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Research article

Return connectedness and portfolio implications of green equities: A comparison of green and conventional investment modes

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ABSTRACT

The notable expansion of the green equity market has opened up new avenues for investment for market participants. This study looks at return connectedness, and the implications for portfolio management of green sector equities, and compares the performance of green and traditional investments. To achieve the research objectives, this study uses the TVP-VAR model along with portfolio strategies such as minimum variance portfolio (MVP), minimum correlation portfolio (MCP), and minimum connectedness portfolio (MCoP). Results demonstrate that the energy efficiency sector leads all others in information spillover while the bio/clean fuels sector is the largest net information absorber. Overall, energy efficiency, water, recycling and green building are found to be closely connected sectors, whereas bio/clean fuels, healthy living, natural resources and advanced materials are the least integrated industries in the system. However, a dynamic analysis demonstrates that inter-sector connectedness is time-varying and event-dependent. The MVP approach excels in the full and pre-COVID-19 sample, whilst the MCoP outperforms other methods in the post-COVID-19 scenario. In general, the portfolio exercise shows that green portfolios outperformed commodities but underperformed conventional equity and cryptocurrency portfolios. In contrast, following the COVID-19 pandemic, green portfolios have shown a greater return performance than all other conventional portfolios. The findings not only provide valuable insights to investors and policymakers in the effective management of investments and the green equity market, but also aid the achievement of objectives of environmental policies such as SDGs and the Paris Agreement.

1. Introduction

Global climate change and environmental deterioration have brought about a need to transform global economies into green and sustainable economies which can be achieved by following the sustainable development path. For that reason, global efforts are being made to tackle these issues e.g., the United Nations 2030 Agenda with 17 Sustainable Development Goals (SDGs), and the Paris Agreement to limit the rise of global temperatures to 1.5 °C (Gonçalves et al., 2021). However, a large amount of capital is required to accomplish these targets. The United Nations Conference on Trade and Development (UNCTAD, 2023) has estimated an annual $4 trillion shortfall in funds, especially in developing countries, to achieve the SDGs, and to combat the climate crisis. To fill this gap, extensive efforts are needed to encourage investors to invest in sustainable projects (Blankenberg and Gottschalk, 2018).

Recently, investors have become more interested in green investments which has led to considerable growth in this area (Gabauer, 2023; Handayani and Rokhim, 2023). A current report indicates that global investments in the green economy reached $7.2 trillion in the first quarter of 2024, a significant increase from under $1.5 trillion recorded in 2009 (Dai et al., 2024). However, this growth rate is not satisfactory to meet the funding requirements of SDGs (Cunha et al., 2020) and their environmental developments. There are multiple factors contributing to the slow advancement of green investment initiatives. One of the possible reasons may be the lack of updated and robust information

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about environment-friendly assets, since Anderson and Robinson (2022) have already stated that investors with financial knowledge are more engaged in environment-friendly investments. For instance, knowledge about the connectedness among financial assets aids in optimal portfolio selection, risk management, crisis monitoring and business cycle analysis (Diebold and Yılmaz, 2015). Another obstacle could be a lack of information about the financial performance of sustainable investments, particularly in stock markets (UNCTAD, 2014). Furthermore, the investor base could be greatly expanded by presenting the positive financial performance of green investment products, even when environmentally conscious investors are willing to forgo profit in favor of sustainability (Gutsche and Ziegler, 2019; Naqvi et al., 2022; Siddique et al., 2024). Consequently, policymakers and investors are interested in understanding the connectedness between different green assets for making efficient policy and investment decisions. They may switch to sustainable investing based on the performance comparison between green and traditional investments (Haddad and Rokhim, 2022).

Recently, an increasing number of researchers have made significant contributions in the growing body of green finance literature. The first set of studies explores the return connectedness within the green assets/markets along with their portfolio implications, e.g., Bai et al. (2023), Hasan et al. (2023), Heng and Lin (2025), and Tiwari et al. (2022). The second area of research investigates connections between green and conventional assets/markets regarding return connectedness and offers their implications for portfolio management, e.g., Abakah et al. (2023), Abdullah et al. (2023), Broadstock et al. (2020), Naeem et al. (2021, 2023), Naifar (2025), Rubbaniy et al. (2024), Siddique et al. (2024), Xu et al. (2024), Yousfi and Bouzgarrou (2024). The third body of literature examines the return connectedness among various sustainable assets or between green and traditional assets, e.g., Ferrer et al. (2021), Lu et al. (2023), Sharma et al. (2022), Wu and Liu (2023). The fourth set of studies explores the risk-return dynamics of clean energy sectoral indices and compares their performance with conventional sectors, e.g., Demiralay et al. (2023), and Kuang (2021). The last group of scholars makes a performance comparison between green and traditional modes of investment, e.g., Boulatoff and Boyer (2009), Cunha et al. (2020), El Ghoul et al. (2023), Gonçalves et al. (2021), Ibikunle and Steffen (2017), Neves et al. (2024), Su (2021), and Twomey (2017).

However, green investment includes equities from companies in various eco-friendly sectors such as biofuels, energy storage, efficiency, fuel cells, recycling/green chemicals, geothermal, transportation, renewable energy, water, solar and wind energy, green buildings and waste management (Boulatoff and Boyer, 2009). Investment in these key economic sectors is necessary for the transition of global economies to green and more sustainable ones, to prevent global collapse in the form of environmental deterioration and climate change (Blankenberg and Gottschalk, 2018; Gonçalves et al., 2021). In addition, the existence of sectoral heterogeneity within the green equity market is essential for promoting portfolio diversification and facilitating effective risk management strategies (Demiralay et al., 2023; Pham, 2021). Therefore, it is important to explore connectedness within green sectoral equities. However, no substantial effort has been made so far to look at the return connectedness and portfolio implications of green sector equities. There is also a scarcity of literature evaluating the performance of green equity portfolios, containing comparisons with their traditional counterparts.

Therefore, this study takes this opportunity by exploring the answers to the following questions. First, what is the static and dynamic return connectedness between green sector equities? Second, what are the portfolio implications of green equities under various portfolio construction approaches? Third, which portfolio strategy is more efficient than others? Fourth, what is the portfolio performance of green investments in relation to conventional counterparts? It has been shown that the COVID-19 pandemic has heightened awareness of climate change and environmental concerns among investors, and they prefer to invest in green investments (Handayani and Rokhim, 2023; Sharma et al., 2022). Thus, it is imperative to investigate the differences in connectedness and portfolio performance of green sector equities before and after the COVID-19 outbreak.

The study contributes to the growing body of green finance literature from different perspectives. First, the extant literature has analyzed the return connectedness between green and non-green markets, mostly at an aggregate level e.g., Naeem et al. (2023), Siddique et al. (2024). In addition, Demiralay et al. (2023) and Kuang (2021) have found heterogeneity in the risk-return attributes of the clean energy sectoral equities. Such diversity within the green equity market enables investors to formulate sector-specific diversification strategies (Pham, 2021). These green equities provide more diversification opportunities than traditional equities (Boulatoff and Boyer, 2009). Thus, to facilitate stakeholders, this study examines return connectedness and portfolio implications of green sector equities under various portfolio construction methods like MVP, MCP and MCoP, using the TVP-VAR model. It also suggests an optimal portfolio strategy based on metrics like Sortino, Omega and Sharpe ratios.

Second, this research sheds light on interconnections between green equities, offering valuable insights for portfolio management. By understanding the dynamic connectedness and shock spillover structure, stakeholders can make timely portfolio adjustments and enhance portfolio risk management. Moreover, policymakers will gain a clearer understanding of the leading sectors in the green equity market that drive price fluctuations in other green sectors, contributing to market instability. Strategies to stabilize these sectors during a crisis reduce the likelihood of systemic risk and market failure. Similarly, they can design industry development plans by considering the spillover path because policy impacts shift across sectors due to the existence of linkages. Third, previous research compared SRI/green fund portfolios and ESG-based indices with traditional counterparts (Cunha et al., 2020; Gonçalves et al., 2021; Neves et al., 2024). Investors now have diverse investment choices, and understanding green investment performance is crucial for transitioning to sustainable options. This study compares green sector equity portfolios with traditional sector equity, commodity and cryptocurrency portfolios. The comparison spans pre- and post-COVID-19 periods to analyze the impact of the pandemic on investor behavior and portfolio performance.

Fourth, the study's findings aid investors in making informed investment decisions, supporting sectors prioritizing green practices. This helps channel capital to eco-conscious enterprises, aligning with Sustainable Development Goals like clean energy access (SDG 7) and sustainable urban development (SDG 11) through initiatives such as green transportation and eco-friendly buildings (Bich and Dinh, 2024; Wen et al., 2020). These investments also combat climate change by boosting energy efficiency and endorsing renewable energy sources (Yan et al., 2024), contributing to SDG 13. Furthermore, they also support the objectives of the Paris Agreement by reducing greenhouse gas emissions (Altın, 2024).

Fifth, substantial evidence suggests that the investor's pro-environmental behavior significantly influences their preference for green investments, aligning with the value-belief-norm theory of Stern et al. (1999) and the theory of planned behavior of Ajzen (1985). In addition, the Modern Portfolio Theory proposed by Markowitz (1952) underlines diversification for portfolio risk management, achieved by integrating the least connected sectors for optimized risk-adjusted returns. Moreover, risk propagation due to interconnected countries or sectors may lead to contagion and systemic risk, as explained by Engle et al. (1990), through the "meteor shower" and "heat wave" hypothesis. This research is grounded in behavioral and financial theories, making a noteworthy theoretical contribution. Finally, this study applied the TVP-VAR model of Antonakakis et al. (2020), which overcomes limitations of traditional VAR models like outlier effect, suboptimal window size, data loss, and unsuitability for high-frequency data analysis (Chirilă, 2022), resulting in more robust findings.

The rest of the paper is organized as follows: Section 2 presents a detailed literature review; Section 3 details the econometric framework, data and preliminary analysis of the study; Section 4 documents the empirical findings and discussion, and Section 5 provides the conclusion of the study along with policy implications.

2. Literature review

The expanding body of literature on green finance can be classified into five distinct groups. A summary of the literature review is presented in Table 1. The first body of literature focuses on the return connectedness among various green assets/markets and highlights their implications for portfolio management. For instance, Tiwari et al. (2022) examined return connectedness among green bonds, carbon markets and renewable energy stocks, and also provide their portfolio implications. They found that green bonds have weak association with renewable energy markets compared to carbon markets. However, renewable energy markets have a more significant impact on green bonds than carbon markets. Results demonstrate that clean energy is the primary shock transmitter; green bonds and wind act as the main receivers. The hedge effectiveness indicates that bivariate and multivariate portfolios effectively mitigate investment risk, except for Green Bonds. The MCoP approach excels in portfolio construction pre- and post-COVID.

Furthermore, Bai et al. (2023) investigate the interdependence among China's Carbon Neutral Bond (CNB) and renewable energy equities. The analysis revealed a little interaction between CNB and clean energy stocks. CNB serve as the main shock receiver. Moreover, various renewable energy equities experience different advantages of diversification from CNB. Portfolio analysis documents that an investment which comprises clean energy equities along with CNB offers a higher Sharpe ratio than all combinations without CNB. They also document that MCoP outperforms MVP and MCP. In addition, Hasan et al. (2024) investigated the time-frequency extreme connectedness between various green equities such as solar, wind, global water, US water, and green economy and green bonds. They found the strong positive connections between green bonds and equities which become negative during the time of crisis. The portfolio exercise explains that the combination of green bonds and green economic equity provides the highest hedge effectiveness. Global water acts as the main net transmitter and the green economic index is the primary shock receiver. Most pairs of both categories show diversification potential due to minimum connectedness at various quantiles. Similarly, Heng and Lin (2025) explore how ESG investments are linked to biofuels markets and their impact on portfolio management. Results show stronger positive return connections between ESG funds and soybean investments compared to ethanol. ESG markets influence biofuel returns unidirectionally, especially during COVID-19. Short-term and long-term interconnections were observed. A mixed portfolio of both markets can enhance diversification and lower risks, and improve the Sharpe ratio due to their imperfect correlation.

The second area of research investigates relationships between green and conventional assets/markets regarding return connectedness and offers their implications for portfolio management. For instance, the work of Broadstock et al. (2020) explains the dynamic connectedness between green and traditional bonds in the US, Europe and China. Portfolio allocation for green bonds ranges from 40 % to 80 %, varying with time and construction method. Chinese green bonds had the highest share in the MVP approach, while the MCoP method evenly spread weights across all regional green bonds. Furthermore, Naeem et al. (2021) examine the impact of COVID-19 on the time-frequency connectedness among green bonds and several conventional assets, including the bond market, global equity market, USD index, oil, bitcoin and gold. The findings revealed significant connections with these variables, particularly with the bond and USD index. However, green bond exhibits a weak association with bitcoin in the short and long term. Regarding portfolio implications, USD and gold (oil and stock) have the highest (lowest) hedge effectiveness. Green bonds showed diverse associations with assets, acting as a hedge for some and causing contagion for others during crises.

In addition, Abdullah et al. (2023) found that green stocks consistently act as return shock senders in all market conditions, while oil (halal tourism equities) as receivers during normal and bearish (bullish) environments. Dynamic analyses show high connectedness among assets during crises like COVID-19 and the Ukraine conflict. It has been determined that investors can enhance diversification by incorporating gold or halal tourism stocks into a portfolio that includes green equities or cryptocurrencies. In the same pattern, Yousfi and Bouzgarrou (2024) elucidate the heightened interrelationship among oil, renewable energy and environmentally sustainable equities during the crisis episodes, across upper, median and lower quantiles. They propose a range of diversification strategies for green investors that have the potential to substantially mitigate portfolio risk. Moreover, Siddique et al. (2024) identified a weak relationship between green and non-green assets (bonds and equities) under normal market conditions than in extreme environments. The costs of sustainable investments are comparable to traditional ones, with potential additional rewards.

Moreover, Xu et al. (2024) found that green bonds exhibit limited connectedness with conventional assets. The findings explained that green bonds were initially shock receivers but shifted to transmitters during COVID-19. Allocating significant weights of green bonds in MVP and Risk-Parity Portfolio (RPP) enhances performance in market declines, while MCP and MCoP thrive in stable conditions. This evidence underscores the potential of green bonds as a viable hedging instrument. Recently, Naifar (2025) studied the return connectedness and portfolio strategies between green bonds, renewable energies, robotics and fintech equities. The study results emphasize that fintech serves primarily as a return shock transmitter, while robotics as a receiver. Portfolio results favor the MCoP strategy when environmental policy changes. This method assigns the highest weights to new energy and carbon indices.

