A thesis on green finance

A thesis

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Abstract

In recent years, green finance has received considerable attention as a key tool for addressing climate change and achieving global sustainable development. It plays a critical role in driving the global transition to a green economy, achieving carbon neutrality targets and advancing environmental governance. This thesis provides an in-depth exploration of the dynamic connectedness of green financial markets and their complex interactions with various types of risks, aiming to comprehensively understand their characteristics and behaviors under different market conditions. First, using advanced econometric techniques such as the Time-Varying Parameter Vector Autoregressive (TVP-VAR) model and wavelet analysis, the study reveals the relationships between green financial markets and key driving risks, including financial and climate risks, in the time and frequency domain. Second, the thesis investigates the connectedness mechanisms between green bond markets in the United States and China and other financial markets. The analyses also reveal the intrinsic nature of the two major green bond markets. Finally, the thesis examines the dynamic relationships between key environmental, social, and governance (ESG) markets and other sources of uncertainty.

The findings reveal that financial risks are the primary drivers of connectedness in green financial markets, with significant impacts on long-term return connectedness, whereas climate risks, particularly physical climate risks, have pronounced short-term effects on volatility connectedness. Furthermore, this thesis highlights the different roles of US and Chinese green bonds in responding to financial crises and geopolitical conflicts (e.g., the COVID-19 pandemic and the Russia-Ukraine conflict). Green bonds in the US have demonstrated stable hedging capabilities, while Chinese green bonds have shown strong market resilience, driven by economic transition and policy support. The analysis of ESG investment markets shows that European markets dominate the global green financial system, characterized by high returns and strong risk mitigation capabilities, while ESG assets in emerging markets are more constrained by regional economic and policy environments. In addition, this thesis explores the potential of optimal portfolio strategies of green financial assets in risk diversification and asset allocation, with green bonds and ESG assets being particularly important in times of crisis.

This work not only contributes to the theoretical understanding of the dynamic characteris-

tics of green financial markets, but also provides practical insights for policymakers in designing effective green financial policies and for investors in optimizing asset allocation. By revealing the dynamic linkages of green financial markets, this study provides crucial empirical evidence and decision-making support for the sustainable development of global green financial markets. The findings of the thesis lay a solid foundation for future research on green finance and suggest novel solutions to address global climate change challenges and promote sustainable economic development.

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Chapter 1

Introduction

Green finance, as a vital component of the modern financial system and a key pathway for green economic transformation, refers to economic activities that support sustainable development and environmental protection through financial instruments and policy measures. It not only promotes the coordination of economic and environmental development but has also become an essential global approach to addressing challenges such as climate change and resource depletion. The concept of green finance covers a wide range of areas, including but not limited to green bonds, ESG investing and green energy. The emergence of these components in global financial markets marks a paradigm shift in financial activities from being solely profit-driven to incorporating social responsibility and sustainable development (Lu et al., 2023).

Green bonds are one of the core tools of green finance, aimed at raising funds for environmentally beneficial projects such as clean energy, sustainable agriculture, and water resource conservation (Reboredo et al., 2020). Since the World Bank issued the first green bond in 2007, the green bond market has expanded rapidly. According to the Green Bond Principles established by the International Capital Market Association (ICMA), green bonds must adhere to strict standards for fund transparency, project evaluation, and reporting to ensure investor confidence (Reboredo et al., 2020). In recent years, China and the United States have made significant progress in developing their green bond markets. China has emerged as the world's largest green bond issuer, while the United States has steadily leveraged its robust market mechanisms to advance green bond investments.

ESG investing has become one of the most influential concepts in green finance in recent years. ESG investing incorporates Environmental, Social, and Governance factors into investment decision-making to achieve long-term sustainable returns. This approach emphasizes corporate social responsibility and governance transparency, which helps reduce investment risks and enhances the sustainable development capacity of companies. According to the Global Sustainable Investment Alliance, the scale of ESG investments has experienced explosive growth in recent years, becoming a significant trend in global asset management (He et al., 2024). Particularly in Europe and the United States, ESG investment is not only prioritized by financial institutions but is also increasingly shaping the decision-making preferences of individual investors (Naeem et al., 2023c).

