autoregressive conditional heteroscedasticity
WC	Wavelet coherence

DY	DYilmaz (2012)
BK	Barunik and Krehlik (2018)
CRO	CRO
ASE	Australian Securities Exchange
AUS	Australia
IND	India
JAP	Japan
USA	United States/America
SEN	Sensex
N225	Nikkei 225
NAS	NASDAQ

Source: Author

1. Introduction

Over the past two decades, global financial markets have faced numerous challenges, including the 2008 GFC, the 2011 Greek sovereign debt crisis, and, more recently, the disruptions triggered by the COVID-19 pandemic and the ongoing Russia-Ukraine conflict. These crises have exacerbated volatility across markets, particularly within sectors closely tied to energy, such as crude oil. Given growing concerns about environmental sustainability and the global energy transition, understanding the interplay between energy markets and financial systems has become increasingly important.

The QUAD nations comprising the USA, Japan, India, and Australia have garnered significant attention in recent years due to their strategic importance in the Indo-Pacific region. Beyond their geopolitical relevance, these nations play pivotal roles in the global economic and financial systems. Moreover, the global association between environmental deterioration, geopolitical risk, crude oil prices, and green bonds was studied based upon "the world is our home" idea (Mustafa et, al., 2024). Their financial markets are intricately linked to global trade, investments, and energy markets, with crude oil serving as a critical factor in these connections. Considering recent global events, including the COVID-19 pandemic and the Russia-Ukraine conflict, the interplay between energy market volatility and financial stability has gained renewed importance. Understanding how crude oil operates as either a transmitter or receiver of shocks within these interconnected economies can offer valuable insights for policymakers and market participants, particularly regarding risk management, portfolio diversification, and sustainability efforts. Furthermore, how foreign portfolio movements and monetary policy reactions influenced Turkey's stock market, particularly during the COVID-19 epidemic. Using nonlinear econometric models, this study examines how pandemic-induced uncertainty affects stock market performance in emerging economies (Mustafa Tevfik Kartal, 2022).

The QUAD nations' financial markets are deeply integrated with global markets. Changes in one market can influence others due to trade linkages, investments, and other economic ties. Understanding the effect of crude oil volatility on various financial markets is crucial for investors, regulators, and economists (Pant, 2022). It may shed light on the extent to which crude oil acts as a transmitter or receiver of volatility within this group of countries. In addition, the degree of connectedness between events like the COVID-19 outbreak and the Russia-Ukraine invasion differs, which underscores the need to explore the connectedness among these markets for diversification opportunities.

The financial markets of the QUAD nations are highly interconnected, and volatility in one region can quickly spread to others due to this global integration. The long-term effects of events such as the COVID-19 pandemic and the Russia-Ukraine war are critical for predicting trends in crude oil and equity markets, which have experienced substantial short-term fluctuations in prices. According to contagion theory, the impact of one event or incident in a country can spread its effects to another economy (Peckham, 2013; Prorokowski, 2013; Balakrishnan et al., 2011). This phenomenon heightens the relevance of exploring connectedness and diversification strategies in times of global uncertainty. Globalisation has increased financial market interconnectivity, offering advantages such as the movement of capital from surplus-saving nations to those in deficit, thereby promoting economic growth (Matsumoto, 2022; Nguyen, 2022; Bernanke et al., 2011). However, it has also introduced challenges, particularly in terms of financial market integration. Markets often move in lockstep, with volatility spreading rapidly from one region to another. This has shifted discussions around financial and economic stability to the forefront, especially in light of current global crises (Bordo et al., 2016; Sánchez et al., 2023).

This study focuses on the QUAD countries, an informal strategic alliance between the USA, JAP, IND, and AUS, whose growing influence in the Indo-Pacific region has drawn increased attention. Formed in 2004 following the Indian Ocean Tsunami to coordinate humanitarian and disaster relief efforts, the QUAD was reinvigorated in the late 2010s as concerns about China's expanding influence in the Indo-Pacific intensified. By 2021, the QUAD held its first leaders' summit, with heads of state from all four nations discussing regional security and cooperation (Pant, 2022). Given the heightened uncertainty during these crises, it is essential to explore these volatility patterns and their implications for financial stability.

The focus on the QUAD nations is significant for several reasons. First, the QUAD occupies an increasingly strategic role in the Indo-Pacific region, with broad implications for global market dynamics. Second, these nations have been profoundly impacted by recent crises, such as the COVID-19 pandemic, which led to stringent lockdowns in the USA, JAP, AUS, and IND. Against this backdrop, the following research questions guide this study:

(i) Is there dynamic connectedness between the crude oil and financial markets of the QUAD nations?
(ii) Which market(s) serve(s) as net transmitter(s) or receiver(s) of shocks in this network?
(iii) Which market offers the most cost-effective or expensive hedging opportunities?

Building on previous studies, this paper seeks to expand the existing literature by focusing on equity stock markets within the QUAD nations and their relationship with the crude oil market. This study contributes to existing research threefold. First, it is one of the few studies focusing on the dynamic connectedness between crude oil and financial markets in the QUAD nations. Second, it covers the COVID-19 pandemic and the Russia-Ukraine invasion periods, offering a comprehensive look at market behaviour under extreme conditions. Third, advanced econometric models, including those proposed by Diebold & Yilmaz (2012) and Barunik & Krehlik (2018), are employed to calculate hedge ratios and assess volatility spillover, enhancing the study's relevance for both academia and industry. This paper examines the crude oil market and stock exchanges in Australia (Australian Securities Exchange), India (Sensex), Japan (Nikkei 225), and the US (NASDAQ), using daily observations from 31 December 2019 to 16 January 2023. Results show that the crude oil market and the US equity market act as net transmitters, while the Indian, Japanese, and Australian markets serve as net receivers. The findings offer practical insights for investors, portfolio managers, and policymakers seeking to understand and manage risk amid energy market volatility.

The remainder of this manuscript is organized as follows: Section 2 comprises an extensive literature review covering volatility, energy markets, and portfolio diversification. Section 3 presents the data and preliminary analysis, outlining the econometric models to be applied. Section 4 provides empirical analysis and discussion, while Section 5 concludes the paper, offering policy implications and suggesting avenues for future research.