The third body of literature investigates the connectedness between various green assets or several sustainable and traditional assets. For instance, Ferrer et al. (2021) examined the time-frequency interdependence among green financial securities (green bonds and green stocks) and traditional assets (treasury, general stock, investment-grade bonds, high-yield corporate bonds, gold, and crude oil). Green and conventional assets show significant interdependence, especially in the long run. Green bonds are closely linked to treasury and investment-grade bonds, while green stocks are connected to general stocks. No connections were found between green bonds and green stocks. Relatedly, Sharma et al. (2022) identified bidirectional causality between green stocks represented by clean energy stocks and conventional counterparts. Spillover analysis showed that both types of indices impact each other in the long run. They also argued that investors can switch to green investments without losing returns. Moreover, Lu et al. (2023) explored the interdependence among clean energy, green bonds and socially responsible stocks. The results explained that clean energy plays the role of net information transmitter whereas green bonds and other stocks act as net receivers.

The fourth stream of literature explores the risk-return dynamics of clean energy sectoral indices and compares their performance with traditional sectors. For example, Kuang (2021) documents the risk-return features of the clean energy sector (bio/clean fuels, energy efficiency, renewable energy and advanced materials) along with sub-sectors, and compares them with benchmark equity market and dirty energy sector equities. The findings revealed that while clean energy equities generally underperform the benchmark market, they outperform dirty energy equities. The developer/operator index shows the best risk-adjusted returns, reducing volatility risk from dirty assets. Energy storage and wind indices help in alleviating tail risk associated with dirty assets. Clean energy indices exhibit varying risk-return characteristics and offer heterogeneous diversification advantages. It is found that the combination of dirty assets with clean energy equities improve portfolio performance significantly.

Lastly, the fifth group of scholars makes a performance comparison

Table 1
Summary of literature review.

Authors	Purpose	Variables and period	Methodology	Key findings
Tiwari et al. (2022)	Examine the return connectedness between green bonds, carbon markets and renewable energy markets during COVID-19. Provide hedging and investment strategies.	S&P Green Bond, prices of CO2 emissions, Solactive Global Solar, Solactive Global Wind and S&P Global Clean Energy indices. (January 4, 2015 to, September 22, 2020)	TVP-VAR model of Antonakakis et al. (2020).	The green bonds market has a minor connection to renewable energy markets compared to its link to the carbon market. Despite this, renewable energy markets have more impact on green bonds than the carbon market.
Bai et al. (2023)	Explore the interaction and diversification benefits of China Carbon Neutral Bond (CNB) on renewable energy equities.	China Carbon Neutral Green Bond index, 5 renewable energy indices developed by Wind Co., Ltd., in China: Biomass, Solar, Wind, Geothermal and Hydropower indices. (March 1, 2021 to, August 30, 2022)	TVP-VAR model of Antonakakis et al. (2020).	CNB weakly interacts with renewable energy equities and is the main shock receiver. Different renewable energy equities benefit differently from CNB in terms of diversification. A portfolio with CNB and clean energy equities has a higher Sharpe ratio compared to combinations without CNB.
Hasan et al. (2023)	Investigate the time-frequency quantile connectedness among green bonds and green economic equities.	S&P Dow Jones Green Bonds index and Nasdaq OMX green stock indices: Solar, Global Water, US Water, Wind, and Green Economy. (July 28, 2011 to, July 28, 2021)	Quantile VAR of Chatziantoniou et al. (2021), Quantile-on-quantile, Dynamic conditional correlation (DCC), Discrete wavelet transforms.	Strong and positive associations exist between green bonds and green equities in all market states and at several frequencies, which turn negative during crisis. The main net shock transmitter (receiver) is Global water (green economy).
Heng and Lin (2025)	Examines the return connectedness between ESG funds and biofuels markets along with portfolio implications.	5 ETFs of ESG indices are used for Europe, US, China, developing and emerging markets. Biofuels indices include ethanol and soybean oil. (January 1, 2019 to, December 31, 2023)	TVP-VAR framework of Antonakakis et al. (2020), asymmetric TVP-VAR of Adekoya et al. (2022), Continuous wavelets transform.	Positive return links are stronger between ESG funds and soybean investments, with a weaker tie to ethanol. ESG markets influence biofuel returns unidirectionally, especially during the COVID-19 pandemic, while multivariate portfolios enhance risk-adjusted returns via diversification.
Abakah et al. (2023)	Analyze the correlation, connectedness and provide portfolio implications among blockchain and environment-friendly assets.	For blockchain, four cryptocurrencies, four DeFis, and four NFTs are selected. Eco-friendly assets, S&P Green Bond and MSCI Global Environment indices. (January 17, 2018 to, July 29, 2022)	Rolling window wavelet correlation (RWWC) method and QVAR of Chatziantoniou et al. (2021).	Weak connections are found between blockchain and green asset (bonds and equities) markets that increases during crisis. Green equities and bonds are the primary recipients of shocks. Incorporating green assets in blockchain portfolios offers optimal diversification and hedging benefits in both short and long terms.
Naeem et al. (2023)	Explore the connectedness between green and traditional financial assets and provide portfolio recommendations.	S&P Green Bonds and Clean Energy indexes, Energy, Precious Metals, Cryptocurrency and MSCI World indices. (August 2014 to, December 2020)	DECO-GARCH and QVAR model of Chatziantoniou et al. (2021).	Green assets closely tied to global stocks at lower and median quantile. Cryptocurrencies, however, remain isolated. Green bonds act as an effective hedge for cryptocurrencies and metals.
Rubbaniy et al. (2024)	Dynamic connectedness and portfolio implications across renewable energy, hydrogen economy, commodity and equity markets.	Clean Energy Equity indexes (S&P/TSX Renewable Energy and Clean Technology, NASDAQ OMX Geothermal and fuel Cell, Global Wind Energy and Stoxx Global Solar Energy indexes), S&P Kensho global hydrogen economy index. Energy commodities (crude oil, natural gas, biofuel), gold and equities (FTSE100, S&P 500, and MSCI GCC equity market index). (May 15, 2019 to, August 15, 2023).	TVP-VAR of Antonakakis et al. (2020).	Pairwise results explain the strong connectedness between renewable energy equities and traditional energy commodities. Moreover, renewable, clean technology, solar and hydrogen economy index consistently act as net transmitters whereas biofuel, geothermal, crude oil, natural gas and gold as net receivers.
Ferrer et al. (2021)	Examine the interdependence between green and traditional financial instruments.	S&P Green Bonds index, NASDAQ OMX green economic sectoral indexes: Solar, Wind, Fuel Cell, Energy Efficiency, Clean Transportation, Green Buildings, Pollution Prevention indexes. Conventional indexes: Bloomberg Barclays indexes for treasury, investment grade and high yield bonds, MSCI world index, oil and gold indexes (October 13, 2010, to November 13, 2020)	Wavelet-based network analysis.	In the long term, close connections are observed among green and conventional assets. Green bonds are closely connected with treasury and investment-grade bonds, while green stocks are related to general stocks. However, no connections are found between green bonds and green stocks.
Sharma et al. (2022)	Examines the spillover between green and conventional finance modes	NASDAQ OMX green indexes: Green Economy, Global Water, Solar and Wind indexes, NASDAQ Composite and Clean Edge Green Energy indexes. (August 2011 to June 2021)	Connectedness approaches of Diebold and Yilmaz (2014) and Baruník and Křehlík (2018)	There exists a bi-directional causal relationship between conventional and green indices over the long term. The COVID-19 pandemic has exacerbated the connections between these two markets. Switching to green

(continued on next page)

Table 1 (*continued*)

Authors	Purpose	Variables and period	Methodology	Key findings
				investments can yield investors satisfactory risk-adjusted returns.
Wu and Liu (2023)	Investigate the dynamic spillover between green financial assets.	NASDAQ OMX green economic indices: Green Transportation, Clean Energy Focused, Global Water and Green Building. S&P Green Bonds and Sustainability World indexes. IHS Markit Global Carbon Index (July 30, 2014, to August 30, 2022)	TVP-VAR model of Antonakakis et al. (2018)	Clean energy, water and ESG markets are the main spillover transmitters, whereas green transportation, green building, carbon and green bonds markets act as information receivers. Green bonds are found more connected with other finance markets after the emergence of COVID-19.
Demiralay et al. (2023)	The risk-return profile of environment-friendly assets are explored.	NASDAQ OMX green indices: Bio/clean fuels, Energy Efficiency, Renewable energy, Advanced materials along with various sub-sectors. (October 13, 2010, to December 31, 2021)	Portfolio evaluation metrics: Sharpe, Omega and Sortino ratios. Moreover, downside risk measures and CAPM based metrics are also used.	Clean energy sub-sectors vary in risk-return features. Solar, fuel cell stocks are riskier; developer/operator equities are less risky. Amid COVID-19, these sectors offer higher risk-adjusted returns. Clean industries outperformed some traditional industries, including dirty ones.

between green and traditional modes of investment. For instance, starting from the study of Boulatoff and Boyer (2009), they found that the equities of green industries underperform NASDAQ conventional firms. Similarly, Su (2021) explored that green stocks in China underperform conventional stocks and provide minimum protection during extreme downside risk. Ibikunle and Steffen (2017) found that European green funds underperform various benchmark stock markets and parallel results are identified by El Ghoul et al. (2023) regarding US green equity mutual funds. Contrary to these studies, Neves et al. (2024) found that SRI and green investment funds in the US are more efficient than their conventional counterparts. Gonçalves et al. (2021) found a positive performance of green funds as compared with conventional funds by considering the European market as a benchmark. Cunha et al. (2020) found that the global sustainable index underperforms the global benchmark market, and also showed inferior progress in Asia and the USA but outperforms in emerging markets and European regions. Twomey (2017) found that global green portfolios provide better returns than non-green portfolios with the application of the Sharpe ratio and Time Weighted Return approaches.

The preceding analysis reveals a substantial body of research examining the nexus between green and conventional markets, primarily focusing on comparative financial performance for stakeholder guidance. However, the connectedness dynamics of green sectoral equity indices have been largely overlooked in existing research, that will be further elucidated in the subsequent discussion. First, past research mainly focused on aggregate indices rather than analyzing individual green sectors, potentially masking their diversity as pointed out by Mensi et al. (2021). It's crucial to delve into various eco-friendly sectors to aid decision-making for investors and policymakers. Additionally, investing in green sectors offers better diversification opportunities compared to traditional sectors (Boulatoff and Boyer, 2009). Second, recent portfolio construction methods like MCP and MCoP are becoming popular but are yet to be extensively applied to sectoral green equities. Third, sustainable indices or green portfolios are compared to benchmark indices but not to other investment modes through constructing portfolios. Moreover, comparing the performance of sustainable portfolios with conventional ones remains inconclusive, warranting further investigation. Fourth, this study employs the TVP-VAR model for more accurate results, considering the limitations of rolling windows analysis. Finally, the impact of COVID-19 on the return performance of green and non-green portfolios are not examined in detail.

In this way, the study fills these research gaps by providing knowledge about the return connectedness among green sectoral equities using the TVP-VAR approach. Furthermore, multivariate portfolio construction methods are used to guide the portfolio implications of green equities and compares the green equity portfolio performance with other conventional portfolios i.e., traditional sector equities portfolio, commodities portfolio and cryptocurrencies portfolio. In addition to this, this comparison is made before and after the emergence of COVID-19 to check the impact of the pandemic outbreak on the investment pattern and behavior of investors.

3. Econometric framework/methodology

The main objective of the study is to explore the return connectedness among green sectoral equities. Generally, linkages between economic sectors can be attributed to upward and downward relationships in the supply chain and investor investment allocations across various sectors (Yin et al., 2020). However, the connectedness between green and conventional markets may be due to investor sentiments and behavior (Kayani et al., 2024; Naeem et al., 2023), by considering the climate-related risk factors when making investment decisions (Ren et al., 2022), government support to green markets (Su et al., 2024) and on the philosophy of the market integration theory (Kearney and Lucey, 2004). To achieve the study objectives, the TVP-VAR approach is utilized.

3.1. *Time-varying parameter vector autoregression (TVP-VAR)*

This study employs the Time-varying Vector Autoregression (TVP-VAR) methodology of Antonakakis et al. (2020) to investigate the return connectedness within green sector equities. This model captures the time-varying parameters, an essential aspect for modeling intricate financial variables with fluctuating relationships due to various factors including policy changes, technological innovation or market fluctuations (Rubbaniy et al., 2024; Heng and Lin, 2025). In the context of TVP-VAR models, the static multicollinearity problem is mitigated (Bekiros, 2014; Caldeira et al., 2015; Koop and Korobilis, 2013) by changing variances and covariances over time (Eisenstat et al., 2016; Huang, 2025) and shrinking the coefficients of less important predictors towards zero (Hauzenberger, 2021; Koop and Korobilis, 2013), leading to more accurate and reliable parameter estimates. Moreover, the standard VAR based models like Diebold and Yilmaz (2012, 2014), DCC and BEKK-GARCH etc., are affected by the presence of outliers, challenges related to determining the optimal window size, and the potential loss of information associated with following the window approach, rendering it inappropriate for high-frequency data analysis (Chirilă, 2022). These shortcomings are addressed by the TVP-VAR model as discussed by Antonakakis et al. (2020) and Wu and Liu (2023). This approach is used by several financial studies e.g., Bai et al. (2023), Heng and Lin (2025), Rubbaniy et al. (2024), and Tiwari et al. (2023). Therefore, TVP-VAR methodology is utilized to estimate time-varying parameters. TVP-VAR (p) model with n variable can be expressed as:

$$Y_t = A_t Z_{t-1} + \varepsilon_t \; \varepsilon_t | \Omega_{t-1} \sim N(0, \Sigma_t) \tag{1}$$

$$(vec)A_t = (vec)A_{t-1} + \xi_t \; \xi_t | \Omega_{t-1} \sim N(0, \Xi_t) \tag{2}$$

Here, $\left(Y_t = y_{1,t}\, y_{2,t}, \ldots, y_{n-1,t}, y_{n,t}\right)$ is a vector $n\times 1$ of variables at time t and $Z_{t-1} = \left(Y_{t-1,}\; Y_{t-2,}\ldots, Y_{t-p,}\right)'$. A_t represents $n \times n$ order parameter matrix at time t and $vec(A_t)$ is the vectorized form of A_t. Moreover, error terms are shown by $\mathcal{E}_t$ and ξ_t and Ω_{t-1} is the information set at time t-1. The variance-covariance matrix for error terms $\mathcal{E}_t$ and ξ_t is denoted by Σ_t and Ξ_t. This TVP-VAR approach uses the multivariate Kalman filtering process proposed by Koop et al. (1996). Thus, A_t and $\mathcal{E}_t$ are used to calculate the Wold representation form of this model as:

$$Y_t = A_t Z_{t-1} + \varepsilon_t = \Sigma_{i=o}^{\infty} B_{i,t} \varepsilon_{t-i} \tag{3}$$

