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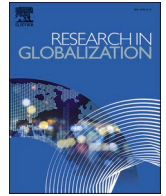
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Information flow between BRVM and ESG stock returns: A frequency-dependent analysis

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ABSTRACT

This paper seeks to analyze the information flow between the Bourse Régionale des Valeurs Mobilières (BRVM) and Environmental, Social, and Governance (ESG) stocks, focusing on the time and frequency domains. By studying these aspects, we aim to gain a deeper understanding of how information is transmitted between BRVM and ESG stocks, shedding light on the dynamics and interactions within this context. The study analyzes the decomposed daily returns of four indices: BRVM Composite Index (BRVMCI), BRVM 10 Index (BRVM10), FTSE/JSE SA All Share Index (FTSEJSE), and FTSE/JSE Top 30 Responsible Investment Index (FTSERI). We employed Rényi transfer entropy estimates to measure the information flow between the stocks returns.

To ensure the robustness of the findings, the study also utilizes the Dynamic Conditional Co-variance-Generalized autoregressive Conditional Heteroscedasticity (DCC-GARCH) method. The study covers the period from June 23, 2014, to April 22, 2022. The results showed positive information flow but a mixture of significant and insignificant transfer entropies. The decomposed findings give evidence to reject the null hypothesis of no information flow in the short-and medium-terms but not in the longterm.

The exchange of seemingly insignificant information among stocks presents opportunities for fund managers to diversify their portfolios across various time frames.

To expedite economic growth and lower equity costs, institutional leaders should collaborate with governments to establish economic and political foundations that integrate markets. Such integration would yield benefits for both markets, but the BRVM stands to gain more due to its less developed and illiquid nature.

1. Introduction

Sustainability is an increasingly widely diffused practice among businesses and investors seeking to aid in accomplishing sustainable development goals (SDGs) by 2030 (De Iorio et al., 2022). Sustainability is linked to globalization. Globalization knowingly has amplified the interconnectedness of economies, societies, and environments across borders, fostering increased trade, technology exchange, and cultural integration. Sustainability, in turn, has emerged as a crucial framework in globalization. As global markets expand, sustainable practices become imperative to ensure long-term viability, equitable growth, and

environmental preservation. Moreover, sustainability principles, such as environmental stewardship, social responsibility, and ethical governance, are increasingly shaping global trade, investment decisions, and supply chains. Thus, sustainability is not just an ethical concern but also a practical necessity in a globally interdependent world, where its principles guide the responsible and equitable conduct of businesses, governments, and societies amidst the forces of globalization.

Therefore, sustainability has been introduced in almost every sector in the world through the transfer of information and sparked researchers' interest in food and agriculture (Venturelli et al., 2022), cities (Giles-Corti et al., 2022), energy (Wang et al., 2022), materials

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(Rathnam et al., 2022), health (Kwon & Kim, 2022), and finance (Nedopil et al., 2022). It can be reasoned from these studies that sustainability practices have come to stay, and the financial markets are not exceptional in adopting them when pricing stocks (Hübel & Scholz, 2020). This transfer of information from the market to market, sector to sector, and from industry to industry has made businesses and corporate investors reorganise and readjust their business activities and portfolios to other markets (Asafo-Adjei et al., 2022; Agyei et al., 2022; Bossman et al., 2022; Duque-Grisales and Aguilera-Caracuel, 2021; Ng et al., 2020; Owusu Junior et al., 2021). Based on the information flow, corporate and individual investors have changed their investment portfolios to include different markets (Asafo-Adjei et al., 2021; Adam, 2020; Nyakurukwa, 2021; Owusu Junior et al., 2021).

The sustainability issues and the ability of a stock market to receive information from another market as explained in many financial theories (Lo, 2004; Müller et al., 1997; Owusu Junior et al., 2021) and literature (Agyei-Ampomah, 2011; Chen et al., 2005; Kwon & Yang, 2008a,b; Nyakurukwa, 2021; Sensoy et al., 2014) holds that information available will make the market participant reorganize their investment from one stock to another stock. This helps diversify portfolios (Liagkouras et al., 2020; Liesiö et al., 2020; Shin et al., 2020). An analogous situation can be said for investors interested in Bourse Regionale des Valeurs Mobilières (BRVM) stocks, who might also find some safe haven in other markets (Essingone & Diallo, 2022; Pamane & Vikpossi, 2014). This can help market participants smoothen their consumption from diversification (Cai et al., 2020). Financial assets share information that may be used to evaluate their mutual ties (Asafo-Adjei et al., 2022).

Africa stocks are candid markets for portfolio diversification (Adam, 2020; Agyei & Alagidede, 2009; Ampomah 2011; Carrière-Swallow & Céspedes, 2013; etc.). West African stock markets and, by and large, African stock markets are not exempted from sustainable investment, the new strain of stocks known as Environmental, Social, and Governance (ESG) stocks. ESG investing is among the growing investment vehicles in Africa (Hörnmark, 2015; Statman, 2020). In 2011, the World Bank Group report revealed that integrating ESG factors into investment decisions in Africa is a problem. Some years down the line, it has even come to the attention of investors that ESG stocks are competing with traditional stocks for diversification and safe havens (Johnson et al., 2019; Kilian, 2021; Statman, 2020; Taplin, 2021). A study that would account for the transmission of information from a growing ESG stock from the South African market and West African market (BRVM) is not out of order. This study used the BRVM market because they do not have ESG-rated stock indices. As a result, an African investor focused on ESG stocks and not ready to sacrifice their utilitarian benefits will form a portfolio with ESG stocks.

As ESG considerations become increasingly vital for investors, analyzing the information flow between BRVM (representing a specific market) and ESG stocks (representing sustainability-driven investments) share light on how sustainability factors influence investment decisions. It provides insights into whether ESG-related events, policies, or practices transfer information to traditional market behaviors and vice versa. Similarly, assessing the information flow helps uncover the degree of interdependence between BRVM and ESG stocks which can be linked to diversification, safe haven, and hedge within these two markets (Agyei et al., 2022; Asafo-Adjei et al., 2021; Aromi & Clements, 2019; Bertelsen et al., 2021; Bossman et al., 2022; Owusu Junior et al., 2021). This analysis reveals whether movements or trends in one market significantly affect or predict the behavior of the other. Understanding such interconnections is crucial for investors diversifying their portfolios or adjusting strategies based on market correlations. For investors specifically targeting ESG-aligned investments, understanding how information flows between traditional markets like BRVM and ESG-focused assets can inform portfolio construction. Insights derived from this study can aid in crafting more sustainable and resilient investment strategies that integrate ESG considerations into traditional investment decisions. Finally exploring information flow between BRVM and ESG stocks can

also highlight the resilience of sustainable investments during market fluctuations or crises. Understanding how ESG factors affect or are influenced by traditional market dynamics can help in assessing risk and potentially identifying opportunities for risk mitigation within diversified portfolios.

Several studies have assessed the information flow of financial markets (Asafo-Adjei et al., 2021; Aromi & Clements, 2019; Bertelsen et al., 2021; Bossomaier et al., 2018; He & Shang, 2017). However, none has considered the information flow between BRVM and ESG stocks. The studies that have been done in Africa concentrated on other stocks from other markets (Agyei-Ampomah, 2011; Alagidede, 2009; Atenya, 2019; Chen et al., 2004; Nyakurukwa, 2021). Nyakurukwa (2021) and Agyei-Ampomah (2011) showed low relationship among African stocks. Atenya (2019) findings showed no evidence empirically that JSE stock returns influence the east African exchanges. Sherehe et al. (2022) proposed that global stock markets are linked together by complex and dynamical interactions to form a global system. Therefore, a study that used ESG and BRVM stocks will provide options concerning investment decisions through information sharing patterns, specifically in a developing region like West Africa. BRVM is used because if they share information with ESG stocks, investors can diversify their portfolios using these stocks. BRVM participates keenly in the Sustainable Stock Exchange Initiative (SSEI), which offers some uniqueness in financial integration and ESG reporting standards (Klagge & Zademach, 2018).

This study is rooted in theories such as arbitrage pricing theory which hold that many factors influence the stock returns (Ross, 1976; Adam & Tweneboah, 2008; Rehman, 2021). As a result, the study could add information flow to the factors influencing stock return. But this will not be possible unless these markets have financial integration. They led to the adoption financial market integration theory (Arouri & Foulquier, 2012). The theory holds that there is increasing integration of the financial market of diverse economies due to institutional, political, economic and behavioural factors (Kearney & Lucey, 2004). Owusu Junior et al. (2020) showed that the financial market of emerging economies is connected and encourages competition. Consequently, Owusu Junior et al. (2021), on a competitive market hypothesis (CMH), posited that information flow and spillover among financial markets account for irrational investors' decision to chase opposing rewards and diversify their portfolios. The CMH is adopted to investigate whether BRVM and ESG in Africa are competing or complementary; however, it requires decomposing the data.

The heterogeneous market hypothesis (HMH) is also used to account for the analyses done through the frequency domain that can help investors decide whether to invest or not in different time horizons (Chin et al., 2017; Muller et al., 1993). Finally, adopting the adaptive market hypothesis (AMH) holds that the financial market changes to time, structural changes and events, among others which cause the efficiency of the market to fluctuate in different time periods (Lo, 2004; Urquhart & McGroarty, 2016). Many financial data are unstable and provide spurious results when employed in analysis (Ghose & Kroner, 1995; Nolan, 2014). Researchers have advanced many decomposition techniques to handle such non-stationary series. Decomposition breaks an unstable financial string into a different number of intrinsic mode functions (IMFs) that can be analysed through time and domain (Rhif et al., 2019; Van Jaarsveldt et al., 2021). Additional issues with financial series are rapid oscillations and carrying noise (Lang et al., 2020). Irrational behaviours of market participants caused by market stress and turbulences at various investment times but more likely in short-to medium-terms, lead to noise in the financial data (Lang et al., 2020).

BRVM and ESG stocks are no different from other financial series; therefore, they experience similar noise-generating processes (Gbenro & Moussa, 2019; Rubbaniy et al., 2021). The existence of a Monday effect in BRVM stock returns was shown by Ferrouhi et al. (2021). This makes it difficult for investors to determine what causes a trend and if it is profoundly changing or just suffering short-term volatility. (Zhang, 2010; Wei & Zhang, 2006). The data was decomposed to account for

non-stationary and non-linearity, among others (Van Jaarsveldt et al., 2021). Also, the decomposition was done to account for different time horizons and reduce the series' noise to account for the actual events markets (Asafo-Adjei et al., 2022; Agyei et al., 2022; Bossman et al., 2022; Owusu Junior et al., 2021). This study uses Torres et al. (2011)'s Complete Ensemble Empirical Mode Decomposition with Adaptive Noise (CEEMDAN) decomposition approach for BRVM and ESG stocks. The CEEMDAN decomposes input signals into primary modes, referred to as IMFs, which are then used to reconstruct the original signal with varying sparsity quality (Jothimani & Yadav, 2019). CEEMDAN was employed ahead of empirical mode decomposition (EMD) and EEMD because it solves the issues of mode mixing from EMD and the Gaussian white noise from EEMD (Niu et al., 2021; Peng et al., 2021; Torres et al., 2011). Mode mixing can distort the intended use of the IMF created by the decomposition (Asafo-Adjei et al., 2022). CEEMDAN also addresses the frequency aliasing issue that might arise with EMD and EEMD (Torres et al., 2011). CEEMDAN uses the original data for IMF filtering and eliminates the two constraints—inconsistency in the number of decomposition scales and some inherent inaccuracy in the reconstructed and original signals (Peng et al., 2021; Zhang et al., 2018). The CEEMDAN extracts modes in a non-recursive manner, making it an entirely intrinsic, adaptive, and quasi-orthogonal decomposition approach (Torres et al., 2011). The IMFs from CEEMDAN are represented as short, medium, and long-term periods in the context of this study (Niu & Hu, 2021). This is consistent with the HMH (Chin et al., 2017), AMH (Lo, 2004) and CMH (Owusu Junior et al., 2021).

After the decomposition, the study employed Renyi Transfer Entropy (RTE) to assess the information flow between BRVM and ESG stocks. Transfer entropy allows investors to separate correlated stocks (Kwon & Yang, 2007). RTE employs a weighting factor to help account for tail events of financial data (Behrendt et al., 2019). Behrendt et al. added that at one RTE converges to Shannon entropy as the weight value approaches. Transfer entropy estimates the decline in uncertainty in forecasting variables, mainly when conditioned on previous values, making it simpler to represent statistical causation between variables in natural phenomena (Asafo-Adjei et al., 2022; Agyei et al., 2022; Bossman et al., 2022; Owusu Junior et al., 2021). As a result, transfer entropy may be used to measure the amount of information that flows between financial markets. After appropriately decomposing the time series data into IMFs, the CEEMDAN-based-RTE would give an asymmetric technique for quantifying the information flow. This method was not used in the previous study on BRVM and ESG stocks. Previous study employed only RTE which leaves out short-term and long-term relationships between these markets (Adam, 2020; Nyakurukwa, 2021; He and Shang, 2017).

The research will add to the literature uniquely that will account for gaps in the literature identified. While prior studies have explored information flow across various stock indices, financial markets, and economic conditions, this research specifically targets the relationship between West African Regional stock market BRVM and ESG stock from the JSE. Little or no studies have used these stocks. It introduces the utilization of CEEMDAN-based RTE to examine the information flow between BRVM and ESG stocks. This methodology, leveraging empirical mode decomposition and transfer entropy, offers a unique approach to analyse the directional transmission of information between these distinct market segments. As a result, this study assessing information flow between BRVM and ESG stocks using their log-return value and their decomposed IMFs adds up to the answers to the problem of the attractiveness of these markets. Information is essential in analysing markets. RTE and CEEMDAN-based-RTE were adopted to study the information flow between BRVM and ESG. The log-return results of RTE provide insight into a situation where there is no assumption about the non-linearity of data. The IMFs produced from the CEEMDAN were grouped in the short, medium, and long term to capture multifrequency events (Niu & Hu, 2021). This would provide intuition into the different behaviour of market participants as proposed by HMH (Chin et al.,

2017) and the AMH (Urquhart & McGroarty, 2016). The CEEMDAN-based-RTE was also adopted to pact with the problems of non-stationarity, non-linearity, and asymmetry present in a particular data set. RTE is a type of transfer entropy that uses log-likelihood to quantify the outcomes in a probability density function (Adam, 2020). The study is interested in information from (towards) ESG to(from) BRVM. The results will help fund managers assess risks and offer diversification advice to investors and help institutional managers and governments decide on whether to adopt economic and political strategies to increase market integration of African markets. It will help advance the African continent's dream of a single currency through market integration (Nyakurukwa, 2021).