2. Review of Literature

In recognition of the large prospective advantages, research involving the diversification of portfolios with developed and emerging nations are currently gaining traction. For instance, Markellos & Siriopoulos (1997) predicted investors who spread their chances throughout European economies that are developing would make bigger profits compared to those with undiversified portfolios. Likewise, Dunis & Shannon, (2005) investigated the equities markets of Central Asia and Southeast Asia and discovered that both sectors provided investors from the United States with foreign diversification advantages. Liu & Tu, (2012), by using the BMCMC approach provided that during stable (instead of a time of crisis) circumstances, jump spillovers dramatically limit the geographic diversification advantages associated with an energy derivatives portfolio.

Globalization and advancements in the economy have pushed commodities and derivatives related to energy to the forefront, particularly in first-world nations. Furthermore, energy-related commodities are crucial to economic development but also give investors and portfolio managers with investment and diversifying options. Diverse classes of assets have the potential to come with cross-market implications, allowing players in the market to employ various hedging methods. Cross-market information spillover was classified by Kavussanos et al., (2014) in three different groups, for instance, information transmission within distinct assets driven by demand and supply dynamics, information transmission of spot with derivatives market, and information transmission among derivatives markets. While exploring the dynamic linkages between energy and stock markets, Jebabli et al., (2014) employ TVP-VAR model and find that during a period of crisis, volatility spillovers grow significantly, particularly after the second half of 2008 when the stock markets turned to be a net transmitter of shocks to volatility along with crude oil becoming a net recipient. In addition, adding crude oil or equities to a diverse portfolio of food-related commodities substantially boosts overall risk-adjusted return. According to D'Ecclesia et al., (2014), the influence of "hedging pressure" impacts not only fast-changing short-term deviations, but it also impacts the fundamental equilibrium of the oil price over the long term.

Bouri et al. (2023) found that as the moment order increases, system-wide connectivity declines and the magnitude of the spillover in all suggested moments is substantially larger at lower frequencies. In addition, they found that the precious metal and gold are net transmitters. But during COVID-19 pandemic, crude oil and gold perform significant roles in the diversification opportunities. Furthermore, Tripathy, (2023) used statistical tools CCC-GARCH, BEKK-GARCH and DCC models to calculate appropriate weights and hedging percentages for oil-bullion portfolio investments. It revealed that the gold price is susceptible to variations in oil prices. As a result, changes in gold prices may be a reliable indicator of oil returns in India. According to the calculated hedging ratio, gold is a useful hedge against variations in the Indian oil price. However, Ozer et al. (2021), studied the effects of monetary policy measures on gold prices in Turkey to characterize gold market reactions to the COVID-19 epidemic.

The swiftly growing popularity of commodity index investing exerts an unintended but considerable influence on futures markets, especially agricultural commodity, and crude oil markets. Much research has been undertaken on the dynamic linkage of the energy market with agricultural commodities (Du et al., 2011; Balli et al., 2019; Pal & Mitra, 2020; Hung, 2021; Tiwari et al., 2022; Jiang et al., 2022 Babar et al., 2023; Khalfaoui et al., 2023). For instance, Tiwari et al., (2022) strong volatility spillovers from agriculture markets to energy markets present under exceptional market situations, as well as agricultural markets' influence on the energy markets. Khalfaoui et al. (2023) reveal that the connectedness of the oil market with the agricultural market is less in both the short and long run. At extreme positive as well as negative values, energy and fertilizers exhibit great coherency. Wei et al. (2023) proved that soybean and maize are among the most significant data transmitters in the temporal domain when compared with alternative futures. they also discovered that carbon futures enhance the hedging performance of agricultural and oil portfolios. Further, Kartal et al., (2024) and Guliyev (2024) examined spillover of various stocks related to ESG globally. Besides that, volatility has the greatest impact on oil prices in both the pre-pandemic and pandemic periods and the impacts of other components differ depending on whether Turkey is in a pandemic or not. The results showed that Turkey should concentrate on reducing the negative impacts of CDSS and USD/TRY on oil prices, which happen to be mostly or partially under its control (Kartal, 2021).
The tabular representation of the literature is presented in Table 2.

Table 2: Literature Review

Author (Year)	Data	Methodology	Findings
Meng, S.; Chen, Y (2023)	2007-2022	RVP	Direction of risk spillovers separated into its input and output sides.

Akihiro et al. (2023)	2011-2022	HARRV	Intrinsic worth of Bitcoin from a cost perspective, indicating that the energy used in mining Bitcoin has an impact on the mining cost of Bitcoin.
Yimin Wu et al. (2023)	2018-2022.	DCC	No market risk was imposed by Shanghai CRO futures on energy stock indices.
Hau, L. et al. (2023)	2008-2018.	QQR	Investors in financial markets may optimise asset allocation and risk management based on the dynamic connectedness of commodity stocks related to energy markets.
Wang, G.; Meng, J.; Mo, B (2023)	2008-2022	DCC	International investors may be able to lower investment risk without sacrificing earnings by implementing a diversification plan that includes equities and commodity assets.
Varsha Ingalhalli and Prachi Kolamker (2023)	2010-2022	BEKK	Diversification options are becoming more limited as different financial assets become more intertwined.
Jiliang S., et al. (2013)	2009-2021	ARMA TGARCH	Investors may create and change their portfolios to anticipate and reduce tail risks.
Jena, S. K., et a. (2021)	2005-2017	DY and BK	Time-varying evolution of the volatility spillover facilitated both in time and various frequencies.
Sahabuddin, M., et al. (2022)	2007-2018	WC	GFC and European debt crisis both had a substantial impact on stock markets in industrialised countries.

Source: Author's own

To sum up, an array of studies has explored the dynamic linkages among diverse markets, revealing a spectrum of evidence of spillover effects. Nevertheless, there exists a noticeable gap in the literature concerning the dynamic connectedness between crude oil (CRO) and the financial markets of QUAD nations. In addition, it is a desideratum to ameliorate the environmental impact since the dynamics of crude oil connectedness with financial markets of QUAD may furnish an insightful managerial implication. This serves as a compelling motivation for us to embark on the current study, seeking to contribute valuable insights to this underexplored facet of financial market interdependence.