Where, $B_{i,t} = \Sigma_{l=1}^{p} A_{l,t} B_{i-l,t}$ is response function and $B_{0,t}$ is one-dimensional matrix and $B_{i,t} = 0$ when $i<0$. By using the equation mentioned above, the H-step-ahead generalized forecast error variance decomposition (GFEVD) is obtained which explains the impact of a shock in variable k on variable j, as mentioned below:

$$\Phi_{jk,t}(H) = \frac{\sigma_{kk,t}^{-1} \sum_{h=0}^{H-1} \left(\theta_j' B_{h,t} \sum_t \theta_k\right)^2}{\sum_{h=0}^{H-1} \left(\theta_j' B_{h,t} \sum_t B_{h,t}' \theta_j\right.} \tag{4}$$

where, θ_j (θ_k) and $\sigma_{kk,t} = (\Sigma)_{kk,t}$ is an $n\times 1$ order vector with the jth (kth) element being 1 and others being 0. To ensure the total of items in each row $\Phi_{jk,t}$ (H) equals 1, the following equation normalizes each entry as:

$$\widetilde{\phi}_{jk,t}(H) = \frac{\Phi_{jk,t}(H)}{\sum_{j=1,k=1}^{n} \Phi_{jk,t}(H)} \times 100 \tag{5}$$

Where, $\sum_{k=1}^{n} \widetilde{\phi}_{jk,t}(H) = 1$ and $\sum_{j=1,k=1}^{n} \widetilde{\phi}_{jk,t}(H) = N$. There, overall interaction among all variables in the TVP-VAR system is measured by total connectedness index (TCI) as:

$$\text{TCI}_t(H) = \frac{\sum_{j,k=1, j\neq k}^{n} \widetilde{\phi}_{jk,t}(H)}{\sum_{j=1,k=1}^{n} \widetilde{\phi}_{jk,t}(H)} \times 100 \tag{6}$$

Moreover, Broadstock et al. (2022) described that pairwise connectedness index (PCI) explains the degree of connectedness between only two variables and is estimated by following the same procedure on the bilateral level as followed in TCI. Therefore, this PCI is used as a basis for portfolio optimization analysis under the minimum connectedness approach in the next stage.

The next equation enlightens the directional connectedness to others which measures the degree of shock spillover by a variable j to all other variables.

$$\text{TO}_{j\rightarrow *,t}(H) = \frac{\sum_{k=1,k\neq j}^{n} \widetilde{\phi}_{kj,t}(H)}{\sum_{j=1,k=1}^{n} \widetilde{\phi}_{jk,t}(H)} \times 100 \tag{7}$$

After this, the following equation estimates the degree of directional connectedness received by a variable j from all other variables.

$$\text{FROM}_{j\leftarrow *,t}(H) = \frac{\sum_{k=1,j\neq k}^{n} \widetilde{\phi}_{jk,t}(H)}{\sum_{j=1,k=1}^{n} \widetilde{\phi}_{jk,t}(H)} \times 100 \tag{8}$$

The difference between the connectedness TO and FROM leads to the net connectedness of a variable j which is presented as under:

$$NET_{j,t}(H) = \text{TO}_{j\rightarrow *,t}(H) - \text{FROM}_{j\leftarrow *,t}(H) \tag{9}$$

The positive (negative) value explains the role of a variable j whether it is a connectedness sender (receiver) in the system. Finally, the net pairwise directional connectedness (NPDC) which describes the connectedness between a variable j and k and is calculated as under:

$$\text{NPDC}_{j\rightarrow k,t}(H) = \left(\frac{\widetilde{\phi}_{kj,t}(H)}{\sum_{j=1,k=1}^{n} \widetilde{\phi}_{jk}(H)} - \frac{\widetilde{\phi}_{jk,t}(H)}{\sum_{j=1,k=1}^{n} \widetilde{\phi}_{jk}(H)}\right) \times 100 \tag{10}$$

where, positive values of NPDC show that the connectedness impact of variable j on k is more than the effect of k on j, implying the leading position of j regarding any change in k.

3.2. Multivariate portfolio construction methods

Investors design their investment portfolios by considering their financial goals, risk tolerance level and prevailing market conditions (Rubbaniy et al., 2024). To measure the financial performance of various portfolio strategies, we use two conventional portfolio construction approaches, namely, minimum variance portfolio and minimum correlation portfolio, in addition to the newly introduced minimum connectedness portfolio approach. These portfolio analyses are based on several assumptions. First and foremost, investors are only interested in green sector equities for their investment choices. Next, they can engage in direct investments in indices. Finally, they are inclined to invest in green equities.

3.2.1. Minimum variance portfolio (MVP)

The minimum variance portfolio, a widely utilized methodology for optimal portfolio construction, prioritizes the minimization of volatility through asset diversification (Markowitz, 1959). This strategy aims to deliver superior risk-adjusted returns by reducing overall portfolio risk, thereby aligning with the objectives of risk-averse investors (Chow et al., 2016). However, this approach is subject to limitations stemming from its reliance on historical data (Cai et al., 2020), which may prove inadequate for accurately predicting future market conditions. The estimated portfolio weights are calculated as follows:

$$w_{Ht} = \left(\frac{H_t^{-1} I}{I\, H_t^{-1} I}\right) \tag{11}$$

Here, w_{Ht} refers to the $m\times 1$ dimensional order portfolio weight vector. I show the m dimensional unit vector and $\sum_t$ is $m\times m$ order conditional variance covariance matrix in the period t.

3.2.2. Minimum correlation portfolio (MCP)

This approach is introduced by Christoffersen et al. (2014), which assigns portfolio weights using a conditional correlation matrix instead of using a conditional covariance matrix. The MCP approach considers assets within a portfolio that exhibit low or negative correlation which is the essence of diversification. First, conditional correlation is calculated as:

$$R_t = diag(H_t)^{-0.5} H_t diag(H_t)^{-0.5} \tag{12}$$

here, R_t refers to the $m\times m$ dimensional matrix. Next, portfolio weights are assigned by minimizing conditional correlation as mentioned below:

$$w_{Rt} = \frac{R_t^{-1} I}{I\, R_t^{-1} I} \tag{13}$$

3.2.3. Minimum connectedness portfolio (MCoP)

This is the most recently developed approach by Broadstock et al. (2022), in which pairwise connectedness indices are used for the construction of a portfolio. The portfolio constructed using bilateral interconnectedness is least affected by network shocks (Abdullah et al., 2023; Broadstock et al., 2022). This approach assigns high weights to the least connected variables which do not get high influence from others and which also do not significantly impact others. Thus, MCoP reduces the impact of systemic risk and contagion on a portfolio by combining the least connected assets. These weights are obtained as under:

$$w_{Rt} = \frac{PCI_t^{-1} I}{I\, PCI_t^{-1} I} \tag{14}$$

where *PCI* refers to the pairwise connectedness index and the identity matrix is expressed by *I*.

3.3. Portfolio evaluation approaches

By following the studies of Broadstock et al. (2022), Demiralay et al. (2023) and Kuang (2021), the portfolio performance is examined using the Sharpe ratio, Omega ratio, Sortino ratio and hedge effectiveness.

The Sharpe ratio is also known as a reward-to-volatility ratio which is widely used by investors and portfolio managers to access risk-adjusted returns (Sharpe, 1966):

$$Sharpe\ Ratio = \frac{\bar{r}_p}{\sqrt{var(r_p)}} \tag{15}$$

Where portfolio return is represented by $\bar{r}_p$ by assuming the risk-free rate equal to zero. $\sqrt{var(r_p)}$ refers to the square root of portfolio return variance. A higher value of the Sharpe ratio indicates higher risk-adjusted returns. Despite the flaws of normal distribution assumption, and ignoring upside and downside volatility (Srivastava and Mazhar, 2018), it continues to serve as a reliable starting point for investors in search of opportunities with appealing risk-reward features (Schwab, 2024).

Therefore, to deal with these limitations, the Sortino ratio (Sortino and Price, 1994; Sortino and van der Meer, 1991) and the Omega ratio (Keating and Shadwick, 2002) are also used to evaluate portfolio performance. The Sortino ratio is almost similar to the Sharpe ratio but the difference is that it considers the downside risk instead of standard deviation. Due to investors' strong risk aversion attributes, the Sortino ratio is viewed as a realistic evaluation metric in the literature, as it solely considers downside risk (Barberis et al., 2001; Benartzi and Thaler, 1995), as cited in Demiralay et al. (2023). This ratio is measured as under:

$$Sortino\ Ratio = \frac{R_i - R_f}{\sigma_{i,downside}} \tag{16}$$

The Omega ratio does not consider the normality assumption. It is considered as a natural performance measure because it incorporates all moments of the return distribution, encompassing both skewness and kurtosis (Keating and Shadwick, 2002). Thus, it provides more accurate and precise evaluation of risk and return to investors in real-world situations. It is calculated as follows:

$$Omega\ Ratio = \frac{\frac{1}{T}\sum_{t=1}^{T} max\left(0, R_{i,t}{}^{+}\right)}{\frac{1}{T}\sum_{t=1}^{T} max\left(0, R_{i,t}{}^{-}\right)} \tag{17}$$

This can be explained as the ratio of probability of weighted profits and losses. The higher the value, the higher the likelihood of attaining profits, a condition that is typically viewed as favorable.

Furthermore, hedge effectiveness proposed by Ederington (1979) measures the percentage of risk reduction of an unhedged asset and obtained as:

$$Hedge\ Effectiveness = 1 - \frac{var\ (R_p)}{var\ (R_i)} \tag{18}$$

Here, $var\ (R_p)$ is the variance of portfolio returns and $var\ (R_i)$ refers to the return variance of unhedged position.

3.4. Data and preliminary analysis

To investigate the connectedness between equities of green sectors to explore their portfolio implications, this study used the daily closing prices of the NASDAQ OMX green economic index family from October 15, 2010 to September 30, 2023.[1] These indices represent the financial performance of the global green economic sector equities. The reasons behind the selection of these indices are the availability of data and their popularity worldwide. These indices include advanced materials, bio/clean fuels, energy efficiency, green transportation, green building, lighting, healthy living, pollution mitigation, natural resources, renewable energy generation, recycling and water.

Moreover, this study compares the financial performance of green portfolios with other conventional modes of investments i.e., conventional sector equity portfolios,[2] commodity portfolios[3] and cryptocurrency portfolios.,[4],[5]

The study was divided into two sub-sample periods i.e., pre-COVID-19 (October 15, 2010 to March 10, 2020), and post-COVID-19 (March 11, 2020 to September 30, 2023).[6] While Fig. 1 depicts the consistent upward trend in the index values of green economic sector indices since the introduction of indices in 2010, a significant upward surge was noticed after the outbreak of the COVID-19 pandemic (Sharma et al., 2022). The notable expansion observed can be attributed to a heightened awareness of climate and environmental challenges (Chatziantoniou et al., 2022), increasing demand for investments including green equities (Pham, 2021), as well as government support initiatives and regulatory reforms, including the Sustainable Development Goals (SDGs), the Paris Agreement and The European Green Deal (Agostini et al., 2024; Ferrer et al., 2021; Gonçalves et al., 2021). In addition, the growth of green energy, advances in green technologies (Li et al., 2022), the implementation of environmental taxes, and increased investment in research and development (Samad and Manzoor, 2015), have all contributed to this trend. It is noteworthy that the growth and performance of green markets have outpaced those of conventional financial markets following the onset of the COVID-19 pandemic (Arif et al., 2021). Green equity indices were converted into daily returns by taking the first difference of logarithm values (Demiralay et al., 2023).

$$R_{i,t} = \left(ln\, p_{i,t} - ln\, p_{i,t-1}\right) \times 100 \tag{19}$$

In Fig. 2, the cumulative returns of all indices show the overall increasing trend and depict the short-term downturns during several episodes of crisis i.e., the Euro debt crisis (2011–2012), the oil market crash (2015–2016), US-China trade conflicts, the COVID-19 disease (2020) and the Russia-Ukraine clash (2022–2023). However, green

[1] These indices were introduced in October 2010 with a base value of 1000 and represented in US dollars.

[2] By following the study of Demiralay et al. (2023), daily closing values of NASDAQ sectoral indices are used i.e. bank, biotechnology, computer, financial, health care, industrial, insurance, technology, telecommunication, transportation, and Dow Jones gas, water & multi utilities index.

[3] In line with the Tsagkanos et al. (2022) Bloomberg daily commodity indices are used which includes coffee, copper, corn, gold, heating oil, lead, natural gas, silver, wheat, and WTI crude oil.

[4] The daily closing prices of NASDAQ conventional sectoral indices, and Bloomberg commodity indices are obtained from investing.com, from October 15, 2010 to September 30, 2023. However, the starting point for cryptocurrency prices is July 25, 2016 for making a balanced dataset and data is retrieved from coinmarketcap.com.

[5] Ranking of top 30 cryptocurrencies based on market capitalization are obtained on September 30, 2023 from Coinmarketcap.com. The selected cryptocurrencies are Bitcoin (BTC), Ethereum (ETH), Tether (USDT), Ripple (XRP), Dogecoin (DOGE), Litrcoin (LTC), Stellar (XLM), Monero (XMR), Ethereum Classic (ETC).

[6] The World Health Organization declared COVID-19 a global pandemic on March 11, 2020 (WHO, 2020).

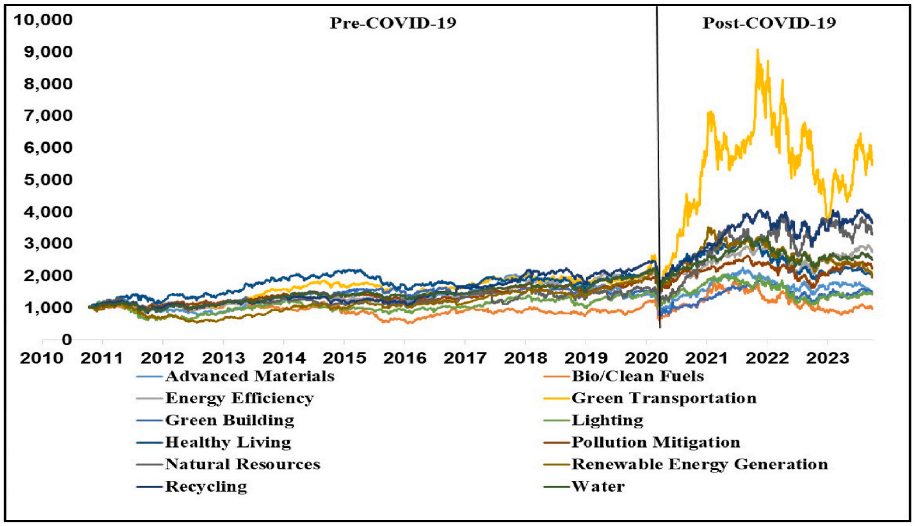

Fig. 1. Plot of price dynamics of green sector equities.