The empirical results showed that most of the information flow between BRVM stock, FSTERI and FSTEJSE at different time scales is insignificant, which is suitable for diversification. However, there is a significant movement of information from BRVM to FSTERI stocks in the short term and a substantial outlay of information from FSTERI to BRVM stocks in the medium term. The positive transmission of information from BRVM stock to FSTERI in the short term. The same applies to the medium-term transmission from FSTERI stock to BRVM. As a result, the mutual information shared by BRVM and FSTERI stocks is less problematic for each other. The significant information flow coefficients are low, indicating low integration among the two markets. However, in the medium and long transmission from BRVM to FSTERI and short and long term of transmission from FSTERI to BRVM, a market participant can trade with caution, which might yield diversification. The long-run results are insignificant, which supports the idea of EMH. None of the stocks dominated the information flow be it BRVM10 or BRVMCI. At these IMFs (IMF1, IMF4, IMF5 and IMF9), the FSTEJSE market transmits positive information flow to BRVM. Which characterised that FSTEJSE stock is less risky than BRVM stocks in information sharing. Nevertheless, the higher values of ESG stocks' information flow coefficient compared to BRVM signals that information flows from ESG (more developed market) more to BRVM (less developed market).

The study will be extended in the ensuing 4 sections. In Section 2, there is a literature review of interrelated articles and theoretical backing for the study. We present a CEEMDAN-based Rényi Transfer Entropy method and data and description in Section 3. Section 4 discusses the statistical results as Theoretical and Practical Underpinnings of the study. Section 5 focuses on conclusions that would be made from the results and their suggestions for practice and theory.

2. Literature review

The review of literature is divided into four sections. The first part discusses the theoretical baking of the study. The following sub-section discusses the linkage between BRVM and ESG stock, followed by empirical research and the Gap identified in the study.

2.1. Theoretical review

The study rest on some economics and finance theories such as the theory of interdependence, information flow theory, heterogeneous market hypothesis, Competitive market hypothesis, and Adaptive market hypothesis.

2.1.1. Theory of interdependence

The theory posited that there is a direct linkage between financial markets and that changes in one market may cause a corresponding change in another related market (Kaur & Arora, 2018). The theory of interdependence is employed in many instances to explain the advancement of many economic and financial markets (Cheung et al., 2010). Finance literature has used it to describe direct relationships between cryptocurrencies and global equities (Asafo-Adjei et al., 2021). Ahmed and Huo (2019) posited that advancement in economic activities of countries increases the interdependence of financial markets. The

theory is employed to elucidate the relationship between BRVM and ESG market. Interdependence may be linked to everyday activity between the financial markets (Ahmed and Huo, 2019). Three theories explain the move in lockstep of various stock markets. First is the “contagion effect, which refers to the portion of stock market co-movement that economic fundamentals cannot explain” (Alqaralleh & Canepa, 2021). Second, economic integration indicates that the more closely two nations’ economies are linked, the more interconnected or integrated their stock markets become (Oatley, 2019). Economic integration includes trade ties and the movement of economic indices like interest rates and inflation, which influence stock market returns (Ahmed & Huo, 2019). The third and last category comprises stock market characteristics such as industry similarity, volatility, and size, all of which influence the degree of stock market interdependence (Pretorius, 2002).

2.1.2. Information flow theory

Reciprocal information is intuitively defined as when two random variables are connected so that one variable may learn about the state of the other by monitoring the other. This is especially true in financial market integration (Asafo-Adjei et al., 2022; Asafo-Adjei et al., 2021). The information flow theory is based on Dretske’s (1981) philosophy and Pearl’s (2009) statistics, where the mathematics of probability and statistics have allowed the amount of information flow to be quantified. Benthall (2019) postulated that the root of information flow is casual linkages among financial markets. That is, among two financial markets, BRVM and ESG, there exists information flow if BRVM can learn about the state of ESG. BRVM is a growing market that has started to gain attention among market participants so is ESG stocks. ESG stock’s attention keeps increasing because of its ability to resend better than traditional stocks. However, BRVM stocks have less market capitalisation, so that the investor can diversify their stocks with ESG. Therefore, this can cause information flow between the financial assets.

2.1.3. Heterogeneous market hypothesis

The Heterogeneous Market Hypothesis asserts that market participants are heterogeneous due to their respective endowments, interest, degree of risk and available information and how they react to this information (Cheong, 2013; Müller et al., 1993; Patil & Rastogi, 2019). Financial time series, like cryptocurrency and gold, are surrounded by noise and endure quick shifts due to the widespread behaviour of unstable signals. The heterogeneous market hypothesis (HMH) considers market participants diverse in terms of information, goals, and investment horizons (Owusu Junior et al., 2020; Owusu Junior et al., 2021). Irrational participants in the market react to information at various times, resulting in highly noisy market data. According to Cheong (2013), HMH is one of the theories that recommends non-homogeneous market players. The behaviour of market players to further information entering the market might cause heterogeneity in a financial market (Heaton & Lucas, 1995). The interests, endowments, risk profiles, contractual limitations, degree of information, trading incentives, and responses to news may all differ across market players (Cheong, 2013). Heterogeneous participants react over different time scales with different interests and strategies (Alfarano et al., 2008).

2.1.4. Competitive market hypothesis (CMH)

CMH was posited by Owusu Junior et al. (2021). According to the CMH, market players’ actions increase the flow of information across markets (Bossman et al., 2022). Because the behaviour of various market players changes over time, our findings are critical for investors who trade on short, medium, and long-term timescales. According to CMH, information flow and spillovers across assets and asset classes become more intense during stormy market scenarios due to logical, irrational investors’ never-ending hunt for opposing rewards and risks to meet broad portfolio objectives (Bossman et al., 2022). Furthermore, CMH hypothesises that market participants would make periodic portfolio changes, resulting in a switch or mix of assets and asset classes (Asafo-

Adjei et al., 2021). Due to the increased information flow to financial markets during a financial and economic downturn. CMH is possible because of market participants’ inherent desire to pursue competitive rewards for their investment (Asafo-Adjei et al., 2022).

2.1.5. Adaptive market hypothesis

The theory holds that people are motivated by their self-interest, which causes them to make mistakes and learn from them (Urquhart & McGroarty, 2016). AMH assumes market participants are not rational or irrational (Tseng, 2006). According to Lo (2004)’s adaptive market hypothesis (AMH), markets develop and adapt due to events and structural changes, and market efficiency varies over time. AMH posits that market participants are mainly rational but sometimes can over-react during periods of heightened market volatility (Neely & Weller, 2011). This attitude can let investors switch from one financial asset (BRVM) to the other, offering more compensation over time (Essingone & Diallo, 2019).

2.2. BRVM and ESG stocks

The BRVM is a regional stock exchange comprising eight West African Economic and Monetary Union (WAEMU) countries (Gbenro & Moussa, 2019). The BRVM market is still tiny, with only 45 companies listed. The BRVM stock market was established in September 1998 as a frontier stock market. Its operations have just recently expanded. The BRVM stock exchange began daily quotations in November 2001, and incessant quotations started in September 2013 (Ouattara, 2016). In June 2014, the BRVM stock market was included in the MSCI, S&P, and Dow Jones indexes due to its quick expansion (Igwill & Sibindi, 2021). In November 2016, the BRVM was included in the MISC frontier markets index and was also classified as a frontier market by S&P, Russell, and FTSE (Gbenro & Moussa, 2019). The leading financial indices of BRVM are the BRVMCI and BRVM10 (Balde et al., 2021). ESG stocks, on the other hand, are, rely heavily on the ESG scores of the various firms (Clementino & Perkins, 2021). By 2025, global ESG assets are estimated to surpass US\$53 trillion, accounting for more than a third of total assets under management (Bhuvanekumar et al., 2022; Rudd, 2022). The ground-breaking of ESG stocks is because of investors’ growing knowledge of ESG risk resulting from climate change and corporate failures, standard quantification of ESG factors, and advancement in communication (Inderst & Stewart, 2018). It is expected that firms that meet ESG standard requirements recoup higher returns than traditional firms (Atan et al., 2016). ESG investment offers market exposure, particularly in a social or economic disaster (Nofsinger & Varma, 2014). S&P analysis found that funds participating in ESG factors outperformed the S&P 500 average of 27.1 %, rising between 27.3 % and 55 % during the COVID-19 pandemic period (Sinha & Juneja, 2020). The ESG stocks included in this analysis are from the JSE, Africa’s largest and most sophisticated stock exchange (Dzomonda & Fatoki, 2020). The JSE’s main board now comprises over 350 established firms with a market capitalisation of more than \$1 trillion (Nyakurukwa, 2021). The JSE has several traditional indexes, including the JSE All Share Index (JALSH), the JSE Industrial Index, the JSE Top 40 index, and the JSE Industrials index, as well as ESG equities such as the FTSE/JSE SA All Share Index (FTSEJSE) and FTSE/JSE Top 30 Responsible Investment Index (FTSERI) (Dzomonda & Fatoki, 2020). These stocks are selected because they are the only ESG stocks in Africa. These stock markets are integrated because of the contagion effect, economic situation (Bracker et al., 1999), market size underlining the African continent, investor behaviour, and stock market liquidity (Nyakurukwa, 2021), among others.

2.3. Empirical review on information flow between financial markets

Many studies have assessed information flow between financial markets and have established that financial markets share information

among themselves through diverse methods such as transfer entropy, correlation analyses, cointegration, and other statistical methods to assess information transmission, ESG stocks or sustainability-related factors into these analyses could offer enhanced understanding of dynamics of stock indices, individual stocks, global equity markets, and other financial instruments. Table 1 provides empirical findings of previous studies on the nexus between financial markets.

2.4. Critiques of the existing literature

Existing empirical work on information flow between financial markets has concentrated on developed economies (Bossman et al., 2022; Bracker et al., 1999; Dimpfl & Peter 2012; Kuang, 2021; Kwon & Yang 2008a; Kwon & Yang 2008b; Kwon & Oh 2012) with few concentrating on Africa (Adam, 2020; Agyei et al., 2022; Agyei-Ampomah, 2011; Alagidede, 2009; Asafo-Adjei et al., 2021; Atenya, 2019; Collins and Biekpe, 2003; Jefferis & Okeahalam, 2015; Nyakurukwa, 2021; Owusu Junior et al., 2021). The results showed that there are situations where it is significant and insignificant (Nyakurukwa, 2021) transfer of information between financial markets, whereas there are positive instances (Adam, 2020; Kwon & Yang, 2008a; Kwon & Yang, 2008b; Kuang, 2021), as well as mixed results (Agyei et al., 2022; Asafo-Adjei et al., 2021; Bossman et al., 2022; Owusu Junior et al., 2021). These help investors diversify or hedge their investments, reorganise their portfolios, and save their assets. Also, very few studies decompose their data to account for a different investment time horizon from the market participant as proposed by AHM, CMH and HMM. Most importantly, none of these studies adopted BRVM and ESG stock. The closest who used BRVM stocks (Essingone & Diallo, 2022; Gnahe, 2021; Ouattara, 2016) accounted for risk returns, and others concentrated on ESG stock from JSE and other stock markets (Bondara, 2014; Statman, 2020). Among the studies that focused on Africa, it was established that African stock markets are less integrated (Agyei-Ampomah, 2011; Alagidede, 2009; Atenya, 2019; Collins and Biekpe, 2003; Jefferis & Okeahalam, 2015; Nyakurukwa, 2021) and that more research is needed to examine to co-movements of Africa stock markets. As a result, Nyakurukwa (2021) suggested in a further study that there is a need to assess the time and frequency domain of information flow between African stock markets.

3. Methodology

3.1. CEEMDAN

Non-linear and non-stationary data are complicated to handle, and sometimes they provide deceptive results (Dimpfl & Peter, 2013). Empirical Mode Decomposition (EMD) techniques which are purely data-driven algorithms, have been introduced by researchers to handle issues of non-linear and non-stationary signals (Flandrin et al., 2004). EMD contrasts Wavelet decomposition, whose mother wavelet is not objectively identified to decompose a signal (Suchetha & Kumaravel, 2013). EMD is a type of data-driven signal separation that distinguishes between fast and slow oscillations (Rilling et al., 2005). Problems with the ground-breaking EMD approach included the inclusion of oscillations of extremely varied amplitudes in a mode, as well as the existence of very similar oscillations in various modes (Huang et al., 2019). However, because of advancements in knowledge, the issues with EMD were solved with the introduction of the EEMD (Wu et al., 2009). EEMD, on the other hand, presents new issues after solving the EMD's dyadic filter bank behaviour. CEEMDAN translates residual noise in reconstructed signals within the EEMD, resulting in a more accurate reconstruction of the original signal and improved spectral separation of the modes at a reduced computational cost (Torres et al., 2011). CEEMDAN, likened to EMD, EEMD, and CEEMD, has numerous advantages. The BRVM and ESG stocks variables were disintegrated into nine IMFs and a residual. This was implemented with the *libeemd* R package. The

mathematical computation following Torres et al. (2011) is shown below.