Green finance markets have witnessed rapid growth and increasing importance in the global financial landscape. As this market expands, however, researchers and investors alike are becoming more attuned to the various risks that could potentially impact the green finance ecosystem. These risks are particularly significant due to the interconnectedness of the green finance market with broader financial and environmental factors (Dutta et al., 2021). In particular, the relationship between green finance and other risk categories—such as financial, climate, and geopolitical—has garnered significant attention. Furthermore, the performance of green finance markets during times of crisis, such as the 2008 global financial meltdown or the COVID-19 pandemic, highlights the reliance of these markets on external conditions (Bouri et al., 2022). Therefore, while green finance supports sustainable development and environmental protection, it is essential to consider the underlying risks that could affect its stability and growth. Financial and climate risks emerge as particularly important among the various risks affecting green finance markets (Rao et al., 2023; Karim et al., 2024).

First, financial risk constitutes the most fundamental and direct source of risk in the green finance market. During investments in green financial instruments, such as green bonds, green funds, and ESG stocks, investors are exposed to traditional financial risks, including price volatility and shocks from extreme events such as trade wars, pandemics, and geopolitical conflicts (Karim et al., 2024; Naeem et al., 2023b). Additionally, fluctuations in interest rates and currency values significantly impact the pricing of fixed-income instruments like green bonds, amplifying the ripple effects across financial markets. In particular, given the intricate relationships between the green finance market and traditional financial markets, financial risks may potentially impinge upon the green finance market. Such risks may be exemplified by price volatility in commodities such as oil and gold, as well as risks in the stock market (Elsayed et al., 2022).

Second, climate risk exerts a profound influence on the green finance market. Climate change poses direct threats to green finance assets and projects while also affecting market stability through a series of indirect effects (Baker et al., 2018). Climate risk can be categorized into two main types: physical risk and transition risk. Physical risk arises from extreme weather events caused by climate change, such as hurricanes, floods, and droughts. These events can directly damage green infrastructure or lead to the failure of green investment projects, thereby adversely affecting returns (Ardia et al., 2023). Transition risk is associated with policy changes and market adjustments during the shift toward a low-carbon economy (Tian et al., 2022). For instance, the implementation of carbon tax policies can significantly increase production costs for businesses, resulting in price fluctuations for high-carbon-emitting companies. The uncertainty surrounding such policies can also have an indirect impact on the green finance market, especially in countries where policy formulation and implementation are not consistent.

Furthermore, the rapid development of the green finance market is contingent not only on policy support and technological innovation, but is also closely linked to the growing environmental awareness of investors. In recent years, there has been an increase in global awareness of climate change and environmental protection. This has resulted in a shift in investor preferences towards green financial products, with institutional investors playing a key role in driving this trend. An increasing number of individual and institutional investors have begun incorporating ESG factors into their investment decisions. This shift is driven by two primary reasons: First, the direct threats posed by climate change have prompted the public to focus more on environmental protection (Uddin et al., 2024). Second, investors are increasingly recognizing that green finance not only delivers social benefits but can also provide stable long-term returns. For instance, some studies suggest that ESG investment portfolios often outperform traditional portfolios, particularly during periods of market volatility (Akhtaruzzaman et al., 2022; Arif et al., 2022).

Specifically, for individual investors, the enhancement of green awareness is directly reflected in changes in investment preferences. In recent years, the pursuit of "green returns" has become a significant investment motivation, and products like green bonds and ESG funds have steadily gained popularity (Ardia et al., 2023). At the same time, investors have shown a strong demand for transparency in green finance, calling for higher standards and clearer reporting on the use of funds. For institutional investors, green financial products are often seen as an essential component of investment portfolios, providing risk diversification and hedging against potential environmental or policy risks (Akhtaruzzaman et al., 2022; Ginglinger & Moreau, 2023). For example, green bonds, as low-risk assets, are frequently included in the investment portfolios of insurance companies and pension funds to enhance portfolio stability. In short, the growing global demand for sustainable development will continue to drive both individual and institutional investors to promote the steady growth of the green finance market through capital flows, market guidance, and project support.

This thesis aims to systematically analyze the development of the green finance system and its role in the interaction of various risks, with a particular focus on investigating the risk transmission mechanisms within the green finance market and its linkages with other financial markets using econometric methodologies. The research emphasizes three key aspects: the relationship between the green finance system and different types of risks, the transmission mechanisms between the green bond markets in China and the United States and other major financial markets, and portfolio allocation and risk management in ESG investing.