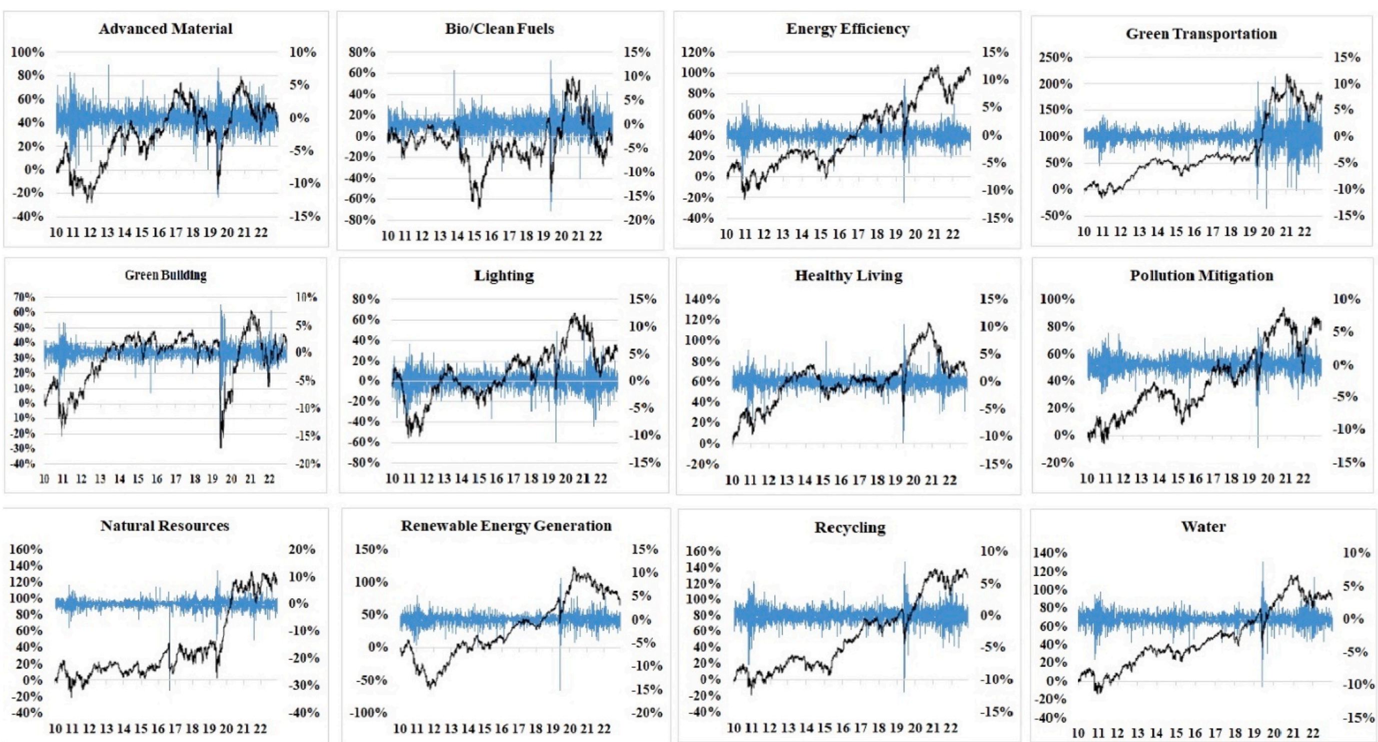

Fig. 2. Plot of daily and cumulative percent returns of green sector equities.
Notes: The black line on the left side refers to the cumulative returns and the blue shaded plot presents the daily returns.

sectors exhibit heterogeneous responses to the crises. For instance, during the COVID-19 pandemic, sectors such as green transportation, natural resources and bio/clean fuels demonstrated notable improvements in their cumulative returns. Conversely, the green building sector faced significant disruptions due to travel restrictions and the implementation of lockdowns significantly disturbed the supply chain of materials and components, resulting in delays and heightened expenses for green building initiatives (TCBU, 2021). In contrast, the water, recycling and energy efficiency sectors experienced minimal impact from the pandemic, maintaining a consistent growth trajectory in their returns. On the other hand, the daily returns of indices displayed large swings during the sample period, especially after the COVID-19 outbreak, which is an indication of a volatility upsurge in the post-COVID-19 period.

The descriptive statistics of daily returns are illustrated in Table 2 with Panels A, B and C representing the full, pre-COVID-19 and post-COVID-19 period. Panel A documents the positive daily mean returns of all green equities except bio/clean fuels. This is a favorable and encouraging sign in the universe of green and sustainable investment. Among the green sectors, the green transportation sector has the highest daily mean return (Chen et al., 2023a) while the bio/clean fuels sector lies at the opposite end of the spectrum with a negative return (Demiralay et al., 2023). In addition to having the lowest return, bio/-clean fuels have the highest risk in terms of standard deviation, possibly due to higher production costs (FASTECH, 2022) and a less competitive advantage over the fossil fuel industry. In contrast, water is the least

Table 2
Summary statistics of green equities' returns.

	AM	BIO	ENEF	TRN	GB	LIGHT	HL	POL	NR	REG	REC	WATER
Panel A. Full Sample Period (October 15, 2010, to September 30, 2023)												
Mean	0.011	−0.002	0.030	0.051	0.011	0.010	0.020	0.024	0.035	0.020	0.038	0.027
SD	1.471	1.838	1.276	1.693	1.319	1.565	1.217	1.172	1.673	1.172	1.210	1.035
Skewness	−0.456	−0.815	−0.369	−0.377	−1.408	−0.219	−0.380	−0.506	−2.484	−0.844	−0.630	−0.524
Kurtosis	5.827	10.932	7.931	7.842	21.689	3.988	9.484	7.608	45.792	13.166	8.085	9.698
Jarque-Bera	4827***	16956***	8804***	8612***	66403***	2232***	12564***	8174***	294528***	24457***	9291***	13205***
ADF	−14.85***	−14.28***	−14.64***	−14.18***	−13.74***	−15.53***	−14.72***	−14.87***	−15.41***	−14.00***	−14.78***	−14.77***
Panel B. Pre-COVID-19 Period (October 15, 2010, to March 10, 2020)												
Mean	0.005	−0.005	0.021	0.030	0.009	0.005	0.023	0.020	0.014	0.027	0.030	0.027
SD	1.377	1.496	1.168	1.040	1.021	1.392	1.093	1.041	1.501	0.996	1.048	0.904
Skewness	−0.391	−0.768	−0.485	−0.734	−0.828	−0.426	−0.480	−0.313	−4.246	−0.602	−0.433	−0.544
Kurtosis	5.022	9.668	4.716	7.775	7.992	2.827	6.667	2.956	86.501	4.169	4.484	4.287
Jarque-Bera	2586***	9599***	2321***	6270***	6673***	872***	4544***	913***	757008***	1885***	2088***	1958***
ADF	−13.51***	−12.96***	−13.31***	−13.07***	−13.04***	−13.82***	−13.65***	−14.21***	−13.52***	−11.85***	−13.57***	−13.60***
Panel C. Post-COVID-19 Period (March 11, 2020, to September 30, 2023)												
Mean	0.028	0.006	0.053	0.105	0.017	0.022	0.012	0.033	0.089	0.002	0.060	0.027
SD	1.692	2.520	1.523	2.742	1.886	1.946	1.494	1.460	2.053	1.539	1.555	1.317
Skewness	−0.543	−0.729	−0.233	−0.267	−1.403	−0.015	−0.244	−0.659	−0.557	−0.901	−0.749	−0.459
Kurtosis	6.069	7.166	9.538	2.135	15.925	3.594	9.698	8.963	7.827	13.370	7.711	10.310
Jarque-Bera	1450***	2041***	3480***	184***	9985***	492***	3598***	3132***	2385***	6948***	2354***	4089***
ADF	−10.15***	−10.25***	−9.83***	−8.68***	−11.18***	−10.21***	−9.60***	−9.70***	−10.35***	−9.63***	−10.20***	−10.23***

Notes: *** denotes 1 % significance level. Sectors including AM: Advanced Materials; BIO: Bio/Clean Fuels; ENEF: Energy Efficiency; TRN: Green Transportation; GB: Green Building; LIGHT: Lighting; HL: Healthy Living; POL: Pollution Mitigation; NR: Natural Resources; REG: Renewable Energy Generation; REC: Recycling; WATER: Water.

risky business. Furthermore, from the descriptive statistics in Panels B and C, it can be observed that daily returns of all green sectors have increased significantly in the post-COVID-19 period, except the renewable energy and healthy living sectors, which experienced a decline in mean returns due to several factors. For instance, the performance of the renewable energy sector has experienced a decline due to disturbances in the supply chain and reduced demand resulting from lockdowns, instability in the oil market, a global economic downturn and a shortage of funds (Pradhan et al., 2024). In addition, bio/clean fuels improved their returns due to increased demand during COVID-19 (Zhang et al., 2024) but their risk increased significantly in the post-pandemic sample. On the other hand, it is important to note that all green sectors experienced a rise in standard deviation after the COVID-19 outbreak, but this increase was smaller than the growth rate of returns.

The diagnostic tests conducted to assess the validity of the TVP-VAR connectedness approach indicated that the skewness and kurtosis of all return series exhibit a left-skewed and leptokurtic distribution, characterized by a pronounced peak and a heavy tail. These observations are corroborated by the Jarque-Bera test, which demonstrates that none of the series conform to a normal distribution. Furthermore, the application of the TVP-VAR connectedness approach necessitates a stable time series, a condition verified by the Augmented Dickey-Fuller (ADF) test. The outcomes of the ADF test confirmed that all return series are stationary, thereby meeting the empirical methodology's requirements.

4. Empirical findings and discussion

4.1. Average connectedness analysis

This section explains the average return connectedness between equities of 12 green economic sectors. Table 3 documents the average connectedness for the full period, Table 4 for the pre- COVID-19, and Table 5 for the post-COVID-19 era. The TCI results in Table 3 indicate that linkages between sectors account for 78.79 % of forecast error variation, indicating close interactions between them. Overall, it is noted that the energy efficiency sector is the main source of information spillover for all other sectors (Chen et al., 2023b) with a net contribution of 22.15 %, followed by water, recycling and green building industries. These four sectors are highly connected and have a significant impact on other industrial sectors of the network. The energy efficiency sector maintains strong ties with other sectors, as the European Environment Agency (2024) explains that its fundamental aim is to ensure the efficient use of energy and to reduce its waste across almost all economic sectors, leading to environmental protection, reduction in greenhouse gas emissions and mitigating the threat of climate change. On the other hand, bio/clean fuel is the largest net information receiver (−22.50 %), followed by healthy living, natural resources and advanced material sectors. These sectors have minimal connectedness with other sectors as indicated by the value of TO and FROM others. These least connected sectors offer more diversification opportunities and this argument is supported by Ji et al. (2019). Additionally, among the moderately connected sectors, lighting, pollution mitigation and green transportation all function as shock absorbers, while renewable energy generation has the characteristic of being a net shock transmitter.[7]

By comparing the connectedness structure among green equities in pre- and post-COVID periods in Tables 4 and 5, several important points may be noted. First, the comparable TCI values in both subsamples suggest that overall total connectivity stays constant but the degree of

[7] A sector is deemed a net shock-transmitter if it exhibits a positive net connectedness value, whereas a sector whose net connectedness value is negative is categorized as a net shock receiver (Antonakakis et al., 2019). Normally, net shock senders and receivers are categorized as risk transmitters and absorbers, as they are responsible for receiving and transmitting shocks to other entities (Dang et al., 2023; Vo, 2023).

Table 3
Average total connectedness between green sectoral equities for the full sample (October 15, 2010, to September 30, 2023).

	AM	BIO	ENEF	TRN	GB	LIGHT	HL	POL	NR	REG	REC	WATER	FROM
Advanced Materials (AM)	21.34	4.05	10.24	6.56	8.12	7.06	4.89	7.52	5.66	6.89	8.68	8.98	78.66
Bio/Clean Fuels (BIO)	5.57	30.88	7.47	6.93	6.94	5.37	5.48	5.18	4.58	6.91	7.38	7.30	69.12
Energy Efficiency (ENEF)	7.74	4.15	15.84	7.40	8.51	8.14	5.45	8.01	6.24	7.61	10.12	10.77	84.16
Green Transportation (TRN)	6.30	5.15	9.53	21.92	7.49	7.12	5.72	6.14	5.17	7.78	8.50	9.19	78.08
Green Building (GB)	6.94	4.38	9.64	6.63	18.81	6.73	5.80	7.33	5.73	7.53	9.95	10.53	81.19
Lighting (LIGHT)	6.77	3.78	10.34	6.70	7.44	20.36	5.62	8.40	5.22	7.97	8.12	9.28	79.64
Healthy Living (HL)	5.68	4.52	8.38	6.72	7.87	6.89	25.39	6.86	4.40	7.10	7.51	8.69	74.61
Pollution Mitigation (POL)	7.04	3.64	10.04	6.03	8.11	8.31	5.74	19.8	5.25	7.76	7.94	10.32	80.20
Natural Resources (NR)	6.39	3.72	9.39	6.08	7.52	6.29	4.22	6.40	26.51	5.47	9.31	8.68	73.49
Renewable Energy Generation (REG)	6.40	4.69	9.38	7.35	8.21	7.78	5.74	7.55	4.49	20.06	7.85	10.50	79.94
Recycling (REC)	7.05	4.42	11.02	7.14	9.37	6.98	5.25	6.87	6.65	6.80	17.60	10.85	82.40
Water (WATER)	6.80	4.11	10.88	7.09	9.26	7.38	5.69	8.29	5.85	8.55	10.06	16.04	83.96
TO	72.68	46.62	106.31	74.63	88.84	78.04	59.62	78.57	59.24	80.36	95.42	105.1	945.44
Net	−5.98	−22.5	22.15	−3.45	7.65	−1.59	−14.99	−1.63	−14.24	0.42	13.02	21.14	TCI = 78.79

Notes: In the table, "TO" refers to the total directional shock spillover by one sector to all other sectors. "FROM" indicates the total directional shock spillover received by one sector from all other sectors. "NET" values represent the net contribution made by each sector to a connectedness network. TCI (Total Connectedness Index) indicates the average impact that a shock in one sector has on all other sectors and represents the overall connectedness within the system. Sector abbreviations are referred to as AM: Advanced Materials; BIO: Bio/Clean Fuels; ENEF: Energy Efficiency; TRN: Green Transportation; GB: Green Building; LIGHT: Lighting; HL: Healthy Living; POL: Pollution Mitigation; NR: Natural Resources; REG: Renewable Energy Generation; REC: Recycling; WATER: Water.