Begin the number of realisations n , noise parameters, the index for IMF $j = 1$

$$\overline{IMF_k}(t) = \frac{1}{N} \sum_{n=1}^N IMF_k^n(t), \text{ where } \overline{IMF_k} \text{ is the } k^{\text{th}} \text{ mode of } S(t) \quad (1)$$

The decomposition of EMD for N realisations; $S^n(t) = S(t) + \delta_o \omega^n(t)$ where $\omega^n(t) [n = 1, \dots, N]$ the white Gaussian noise series added to the original signal $S(t)$, and δ_o Is the noise parameter for the initial step. When $S^n(t) [n = 1, \dots, N]$ is decomposed, their modes are represented by $IMF_k^n(t)$, Where $k = 1, \dots, K$ represents the modes. To obtain EEMD

Following Torres et al. (2011), the decomposition of CEEMDAN is represented by. (\widetilde{IMF}_k)

The special first residue can be determined as

$$r_1(t) = s(t) - \widetilde{IMF}_1(t) \quad (4)$$

Evolve n number of realisations, then the operator $E_j(\cdot)$ produces J^{th} the mode obtained by EMD.

decompose realisation

$$r_k(t) + \delta_k E_k(\omega^n(t)), n = 1, 2, 3, \dots, N$$

Until the first EMD is determined and the next EMD is defined (2)

$$\widetilde{IMF}_{k+1}(t) = \frac{1}{N} \sum_{n=1}^N E_1[r_k(t) + \delta_k E_k(\omega^n(t))] \quad (3)$$

The final residue must meet the requirement of

$$R(t) = S(t) - \sum_{k=1}^K \widetilde{IMF}_k(t) \quad (5)$$

Finally, the $S(t)$ can be made the subject to express the final signal. Which is the construction from the original data

3.2. Transfer entropy

A nonparametric quantification of the amount of information transmission from one variable to another is transfer entropy (Shannon or Rényi transfer entropy). Shannon entropy (STE), introduced in 1948, is an excellent concept in information theory that many scholars and researchers have adopted to understand uncertainties (Schreiber, 2000; Rogers & Valente, 2017). The theories of Shannon entropy were elaborated upon by RTE (Jizba et al., 2012). Therefore, RTE cannot be discussed exclusively. This paper adopts the ideas of Hartley (1928), who posited that information could be calculated by the log of the number of all probable event sequences, which is likely to be based on a specified probability distribution. The mathematical development of the idea of transfer entropy is as follows (Behrendt et al., 2019). Assuming there is a known probability distribution with multiple outcomes which also have diverse probabilities ρ_τ . Following Hartley, the average information of the event is represented as

$$H = \sum_{\tau=1}^{\eta} \rho_\tau \log_2 \left(\frac{1}{\rho_\tau} \right) \text{ bits} \quad (6)$$

where η represents several diverse events accompanying the probabilities ρ_τ .

Shannon entropy posited that for a certain distinct random variable represented as (τ) whose probability distribution is (ρ_τ) , the numerical average of bits needed to optimally encrypt independent draws is shown in equation (7) (Shannon, 1948).

$$H_\tau = - \sum_{\tau} \rho_\tau \log_2 \rho_\tau \quad (7)$$

Table 1
Empirical review of related articles.

Author(s) and Year	Title and Year	Method and Study period	Variable	Results
Kwona & Yang (2008)	Information flow between composite stock index and individual stocks	Transfer entropy June 1, 1983 to May 31, 2007	S&P 500 index (GSPC), Dow Jones index (DJI) and stock price (125 individual companies)	They indicate that there is a stronger flow of information from the stock index to the individual stocks than vice versa, and the transfer entropy for both directions have positive correlations.
Kwon & Yang, (2008)	Information flow between stock indices	Transfer Entropy January 2000–December 2007	25 stock exchange indices MERV, BVSP, GSPTSE, MXX, GSPC, DJA, DJI, AORD, SSEC, HSI, BSESN, JKSE, KLSE, N225, STI, KS11, TWII, ATX, BFX, FCE.NX, GDAXI, AEX, MIBTEL, SSMI, FTSE	The findings showed that the value of the outgoing transfer entropy from the American markets is high, as it is from the European markets. The information flow mainly streams to the Asia/Pacific region.
Dimpfl & Pete, (2012)	Using transfer entropy to measure information flows between financial markets	Transfer Entropy January 1, 2004 to December 31, 2011	27 iTraxx companies	The results show that even though information flows in both directions, the CDS market dominates the market for credit risk. Also, information flows mainly from the VIX to the iTraxx.
Kuang (2021)	Measuring information flow among international stock markets: An approach of entropy-based networks on multi time-scales	Empirical mode decomposition Transfer entropy Kernel estimation Bootstrap test Weekly stock indices from 2007 to 2018	31 major stock markets, United Kingdom (GBR), France (FRA), German (DEU), Italy (ITA), Spain (ESP), Netherlands (NLD), Belgium (BEL), Switzerland (CHE), Sweden (SWE), Norway (NOR), the United States (USA), Canada (CAN), Australia (AUS), New Zealand (NZL), Japan (JPN), South Korean (KOR), Hong Kong (HKG), and Singapore (SGP), and the 13 developing countries, including Russia (RUS), Turkey (TUR), China (CHN), Thailand (THA), Indonesia (IDN), India (IND), Saudi Arabia (SAU), Mexico (MEX), Brazil (BRA), Argentina (ARG), Chile (CHL), Egypt (EGY), and Nigeria (NGA)	The results of network analysis reveal that developed markets are more dominant but vulnerable to short-term risk contagion, and information flows inside of these stock markets only cluster on short time-scale but not on mid-long time-scale. Besides, the emerging stock markets in Indonesia, Saudi Arabia, and Egypt, are isolated to the global co-movements on short timescale. The above intuitions overall support the dominant role of short time-scale co-movements among international stock markets.
Bossman et al. (2022)	Flights-to-and-from-Quality with Islamic and Conventional Bonds in the COVID-19 Pandemic Era: ICEEMDAN-Based Transfer Entropy	Improved Complete Empirical Ensemble Mode Decomposition with Adaptive Noise (ICEEMDAN) Renyi Transfer Entropy January 02, 2020, to September 08, 2021	5 key Islamic (India, Indonesia, Malaysia, Pakistan, and Qatar) and G4 (Canada, Italy, the UK, and the USA) markets Global equity indices for 5 market blocs (BRIC, developed markets index, emerging markets index, Europe Index, and Global market composite index)	The results suggest that there exists information flow between the studied global equities and the Islamic and conventional bond yield market
Owusu Junior et al. (2021)	COVID-19 as Information Transmitter to Global Equity Markets: Evidence from CEEMDAN-Based Transfer Entropy Approach	Complete Ensemble Empirical Mode Decomposition (CEEMDAN) Renyi Transfer Entropy 9 from December 31, 2019, to April 18, 2021.	27 world equity indices from 20 countries, 4 economic blocs (Developed Markets, Emerging Markets, Europe, Middle East, Africa (EMEA), and Eurozone), and the Nasdaq Global Equity Index.	The summary of our empirical results is that, in the long run, both the Renyi and Shannon transfer entropies fail to reject the null hypothesis of no information flow from COVID-19 to the selected global equity markets.
Agyei et al. (2022)	Situated Information Flow between Food Commodity and Regional Equity Markets: An EEMD-Based Transfer Entropy Analysis	Ensemble Empirical Mode Decomposition (EEMD) Renyi Transfer Entropy. December 2012 to September 2021	The aggregate world food commodity index and its constituents including cereals, dairy, meat, vegetable oil, and sugar and 11 regional NASDAQ equity indices for Asia, Asia-Pacific, BRIC, developed markets, emerging markets, Europe, Eurozone, global market, Latin America, the Middle East and Africa, and North America.	The information flow between commodity and equity markets varies across time scales or frequencies. To inform interested market participants, the composite transfer entropies suggest that out of the food commodity classes, only sugar serves as a significant diversifier.
Adam (2020)	Susceptibility of Stock Market Returns to International Economic Policy: Evidence from Effective Transfer Entropy of Africa with the Implication for Open Innovation	Renyi Transfer Entropy 31 December 2010 to 27 May 2020	Daily US economic policy uncertainty index (EPU) and daily stock market indexes for nine African countries, namely, Nigeria Stock Exchange All Share Index (Nigeria), Nairobi All Share Index (Kenya), Zambia All Share Index (Zambia), FT/JSE All Share Index (South Africa), Ghana Stock Exchange All Share Index (Ghana), Botswana Domestic Company Index (Botswana), Casablanca All Share Index (Morocco), Namibia Stock Exchange	The results show that international economic policy uncertainty transmits significant information to all the stock markets studied, except Botswana, Kenya, Nigeria, and Zambia. The positive Rényi transfer entropy indicates that the risk about the future returns of African stocks is reduced by the knowledge of the international economic policy uncertainty.

(continued on next page)

Table 1 (continued)

Author(s) and Year	Title and Year	Method and Study period	Variable	Results
Bracker et al. (1999)	Economic determinants of evolution in international stock market integration	Geweke Analysis Pooled Regression Years 1972–1993	Overall Index (Namibia), and Egypt EGX30 (Egypt). Japan, Australia, Hong Kong, Singapore, Switzerland, Germany, UK, US and Canada.	The result suggests a high degree of both market integration and market efficiency, as all possible pairs of markets interact significantly. Results for the same day relationships indicate several different macroeconomic factors are significantly associated with the extent of stock market integration over time.
Collins and Biekpe (2003)	The Price-Volume Relationship of the Shanghai Stock Index: Structural Change and the Threshold Effect of Volatility	Correlation Granger causality January 2, 1997 to November 28, 1997	Africa Stock markets; Egypt, Kenya, Mauritius, Morocco, Namibia, Nigeria, South Africa, Zimbabwe, FT World index Hong Kon Hang Seng Index	The unadjusted correlation coefficients suggest that some markets, including small markets like Mauritius and Namibia, showed evidence of contagion from Hong Kong in 1997. The results showed that Egypt Granger cause returns in Morocco and South African stock market returns Granger cause those in Zimbabwe.
Agyei-Ampomah (2011)	Stock market integration in Africa	Vector Autoregression Year 1998–2007	Egypt, Morocco, Nigeria and South Africa, Botswana, Ivory Coast, Ghana, Kenya, Mauritius and Tunisia	The results showed cross-country diversification among Africa market but the liberalisation efforts in Africa has not achieved the targeted financial integration with the global financial market.
Alagidede (2009)	Are African stock markets integrated with the rest of the world	Maximum likelihood based cointegration	South Africa, Egypt, Nigeria and Kenya Brazil and Mexico United States, Japan and the United Kingdom	The results showed that there are weak stochastic trends between African markets and world markets. With the exception of South Africa and Mauritius, African markets are not integrated regionally either. However, analysis of the short run dynamics indicates that size and extent of financial market development drives equity market interdependence, with South Africa accounting for most of the innovations to and, from global markets.
Atenya (2019)	The status quo of East African stock markets: Integration and volatility.	Vector Autoregressive (VAR) and Granger causality 17th January 2008 to 31st March 2017	Weekly price indices of Kenya, Tanzania, Rwanda, and Uganda, South Africa	The results showed relatively moderate-to-low volatility. The linear interdependencies among the given markets illustrate that JSE has a low contributory impact on the returns on the East African markets. The results further states that integration is still underway
Jefferis & Okeahalam, (2015)	International Stock Market Linkages in Southern Africa.	Correlations of market returns (for short term linkages) Cointegration analysis of market indices (for long term linkages) . Year 1989–1996.	South Africa, Botswana and Zimbabwe, Latin America and Asia, USA and the UK	The results show that in the short-term South Africa market is closely related to international markets, particularly the UK and Asian markets. Botswana is related to the two other regional markets but not other emerging while Zimbabwe shows little evidence of relationships with other markets. Longer term relationships are not however except between Botswana and South Africa. The results indicate that the process of integration between Southern African markets, and of those markets into the international financial system, is still at an early stage.
Nyakurukwa (2021)	Information Flow Between the Zimbabwe Stock Exchange and the Johannesburg Stock Exchange: A Transfer Entropy Approach	Shannonian transfer entropy Rényian transfer entropy 27–06-2010 and 09–09-2018	Zimbabwe Stock Exchange; Industrials index and mining index JSE All Share index, JSE industrial index, and the JSE resources index.	Shannon entropy reveal a significant information flow is from the JSE resources index to the ZSE industrials index. The Rényian entropy transfer estimates show that there is significant information flow from the JSE resources index and JALSH to the ZSE mining index. The significant coefficients were very low, indicating weak integration among the indices.

H_τ is the measure of uncertainty. It increases as the number of bits increases to encode the realisation classification of τ , a discrete random variable. Where the bits are from \log_2 . H_τ is calculated under the assumption of Markov processes (Schreiber, 2000) since the STE follows the idea of Kullback and Leibler (1928). The Kullback-Leibler distance is a notion that may be adopted to compute the information flow between two-time series.

Assuming A and B are two discrete random variables with matching

marginal likelihoods of $P(A)$ and $P(B)$, joint probability $P(A, B)$, with dynamic structures following order κ (Process A) and t (process B) of a stationary Markov process. The Markov assumptions posit probability of detecting A at time $t + 1$ in state α conditional on the κ previous observations are $\rho(\alpha_{t+1} | \alpha_t, \dots, \alpha_{t-\kappa+1}) = \rho(\alpha_{t+1} | \alpha_t, \dots, \alpha_{t-\kappa})$. To encode the reflection in $t + 1$, the average bits number required once the ex-ante k values are known can be illustrated as

$$h_{\beta}(\kappa) = - \sum_i \rho(\alpha_{t+1}, \alpha_t^{(\kappa)}) \log P(\alpha_{t+1} | \alpha_t^{(\kappa)}) \quad (8)$$

where $\alpha_t^{(\kappa)} = (\alpha_t, \dots, \alpha_{t-\kappa+1})$ (similar in the same respect for process B). In a bidirectional perspective, information flow from process-to-process A is estimated by computing the deviation out of the Markov property (Kullback & Leibler, 1928) and relying on the Kullback-Leibler distance. $\rho(\alpha_{t+1} | \alpha_t^{(\kappa)}) = \rho(\alpha_{t+1} | \alpha_t^{(\kappa)}, \beta_t^{(i)})$. Behrendt et al. (2019) presents the Shannon transfer entropy as

$$T_{B \rightarrow A}(\kappa, i) = \sum \rho(\alpha_{t+1}, \alpha_t^{(\kappa)}, \beta_t^{(i)}) \log \frac{\rho(\alpha_{t+1} | \alpha_t^{(\kappa)}, \beta_t^{(i)})}{P(\alpha_{t+1} | \alpha_t^{(\kappa)})} \quad (9)$$

where $T_{B \rightarrow A}$ computes the information flow from B to A. Likewise, $T_{A \rightarrow B}$. The quantity for the information flow from A to B can be computed. The focal direction of the information flow can be estimated by identifying the changes between $T_{B \rightarrow A}$ and $T_{A \rightarrow B}$.