3. Methods

3.1 Data description

The dynamic connectedness among crude oil (CRO) and stock exchanges of QUAD countries has been examined using the daily observation of CRO prices and historical prices of QUAD stock exchanges. The ASE, SEN, N225 and NAS are considered for AUS, IND, JAP, and the US markets respectively. For the investigation, the data ranges from December 31, 2019 to January 16, 2023 which covers both COVID-19 and Russia Ukraine invasion (Malhotra, G. et al., 2023; Goodell et al., 2022). The log return has been obtained using the following formula:

$$R_{it}=LN(P_t/P_{t-1}) \tag{1}$$

where R_{it} = Daily return on the respective index
LN = Natural Log
P_t = Price at t day
P_{t-1} = Price at t-1 day

Table 3: Variables of the Study

Variable Input	Proxy Variable	Data Range	Source
CRO	CRO	2019-2023	Bloomberg
Australia (AUS)	ASE		
India (IND)	SEN		
Japan (JAP)	N225		
USA (US)	NAS		

Source: Author's creation

3.2 Econometric Models

To analyze the dynamic connectedness among examined markets, Diebold-Yilmaz (2012) is deployed which determines the average connectedness (Yadav et al., 2022a; Yadav et al., 2023; Goodell 2022). In addition, the Kroner and Sultan (1993) and Kroner and Ng (1998) are used to determine the hedge ratio and portfolio weight respectively. Following is the elaboration of these two models:

3.2.1 Diebold-Yilmaz (2012) Model

This model analyzes the average connectedness/linkage among various asset classes. It is based on the dynamic forecast error variance decomposition within the VAR model (Yadav et al, 2022b; Yadav et al., 2023b). The major benefit of this model is that it furnishes spillover in the form of the "transmission" and "receipt" of the shock. "TO" indicates the transmission of shock from one asset to another while "FROM" The goal of this model is to examine the spillover contributions of "TO" and "FROM" infers the receipt of the shock from examined markets. (Rajwani, S., et al, 2023: Yadav et al., 2023c). In addition, this model also helps to know the net connectedness differentiating the receipt of shock from transmitted shock. In this model, $t=1,\ldots T$, structured VAR(p) with n-variate method $X_{t,1}$, ...$X_{t,n}$ are depicted as below:

$$\Upsilon(L)x_t = \varepsilon_t \tag{2}$$

Where, $\Upsilon(L) = \sum_h \Upsilon_h L^h$denotes a nxm coefficient matrix t by means of an infinity-length. As per this model, the quantum of connectedness is a sort of the combined elements which is depicted in the off-diagonal total matrix appended below:

$$C_H = \frac{\sum_{j\neq k}(\bar{\theta}_H)_{j,k}}{\sum(\bar{\theta}_H)_{j,k}} \text{X } 100 = \left(1 - \frac{Tr\,\{\bar{\theta}_H\}}{\sum(\bar{\theta}_H)_{j,k}}\right) 100 \quad (3)$$

In equation 3, CH stands for overall spillover of examined markets and Tr{} is the trace operator. Further, the transmitted shock and recipient of the shock among markets are appended in equation 4 and 5 respectively:

$$(C_H)_{j\to} = 100 \times \frac{1}{n}\sum_{j\neq k,k}(\bar{\theta}_H)_{j,k} \quad (4)$$

$$(C_H)_{j\leftarrow} = 100 \times \frac{1}{n}\sum_{j\neq k,k}(\bar{\theta}_H)_{j,k} \quad (5)$$

Where $(C_H)_{j\to}$ denotes the transmitted of shock or spillover contributed to the markets while $(C_H)_{j\leftarrow}$infers the recipient of the shock which is also known as "FROM spillover".

Next, net connectedness/spillover is computed following equation 6 appended below:

$$(C_H)_{j,net} = (C_H)_{j\to} - (C_H)_{j\leftarrow} \quad (6)$$

If $(C_H)_{j,net}$ is positive, it indicates the net transmitter of the shock whereas negative $(C_H)_{j,net}$ denotes the net receiver of the shock from examined markets.

3.2.2 Hedge Ratio and Portfolio Weights

After investigating the average connectedness among the examined markets, the optimal hedging ratio and the optimal portfolio weights are computed to check the most efficient diversification strategy. For the same, a minimum variance ratio is considered as one of the suitable strategies (Yadav et al., 2024). To be explicit, these models use conditional variance and covariance before computing the hedging ratios and portfolio weights.

According to Kroner and Sultan (1993), the methodological approach can be used to calculate the assets' risk-minimizing hedge ratios at time t without comprising the expected return. The hedge ratio is using eq. (7):

$$\beta ij,t=h_{ij,t}/h_{jj} \quad (7)$$

Kroner and Ng (1998) recommended using the conditional covariance between *I* and *j* at time i (hij,t), the conditional variance of *j* (hjj,t), and the optimal hedge ratio (ij,t) to determine the best portfolio weights between *I* and I.

be calculated by:

$$w_{ij,t} = \frac{h_{jj,t}-h_{ij,t}}{h_{ii,t}-2h_{ij.t}+h_{jj.t}} \qquad (8)$$

Where, $w_{ij,t}$ denotes the weight of i in one unit portfolio of two variables i and j at time t; meanwhile, the weight of variable j in the portfolio at time t is $(1 - w_{ij,t})$.

4. Empirical Analysis

This section contains descriptive statistics, empirical results of econometric models, and robust testing.

4.1 Descriptive Statistics and Preliminary Analysis

As regards table 4, it encapsulates the descriptive statistics of CRO and stock exchanges of QUAD economy namely AUS, IND, JAP, and the US. As regards this table, the difference between the lowest and largest returns indicates the range. It is observed that the Australian (AUS) stock market only realised a positive average return (0.022) while the rest of the markets spotted negative average returns; the CRO is witnessed with the largest negative mean return (-0.897). In addition, CRO exhibits the highest daily return volatility since its variance is highest (343.04) followed by the US market (3.51). The Japanese market realizes the least variance (1.85). Considering the distribution pattern, it is seen that CRO and the Australian market exhibit negative skewness, and the remaining markets are spotted with positive skewness. In addition, the kurtosis value of each series is greater than three except Japanese market which infers the return realised from these markets follows non-normality; the same is verified by the JB test since the p-value is significant. Furthermore, the autocorrelation and arch effect are represented by Q(10) and Q2(10). It is observed that there is autocorrelation and arch effect since they have significant values. At the end of this table, the stationarity of each examined market is tested employing ADF test which confirms the stationarity in each series.