First, the primary objective of this thesis is to analyze the dynamic relationships between the green finance system and various risk factors. As the interplay between global financial markets and climate risks intensifies, green finance has become an increasingly important tool for mitigating these risks. This research aims to uncover how the green finance market functions in the context of financial and climate risks, focusing on risk transmission mechanisms and interaction pathways. Specifically, this thesis dynamically explores the overall interconnectedness of the European green finance system using the TVP-VAR model. Furthermore, by applying the wavelet approach, it decomposes the relationships between the green finance system and different types of risks, identifying the characteristics of risk transmission across various temporal and dimensional scales. This provides a novel perspective for understanding the impact of different types of risk on the green finance market.

Second, this thesis also conducts separate studies on the green bond markets in China and the United States. As a critical component of green finance, green bonds show significant differences in their development across countries and regions. Specifically, this thesis analyzes the dynamic spillover effects between the green bond markets in China and the United States and other major financial markets. Additionally, it examines how green bonds function as safe-haven assets under the impact of extreme events and observes the evolving awareness of green investment among investors in different countries.

Third, this thesis also focuses on analyzing the portfolio allocation and risk management functions of ESG investments. ESG investing has rapidly gained prominence globally, becoming a key investment philosophy in financial markets. However, questions remain regarding the performance of ESG portfolios in different market environments and their role in risk management. This research employs the TVP-VAR model and four different portfolio strategies to evaluate the risk diversification capabilities and investment strategies of ESG investments.

1.1 Background of research

1.1.1 Green finance

Green finance, also known as sustainable finance, is rapidly emerging as a critical tool in addressing climate change and promoting sustainable development within the financial system. For instance, in June 2019, the Global Sustainable Investment Alliance reported that at least $30.7 trillion was invested in sustainable or green assets, representing a 34% increase compared to 2016.[1] Similarly, in September 2020, the International Finance Corporation (IFC) and the Dutch Development Bank jointly provided a $225 million loan to FirstRand Bank to support

[1] https://www.bloomberg.com/graphics/2019-green-finance/

South Africa's "energy and water efficiency" initiatives.

In recent years, green finance has gained significant attention for its ability to integrate financial growth, environmental protection, and sustainable technological development. This has attracted considerable interest from academic researchers and policymakers. Since the onset of the COVID-19 pandemic, green finance has been recognized as an effective tool for driving economic recovery.[2]

Previous studies have defined green finance as an innovative form of financial investment specifically aimed at improving environmental outcomes, including investments in sustainable development projects and eco-friendly products (Zhou et al., 2020; Wang & Zhi, 2016). Furthermore, Lu et al. (2023) highlight that green finance encompasses not only climate financing but also other environmental goals such as industrial pollution control, water sanitation, and biodiversity conservation. Unlike conventional investments, green investments prioritize environmental benefits, with a focus on supporting eco-friendly products and industries (Wang & Zhi, 2016). The green finance market can be categorized into two main components: market-driven mechanisms and green financial products. Market-driven mechanisms, such as carbon emissions trading platforms, aim to reduce corporate pollution. Green financial products (green assets), on the other hand, provide funding for green companies by offering financial products to individuals, corporations, and governments. Examples of these products include environmental funds, weather derivatives, nature-linked securities, ecological options, and green bonds. In summary, the development of the green finance market not only accelerates the transition to a green economy but also creates new investment opportunities for green investors.

1.1.2 Green bonds

Green bonds, also known as climate bonds, play an important role in the development of green finance and have become an increasingly important topic for both investors and academics. These bonds have garnered significant attention from investors and researchers seeking opportunities in "responsible" or "sustainable" projects (Billah et al., 2023). As a novel fixed-income

[2] https://www.weforum.org/agenda/2020/11/what-is-green-finance/

instrument within the realm of green financial products, green bonds share similarities with traditional bonds in terms of rating and pricing mechanisms. However, what sets them apart is the explicit allocation of proceeds to environmentally sustainable initiatives.

Funds raised through green bonds are directed toward projects that promote environmental sustainability, including renewable energy generation, waste management, and water pollution control. By channeling investments into these areas, green bonds not only support the transition to a low-carbon economy but also provide a transparent mechanism for aligning financial goals with environmental objectives. Their growing popularity underscores their potential to serve as a bridge between capital markets and the global sustainability agenda, making them a cornerstone in the evolution of green finance (Reboredo & Ugolini, 2020; Pham, 2016; Reboredo, 2018; Broadstock & Cheng, 2019).