Rényi transfer entropy (RTE)

Another form of Transfer entropy estimation is RTE (Jizba et al., 2012; Rényi, 1970). RTE introduce a weighting parameter labelled q into the average information (Behrendt et al., 2019). The formula for the entropy then becomes

$$H_{\tau}^q = \frac{1}{1-q} \log \sum_{\tau} \rho^q(\tau), q > 0 \quad (10)$$

As q approaches 1, RTE goes back to STE discussed early (Shannon, 1948). In the situation of $0 < q < 1$, an event with a low probability will have a higher weight, whereas in the opposite $q > 1$, the weights profit outcomes τ with a more significant opening probability (Adam, 2020). Therefore, RTE by the value of parameter q shows the importance of diverse distribution areas (Adam, 2020; Behrendt et al., 2019).

The Rényi entropy adopts the escort distribution (Beck & Schögl, 1993), $\varphi_q(\tau) = \frac{\rho^q(\tau)}{\sum_i \rho^q(\tau)}$ where q is greater than 0 to regularise the weighted distributions, Rényi transfer entropy (Jizba et al., 2012) is modelled as

$$RT_{B \rightarrow A}(\kappa, i) = \frac{1}{1-q} \log \frac{\sum_i \varphi_q(\alpha_t^{(\kappa)}) \rho^q(\alpha_{t+1} | \alpha_t^{(\kappa)})}{\sum_{\alpha, \beta} \varphi_q(\alpha_t^{(\kappa)}, \beta_t^{(i)}) \rho^q(\alpha_{t+1} | \alpha_t^{(\kappa)}, \beta_t^{(i)})} \quad (11)$$

The final value of RTE can be negative values. Therefore, the meaningful history of B represents even more uncertainty than would if not be specified by first checking the account of A.

3.3. Diagnostics and inference

Most estimation limits are unfair in small samples, and the transfer entropy parameters are no exception (Behrendt et al., 2019; Marschinski & Kantz, 2002). Marschinski and Kantz posited that this biasness is corrected through the calculation of the effective transfer entropy (ETE) as

$$ETE_{B \rightarrow A}(\kappa, i) = T_{B \rightarrow A}(\kappa, i) - T_{B_{shuffled} \rightarrow A}(\kappa, i) \quad (12)$$

where $T_{B_{shuffled} \rightarrow A}(\kappa, i)$ is the transfer entropy through the time series B, which is a shuffled form; that is, the values are selected randomly from the known values of time series B and rearranged with the observed values of B to form a new time series. This destroys the time series dependencies of B, in conjunction with the statistical dependencies between B and A. The convergence of $T_{B_{shuffled} \rightarrow A}(\kappa, i)$ with increasing sample size is zero, whereas small sample effects of $T_{B_{shuffled} \rightarrow A}(\kappa, i)$ results from nonzero value.

To get the bias-corrected transfer entropy estimate, take the average

of the shuffled transfer entropy estimates over all replications and subtract it from the Shannon or Rényi transfer entropy estimate.

The significance of the transfer entropy coefficients obtained by Eq. (12) may be investigated using a Markov block bootstrap (Dimpfl & Peter, 2013). This preserves the dependence between variables A and B yet ignores the statistical relationships that would be upset by shuffling. Repeated calculations of transfer entropy yield the coefficients with the null hypothesis of no information transmission. The related p-value is $1 - \hat{q}_T$, where \hat{q}_T represents the quantile of the simulated distribution, which is described by the transfer entropy estimate (Behrendt et al., 2019).

As Behrendt et al. (2019) described, transfer entropy calculations are based on discrete data; therefore, continuous data needs to be discretised perfectly to suit the distribution of the information used. Detailed explanations can also be found online by Behrendt et al. (2023) at this website <https://cran.r-project.org/web/packages/RTransferEntropy/vignettes/transfer-entropy.html>.

3.4. Data sources and description

The authors adopted 4 African daily stocks, divided equally between BRVM and ESG stocks. BRVM is a rapidly growing regional stock of eight members of WAEMU, which was started in 1998 but its daily quotation and continuous quotation began in 2001 and 2013, respectively. BRVM market, as tiny as it is, uses two value-weighted indexes to exhibit its market activities; the BRVM composite index (BRVMCI) comprises 0 ESG stocks that are gaining predominate in the world of investors and policymakers. However, information relating to ESG stocks relating to African markets is limited until the recent ESG stock from the Financial Times Stock Exchange (FTSE)/(JSE), which has two indices FTSE/JSE SA All Share Index (FTSEJSE) and FTSE/JSE Top 30 Responsible Investment Index (FTSERI). The composite stock price index is among the exceptional data reflecting economic realities. The index data is adopted to analyse and predict the perspective of markets. Therefore, the daily span data of BRVMCI, BRVM10, FTSEJSE, and FTSERI from 23/06/2014 to 22/04/2022. The dataset was merged to have a balance data of 1,899 observations. The period for the study was based on data availability, but it captured the birth of COVID-19 as a global pandemic and the 2007–2009 global financial crisis, among others. Daily data were used because the higher the frequency, the better the data can capture the fluctuation in the economical series. The BRVM stocks' data were obtained from the BRVM website, while the ESG stocks were downloaded from the SA shares website. All the stocks had US dollars as their currency value. As proven in numerous finance literature, working with asset prices directly less preferred to returns. Therefore, the study used daily log-returns of $\ln(\mathcal{R}_t) = \ln\left(\frac{\mathcal{P}_t}{\mathcal{P}_{t-1}} - 1\right)$, $r_t = \ln(1 + \mathcal{R}_t) = \ln(\mathcal{P}_t) - \ln(\mathcal{P}_{t-1})$, where r_t is the continuously compounded return and \mathcal{P}_t and \mathcal{P}_{t-1} are price at time t and its preceding price, respectively.

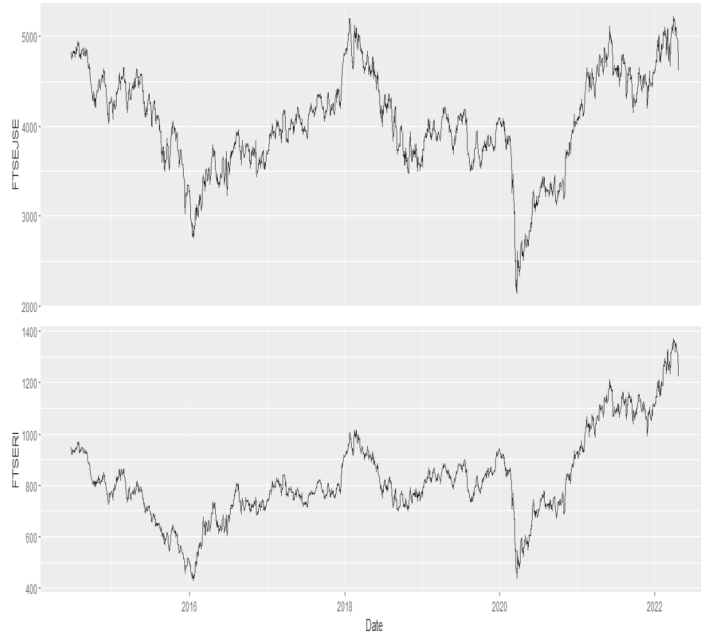
4. Results and discussion

The study description is first presented, and then Rényi Transfer Entropy. The descriptive statistics of the stocks are to validate the assumption underlining the adoption of Rényi Transfer Entropy.

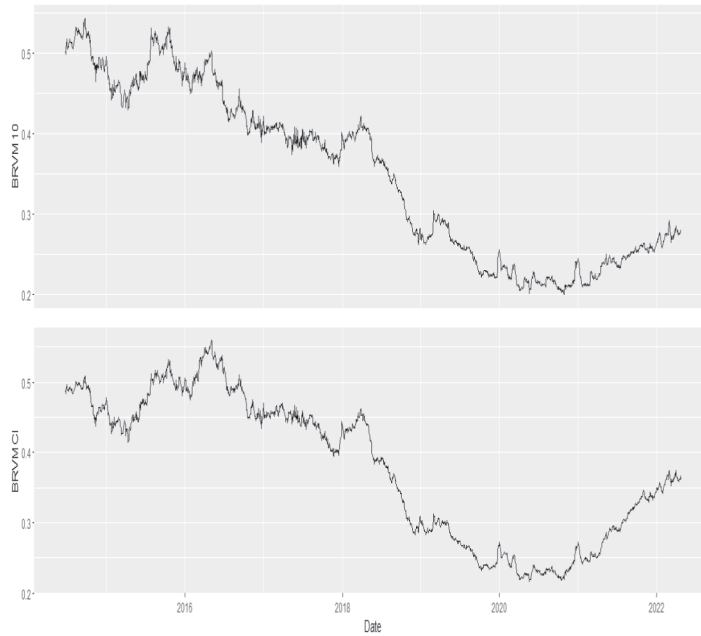
4.1. Descriptive analysis

Fig. 1 is grouped into four-part showing prices and returns of BRVM and ESG stocks. Prices and returns of ESG stocks are shown in quadrants A and B, respectively. Analogous to the prices and returns of BRVM stock in quadrants C and D. One can observe from the plots that the prices of FTSEJSE and FTSERI flatulated over the study period. It can be observed that the period with the most significant drop was 2020. This can be linked to the economic downturn that the health crisis, COVID-19, to various markets. After the early times of 2020, it can be noted that the

Prices

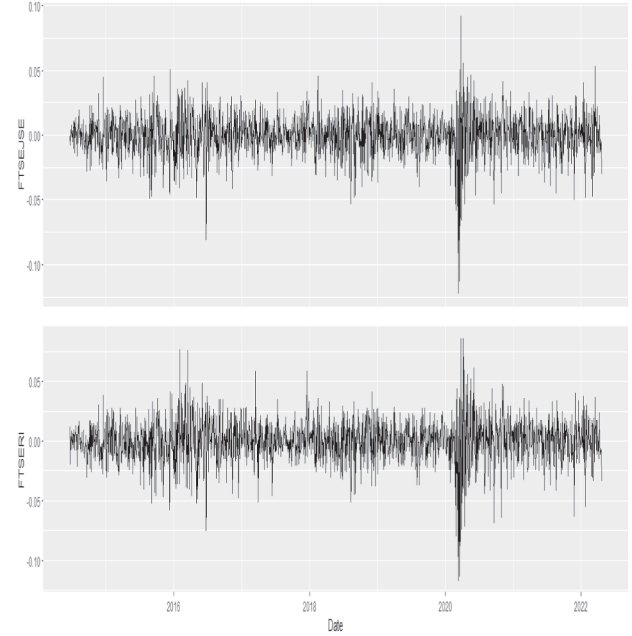


(a)

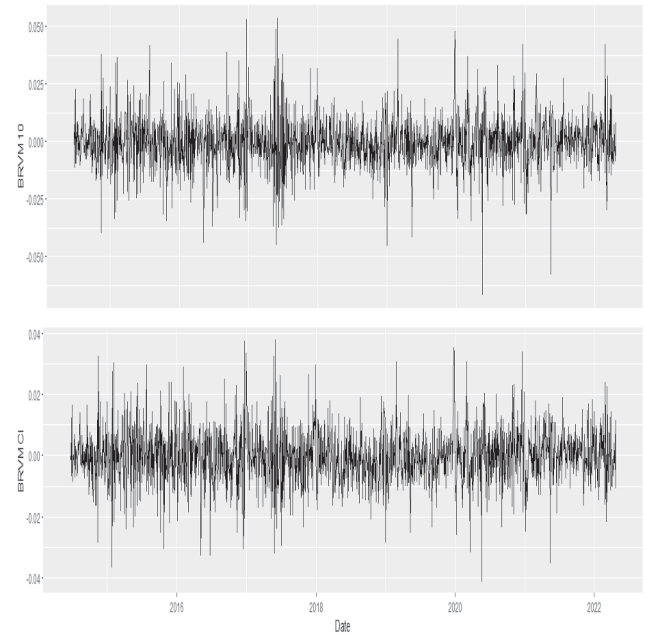


(c)

Returns



(b)



(d)

Fig. 1. Plots of price and returns series for BRVM and ESG stocks.

prices are rapidly rising; those times marked the beginning of the period where businesses have learned to deal with the pandemic. Quadrant C of Fig. 1 showed that BRVMCI and BRVM10 started experiencing a drop in prices in the early part of 2018 and started rising in the early part of 2021. Fluctuations in the BRVM stocks are more than that of the ESG stocks. This confirms the assertion of many researchers that ESG stocks are less risky than traditional stocks. The plot of the log-returns depicted volatility of return processes is not constant to time which is expected from any log-return financial series evidence from the stylised facts of asset returns.

The descriptive of the stocks used in this study is presented in Table 2. All the stocks had a negative mean return except FTSEI. The negative mean yields reflect the meagre performance of the financial assets during the study period, while the positive returns showed that the stock performs better (Asafo-Adjei et al., 2022). The negative skewness values for the ESG stocks propose that investors should trade in these stocks with caution since it carries features of lower returns and few significant losses in an unforeseen future. Also, the skewness results depicted nonnormality for all stocks, with BRVM10 showing a skewness value close to the normality of 0.086583. The kurtosis value expressed

Table 2
Descriptive statistical analysis.

	Mean	Std. Dev.	Skewness	Kurtosis	Jarque-Bera	KPSS
BRVM10	−0.00030394290	0.011164	0.086583	6.342616	886.4427***	0.15919
BRVMCI	−0.00015149160	0.008998	0.093521	4.781119	253.7833***	0.34695
FTSEJSE	−0.00004994269	0.016549	−0.658738	8.361442	2411.793***	0.08297
FTSERI	0.00014557370	0.018334	−0.476741	7.427193	1622.787***	0.17187

Note. significance level of 10%, 5%, and 1% levels are represented with *, **, and ***, respectively.

that the distribution of the stocks is leptokurtic, with FTSEJSE having the highest value of 8.361442. The significance of the Jarque-Bera values confirms that the dataset is not normally distributed. The stationarity test from Kwiatkowski–Phillips–Schmidt–Shin (KPSS) shows that all the return series are stationary with a null hypothesis of stationarity condition. Though the returns are stationary, CEEMDAN-based-Rényi transfer entropy handles issues such as non-normality, dormant non-stationarity and asymmetry relationship (Torres et al., 2011).