Table 4 Descriptive Statistics of CRO and QUAD countries' financial markets

Statistics	CRO	AUS	IND	JAP	USA
Mean	-0.897	0.022	-0.038	-0.011	-0.001
Variance	343.047	2.214	2.156	1.85	3.515
Skewness	-22.890***	-0.034	1.989***	0.022	0.802***
Ex. Kurtosis	573.203***	7.722***	20.582***	2.990***	6.607***
JB	10470836.434***	1888.609***	13915.317***	283.123***	1463.958***
Q (10)	81.024***	74.322***	35.439***	11.607**	67.371***
Q2 (10)	7.375	310.763***	241.064***	253.034***	416.187***

ADF Test	0.000***	0.000***	0.001**	0.000***	0.000***

Source: Author's own presentation, ***, ** and * represent significance level at 0.1%, 1% and 5% respectively

The trend of the raw series and return series are shown in Fig 1 and 2 respectively. It is noticed that each series has a stochastic trend since the change is not constant over time. Therefore, this trend has been removed converting the raw series into log return series by applying log differencing (Khera and Yadav, 2022; Khera et al., 2022; Sharma and Yadav, 2021). In addition, each return series depicts the mean reversal process.

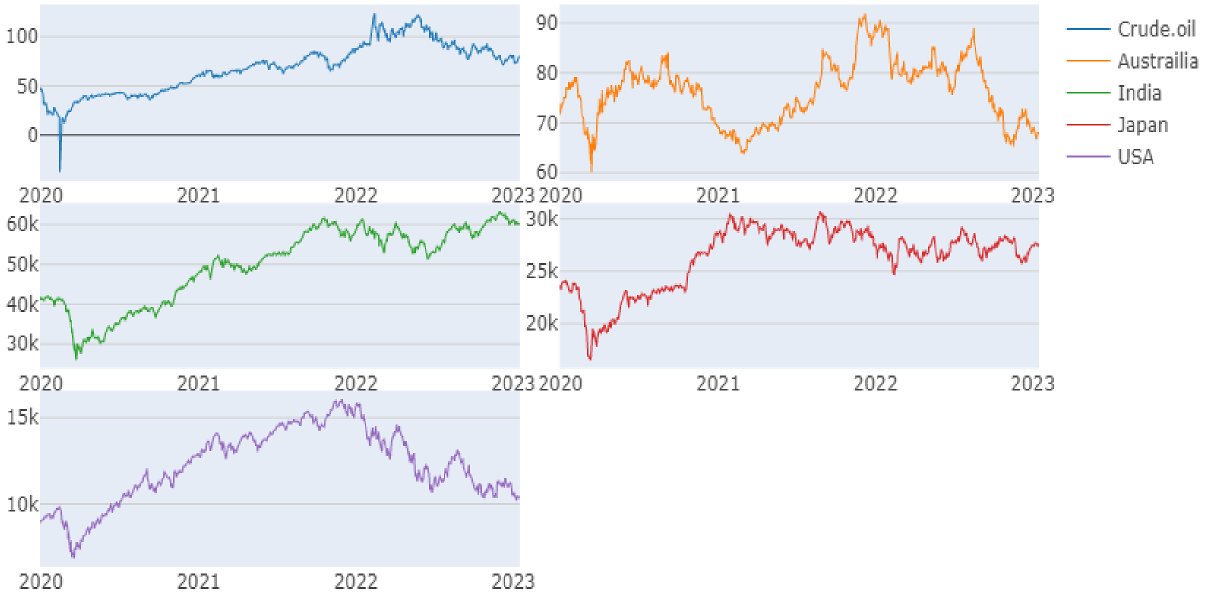

Fig 1: Time series plot of raw series

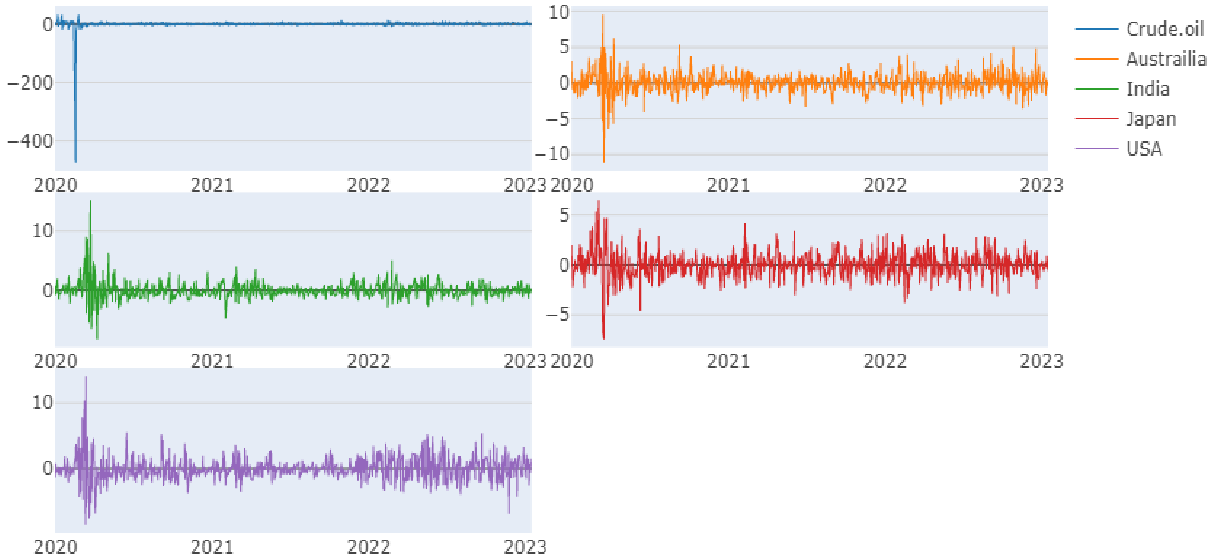

Fig 2: Time series plot of return series

4.2 Results of Diebold-Yilmaz (2012) model

The findings in section 4 present the average connectedness between CRO and the QUAD equity indices, derived from the DY (2018) model. The diagonal of the matrix indicates idiosyncratic shocks, also referred to as own-variable shocks. "FROM" represents the average connectedness as recipients of shocks, and "TO" represents the average connectedness as transmitters of shocks, while "NET" denotes the difference between the contribution to and reception of shocks. In terms of own-variable shocks, the volatility evolution within various markets is largely attributed to internal shocks: 89.85% for CRO, 83.5% for the Australian equity market, 83.19% for the Indian market, 86.88% for the Japanese market, and 82.1% for the US market. Referring to the network connection, it has been observed that the US equity market receives the highest proportion of shocks from the network (18.3%), followed by the Indian equity market (18.08%) and the Australian market (17.66%). In contrast, CRO is the least affected, receiving only 10.51% of shocks. This indicates that CRO is comparatively less influenced by events in the QUAD equity markets, whereas the US equity market is more susceptible to shocks from the other examined markets.