Since the European Investment Bank issued the first green bond in 2007, the issuance of green bond has increased significantly from 4.2bn USD in 2012 to 14.7bn in 2013, 37.3bn USD in 2014, 51.7bn USD in 2015, 103.1bn USD in 2016, 173.6bn USD in 2017, 176.6bn USD in 2018, 258.9bn USD in 2019, 297bn USD in 2020, and reaching 190bn by mid-2021 [3] — Morgan Stanley Research refer to the situation of issuance of green bond as "green bond boom" [4].

Figure 1.1: Green bond issuance

Figure 1.1 presents an overview of the trends in green finance bonds from 2013 to 2021, encompassing three categories: green bonds, social bonds, and sustainability bonds. The key

[3] https://www.climatebonds.net/
[4] https://www.morganstanley.com/ideas/green-bond-boom

difference between these types of bond lies in the allocation of the proceeds. Social bonds primarily fund projects aimed at achieving social welfare objectives, addressing issues such as unemployment, support for vulnerable populations, and education. Sustainability bonds, on the other hand, combine features of both green and social bonds, with proceeds directed toward projects that deliver both environmental and social benefits, including initiatives in education, sustainability research, and public health infrastructure. Green bonds specifically allocate their proceeds to environmentally focused projects that support environmental protection or low-carbon development, such as renewable energy and low-carbon building projects. As illustrated in the figure, the issuance of green bonds has been consistently higher than that of social and sustainability bonds, with a notable surge in green bond issuance over the past decade. This trend highlights the growing demand for financial instruments that align with environmental objectives and the increasing role of green bonds in driving sustainable investment.

As an emerging asset class and an essential component in the transition to a low-carbon economy, green bonds have attracted significant attention from investors, researchers, and policymakers, with proceeds primarily directed toward environmental projects. Between 2019 and 2021, the green bond market demonstrated remarkable growth (Bhutta et al., 2022), exhibiting resilience even in the face of substantial economic disruptions [5].However, in 2022, green bond issuance saw a sharp decline, with the first quarter alone recording a 34.63% reduction in total issuance. Notably, the United States, which had previously been the top issuer, fell to fourth place globally in 2022. This decline has been attributed to significant industry pressures stemming from widespread uncertainty caused by the Russia-Ukraine conflict (Conlon et al., 2024).

Green bonds, known for their clear commitment to financing environmentally sustainable projects, have quickly become a unique tool in the investment market. These bonds have two main goals: providing financial returns and supporting environmental initiatives. Unlike traditional financial products, the proceeds from green bonds are specifically directed toward projects with positive environmental impacts, such as renewable energy, pollution control,

[5] According to the Climate Bonds Initiative (CBI), green bond issuance experienced explosive growth, rising from approximately $250 billion in 2019 to $532 billion in 2021, with the United States leading in issuance volume.

or sustainable water management. This ensures that issuers take on greater environmental responsibility, often verified by third-party processes to guarantee the proper use of funds. Green bonds also appeal to a growing group of environmentally conscious investors, creating unique demands in the market. With rising investor interest and stronger commitments to sustainability from organizations, the green bond market continues to grow. This growth highlights the importance of understanding how these green bonds work financially. While green bonds share some features with traditional bonds, their focus on environmental goals has made them an important topic in the field of finance.

1.1.3 Sustainable investment (ESG assets)

ESG, as a key component of green finance, focuses on long-term financial returns while addressing critical ESG issues. Due to its distinct market characteristics, the ESG sector has drawn considerable attention from green investors and institutional participants. In recent years, the global ESG equity market has shown remarkable growth, as illustrated in Figure 1.2. The scale of ESG assets expanded from $22 trillion in 2016 to $37.8 trillion in 2021. This rapid expansion not only highlights the importance of ESG markets but also demonstrates their unique resilience to risks. For instance, during the global market turbulence caused by the COVID-19 pandemic in 2020, ESG funds attracted widespread attention from investors due to their perceived stability and long-term value. Compared to traditional financial markets, ESG markets display distinct behaviors as they incorporate environmental and social standards. Investors in ESG markets are motivated not only by financial returns but also by ethical responsibilities and long-term sustainability goals, creating a unique investment model (Linnenluecke et al., 2016; Pástor et al., 2021; Avramov et al., 2022; Pástor et al., 2022).