Five different non-linearity tests were done for each of the four stocks. The results indicated a mixture of linear and non-linear relationships at different significant levels, as displayed in Table 3. CEEMDAN-based-RTE was employed to deal with the non-linearity issues in the log returns.

4.2. Ceemdan-based- Rényi transfer entropy

The transmission of information between the BRVM and ESG stocks is investigated. We concentrated on the bidirectional movement from BRVM to ESG markets. ETEs with both negative (high risk) and positive (low risk) are generated using the RTE approach (low risk). Negative and positive receiving ETEs are paired to provide diversification. The results were analysed from a portfolio diversification perspective. Diversification is achievable among BRVM when negative ETEs receivers are matched with positive ETEs recipients. Still, diversification is possible between BRVM and ESG when ESG that negatively responds to shocks from (to) BRVM is used (Bossman et al., 2022). A parameter weight of 0.30 is used to deal with fat tails in the return series, which corresponds to the stylised truth about financial time series (Behrendt et al., 2019). Black spots inside blue bars represent ETEs. Confidence bounds of 95 percent are seen at the tip of the blue bars. The decision rule is that the null hypothesis of “no information flow” is rejected if these confidence limits overlap at the origin.

The results are presented from the 9 IMFs and a residue obtained CEEMDAN for BRVM and ESG stocks, as well as their log-return values. This was done to fully present and gain more insight into the time variability of the flows and further deal with non-linearity, non-stationarity, and asymmetry that distract the true nature of the time series. The 9 IMFs and the residual were grouped into the short-term, medium and long-term. The IMFs were characterised from (IMF 1–3) as short term, (IMF 4–6) as medium-term and (IMF 7–9) as a long term. The residue is the non-oscillating drift of the data that is unaffected by short-to-medium-term variations (Asafo-Adjei et al., 2022; Agyei et al., 2022; Bossman et al., 2022; Owusu Junior et al., 2021). It is the long-term trend of BRVM and ESG stocks which is influenced by factors such as earning base and valuation multiple (Adam & Owusu Junior, 2017); technical factors (Narayan et al., 2014); market sentiment factors

(Hasselmann & Kovalevsky, 2013); and market anomalies (Hasselmann & Kovalevsky, 2013). (Ferrouhi et al., 2021).

According to Yang et al. (2018), the short term is defined by market dynamics and investor attitudes; the medium period is determined by the effect of key proceedings, whereas fundamental market characteristics define the long run. The IMFs help distinguishes between the market dynamics for BRVM and ESG stock markets in this study, which is necessary to establish or foresee how shocks to one market (BRVM or ESG) affect the other (BRVM or ESG) over asymmetric periods. The entropies of the residual might be used to identify whether short and intermediate market dynamics persist through the long-term trend.

Identifying these processes is critical for market players to forecast the responses of ordinary investors, speculators, hedgers, and institutional investors during uncertain periods. The log return entropies are insufficient to solve this problem since they imply symmetric information flow, implying that investors react to market dynamics similarly. Using log return data series and the resulting RTE only reinforces the idea that market member behaviour and reaction are uncomplicated, which runs counter to the AMH, HMH, and CMH.

4.2.1. Information flow between BRVM and FSTERI stock

Rényi's effective transfer entropy for Fig. 3 has numerical representation in Tables 4 and 5. The results show that most of the information flow between BRVM stock and FSTERI at different time scales is insignificant, consistent with the information between African stock markets (Nyakurakwa 2021). This is not surprising as JSE is reported to be integrated more with the global market than regional connectedness to other African markets (Agyei-Ampoah 2011). However, in the short term, there is a significant flow of information from BRVM to FSTERI; in the medium term, there is a substantial flow of information from FSTERI to BRVM stocks. The short- and medium-term results move away from the results of Alagidede (2009). The returns value showed a positive significant information flow between BRVM and FSTERI stocks which is inconsistent with (Agyei-Ampoah 2011; Alagidede, 2009; Nyakurakwa 2021). It is observed that the flow of information between these markets is positive at all investment horizons with a mixture of significance and insignificance, with consistent literature concentrating on the integration of the African market (Agyei-Ampoah 2011; Alagidede, 2009; Jefferis & Okeahalam, 2015; Nyakurakwa 2021). The positive transmission of information from BRVM stock to FSTERI in the short term is not encouraging for diversification purposes (Bossman et al., 2022). The same applies to the medium-term transmission from FSTERI stock to BRVM. As a result, the mutual information shared by BRVM and FSTERI stocks is less problematic for each other. However, in the medium and long transmission from BRVM to FSTERI and short and long-term transmission from FSTERI to BRVM, a market participant can trade

Table 3
Non-linearity tests for brvm and esg stocks.

	Teraesvirta's Neural Network Test	White neural network test	Keenan's one-degree test for non-linearity	Tsay's test for non-linearity	Likelihood ratio test for threshold non-linearity
BRVM10	5.5009*	3.1705	0.3414077	3.072***	16.13848
BRVMCI	5.8142*	4.799*	2.853008*	2.351***	20.65915*
FTSEJSE	5.3336*	10.711***	13.11993***	5.05***	28.23684**
FTSERI	13.652***	8.6587**	2.951394*	3.873***	76.25924***

Note. significance level of 10%, 5%, and 1% levels are represented with *, **, and ***, respectively.

Table 4
Information flow towards FSTERI.

	BRVM10			BRVMCI		
	ETE	se	T.S	ETE	se	T.S
Returns	0.001972675	0.000815657	2.418511	0.00210616	0.000902593	2.333459
IMF.1	0.003774447	0.000907831	4.157655	0.00380116	0.000895599	4.244264
IMF.2	0.003674197	0.000867488	4.235444	0.00347664	0.000919898	3.77937
IMF.4	0.000050701	0.000864558	0.058644	0.00007299	0.000822742	0.088715
IMF.5	0.000063804	0.000841962	0.07578	N/A	N/A	N/A
IMF.6	0.001212803	0.000715871	1.694165	0.00120177	0.000712773	1.686054
IMF.9	0.0003332	0.00058172	0.572783	0.00037479	0.000644155	0.581837

Note: Some of the IMFs were not presented because they had ETE of zero.

Table 5
Information flow from FSTERI.

	BRVM10			BRVMCI		
	ete	se	T.S	ete	se	T.S
Returns	0.004538089	0.000845301	5.368609	0.004677641	0.000815075	5.738905
IMF.1	0.000358	0.000939251	0.381486	0.000475	0.000965779	0.4914
IMF.2	0.001238	0.000855733	1.44668	0.001143	0.00088716	1.288691
IMF.3	0.000873	0.000882797	0.988359	0.000842	0.000854166	0.985968
IMF.4	0.004748	0.00086256	5.504834	0.004815	0.000844132	5.704144
IMF.5	0.004687	0.000742523	6.311627	0.004598	0.000833648	5.515595
IMF.6	0.001771	0.000691143	2.561766	0.001767	0.000658433	2.684207
IMF.9	0.000322	0.000600395	0.536682	0.000403	0.000689631	0.584875

Note: Some of the IMFs were not presented because they had ETE of zero.

with caution, which might yield diversification (Nyakurakwa 2021).

The results of the information flow between the BRVM and FSTERI attempt to monitor each other's behaviour directly with little ambiguity. However, because market players react to information at various periods, the multiscale reveals distinct information flow values at different terms, resulting in the AMH, HMH, and CMH. The non-significant flow from both markets helps investors diversify from the short-medium-long term. Therefore, investors with a medium to long-term interest can invest in BRVM stocks to gain higher earnings in the future because the information flow in these horizons is insignificant. Looking at the two BRVM stocks in Fig. 3, it can be observed that the one stock could not dominate the information flow in all investment horizons. There were variations in the flow; in the short term, it was BRVM10 having the least ete values, but in the medium term, BRVMCI took over. This illustrates the dynamic in investment decision-making and how market players respond to market information differently at different investment horizons.

4.2.2. Information flow between BRVM and FSTEJSE

We further showed if there is information sharing between BRVM stocks and FSTEJSE in Fig. 4 and presented their ETEs values in Tables 6 and 7. In the short, medium and long term (Fig. 4, Table 6), we find less diversification potential from the ETEs. However, at IMF1, IMF4, IMF5 and IMF9, we have significant positive ETEs that need to be singled out as positive Rényi transfer entropy; according to Behrendt et al. (2019), means that knowing the other variable reduces the risk of knowing the

dependent variable. At these IMFs, the FSTEJSE market transmits positive information flow to BRVM. Which characterised that FSTEJSE stock is less risky than BRVM stocks in information sharing. The less risk coverage between FSTEJSE and BRVM indicates that on the horizon where financial markets are experiencing a rebound, there will be no need to reconstruct their portfolio. The returns ETE also follow this same sharing habit which is positive. Fig. 4, with values confirmed from Table 7, shows that only the returns and the first two IMFs have significant positive ETE. The remaining ETEs are insignificant. This indicates that investors looking at medium- and long-term returns can diversify their investment with BRVM. As a result, knowledge of BRVMCI and BRVM10 can lower the risk of the FSTEJSE in comparison to the key information flows represented in Fig. 4. However, the extents of the Rényi ETE estimates are similarly very low, indicating that the value of tail dependency is close to zero yet considerable, as seen in Fig. 4. This shows that there is weak integration between the two markets. Fig. 4 further indicates that the flow of information from the FSTEJSE to the BRVM is unidirectional at extreme distributions, showing information flow from the more developed FSTEJSE to the less developed BRVM. The findings confirm the assertion of Alagidede (2019), which is that African market integration has low geographical and economic ties.

4.3. Model robustness check using DCC-GARCH

The results from the log-returns RTE are static in the time and

Table 6
Information flow from FSTEJSE.

	BRVM10			BRVMCI		
	ETE	Se	T.S	ETE	se	T.S
Returns	0.004329861	0.000893143	4.847889	0.004288771	0.000826817	5.187086
IMF.1	0.002496038	0.000940904	2.652807	0.002299548	0.000916463	2.509154
IMF.2	0.000866299	0.000851046	1.017923	0.000804298	0.000933232	0.861841
IMF.4	0.002589888	0.000823237	3.145981	0.002647819	0.000934944	2.832061
IMF.5	0.004138538	0.000837575	4.941093	0.004054681	0.00085092	4.765055
IMF.9	0.001308632	0.000607164	2.155317	0.001313677	0.000591064	2.222562

Note: Some of the IMFs were not presented because they had ETE of zero.

Table 7
Information flow towards FSTEJSE.

	BRVM10			BRVMCI		
	ETE	se	T.S	ETE	se	T.S
Returns	0.00556700	0.00085400	6.515158	0.00562921	0.000922933	6.099263
IMF.1	0.00417602	0.000885009	4.71861413	0.00406482	0.000971964	4.182068
IMF.2	0.00446931	0.00093296	4.790456555	0.004659744	0.000951626	4.896612
IMF.3	0.00218326	0.00084692	2.577880573	0.002125476	0.000819669	2.593091
IMF.4	0.00008754	0.000844288	0.103688379	0.0000775131	0.000867873	0.089314
IMF.6	0.00011877	0.000707424	0.167892769	0.000166864	0.000687478	0.242719
IMF.7	0.00078175	0.000609919	1.281719804	0.000843705	0.000643027	1.312084
IMF.9	0.00012966	0.000677075	0.191506609	0.0000430952	0.000574252	0.075046

Note: Some of the IMFs were not presented because they had ETE of zero.

frequency domain. This type of model comes with a weakness. Therefore, the authors employed Dynamic Conditional Co-variance-generalised auto-regressive Conditional Heteroscedasticity (DCC-GARCH) postulated by Engle (2002) to check the robustness of the log-returns RTE through re-estimation of the nexus between BRVM and ESG. DCC-GARCH addresses the static weakness by estimating time-varying volatility and correlations between BRVM and ESG. It focuses on assessing the degree of co-movement or correlation between variables, while considering volatility clustering and time-varying correlations. The rationale for comparing or equating these two methods stem from their common goal of capturing interdependencies between variables, albeit through different statistical approaches. The researchers aimed to cross-validate our findings by using different methodologies to study the same phenomenon. While CEEMDAN based RTE delves into the information flow aspect, DCC-GARCH focuses more on conditional correlations but could still reveal similarities or patterns in the relationship between variables. The mathematical computation of the DCC-GARCH model is presented in Appendix. However, Fig. 2 shows the conditional correlation results from the DCC-GARCH model. Fig. 2 confirms the results presented for the log-returns RTE in Figs. 3 and 4. The results showed a positive condition correlation between BRVM and ESG stock, confirming the positive information flow from results presented in

Figs. 3 and 4. The correlation value fluctuates between -0.25 and 0.25 , with the majority above 0 . This confirms the weak connection postulated from the RTE results. The decomposed series were ignored because they are already a time-varying dynamic model.