Table 5: Average Connectedness using Diebold-Yilmaz (2012) model

Examined Assets	CRO	AUS	IND	JAP	USA	FROM
CRO	89.85	2.05	3.3	3.22	1.59	10.51
AUS	1.6	83.5	2.7	2.91	9.3	17.66
IND	5.75	1.92	83.19	3.2	5.95	18.08
JAP	7.48	2.4	1.67	86.88	1.58	13.75
USA	5.74	3.1	7.75	1.31	82.1	18.3
TO	21.59	9.92	16.33	11.31	19.15	78.31
NET	11.08	-7.74	-1.75	-2.44	0.85	TCI=15.66

Source: Author's own presentation, TCI refers to total connectedness index and NET represents pair wise directional connectedness

In terms of shock transmission, CRO is the largest transmitter, contributing 21.59% of shocks to the network, followed by the US stock market (19.15%) and the Indian stock market (16.33%). The Japanese stock market, however, transmits the least shocks (11.31%). These results suggest that CRO is the major transmitter of shocks, corroborating the findings of A.K. Tiwari et al. (2022) and Nazlioglu et al. (2013).

Next, NET spillover/connectedness is computed for the markets under examination across the entire system. The market with positive net spillover signifies a net transmitter (overall a contributor) while negative net spillover denotes net receiver (overall receiver). Are result demonstrate that CRO and US equity markets are net transmitters to network connections with

11.08% and 0.85% respectively. On the other hand, Australian, Indian and Japanese stock markets are net receivers with -7.74%, -1.75% and -2.44% respectively. These results imply that CRO is the largest transmitter of shocks to the network connection followed by the US equity market. These results corroborate the findings of A.K. Tiwari et al. (2022). CRO emerges as a market which dominates other markets except the US equity market. Overall, the TCI is 15.66% which implies that CRO and QUAD financial markets are interconnected marginally.

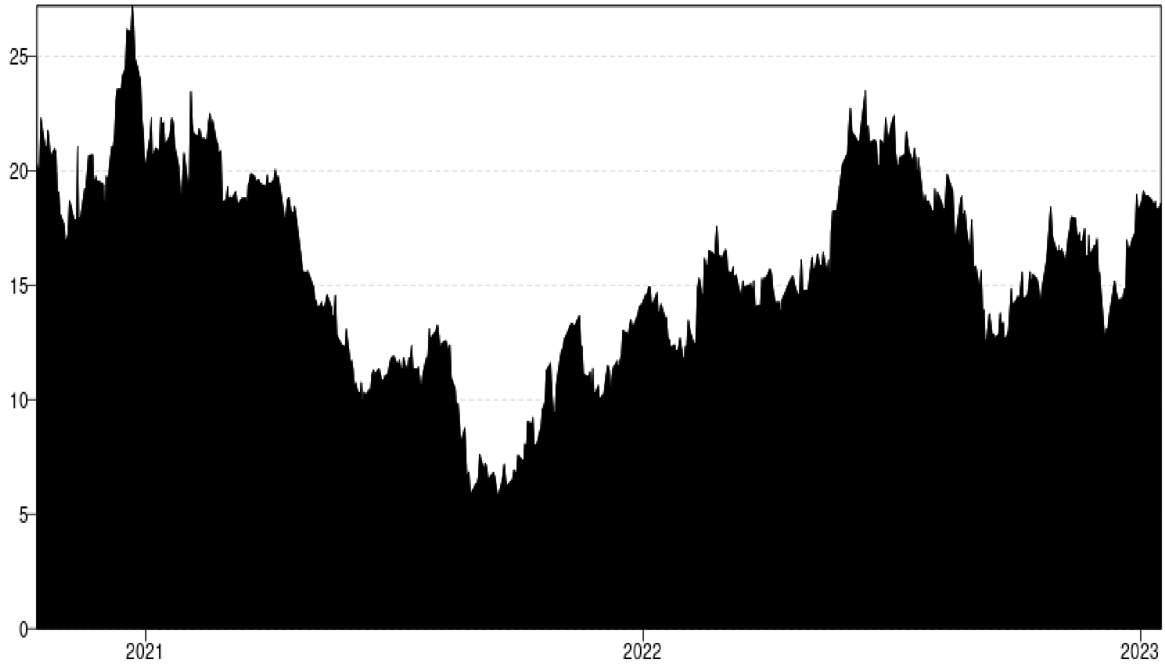

Fig 3: Graphical display of total connectedness

Further, upon a deeper dive of connectedness amongst the market, the figures of total connectedness, transmission and recipient of shocks are displayed in fig 4, 5 and 6 respectively. As displayed in fig 3, the total connectedness ranges from approximately 6% to 30% during the sample period. The highest peak is seen during the end of 2020 and beginning of 2021 with 30% due to COVID-19 outbreak while least connectedness is noticed during September-October 2021. The reason behind highest connectedness might be because of disastrous consequences of COVID-19 outbreak which dented entire globe and pushed the economy on precipice. Further, the spillover decreases gradually and reached the lowest level to 6% during September-October 2021 because of the normalcy in CRO prices and economic activity post COVID-19 but it does not remain constant. After this period, connectedness starts increasing. On February 24, the invasion of Russia takes place over Ukraine which erupts global energy market, commensurately, the connectedness is reached 23% during mid of 2022. However, this spillover dwindles gradually and reaches to 12%. On this note, it can be inferred that the highest connectedness is witnessed during COVID-19 than Russian-Ukraine invasion.