Globally, the development of ESG markets is shaped by regulatory frameworks, market maturity and investor preferences. The European market, with its advanced and rigorous ESG regulatory framework, achieves higher levels of market recognition and stability. In contrast, emerging markets such as China and India, where ESG frameworks are still developing, are more volatile. These regional differences reflect the diversity of global ESG investment markets and offer opportunities for further research into the link between market maturity and investment stability.

Additionally, ESG investing has influenced investor decision-making processes. Investors often prioritize pro-social and pro-environmental performance rather than focusing solely on financial returns. ESG indices, by incorporating social responsibility criteria, improve market transparency, reduce information asymmetry, and enhance market efficiency. Research suggests that ESG investments, particularly during times of crisis, deliver lower risks and higher returns by providing a comprehensive assessment of firm quality. Furthermore, the growing cross-border interconnectedness of ESG markets highlights the importance of globalized investment portfolios.

Moreover, ESG investors prioritize a range of criteria to guide their investment decisions, extending beyond purely financial returns (Hartzmark & Sussman, 2019; Pástor et al., 2021). For instance, pro-social and pro-environmental performance plays a key role in shaping their choices (Zerbib, 2019), while ESG indices, which incorporate social responsibility screening, enhance transparency, reduce information asymmetry, and improve market efficiency (Plastun et al., 2022). Additionally, ESG investments often deliver higher returns at lower risk, particularly during periods of crisis, owing to the comprehensive assessment of firm quality. At the same time, economic globalization has amplified the interconnectedness of global equity markets, with cross-border contagion dynamics influencing investment decisions. ESG investors maintain globally oriented portfolios, emphasizing cross-country risk dynamics. Understanding the spillover effects of returns in global ESG equity markets is essential for constructing diversified portfolios (Chen & Lin, 2022). More specifically, ETFs serve as an ideal vehicle for tracking performance, enabling efficient asset allocation, diversification, liquidity management, and hedging opportunities (Miralles-Quirós & Miralles-Quirós, 2019; Akhtaruzzaman et al., 2022; Naeem et al., 2023a).

1.2 Research questions

Building on the discussions above, this thesis focuses on addressing the following research questions:

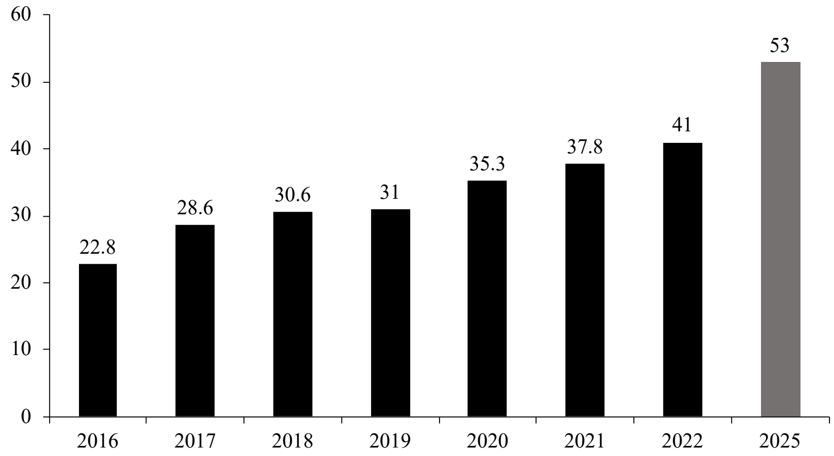

Figure 1.2: ESG assets scale (trillion $).

1) What is the major factor driving the connectedness among green equity markets, financial risk, or climate risk?

    (a) Is there heterogeneity in return/volatility connectedness of green finance across different sources of risk?

    (b) Do the physical climate risk and transition climate risk have the same impacts on the return and volatility connectedness to green assets?

2) What is the specific role of the US green bond in the financial system?

    (a) Has the dynamic connectedness of the US green bond and traditional and emerging financial markets differed in facing various episodes of crisis?

    (b) Does the connectedness differ under the various frequency bands?

    (c) Is the investor expectation of the US green bond influenced by the turmoil?

3) Do green bonds in China exhibit a relatively low level of connectedness with traditional financial assets due to their unique nature and objectives?