Table 4
Average total connectedness between green sectoral equities for the pre-COVID-19 Period (October 15, 2010, to March 10, 2020).

	AM	BIO	ENEF	TRN	GB	LIGHT	HL	POL	NR	REG	REC	WATER	FROM
Advanced Materials (AM)	22.37	3.83	10.08	7.75	7.71	6.48	4.54	7.99	5.26	6.63	8.24	9.11	77.63
Bio/Clean Fuels (BIO)	5.39	32.66	7.55	7.44	6.55	4.43	4.85	5.59	4.31	6.30	7.12	7.82	67.34
Energy Efficiency (ENEF)	7.30	3.94	15.98	8.72	8.27	7.73	5.04	8.57	6.43	7.33	9.92	10.77	84.02
Green Transportation (TRN)	6.57	4.62	10.25	18.95	8.14	6.29	5.30	7.36	5.66	7.43	9.27	10.16	81.05
Green Building (GB)	6.24	3.85	9.27	7.83	19.13	6.36	5.64	7.88	5.40	7.66	9.60	11.11	80.87
Lighting (LIGHT)	6.25	3.07	10.28	7.09	7.45	21.18	5.06	9.27	5.29	7.30	8.04	9.72	78.82
Healthy Living (HL)	5.29	3.97	8.15	7.36	8.01	6.24	26.89	6.80	4.51	6.62	7.32	8.84	73.11
Pollution Mitigation (POL)	6.78	3.48	10.09	7.38	8.21	8.39	4.95	18.95	5.67	7.40	8.06	10.64	81.05
Natural Resources (NR)	5.58	3.21	9.63	7.18	7.04	6.05	4.11	7.26	26.84	5.29	8.51	9.31	73.16
Renewable Energy Generation (REG)	6.12	4.15	9.29	8.13	8.61	6.98	5.24	7.90	4.49	20.62	7.76	10.70	79.38
Recycling (REC)	6.47	4.10	10.95	8.56	9.21	6.66	4.93	7.47	6.24	6.57	17.95	10.87	82.05
Water (WATER)	6.45	4.08	10.54	8.42	9.54	7.17	5.34	8.85	6.13	8.20	9.65	15.63	84.37
TO	68.44	42.30	106.07	85.86	88.74	72.78	55.00	84.95	59.40	76.74	93.50	109.06	942.84
Net	−9.19	−25.04	22.05	4.82	7.87	−6.04	−18.11	3.90	−13.76	−2.64	11.45	24.69	TCI = 78.57

Notes: In the table, "TO" refers to the total directional shock spillover by one sector to all other sectors. "FROM" indicates the total directional shock spillover received by one sector from all other sectors. "NET" values represent the net contribution made by each sector to a connectedness network. TCI (Total Connectedness Index) indicates the average impact that a shock in one sector has on all other sectors and represents the overall connectedness within the system. Sector abbreviations are referred to as AM: Advanced Materials; BIO: Bio/Clean Fuels; ENEF: Energy Efficiency; TRN: Green Transportation; GB: Green Building; LIGHT: Lighting; HL: Healthy Living; POL: Pollution Mitigation; NR: Natural Resources; REG: Renewable Energy Generation; REC: Recycling; WATER: Water.

Table 5
Average total connectedness between green sectoral equities for the post-COVID-19 Period (March 11, 2020, to September 30, 2023).

	AM	BIO	ENEF	TRN	GB	LIGHT	HL	POL	NR	REG	REC	WATER	FROM
Advanced Materials (AM)	20.00	4.11	10.70	3.63	9.28	8.39	5.54	6.11	6.58	7.43	9.84	8.39	80.00
Bio/Clean Fuels (BIO)	5.75	28.75	7.10	5.76	7.81	7.48	6.68	3.78	5.04	8.39	7.82	5.65	71.25
Energy Efficiency (ENEF)	8.77	4.27	16.16	4.32	9.25	9.03	6.28	6.48	5.55	8.31	10.68	10.89	83.84
Green Transportation (TRN)	5.45	6.29	7.78	30.62	5.75	9.20	6.66	2.95	3.74	8.78	6.29	6.49	69.38
Green Building (GB)	8.72	5.43	10.75	3.71	18.98	7.37	5.98	5.67	6.51	6.90	11.04	8.93	81.02
Lighting (LIGHT)	8.05	5.24	10.62	5.98	7.33	19.35	6.77	5.99	4.81	9.63	8.16	8.08	80.65
Healthy Living (HL)	6.48	5.50	8.90	5.17	7.39	8.30	23.30	6.95	3.90	8.25	7.71	8.15	76.70
Pollution Mitigation (POL)	7.52	3.48	9.83	2.74	7.66	8.02	7.61	24.42	3.85	8.30	7.32	9.24	75.58
Natural Resources (NR)	8.40	4.70	8.73	3.39	8.73	6.54	4.28	3.90	27.09	5.81	11.57	6.88	72.91
Renewable Energy Generation (REG)	7.13	5.85	9.80	5.67	7.10	9.71	6.84	6.23	4.35	19.54	7.93	9.84	80.46
Recycling (REC)	8.55	4.88	11.40	3.66	10.00	7.48	5.78	5.11	7.68	7.18	17.41	10.86	82.59
Water (WATER)	7.55	3.71	12.07	3.90	8.57	7.69	6.33	6.57	4.92	9.28	11.31	18.10	81.90
TO	82.36	53.44	107.69	47.93	88.85	89.21	68.76	59.74	56.95	88.27	99.67	93.4	936.28
Net	2.36	−17.81	23.85	−21.45	7.84	8.56	−7.93	−15.85	−15.96	7.81	17.08	11.5	TCI = 78.02

Notes: In the table, "TO" refers to the total directional shock spillover by one sector to all other sectors. "FROM" indicates the total directional shock spillover received by one sector from all other sectors. "NET" values represent the net contribution made by each sector to a connectedness network. TCI (Total Connectedness Index) indicates the average impact that a shock in one sector has on all other sectors and represents the overall connectedness within the system. Sector abbreviations are referred to as AM: Advanced Materials; BIO: Bio/Clean Fuels; ENEF: Energy Efficiency; TRN: Green Transportation; GB: Green Building; LIGHT: Lighting; HL: Healthy Living; POL: Pollution Mitigation; NR: Natural Resources; REG: Renewable Energy Generation; REC: Recycling; WATER: Water.

inter-sector connections varies in the post-COVID era. For example, the extent of spillover effects from the lighting, advanced materials and healthy living sectors to other sectors has risen, thereby constraining their potential for diversification. Conversely, the interconnectedness of the green transportation, pollution mitigation and water sectors with other industries has diminished, indicating potential avenues for diversification. Second, following the pandemic, several sectors changed their net status from transmitter to receiver or vice versa, such as green transportation, pollution mitigation, renewable energy generation, lighting sectors and advanced materials. This heterogeneous connectedness among green equities enables investors to construct a well-diversified green portfolio.

The network of pairwise connectedness among green sector equities is illustrated in Fig. 3, with panels (a, b, c) representing the connectedness across the full sample, the pre- and post-COVID-19 periods. Panel (a) identifies pairs that demonstrate significant interconnectedness, particularly between energy efficiency and sectors such as recycling, water, lighting, pollution mitigation, green building, advanced materials and renewable energy generation. Anyanwu and Kur (2024) stated that energy is an essential requirement for all economic sectors, and efforts are being made to enhance its efficiency in order to safeguard the environment from the detrimental effects associated with economic growth. Consequently, the energy efficiency sector is intricately connected to various other sectors, as it facilitates their goals by enabling more effective energy consumption. Additionally, strong connections are observed between water and recycling, green building, pollution mitigation and renewable energy generation, as well as between recycling and green building. It is noteworthy that the energy efficiency, recycling, and water sectors not only exhibit close interrelations but also maintain robust ties with a majority of the green sectors.

A comparative analysis of panels (b) and (c) reveals that the connections between energy efficiency and water, recycling, green building and lighting have notably strengthened in the post-COVID-19 period. Conversely, its pairwise connections with green transportation and pollution mitigation have diminished, a trend that was more evident during the pre-COVID-19 period. Similarly, the water sector's linkages with recycling and renewable energy generation have intensified, while connections with green building and pollution mitigation have weakened. These heterogeneous associations should also be considered in the construction of a portfolio. Overall, it is essential to highlight that the interconnectedness of nearly all sectors with one another has increased significantly, with the exception of green transportation and pollution mitigation which have experienced a marked decline in their connections with other sectors in the post-COVID-19 context, compared to the pre-COVID-19 period.

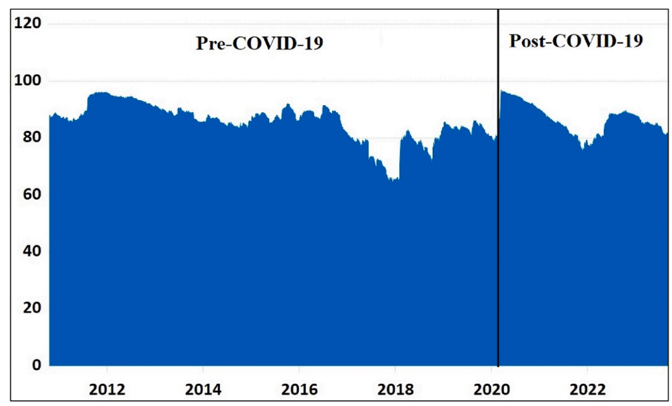

Fig. 4. Dynamic connectedness among green sector equities from October 15, 2010, to September 30, 2023.

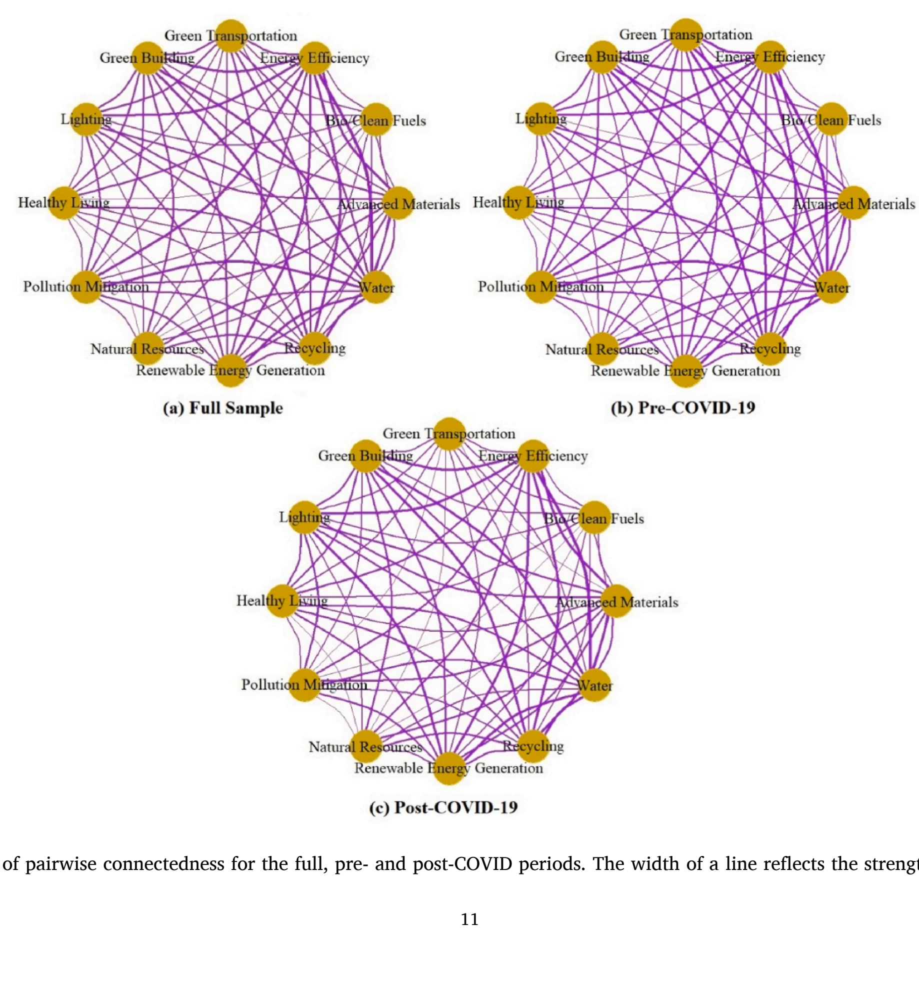

Fig. 3. Networks of pairwise connectedness for the full, pre- and post-COVID periods. The width of a line reflects the strength of connectedness.

4.2. Dynamic connectedness analysis

The dynamic connectedness among green sector equities is displayed in Fig. 4. The total TCI oscillated between 65 % and 97 % which confirms the time-varying features of sector interaction. The first important rise in the TCI at 96 % was noticed during the European debt crisis in the last quarter of 2011, which gradually bounced back at the end of May 2013. These kinds of unforeseen events cause investors to react strongly, and they modify their portfolios appropriately which leads to an increase in the interconnectedness of financial assets (Rubbaniy et al., 2024). After a stable period from June 2013 to mid-2014, there was a slump in the oil market from 2014 to 2016, with the TCI staying between 84 % and 92 %. However, since June 2016, a declining trend has been noticed, followed by a sudden jump in the connectedness on February 5, 2018. This huge spike is due to the biggest one-day downturn in the Dow Jones industrial average index. Furthermore, some significant spikes can be seen in connectedness during 2018–2019, being attributed to the US–China trade war.

COVID-19, a first and foremost health crisis, was later declared a global pandemic by the World Health Organization (WHO) on March 11, 2020. This announcement resulted in a sudden fall in financial markets on the next day, including NASDAQ, Dow Jones and S&P 500 (Kuloğlu, 2022). This led to a skyrocketing TCI value of 96 % on March 12, 2020, which gradually decreased till December 2021. This decline may be due to the announcement of stimulus packages and steps taken by governments for financial stability and control of the health crisis. Following the recovery process from the pandemic, instantly the Russia–Ukraine war in 2022 disrupted the supply chain which negatively impacted global economic growth and increased inflation throughout the world (Ngoc et al., 2022). This tense environment resulted in a dramatically amplified connectedness during 2022 with the TCI climbing to 90 % at the end of 2022, followed by a decreasing trend, which shows the movement toward market stability. The above supports the phenomenon of rising connectedness during crises and reducing during periods of stability. The inter-sector connectedness is time-varying and depends on various types of financial, economic and geopolitical events.