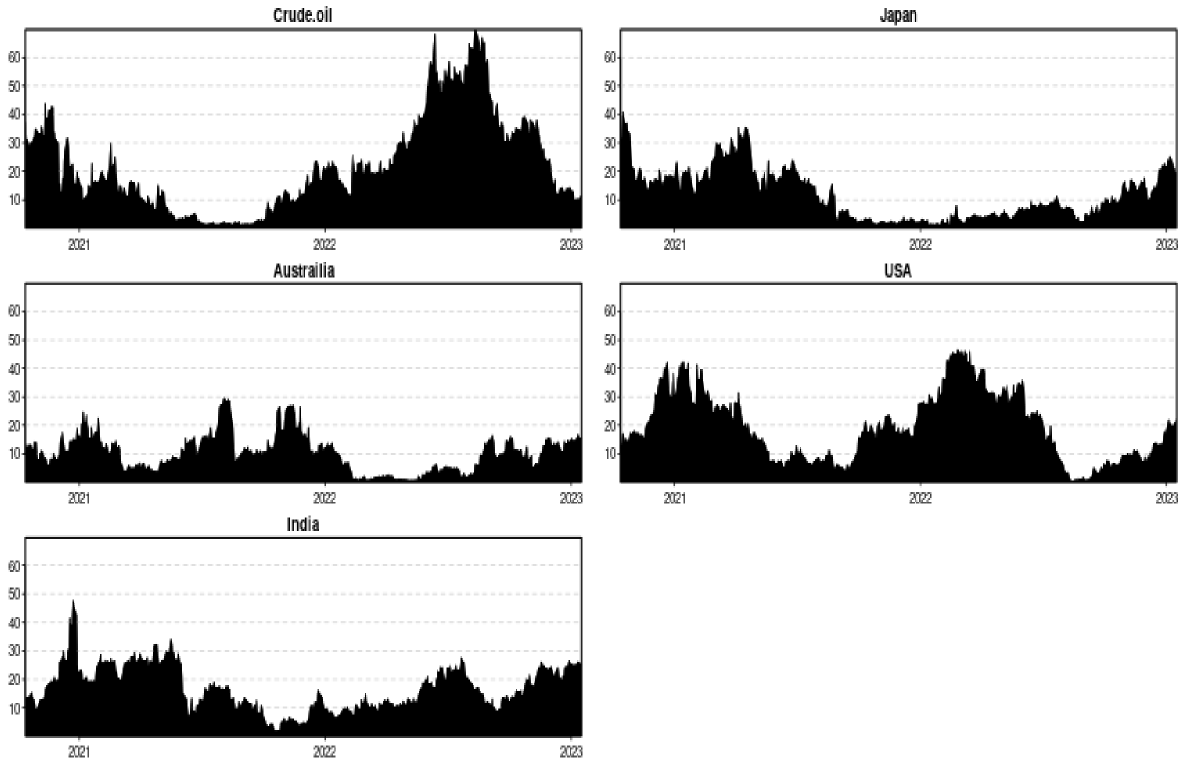

Fig 4: Graphical representation of connectedness to other

In continuation with connectedness graphically, fig 4 comprehends an enigma of contribution to the network connection over examined time period. During 2021, the volatility transmission has been low as compared to 2022 from CRO owing to abnormal and recessionary trends for energy during this period. In addition, CRO is largest transmitter to the network connection with 65% shocks followed by US equity market with approximately 42% of shock. Indian market emerged as third in the row to transmit volatility during the sample period. Australian and Japanese markets have shown lesser transmissions as compared to these three markets to other.