4.4. Theoretical and practical underpinnings

The results are essential to diverse investors on the different horizons; short-, medium-, and long-term. These investors' behaviours are not constant as posited by the competitive markets' hypothesis CMH that information sharing among markets intensifies due to participant behaviour (Owusu Junior et al., 2021). Individual financial markets may be vulnerable to significant integration due to the intensity of information flows across markets (both comparable and different) (Nyakurukwa, 2021). From the mutual information supplied by these BRVM and ESG stocks monitoring each other, information flows are minimal causal fluxes. The lack of connection between these two stocks, as shown by the decomposed results, can be linked to the lack of economic integration between these two stock markets. Also, the low linkage can be attributed to a lack of liquidity (Gbenro & Moussa, 2019; Ouattara, 2016) from the stock exchanges. Elyasiani et al. (1998) posited that weak interdependence between Sri Lankan stock exchanges and their trading partners is

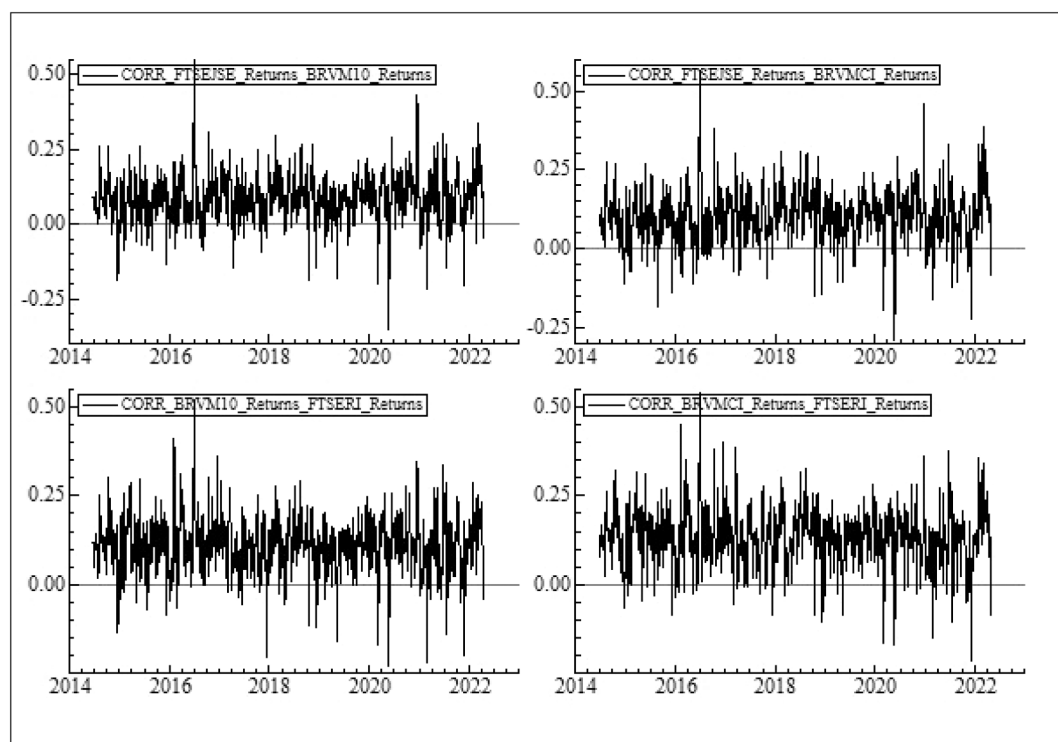


Fig. 2. Condition Correlation between BRVM and ESG stocks.

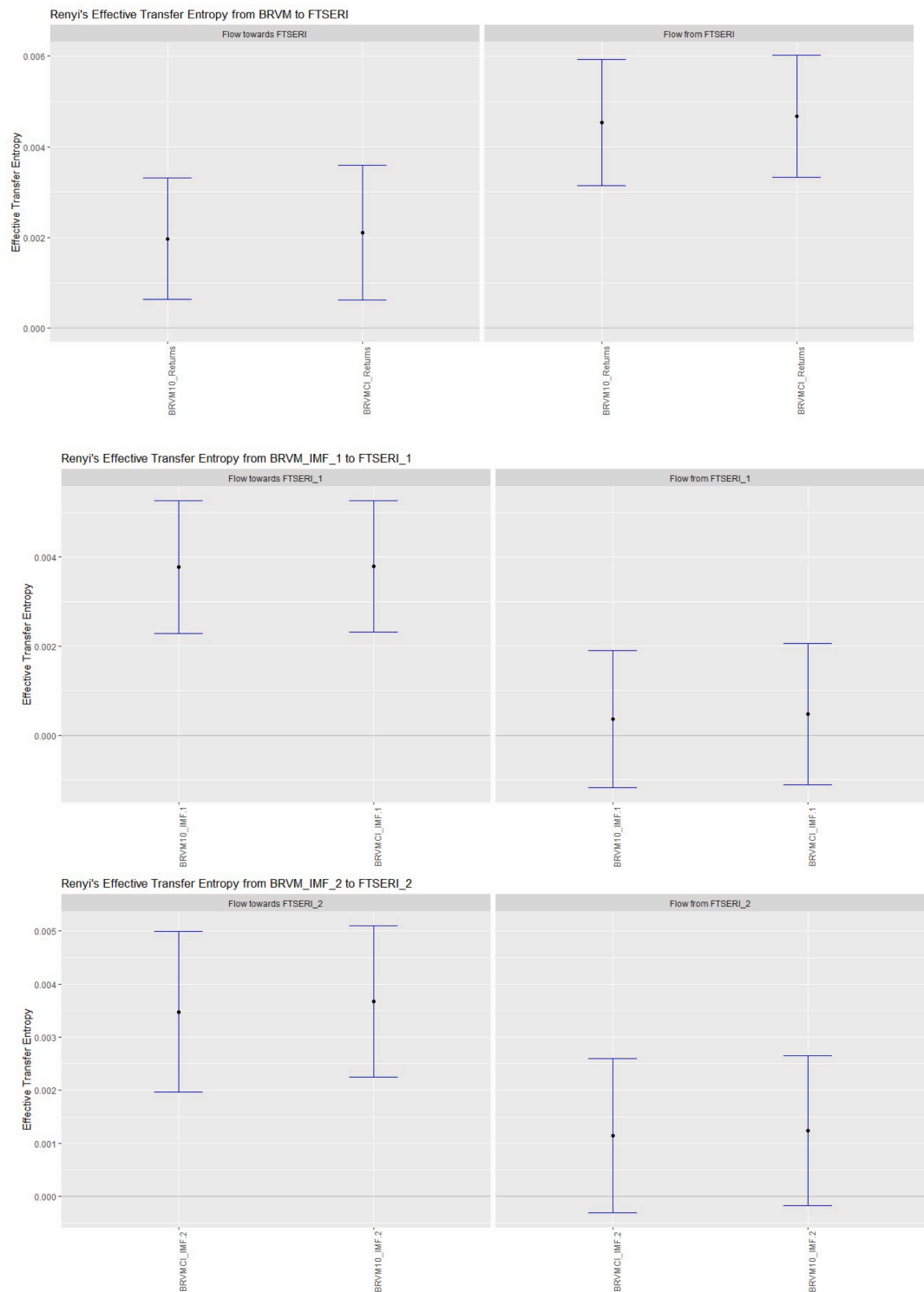


Fig. 3. Rényi transfer entropy between BRVM and FTSERI.

a problem of illiquidity. The lack of information flow between BRVM and ESG stock from JSE confirms the proposition made by [Mollah & Mobarek \(2016\)](#) that internationalisation and globalisation have not led to the co-movement of the between these specific stock exchanges. Although, internationalization and globalization typically suggest increased interconnectedness and integration among global financial markets.

From the return results, where the data was not decomposed to

overcome the complexity and non-linearity of the data series, we saw a positive information flow between BRVM and ESG stocks. Positive information flow suggests that changes or movements in BRVM tend to influence or predict similar movements in ESG stocks. This indicated that the risk of ESG stocks could be reduced by the knowledge of BRVM stocks ([Behrendt et al., 2019](#)). Thus, there is a degree of synchrony or co-movement between the variables or markets involved. CEEMDAN was used to break down the returns into intrinsic periods, which reflect the

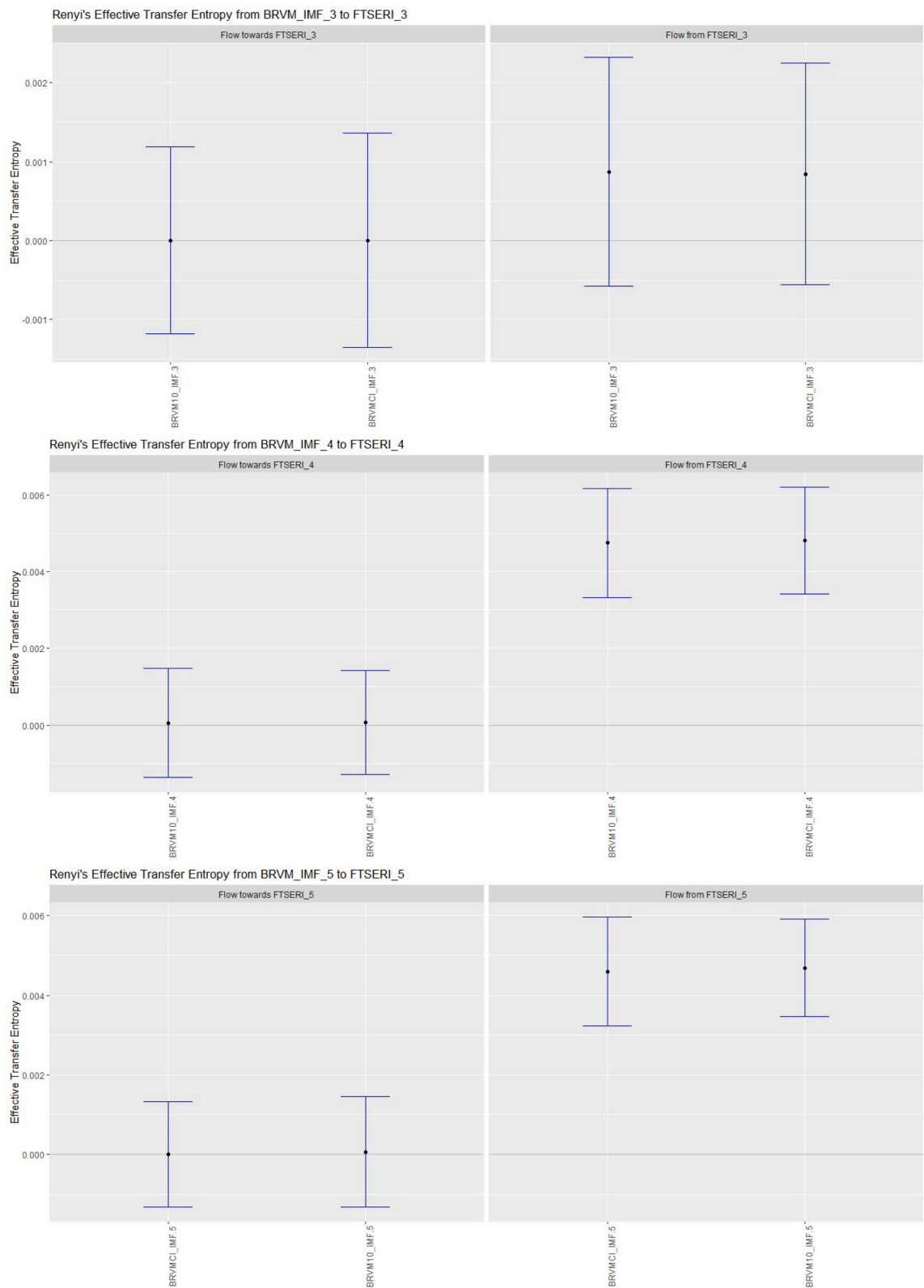


Fig. 3. (continued).

short, middle, and long-term perspectives. This allowed researchers to understand investor reactions' dynamic nature better while reducing noise in the data. This will also help short-term gain-seeking investors (speculators and hedgers), whereas institutional investors are more concerned with long-term returns (Bossman et al., 2022). Medium-term

investors sit between short- and long-term investors, regularly monitoring and rebalancing their portfolios to take advantage of medium-term profits. Our results in the frequency domain contribute significantly as crucial inputs for time-scale-based investment decisions. In the near run, our research revealed that BRVM and ESG stocks do not

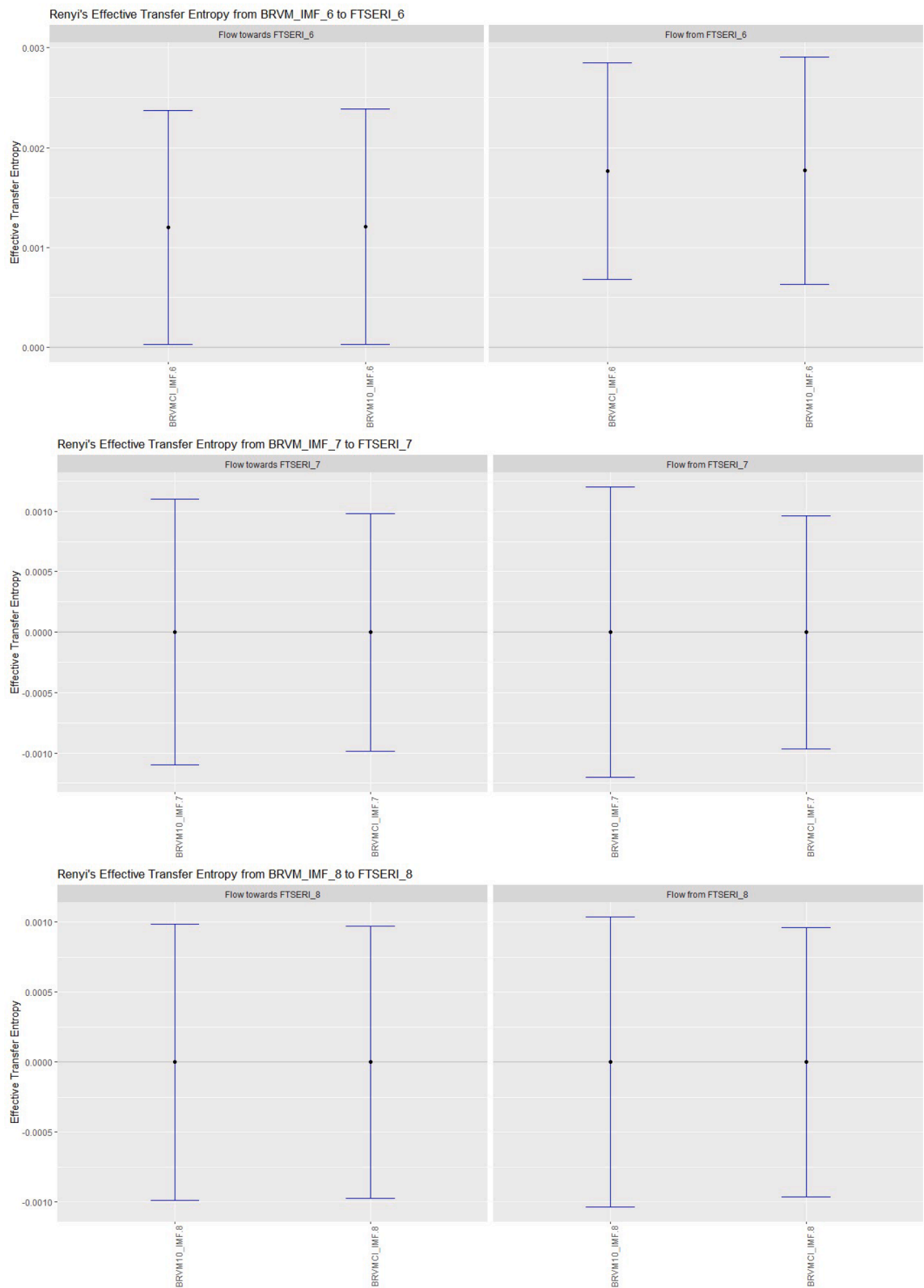


Fig. 3. (continued).

provide investors with diversification benefits. These investment vehicles are suitable for speculators and hedgers since they are less problematic. BRVM may be potential ESG diversifiers for medium-term investors, although their usefulness as diversifiers may be inconsistent due to the significant connections discovered with ESG stocks. It is implied that ESG and BRVM assets portfolios should be monitored in the

medium term to conduct successful rebalancing evaluations. On a more positive note, long-term investors, such as institutional investors, may also gain from BRVM and ESG. BRVM act as a long-term diversifier for ESG investments.