Next, the dynamics of TO, FROM, and net directional connectedness of the green economic sectors are highlighted in Fig. 5a, b, and 5c. The analysis shown in Fig. 5a and b validates the static results concerning the least integrated and closely connected industries. Following the pandemic, the connectedness of lighting, advanced materials and healthy livings sectors with other industries has increased due to several reasons. For example, the heightened emphasis on sustainability in the wake of the COVID-19 pandemic necessitates the development of more sustainable lighting solutions (Widartha et al., 2024). Concurrently, there has been a surge in public demand for sustainable products, driven by a growing awareness of environmental issues, which has led to increased demand for advanced materials (Sijabat, 2024). Furthermore, the pandemic has rekindled interest in and the necessity for healthy living (Jevtic et al., 2022; Kolakowski et al., 2021). Therefore, these sectors have experienced growth in the aftermath of the pandemic possibly due to environmental protection policies such as the green stimulus packages (Economics, 2021), which ultimately strengthen their connections with other green economic sectors. In contrast, green

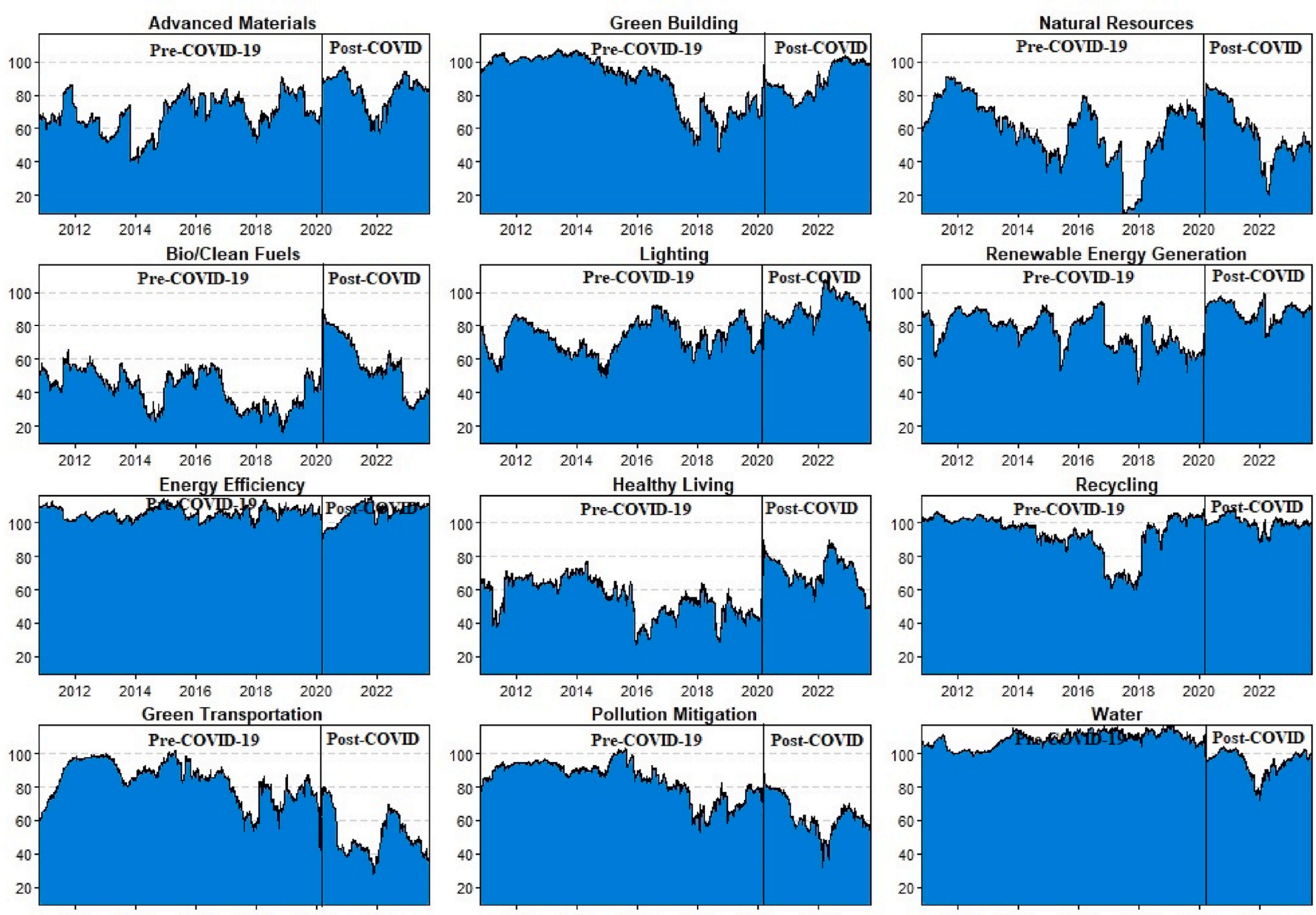

Fig. 5a. Dynamic directional connectedness from an individual green economic sector TO others.

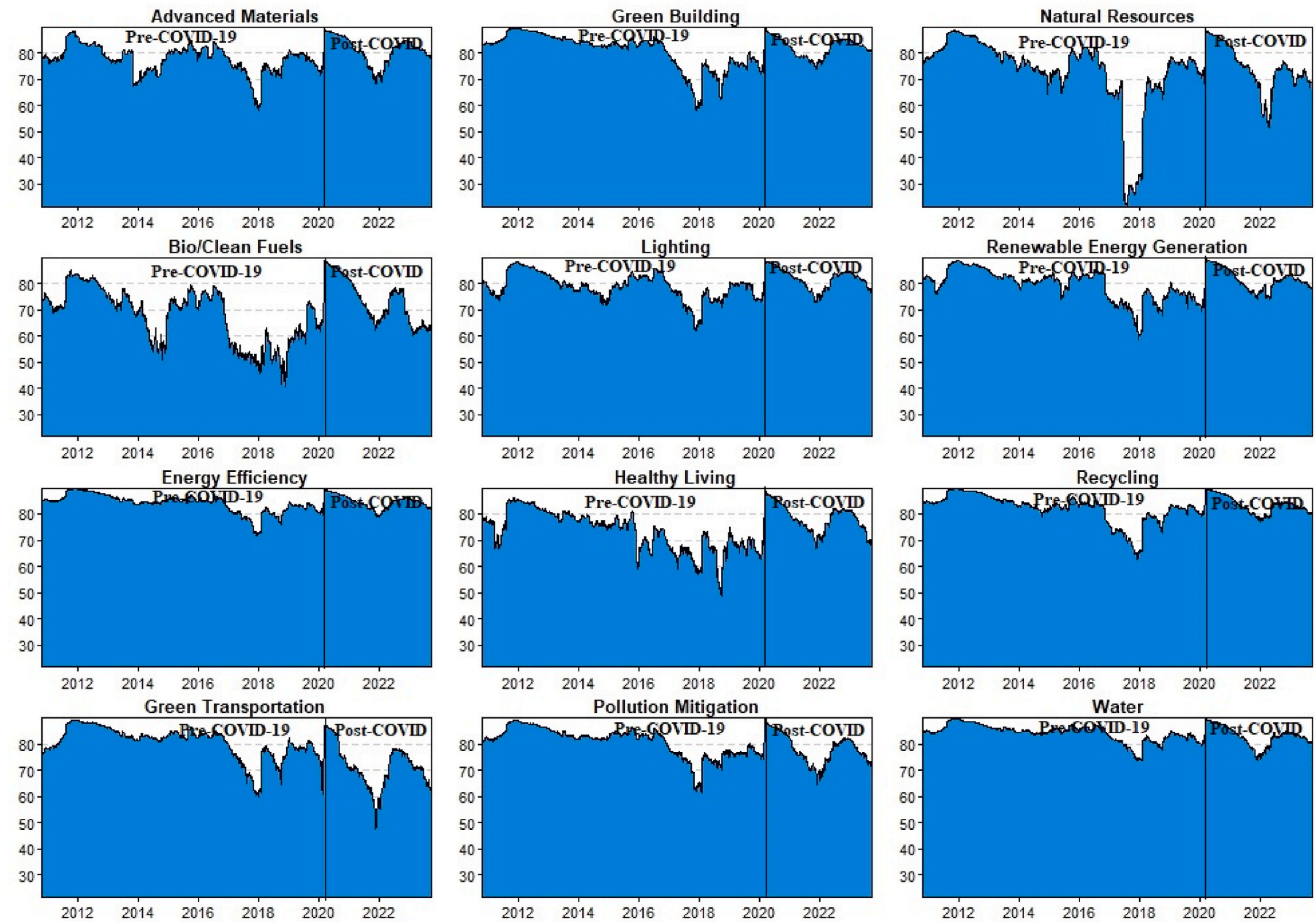

Fig. 5b. Dynamic directional connectedness received by an individual green economic sector FROM others.

transportation, pollution mitigation and the water sector experienced decreases in connectedness with other sectors. Furthermore, Fig. 5c documents that most sectors continued to function primarily as net transmitters or receivers both before and after the pandemic, except green transportation, pollution mitigation, renewable energy generation, lighting sectors and advanced materials, which reversed their status from net transmitter to receiver or vice versa. Thus, dynamic connectedness among green equities enables investors to diversify their portfolios by restructuring them during extreme occurrences to mitigate risk.

4.3. Portfolio management implications

4.3.1. Portfolio weights and hedge effectiveness

In this section, the multivariate average portfolio weights for the full, pre- and post-COVID-19 periods, along with hedge effectiveness (HE), are presented in Table 6, for the purposes of optimal portfolio diversification and risk management. First, full sample results show that MVP assigned maximum weights to water (29 %), renewable energy generation (14 %) and healthy living (13 %), while the lowest weights were assigned to energy efficiency (0 %), lighting (0 %) and the advanced materials sector (1 %). In addition, HE suggests that each green sector equity has some hedging power in a portfolio, and guides risk-averse investors to make the safest investment across green sectors. Secondly, MCP and MCoP strategies give the highest weights to natural resources (17 %, 16 %), bio/clean fuels (16 %, 15 %) and healthy living (12 %, 12 %), whereas the least allocation is given for energy efficiency (0 %, 0 %), recycling (3 %, 3 %) and the water sector (3 %, 3 %), respectively. The HE results show positive values for every stock, except the water sector, which has a negative value. Here, positive values explain the significant risk reduction ability of some sectors, but negative values refer to the rise in hedging cost and volatility, or a decrease in return (Pham, 2016). Based on full sample results, the bio/clean fuels, green transportation, natural resources, lighting and advanced materials sectors have higher HE scores than other sectors in all portfolios.

Moreover, when comparing the weights and HE of green equities between the pre- and post- COVID-19 periods, some important conclusions may be drawn. First, Table 6 shows the change in weights in both sub-samples, which is caused by changes in variance and interactions between the equities. For instance, when the MVP approach was considered, the water sector's assigned weight increased from 24 % to 37 % and the average weight of green transportation declined from 16 % to 1 % in the post-COVID period. Similarly, the weights of most sectors in MCP and MCoP decreased following COVID-19 except for green transportation, pollution mitigation, natural resources and water sectors, which experienced an increase. Secondly, under all three portfolio strategies, the bio/clean fuels, natural resources, lighting, advanced materials and green transportation offer considerable hedge effectiveness in both sub-samples. Overall, MVP provides more HE when compared to MCP and MCoP.

Next, Fig. 6 demonstrates the dynamic portfolio weights of individual green equities under MVP, MCP, and MCoP. On close inspection, it is found that portfolio weights assigned to various green equities in MVP have a more fluctuated pattern and differ considerably from the other

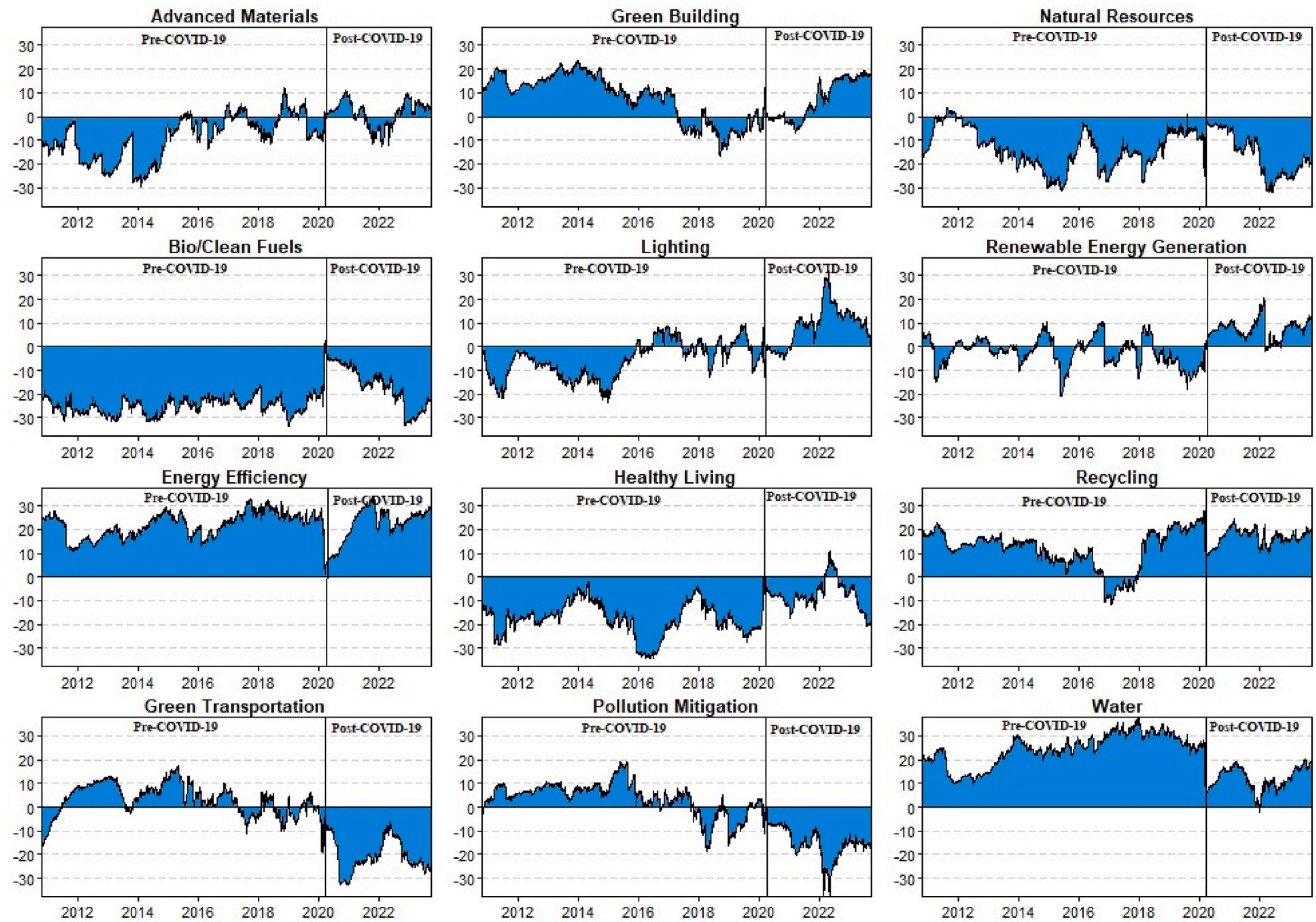

Fig. 5c. Dynamic net directional connectedness.