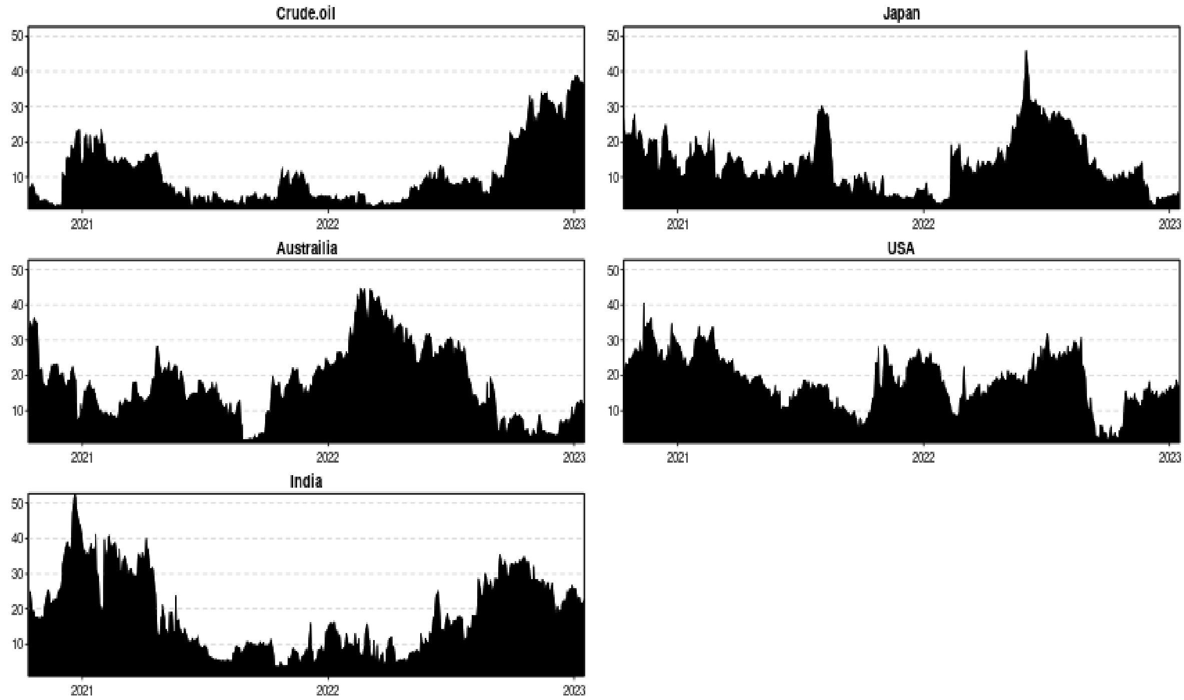

Fig 5: Graphical representation of connectedness from other

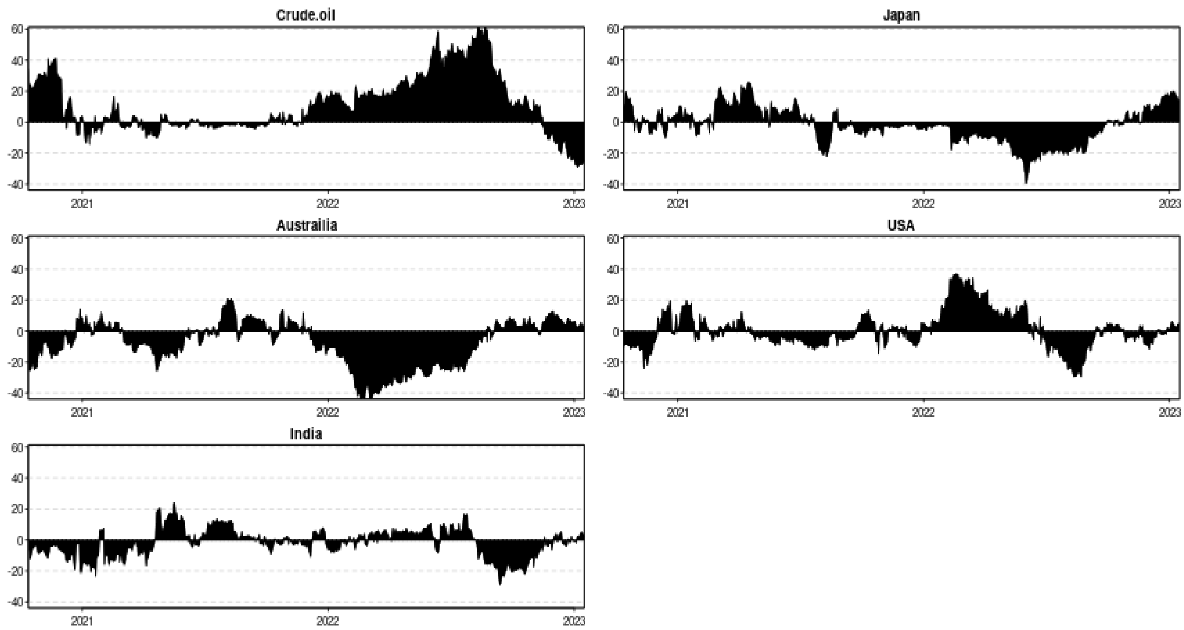

Fig 6: Graphical depiction of Net Spillover

Fig 5 displays the recipient of shocks from the network connection (QUAD equity markets) over the period. Of note is that Indian equity market received the highest shocks (51%) in the beginning of 2021. Gradually, the recipient of shocks decreases over time amongst the market. Turning to 2022, the Japanese market received the highest shock (43%) followed by the Australian equity market (42%), surprisingly, the Indian equity market received the lowest shock levels. Our results suggest that shocks arising in examined markets do not affect Indian equity. However, CRO received larger shocks in 2023 than in 2021 and 2020 comparatively. For better clarity of net connectedness, Fig 6 displays the positive domain value area and signifies that the respective market is a net transmitter whereas the negative region domain shows a net recipient of the shock in the network system. A critical look at these figures represents that no market is witnessed with value on positive domain region throughout the entire period, rather it scatters over the period. To be precise, the examined markets act as transmitters and receivers of the shocks in different periods. The fig illustrates that CRO is a net transmitter of the shocks in 2022, however, it receives the shocks at the end of 2022 and the beginning of 2023. On this note, it can be said that CRO is dominant over the QUAD equity markets except the US equity market which confirms the diversification benefits considering CRO with remaining of the markets.

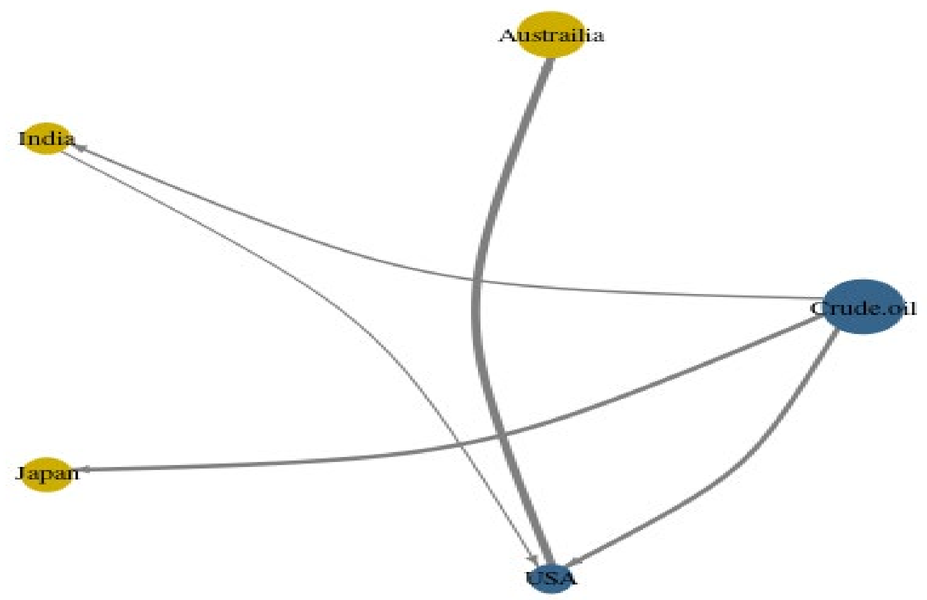

Fig 7: Network Plot

For robustness, a network plot of the net spillover of connectedness of shocks from one market to another has been displayed in fig 7. It is exhibited that markets with dark blue circles signify net transmitter to the network connection while circles with yellow colour signify the net receiver. In alignment with table 4 the result indicates that CRO and the US equity market are net transmitters whilst Indian, Japanese and Australian markets as net receivers.