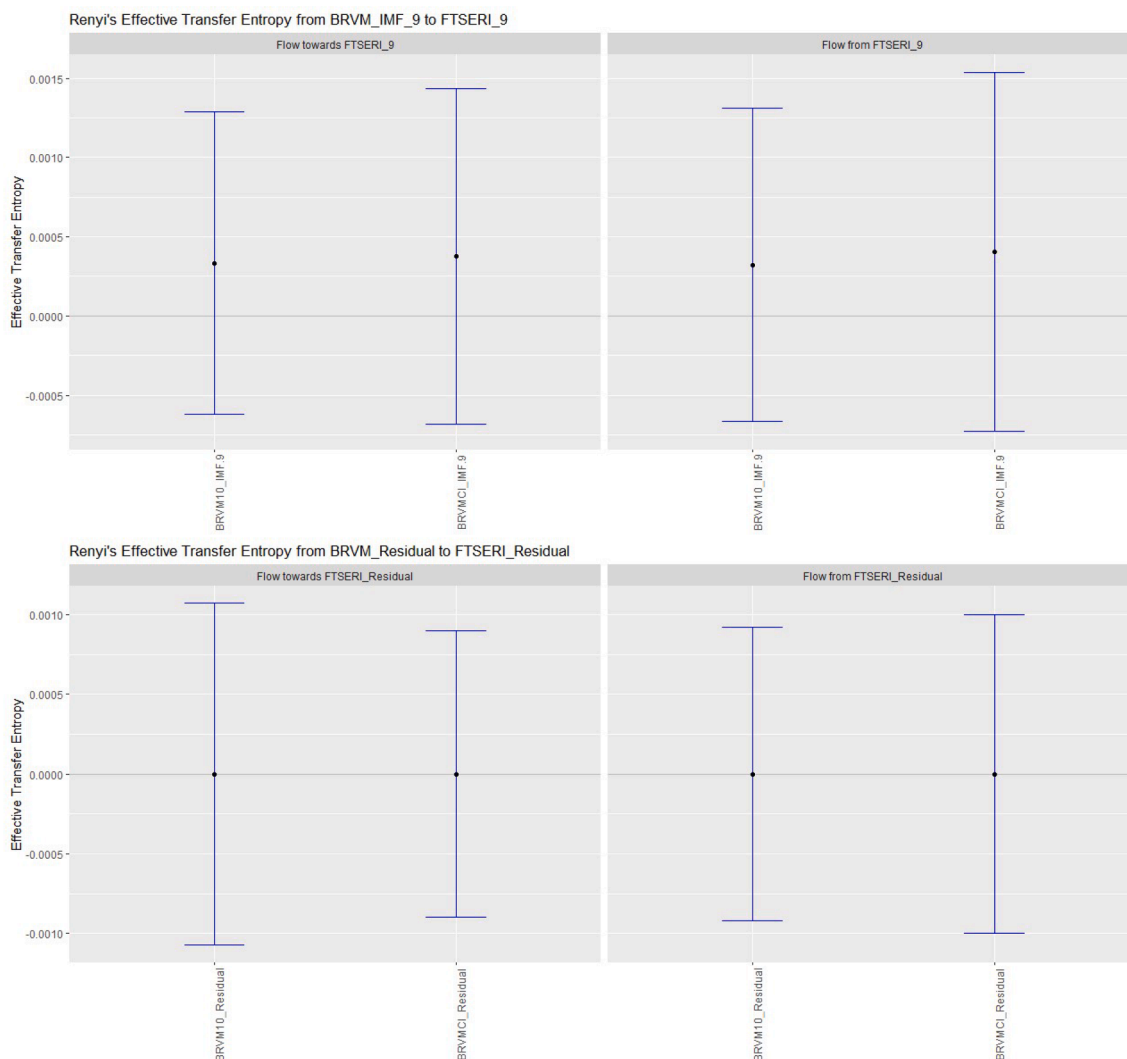


Fig. 3. (continued).

5. Conclusion

The study aimed to assess the information flow between BRVM and ESG stocks from the time and frequency domain perspective and to examine if the information flow offers diversification, haven or hedging options for market participants. The study answered (i) Is there information flow between BRVM and ESG stocks? And (ii) at what time horizon would diversification, haven or hedging options for market participants be possible? Four daily stock markets were employed, and BRVM and ESG stocks were shared equally. Therefore, the daily span data of BRVMCI, BRVM10, FTSEJSE, and FTSEI from 23/06/2014 to 22/04/2022. The returns were also decomposed with CEEMDAN into short, medium and long-term ranging from IMF of 1–9 and a residual value. The decomposition helps to relate the study to the propositions made by AMH, CMH, and HMH, which move away from the ideas of EMH. The RTE follow a parameter weight of 0.30, which was postulated by Behrendt et al. (2019). The results are presented with standard errors and t statistics for hypothesis testing.

The log-return results showed a positive significant information flow between BRVM and ESG stocks. However, the value of the coefficient was low, indicating that the integration between the two markets is low. According to the literature, the larger the quantity of information exchange among financial markets, the more integrated those markets are. The positive results also indicate that the risk of ESG stock can be reduced by knowledge about BRVM stocks. The results showed that

information flowed more from the ESG to BRVM, representing developed and less developed stock markets.

The results revealed different market participant attitudes at various time horizons. This leads to diversification options for investors interested in BRVM and FTSEJSE between the medium and long term. In contrast, in the medium and long transmission from BRVM to FTSEI and short and long-term transmission from FTSEI to BRVM, a market participant can trade with caution, which might yield diversification. The findings lead the research to support the EMH (Fama, 1970; Fama, 1977) in the long run; however, it deviates from endorsing AMH (Lo, 2004), the HMH (Müller et al., 1993) and the CMH (Owusu Junior et al., 2021) in the short and medium-term. The EMH was supported because there was no information flow between BRVM and ESG stocks in the long term (Bossman et al., 2022).

The results postulated that market participants' behaviours are not constant. They respond to what the market offers them every time by organising their portfolio to meet their set objectives. The findings are solely positive significant, and insignificant information flow. This indicates that BRVM and ESG stocks share less risk and that the two markets have little influence on one another (Asafo Adjei et al., 2021). The behavioural change in the short and medium-term can be linked to Speculators and hedgers who are interested in now-gains which most investors feel that they are not sustainable and therefore are classified as noise and dismissed (Bossman et al., 2022; Cornell et al., 2018; Hassani et al., 2010; Owusu Junior et al., 2021).

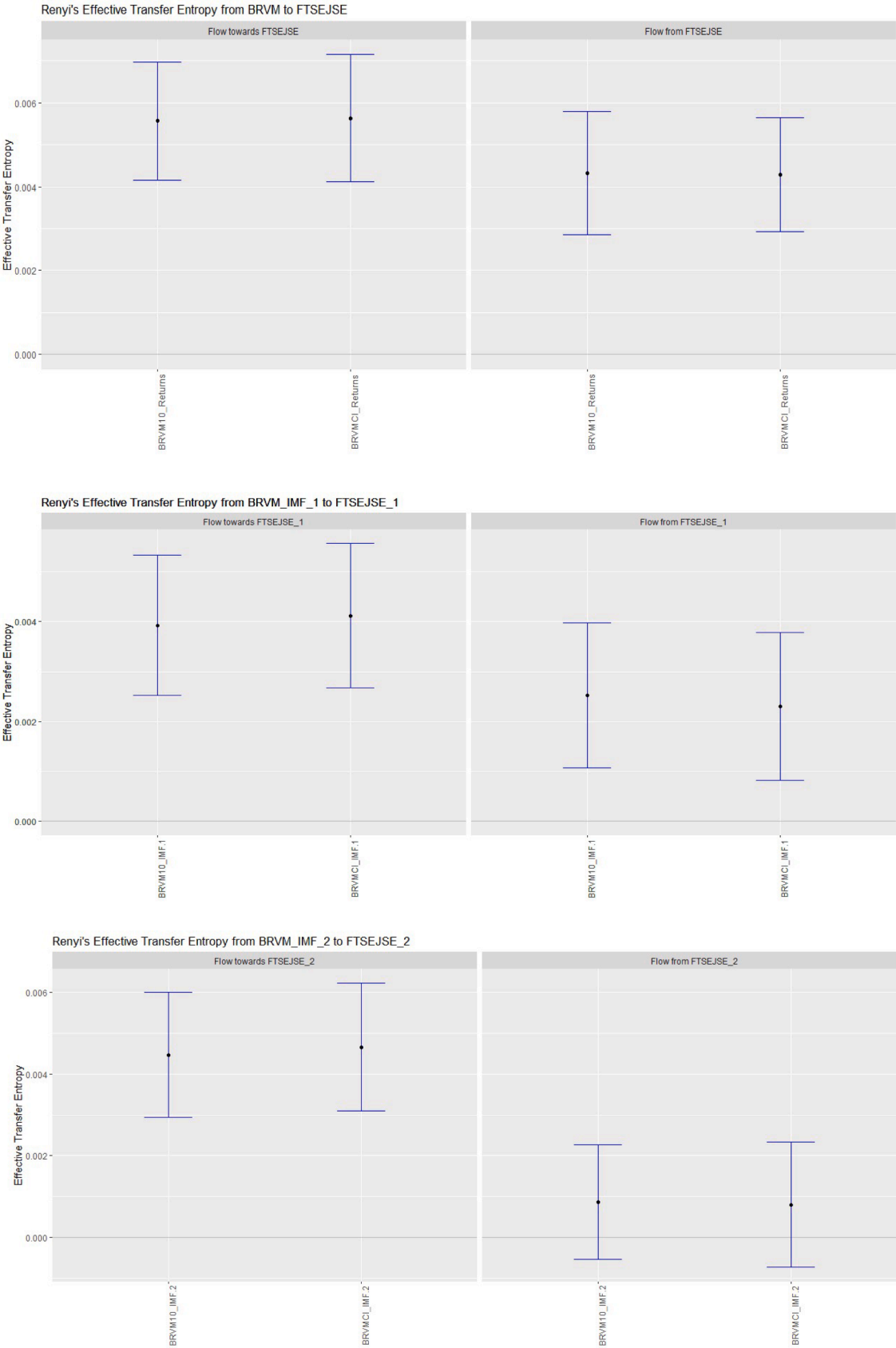


Fig. 4. Rényi transfer entropy between BRVM and FTSEJSE.

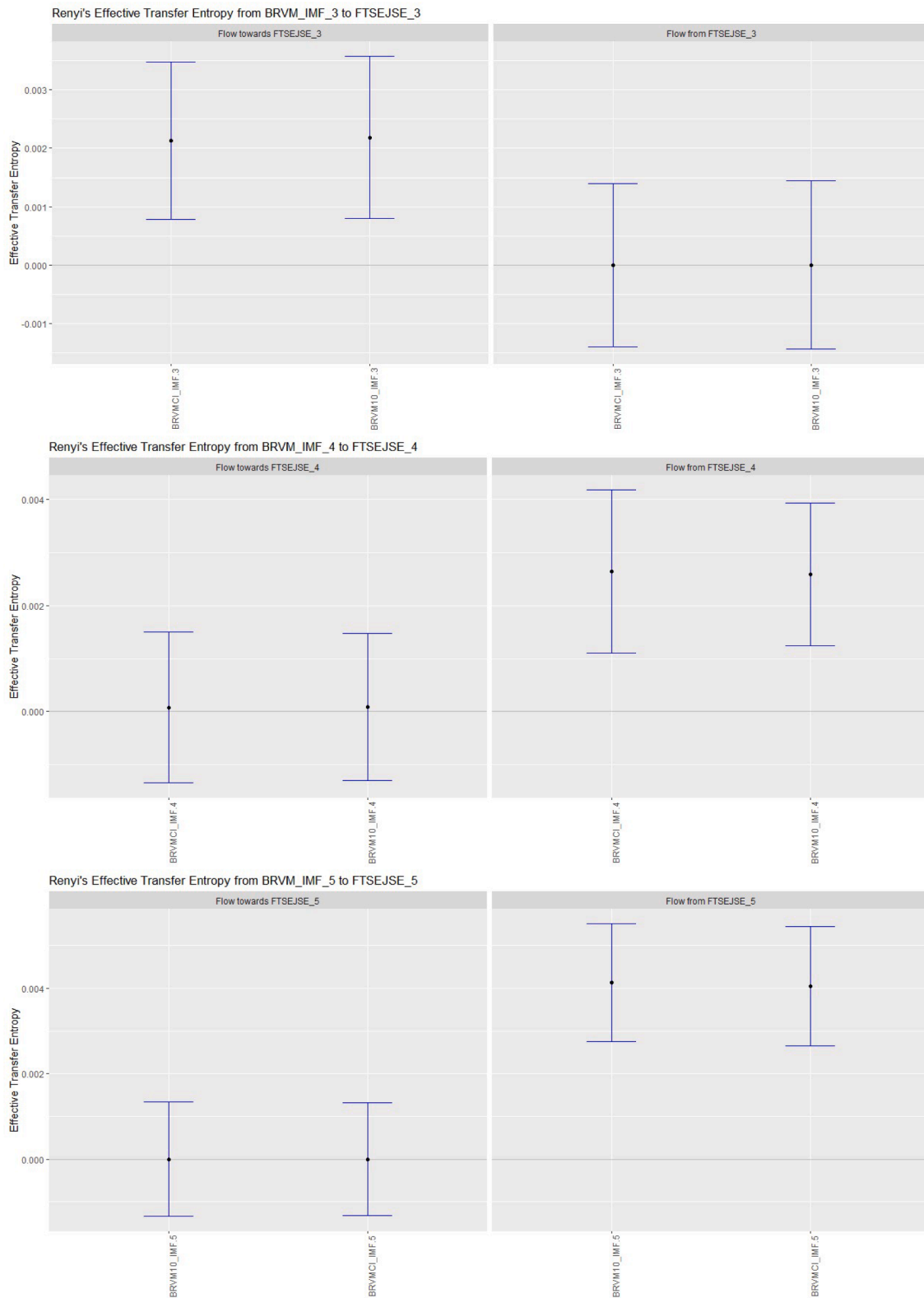


Fig. 4. (continued).