two methods. However, portfolio weights in MCP and MCoP are almost similar and constant throughout the sample. For example, the MVP gives substantial weight to the water sector throughout the sample, while MCP and MCoP allocated no funds to this sector before COVID-19 but assigned more weight during the post-COVID-19 period. Furthermore, it is noticed that weights assigned to individual equities are affected by financial market conditions. For example, renewable energy generation fails to get scores during the post-COVID-19 but gets significant allocation in the course of the Russia–Ukraine conflict under all scenarios. Therefore, it is reasonable to say that diverse market conditions have a big influence on the risk characteristics and connections between different assets. So, the dynamic nature of portfolio weights offers diversification opportunities between green equities, and recommends timely portfolio restructuring by considering the prevailing market conditions. For example, during the COVID-19 crisis, investors had the opportunity to rebalance their portfolios by allocating more resources to the green transportation, pollution mitigation and water sectors under the MCoP framework. This strategic shift was warranted as the interconnections of these sectors with other industries diminished during the specified period. Conversely, investment weights could be reduced in renewable energy generation, healthy living and bio/clean fuels, attributed to an increase in their interconnectedness with other sectors.

A negative hedge ratio in the water sector can be attributed to several factors, primarily revolving around the unique challenges and uncertainties inherent in water resource management. For instance, legal conflicts related to Uncertain Property Rights not only increase complexity and cost of trading water rights and high risks (Womble and Hanemann, 2020), but also an Inefficiency of Water Markets (Gramlich and Ohlsen, 2023; Janmaat and Rahimova, 2018). This can deter companies from engaging in hedging activities as the potential benefits may not outweigh the costs and risks involved. Likewise, water scarcity, which affects the profitability and liquidity of companies, makes it challenging to predict future water prices, reduced production capacity and increased operational costs (Gramlich and Ohlsen, 2023; Larson et al., 2012). The other factors which can create uncertainty in the water sector include regulations and policies related to water management (Paydar and Qureshi, 2011) and the impact of climate change (Luís et al., 2016). These uncertainties can complicate the development of effective hedging strategies and can lead to a negative hedge ratio, as the costs of hedging may exceed the potential benefits.

These analyses guide sustainable investors to make efficient investment decisions across equities in green sectors. These green investments provide capital to companies that are engaged in the development and application of environment-friendly technologies and solutions. Apart from providing social and economic benefits, these investments protect the natural environment by reducing greenhouse gas emissions, air, water and soil pollution, and biodiversity loss, and they preserve natural resources and increase water and energy efficiency (Zahan and Chuanmin, 2021).

4.3.2. Performance analysis of multivariate portfolio approaches

To find the best portfolio construction strategy, the performance of green portfolios designed under MVP, MCP, and MCoP are examined with the help of Sharpe, Omega and Sortino ratios. The full sample

Table 6
Multivariate portfolio weights of green sectoral equities.

	Full sample						Pre-COVID-19						Post-COVID-19					
	October 15, 2010, to September 30, 2023						October 15, 2010, to March 10, 2020						March 11, 2020, to September 30, 2023					
	MVP		MCP		MCoP		MVP		MCP		MCoP		MVP		MCP		MCoP	
	Mean	HE	Mean	HE	Mean	HE	Mean	HE	Mean	HE	Mean	HE	Mean	HE	Mean	HE	Mean	HE
Advanced Materials	0.01	0.60	0.10	0.41	0.11	0.42	0.01	0.66	0.12	0.51	0.12	0.52	0.03	0.51	0.06	0.24	0.07	0.25
Bio/Clean Fuels	0.05	0.75	0.16	0.62	0.15	0.63	0.07	0.71	0.18	0.59	0.16	0.59	0.01	0.78	0.14	0.66	0.14	0.66
Energy Efficiency	0.00	0.47	0.00	0.22	0.00	0.23	0.00	0.52	0.00	0.32	0.00	0.33	0.02	0.4	0.00	0.06	0.00	0.07
Green Transportation	0.10	0.70	0.08	0.56	0.09	0.56	0.16	0.4	0.04	0.15	0.04	0.15	0.01	0.81	0.18	0.71	0.17	0.71
Green Building	0.07	0.51	0.05	0.27	0.05	0.28	0.08	0.38	0.05	0.12	0.06	0.12	0.03	0.61	0.03	0.39	0.04	0.39
Lighting	0.00	0.65	0.09	0.48	0.09	0.49	0.00	0.67	0.11	0.52	0.11	0.53	0.01	0.63	0.03	0.42	0.03	0.43
Healthy Living	0.13	0.42	0.12	0.14	0.12	0.15	0.10	0.46	0.14	0.23	0.13	0.24	0.19	0.37	0.08	0.02	0.07	0.03
Pollution Mitigation	0.11	0.37	0.10	0.08	0.10	0.08	0.08	0.4	0.07	0.15	0.07	0.16	0.18	0.34	0.18	−0.02	0.17	−0.01
Natural Resources	0.04	0.69	0.17	0.55	0.16	0.55	0.04	0.71	0.16	0.59	0.16	0.59	0.04	0.67	0.18	0.48	0.17	0.49
Renewable Energy Generation	0.14	0.37	0.07	0.08	0.08	0.08	0.16	0.35	0.10	0.07	0.10	0.08	0.11	0.41	0.02	0.08	0.02	0.09
Recycling	0.06	0.41	0.03	0.13	0.03	0.14	0.06	0.41	0.04	0.16	0.04	0.17	0.02	0.42	0.00	0.1	0.00	0.11
Water	0.29	0.20	0.03	−0.19	0.03	−0.18	0.24	0.21	0.00	−0.13	0.00	−0.12	0.37	0.19	0.11	−0.26	0.12	−0.24

Notes: The results are based on TVP-VAR model with lag order 1 (BIC) and 20 step-ahead generalized forecast error variance decomposition.

results in Panel A of Table 7 reveal that MVP has a higher risk-adjusted return performance with the highest Sharpe (0.0246), Omega (1.076) and Sortino (0.033) ratios, followed by MCoP and MCP. However, MCoP has the highest daily mean return, while ranking second in terms of risk-adjusted performance due to high risk. Moreover, by comparing the statistics in Panels B and C, it is observed that MVP produces more returns and higher Sharpe (0.0298), Omega (1.089) and Sortino (0.040) ratios than other methods in the pre-COVID-19 sample, whereas the MCoP strategy provides the highest risk-adjusted returns based on all evaluation ratios (0.0343, 1.104, 0.047), followed by MCP and MVP during the post-COVID-19 period.

The superior performance of MCoP in the aftermath of the pandemic can be attributed to several factors. Primarily, MCoP aims to integrate the least connected sectors within a portfolio, thereby mitigating the transmission of shocks or contagion from one financial asset to another (Broadstock et al., 2022). The ongoing health crisis has heightened volatility and systemic risk across financial markets and sectors (Haroon et al., 2021; So et al., 2021), leading to increased interconnectedness among assets due to disruptions in supply chains, shifts in investor risk tolerance, and changes in investors sentiments (Heng and Lin, 2025; Rubbaniy et al., 2024). Consequently, MCoP may provide enhanced protection against contagion and market risk compared to conventional strategies. Additionally, traditional approaches, such as the Minimum Variance Portfolio (MVP), which rely on historical data, may prove inadequate for predicting future risks due to the unprecedented market conditions created by the COVID-19 pandemic. In this context, MCoP's focus on asset interconnectedness may render it more adaptable to evolving market dynamics. Moreover, it is important to note that the pandemic has not uniformly impacted all economic sectors (Nadeem et al., 2022). By taking into account the interconnectedness among sectors, MCoP can capitalize on the growth of certain sectors while simultaneously minimizing exposure to the downside risks associated with other industries. Lastly, it has already been stated that green investment increased after the COVID-19 outbreak due to a rise in awareness about climate change and environmental issues. This significant growth in green economic sectors has provided higher returns in the post-COVID-19 period, as shown in Table 2. Therefore, MCoP shows better performance by combining the least connected green equities. Therefore, MCoP is preferred over MVP and MCP techniques for achieving the optimum risk-adjusted returns in the present era of growing green equity markets. Furthermore, Fig. 7 reinforces the preceding findings and demonstrates that MVP's cumulative return performance is superior in the pre-pandemic era, but MCoP performs better in the post COVID-19 period. Finally, the performance of MCP is marginally lower than MCoP in all samples.

4.3.3. *Portfolio performance comparison of green and conventional investments*

Table 7 shows the performance of green and conventional portfolios under MVP, MCP and MCoP for the full, pre- and post-COVID-19 periods. According to the full sample results in Panel A, the green portfolios designed under MVP, MCP and MCoP outperformed the commodity portfolio, while underperforming conventional and cryptocurrency portfolios. On the other hand, by comparing the results of the pre- and post-COVID-19 period, it is noted that the performance results in the pre-COVID-19 period are almost similar to the full sample results. These findings suggest that, during the pre-COVID-19 period, green investors had to sacrifice returns by investing in sustainable investments. However, several interesting changes are noticed in the post-COVID-19 period. First of all, it is observed that the daily green portfolio returns significantly increased under MCP (0.00050) and MCoP (0.00050) strategies as compared to other conventional portfolios in the post-COVID-19 era. Secondly, similar to conventional portfolios, the volatilities of green portfolios also increased but this increase was smaller than a rise in green portfolio returns. Thirdly, the green portfolio has better risk-adjusted performance than all other conventional investment

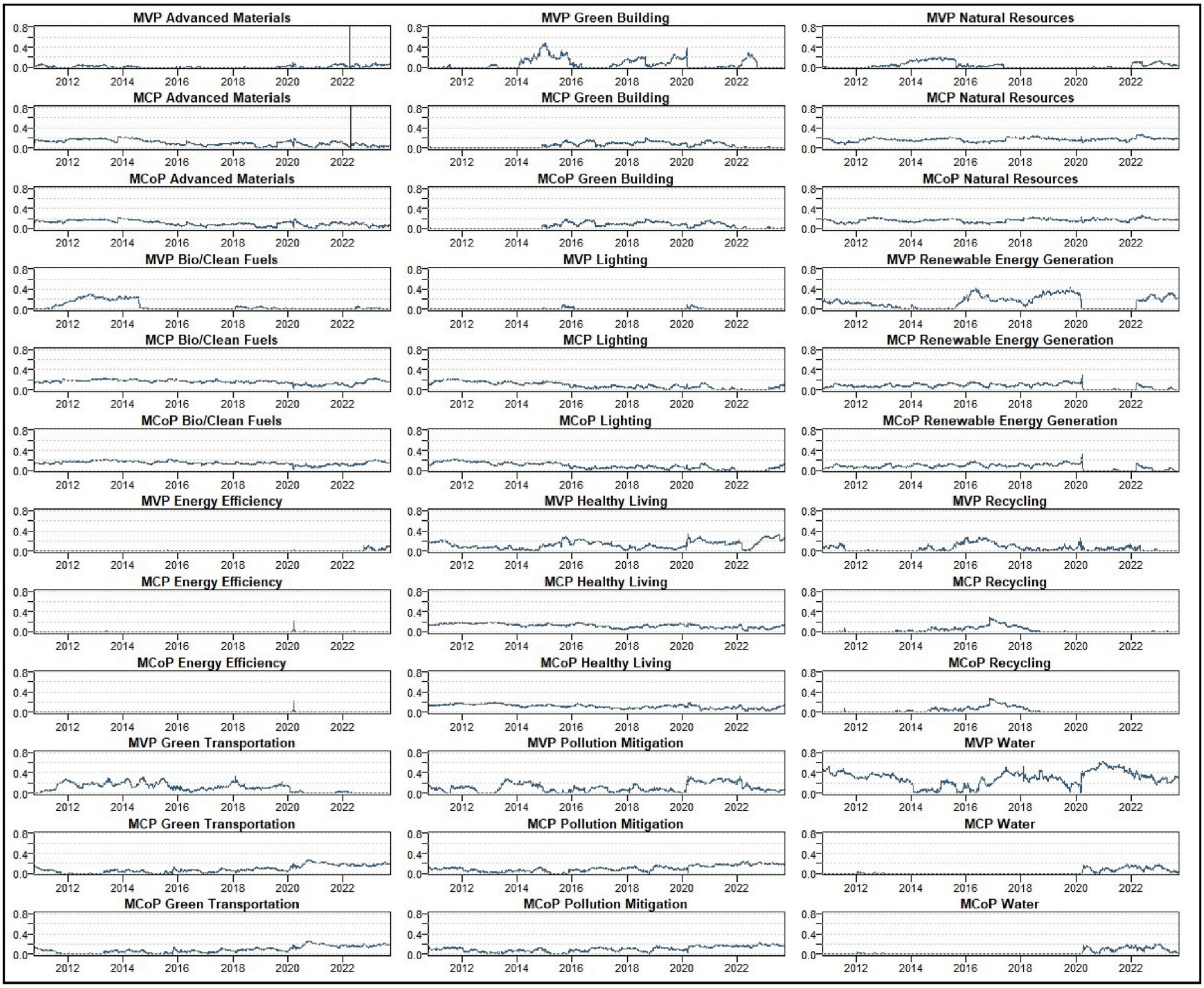

Fig. 6. Dynamic multivariate portfolio weights of green sector equities under minimum variance portfolio (MVP), minimum correlation portfolio (MCP) and minimum connectedness portfolio (MCoP).

portfolios with the highest Sharpe (0.0344) and Sortino (0.047) ratios. These ratios provide the risk adjusted return to investors, especially the Sortino ratio which is more suitable for risk-averse investors because it considers downside risk as measure of risk (Barberis et al., 2001). However, when the omega ratio of MCoP is considered, the green portfolio has a higher ratio (1.104) than conventional equity and commodity portfolios but is marginally lower than that of cryptocurrency portfolios (1.107). Omega ratio results are considered as more realistic measures of performance as they consider the whole distribution of returns (Keating and Shadwick, 2002) and are suitable for investors who want to consider both upside and downside return distributions (Samaniego Alcántar, 2022). The outperformance of an environment-friendly portfolio is in line with the findings of Gonçalves et al. (2021) and Neves et al. (2024) but contradicts the results of El Ghoul et al. (2023), Ibikunle and Steffen (2017). Overall, green investments are performing better throughout the world in the present era but with some variations noted across regions (Cunha et al., 2020). It is expected that these investments will continue to provide higher returns to eco-friendly investors whilst meeting the objectives of sustainability.