4.3 Portfolio weight and hedge ratio

After identifying the connectedness among markets, the portfolio hedge ratio and portfolio weight are computed and exhibited in Tables 6 and 7 respectively. The mean average between pairs has been studied assuming that if future volatility goes high, investors may like to take a long position. However, if future volatility goes low, investors may like to take a short position (Yadav et al., 2022). The portfolio planning may be done as per the results obtained from different combinations of portfolio matrices. Table 6 presents the hedge ratio between CRO and the other four equity markets. The pairs have been presented as AUS/CRO, IND/CRO, JAP/CRO and USA/CRO. Taking a long position of $1 in CRO has emerged as the most expensive for the US equity market (0.03). It may be inferred that to take a long position and hedge for $1 in CRO, investors have to put 3 cents in the US market for taking a short position. The lowest expense for taking a long position in CRO for $1 and a short position in the Australian market may cost the minimum to investors. Thus, the hedging possibilities may be the most expensive in the US market and cheapest in the Australian market.

Finally, Table 7 articulates the portfolio weight for the pair CRO/AUS, CRO/IND, CRO/JAP and CRO/USA. The highest mean average is spotted for the pair CRO/USA which indicates that for a portfolio of $1, an investor can distribute 28 cents into CRO and the remaining 72 cents into the US market. Thereafter, it has been observed that for the Australian market, an investor can invest 78 cents in these markets keeping 22 cents for CRO in a particular portfolio. Turning to the Japanese market, and CRO combinations, investors can allocate 80 cents to these markets and the remaining 20 cents to CRO for a portfolio of $1. The Indian market furnishes the lowest mean average amongst all other QUAD members. For this market, investors can allocate 18 cents to CRO and 82 cents to the Indian market for a portfolio of $1.

Table 6 Hedge Ratio Table

Examined Assets	Mean	Std.Dev.	5%	95%	HE	p-value
AUS/CRO	-0.0100	0.0000	-0.0200	0.0000	0.0000	0.9600
IND/CRO	0.0000	0.0000	0.0000	0.0100	0.0000	0.9900
JAP/CRO	0.0000	0.0000	0.0000	0.0100	0.0000	0.9900
USA/CRO	0.0300	0.0100	0.0100	0.0500	0.0100	0.8900

Source: Authors

Table 7 Portfolio Weight

Examined Assets	Mean	Std.Dev.	5%	95%	HE	p-value
CRO/Austrailia	0.22	0.1	0.03	0.36	0.99	0
CRO/IND	0.18	0.13	0.02	0.45	0.99	0
CRO/JAP	0.20	0.09	0.02	0.35	0.99	0
CRO/USA	0.28	0.15	0.02	0.54	0.98	0

Source: Authors

5. Discussion and Implications

The empirical findings provide insightful results for both market participants and policymakers. Crude oil (CRO) emerges as the most significant transmitter of shocks across the network, while the US equity market shows the highest susceptibility to external disturbances. In contrast, CRO appears less affected by shocks from the QUAD equity markets, suggesting a degree of resilience that aligns with previous studies (A.K. Tiwari et al., 2022; Nazlioglu et al., 2013). Furthermore, both the CRO market and the US equity market are identified as net transmitters of shocks, while the IND, JAP, and AUS markets primarily serve as net receivers (Zhang and Hamori, 2021; Perifanis and Dagoumas, 2020). Hedge ratio calculations reveal that the US market is the most expensive for hedging, whereas the AUS market offers the least expensive option (Asadi et al, 2023).

Investors, both domestic and international, must carefully consider the interconnectedness of these markets when allocating capital. Given CRO's role as a net transmitter of shocks but relatively lower susceptibility to external market disturbances, it could serve as a useful tool for mitigating portfolio risk. However, investors should exercise caution during periods of geopolitical and natural crises, such as the Russia-Ukraine conflict and COVID-19, when the behaviour of CRO and equity markets may shift.

Portfolio managers should consider the cost-effectiveness of hedging options in these markets. The findings suggest that while the US market offers strong returns, it also comes with higher hedging costs. Conversely, the AUS market provides a more affordable hedging alternative, which could be beneficial in risk management strategies, especially during periods of market uncertainty. Policy analysts should consider the differential impacts of natural and geopolitical crises on these interconnected markets. CRO’s resilience during man-made crises, like the Russia-Ukraine war, compared to natural crises such as COVID-19, highlights the importance of adapting policies based on the nature of the shock. For instance, energy market regulation and financial policies should integrate strategies to manage volatility, ensuring that responses to crises do not exacerbate market instability.

The findings also carry environmental implications, particularly concerning CRO's role in financial stability. Given the global transition towards greener energy sources, CRO’s centrality in market volatility needs to be considered in the context of sustainability goals. Policymakers and managers must balance short-term financial decisions with long-term environmental objectives. Transitioning to renewable energy could not only reduce market volatility related to CRO prices but also align with broader sustainability goals, particularly within the QUAD nations, which are increasingly prioritising clean energy.

6. Conclusion

Analysing how crude oil operates as either a transmitter or receiver of shocks within select economies can offer valuable insights for all the market participants including the environment and policymakers, particularly for risk management and portfolio diversification. The QUAD nations (the USA, Japan, India, and Australia) have garnered attention because of their strategic importance in the Indo-Pacific region. On this note, it is a desideratum to undertake a study on dynamic connectedness considering daily observation ranging from December 31, 2019 to January 16, 2023. The study concluded that crude oil and the Japanese market are the least receivers and transmitters of the shock. Additionally, Australian, Japanese, and Indian markets are net receivers whilst the US equity market and crude oil are net transmitters. It is found that the hedging is most expensive in the US market while cheapest in Australian market.

The outcomes of the study may be carried further for future research with several factors into consideration. International events and domestic influence may be captured to study the impact of energy elements on stock market indices. Financial markets of various emerging groups of nations like Mexico, Indonesia, Peru, Turkey, Poland, and Argentina may be explored. Such markets may offer ample scope for returns and hedging diversification with energy instruments.

The present study has been focussed and limited to the historical prices of conventional instruments. It may be expanded with the analysis of emerging asset classes such as NFTs and DeFi which could offer fresh perspectives on market connectedness. Also, employing additional statistical tools like wavelet analysis, Quantile VAR, R2 connectedness, and TVP-VAR models could enhance the robustness and depth of future investigations into market volatility and spillovers.

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