The policy implication from this study offers different importance to diverse stakeholders. First, the positive significant information flow provides investors insight that the two stocks have little risk sharing. Also, the little information flow between BRVM and ESG stocks from JSE provides a diversification option for institutional investors and fund managers. Managers of these stock exchange markets should offer

opportunities and negotiate which governments can deliver economic and political ideas to improve these markets' integration. The integration will provide more benefit to BRVM than JSE because BRVM is less developed and illiquid. The integration will also minimise the cost of equity and increase economic growth. Also, the tail dependence shown from the results revealed a high probability of these markets coming

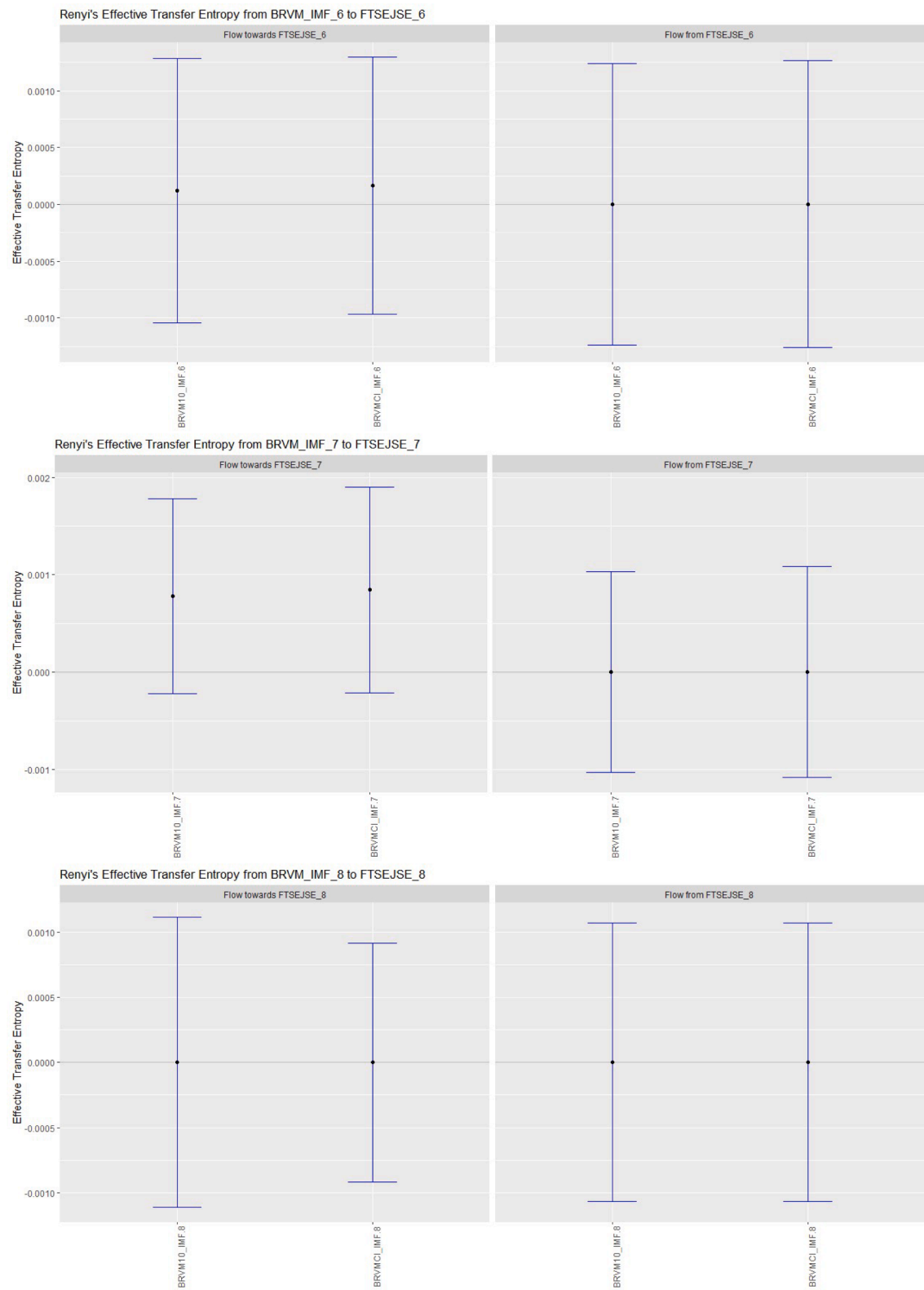


Fig. 4. (continued).

together.

The study is limited to four stock returns from two stock exchange markets. Also, the study is limited to one value of the parameter weight of 0.3. Further studies can employ more stock markets in Africa to assess information flow between the markets to account for the integration of the financial market. Another method should provide more insight into

the interconnection to African stock markets. Future researcher can apply network analysis techniques to visualize and comprehend the complex relationships between BRVM and ESG stocks. Investigate the network structures, centrality measures, or clustering patterns to identify key influencers, critical pathways, or nodes affecting information flow. Individual stock market returns can also be employed as well as

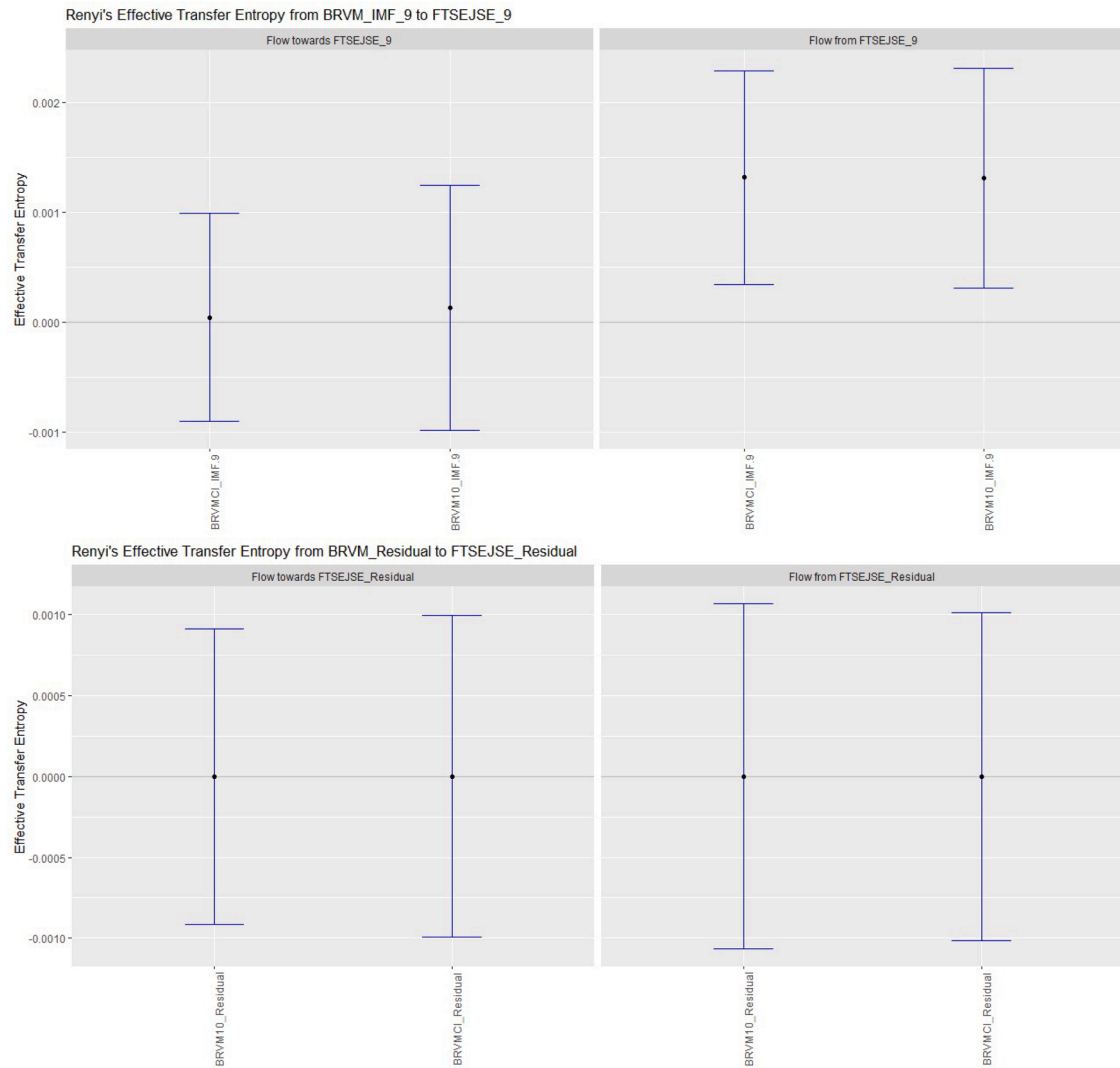


Fig. 4. (continued).

stocks and exchange rates of various countries on the stock exchange.

CRedit authorship contribution statement

Collins Baffour Kyei: Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **George Oppong Appiagyei Ampong:** Methodology, Writing – original draft. **Peterson Owusu Junior:** Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Kwame Simpe Ofori:** Data curation, Visualization, Visualization. **Kan David N'Dri:** Investigation, Supervision. **Koffi N'Da:** Formal analysis, Software, Visualization.

Appendix

DCC-GARCH model follows:

$$H_t = \mathcal{D}_t \mathcal{R}_t \mathcal{D}_t$$

H_t is a conditional variance matrix, \mathcal{D}_t is a $k \times k$ diagonal matrix with a conditional variance $\sqrt{H_{it}}$ on its diagonals and \mathcal{R}_t vary with time (off-diagonal elements). The conditional variance \mathcal{H}_{it} for the indices is estimated using the univariate GARCH (X, Y) model as shown below:

$$\mathcal{H}_{it} = \omega_i + \sum_{s=1}^{s_i} \alpha_{is} \mathcal{H}_{it-s}^2 + \sum_{y=1}^{y_i} \beta_{iy} \mathcal{H}_{it-y} \text{ for } i = 1, 2, \dots, \mathcal{K}$$

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The dataset employed in the study is publicly available on the website stated in the data description section. Therefore, the authors did not share the data.

Where α_i , α_i and β_{iy} are non-negative and

$$\sum_{i=1}^{x_i} \alpha_{ix} + \sum_{y=1}^{y_i} \beta_{iy} < 1,$$

α_{ix} is the short-run tenacity of the shocks to returns Y to long-run persistence (the GARCH effects), and the number of assets is denoted by k . Furthermore, the residuals (ε_t) and the conditional standard deviations ($\sqrt{H_{it}}$) are obtained. A diagonal matrix expresses the conditional standard deviation D_t , which consists of ($\sqrt{H_{it}}$)

$$\mathcal{D}_t = \begin{bmatrix} \sqrt{h_{11,t}} & 0 & \dots & 0 \\ 0 & \sqrt{h_{22,t}} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \vdots & \sqrt{h_{kk,t}} \end{bmatrix}$$

The standardised residuals ($\sigma_{jt} = \frac{\varepsilon_{jt}}{\sqrt{h_{11,t}}}$) are further used for estimating time-varying (namic) correlation matrix \mathcal{R}_t :

$$R_t = \dot{Q}_t^* \dot{Q}_t^*$$

$$\dot{Q}_t^* = \begin{bmatrix} \sqrt{q_{11}} & 0 & \dots & 0 \\ 0 & \sqrt{q_{22}} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \vdots & \sqrt{q_{kk}} \end{bmatrix}$$

Where \dot{Q}_t^* is the diagonal matrix of its diagonal elements as expressed in the above equation. \mathcal{Q}_t is a symmetric positive definitive conditional variance matrix $\mathcal{Q}_t = (q_{ijt})$ and \dot{Q} is unconditional covariance of the standardised residual of the univariate GARCH model.

$$Q_t = (1 - \alpha - \beta)\dot{Q} + \alpha\varepsilon_{t-1} - \alpha\varepsilon_{t-1} + \beta Q_{t-1}$$

The conditional correlation

$$\rho_{ijt} = \frac{q_{ijt}}{q_{ij,t}q_{ij,t}} \text{ can be expressed in a typical correlation form by putting } \mathcal{Q}_t = (q_{ijt})$$

$$\rho_{ijt} = \frac{Q_t = (1 - \alpha - \beta)Q + \alpha\varepsilon_{t-1} - \alpha\varepsilon_{t-1} + \beta Q_{t-1}}{\sqrt{(1 - \alpha - \beta)Q + \alpha\varepsilon_{t-1} - \alpha\varepsilon_{t-1} + \beta Q_{t-1}} \sqrt{(1 - \alpha - \beta)Q + \alpha\varepsilon_{t-1} - \alpha\varepsilon_{t-1} + \beta Q_{t-1}}}$$

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