There are several possible reasons for the outperformance of green portfolios when compared with other non-green investments in the post-pandemic period. First, there was a notable shift in the focus of international investors towards sustainable investments after the COVID-19 outbreak (Sharma et al., 2022). By early 2024, the volume of green investments had surged to $7.2 trillion, a significant increase from the pre-COVID-19 level of approximately $4 trillion, as reported by Dai et al. (2024). Moreover, this growth was expected due to an increase in environmental awareness and the demand for eco-friendly assets (Handayani and Rokhim, 2023; Sharma et al., 2022, 2023). The second possible reason may be the crisis resilience safe haven characteristics of green assets, as pointed out by Gonçalves et al. (2021) and Siddique et al. (2024), which provide higher risk-adjusted returns during times of crisis (Gonçalves et al., 2021). These attributes incentivize investors to switch from traditional to environmentally conscious investing. Third, green securities have experienced a better return performance in the aftermath of the COVID-19 pandemic (Chen et al., 2023a; Garel and Petit-Romec, 2021), which may have led to higher return performances of green portfolios. Finally, government regulations like the SDGs and the Paris Agreement, and support packages such as The European Green Deal, improve the performance of green investments (Agostini et al., 2024; Ferrer et al., 2021; Gonçalves et al., 2021).

Table 7
Green portfolio performance comparison with traditional investments.

	Green Portfolio			Conventional Portfolio			Commodity Portfolio			Cryptocurrency Portfolio		
	MVP	MCP	MCoP	MVP	MCP	MCoP	MVP	MCP	MCoP	MVP	MCP	MCoP
Panel A. Full sample (October 15, 2010, to September 30, 2023)												
Mean	0.00023	0.00024	0.00025	0.00041	0.00035	0.00036	−0.00006	−0.00031	−0.00031	0.00584	0.13956	0.14138
Std. Dev.	0.0093	0.0113	0.0112	0.0104	0.0121	0.0122	0.0074	0.0098	0.0098	0.4598	3.2269	3.3558
Sharpe Ratio (SD)	0.0246	0.0210	0.0221	0.0392	0.0285	0.0291	−0.0077	−0.0316	−0.0341	0.0127	0.0432	0.0421
Omega Ratio	1.076	1.063	1.066	1.122	1.086	1.088	0.979	0.918	0.913	1.054	1.141	1.137
Sortino Ratio	0.033	0.029	0.030	0.054	0.039	0.040	−0.010	−0.043	−0.046	0.019	0.062	0.060
Panel B. Pre-COVID-19 Period (October 15, 2010, to March 10, 2020)												
Mean	0.00024	0.00012	0.00013	0.00045	0.00040	0.00040	−0.00015	−0.00047	−0.00050	0.00639	0.18607	0.18540
Std. Dev.	0.0081	0.0096	0.0096	0.0091	0.0105	0.0105	0.0072	0.0087	0.0088	0.5964	3.2709	3.3329
Sharpe Ratio (SD)	0.0298	0.0128	0.0138	0.0498	0.0379	0.0379	−0.0212	−0.0536	−0.0563	0.0107	0.0569	0.0556
Omega Ratio	1.089	1.037	1.040	1.154	1.113	1.113	0.943	0.867	0.862	1.038	1.183	1.175
Sortino Ratio	0.040	0.017	0.019	0.069	0.052	0.052	−0.028	−0.072	−0.075	0.016	0.084	0.081
Panel C. Post-COVID-19 Period (March 11, 2020, to September 30, 2023)												
Mean	0.00019	0.00050	0.00050	0.00026	0.00018	0.00021	0.00019	0.00010	0.00012	0.00328	0.10383	0.10156
Std. Dev.	0.0118	0.0148	0.0147	0.0134	0.0160	0.0162	0.0079	0.0127	0.0118	0.2575	3.2334	3.3495
Sharpe Ratio (SD)	0.0162	0.0341	0.0344	0.0192	0.0115	0.0130	0.0244	0.0077	0.0102	0.0127	0.0321	0.0303
Omega Ratio	1.050	1.102	1.104	1.059	1.034	1.038	1.068	1.021	1.028	1.076	1.107	1.102
Sortino Ratio	0.0221	0.0468	0.0473	0.026	0.016	0.018	0.033	0.011	0.014	0.018	0.046	0.043

Notes: The results of the minimum variance portfolio (MVP), minimum correlation portfolio (MCP), and minimum connectedness portfolio (MCoP) are based on (Markowitz, 1959; Christoffersen et al., 2014; Broadstock et al., 2020) respectively. The values of all HE ratios are significant at the 1 % level.

5. Conclusion and policy implications

The global initiatives and increased awareness regarding environmental challenges support the transition to low-carbon and sustainable economies. To boost this process, this research conducted an extensive analysis of return connectedness, evaluated portfolio implications, and assessed the performance of green sector equities using different portfolio construction methods. Furthermore, green portfolio performance is compared with other conventional investment portfolios to determine whether sustainable investors can earn higher risk-adjusted returns or if they must pay a premium for engaging in environmentally friendly investments. These analyses are performed before and after the COVID-19 pandemic to examine any alterations in the connectivity patterns and the performance of green equity portfolios in the aftermath of the outbreak. To achieve these objectives, daily closing values of the NASDAQ OMX green economic index family are used, spanning from October 15, 2010 to September 30, 2023 by applying the TVP-VAR connectedness approach.

The overall results of the TVP-VAR model revealed the close connectedness between equities of green economic sectors. The static connectedness analysis indicates that energy efficiency is the main net information transmitter, followed by water, recycling, green building and renewable energy generation sectors. In contrast, the largest receiver of net return connectedness is bio/clean fuels, followed by healthy living, natural resources, advanced materials, green transportation, pollution mitigation and lighting sectors. Furthermore, the pairwise connectedness results show the close ties of energy efficiency with sectors such as recycling, water, lighting, pollution mitigation, green building, advanced materials and renewable energy generation. Similarly, strong connections are observed among water and sectors including recycling, green building, pollution mitigation, and renewable energy generation, as well as between recycling and green building. The overall level of connectedness has largely remained consistent before and after the COVID-19 pandemic. However, the nature and intensity of interactions among various sectors have shifted in the period following the outbreak.

The portfolio strategy evaluation shows that the MVP exhibited superior performance during the overall and pre-COVID-19 periods, while the MCoP method outperforms in the post-COVID-19 period relative to alternative strategies. Furthermore, the dynamic multivariate portfolio weights exhibit a fluctuating pattern under all approaches and corroborate that weights assigned to individual equities are affected by prevailing financial market conditions, which have a significant impact on the risk attributes and relationships across various assets. The analysis of the HE results indicates that all portfolio strategies substantially mitigate the risk associated with allocating funds to a single green equity except the water sector under MCP and MCoP. The portfolio exercise reveals that green portfolios outperform commodity portfolios in terms of risk-adjusted returns, while underperforming conventional and cryptocurrency portfolios during the full sample and pre-COVID times. These results demonstrate that particularly before COVID-19, green investors had to pay a premium for going green. However, the green portfolios exhibit superior performance than all other conventional investment portfolios in the post-COVID era.

The findings of the study carry significant implications for sustainable investors and policymakers. First, the heterogeneous connectedness between green equities helps investors to construct a well-diversified green portfolio. The dynamic total and directional connectedness between green equities enable investors to diversify their portfolios by restructuring them in timely fashion to mitigate risk during times of crisis. Second, in the aftermath of the COVID-19 pandemic, investors seeking higher risk-adjusted returns may employ the MCoP strategy to construct pure green equity portfolios. Third, dynamic multivariate portfolio weights can play a significant role in portfolio rebalancing by incorporating the weights across various market conditions. Fourth, investors and portfolio managers can design optimal portfolios aimed at minimizing investment risk by considering the hedge effectiveness ratios. Furthermore, understanding the interconnectedness of green equities allows policymakers to develop effective expansion policies, given that policy impacts can be transmitted across sectors through existing linkages. For example, a policy that fosters the development of green buildings might include various incentives for utilizing energy-efficient materials, integrating renewable energy solutions, and managing water resources sustainably. In addition, to mitigate the associated risks and accelerate the growth of green industries, it is imperative to establish new regulations and support mechanisms including consistent policies and setting of long-term emission targets, tax breaks, green credits, subsidies and grants, more specifically in developing and emerging nations. Apart from attracting private sector investors towards green initiatives, these measures facilitate the realization of the goals set forth in environmental policies, such as SDGs, the Paris Agreement and the European Green Deal, by mitigating the effects of unsustainable human activities on the environment and natural resources. Importantly, during a time of crisis, strategies can be designed to stabilize leading sectors such as the energy efficiency, recycling and water sectors, to reduce the chances of contagion and systemic risk.

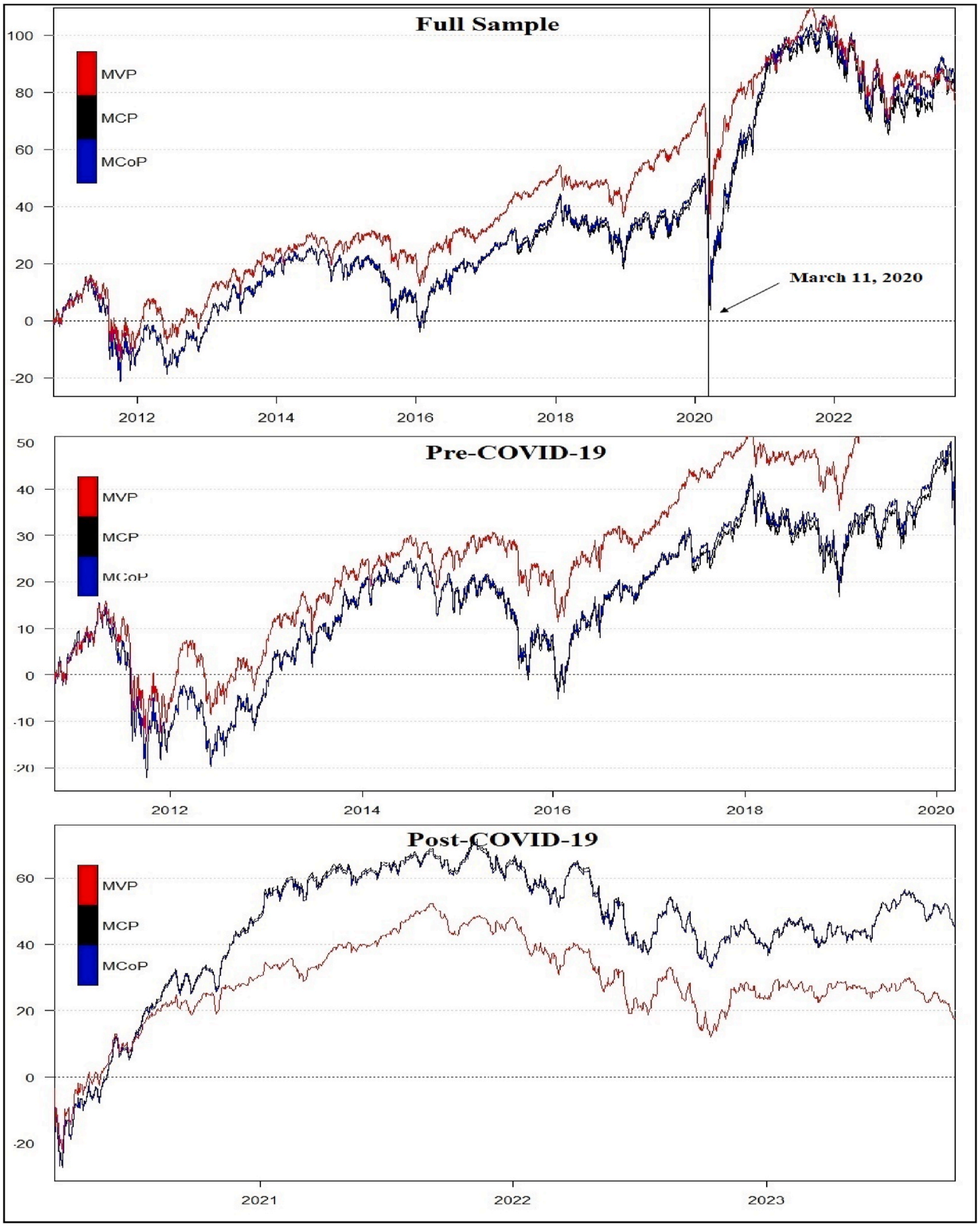

Fig. 7. Cumulative returns of green sector equities portfolio under minimum variance portfolio (MVP), minimum correlation portfolio (MCP) and minimum connectedness portfolio (MCoP).

This research presents several limitations and indicates potential avenues for future inquiry. Firstly, the analysis is confined to the NASDAQ OMX green economic index family for assessing the performance of green investments. Subsequent studies could explore alternative datasets, such as the MSCI or S&P ESG indices, to assess their financial outcomes. Furthermore, this research focuses exclusively on green equities for portfolio construction. However, incorporating a broader array of environmentally sustainable assets, including fixed income securities, could potentially enhance returns and provide greater diversification. Future studies could expand this work by integrating a wider variety of sustainable assets into the portfolio and subsequently evaluating its performance against traditional investments. Moreover, the existing literature, indicates variations in the financial performance and growth of green markets across different global regions, such as the United States, Europe and Asia. This suggests that the interconnectedness and performance of green sectors may differ at regional levels. Therefore, further research is warranted to explore the relationships between regional green sector equities, which would aid local sustainable investors. The outcomes of such investigations are anticipated to enhance sustainable development efforts across various regions worldwide.

CRediT authorship contribution statement

Nasir Nadeem: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Imran Abbas Jadoon:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Faheem Aslam:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Paulo Ferreira:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

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

Data will be made available on request.

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