    (a) Do major geopolitical and economic events, such as the COVID-19 pandemic and other recent geopolitical incidents, increase investor uncertainty and risk aversion, thereby strengthening this connectedness?

    (b) Can green bonds serve as an effective hedging tool in investment portfolios?

4) What is the interconnectedness among major ESG leaders' index ETFs worldwide?

    (a) Which region's ESG market drives the ESG leaders' ETF markets?

    (b) What are the optimal investment portfolio strategies using ESG leaders' ETFs?

    (c) How does the connectedness among ESG indices vary during the COVID-19 outbreak and the ongoing Russia-Ukraine conflict?

    (d) How does the evolution of connectedness among ESG ETFs impact portfolio diversification benefits?

5) Does the COVOL play the same role as other major implied volatility indexes on an aggregated ESG market measure?

    (a) Does separating worldwide ESG markets based on their sovereign economic development status, lead to differences in connectedness compared to developing markets?

    (b) When separating worldwide ESG markets by region, do the linkages differ across regions?

    (c) Which region is least affected by global factors and regional ESG markets?

1.3 Contribution to the literature

This thesis has made several notable advancements in research on green finance, as outlined below.

- First, this thesis provides profound insights into the impact of different risk factors on green financial markets.
    - This thesis distinguishes between the impact of financial and climate risks on green financial markets, thereby enriching the existing literature. Previous studies have extensively examined the impact of individual risk factors on green financial performance, such as climate risks or climate issues (Engle et al., 2020; Bouri et al.,

2023), financial crises or uncertainty (Banerjee et al., 2024; Zhao et al., 2022), oil price shocks (Xu et al., 2024c), and geopolitical risks (Zhang et al., 2023). However, we argue that it is crucial to explore and compare the effects of different risk factors to identify the primary drivers of green finance. Notably, our findings provide strong evidence that financial risk, rather than climate risks, serve as the main drivers of the dynamic connectedness in green financial markets. This significant discovery advances the understanding of risk factors' influence on green finance, deepens insights into its determinants, and contributes to the existing body of literature.

– In addition, this thesis extends the literature on European green finance by demonstrating the heterogeneous impacts of specific risk factors on the return and volatility connectedness of European green assets. It is widely acknowledged that the return and volatility connectedness among green financial markets often exhibit different patterns. For instance, return connectedness reflects return spillovers within a specific system, capturing the dynamic interactions of returns across different markets (Lu et al., 2023), while volatility connectedness highlights volatility spillovers within the system, indicating changes in information transmission or investor sentiment (Yarovaya et al., 2022). The results suggest that in European financial markets, financial risks have a more pronounced effect on the return connectedness of green finance than on its volatility connectedness, whereas climate risks exert a stronger influence on volatility connectedness than on return connectedness. These findings not only expand research on the impact of different sources of risk on green finance but also provide a novel and comprehensive perspective for the study of European green financial markets.

– Meanwhile, building on the work of Naeem et al. (2023a) and Jiang and Yoon (2020), this thesis adopts a novel multi-step framework to analyze the co-movements between risk factors and green finance. This framework combines the time-varying connectedness approach Antonakakis et al. (2020) with two types of wavelet transformation: the maximal overlap discrete wavelet transform (MODWT) Percival and Walden (2000) for multi-scale decomposition and the continuous wavelet transform

(CWT) Torrence and Compo (1998) and Torrence and Webster (1999) for wavelet coherence analysis. In the first stage, the overall return and volatility connectedness of all green assets are computed using the connectedness approach. In the second stage, both MODWT and CWT techniques are employed to study the co-movements between various risks and the overall connectedness of green finance. These two wavelet methods reveal distinct features of the relationships between risk indicators and green financial assets. Specifically, the MODWT highlights the behavior of sequences across different frequency scales, enabling further analysis for each decomposition, while the CWT emphasizes the time and correlation relationships between two-time series. By employing these two complementary wavelet methods, this thesis provides new evidence on the causal linkages between financial risks, physical climate risks, and transition climate risks, as well as their connections with the green finance market across different time horizons. Additionally, it explores the co-movement relationships between the two major risk factors and green assets.

- Second, this thesis shows the connectedness between the green finance markets (Green bond and ESG) and various financial markets.

  - This thesis, from the perspective of Chinese investors, examines the return connectedness between green bonds and several key investment channels by employing the frequency connectedness approach proposed and various portfolio construction methods. Unlike existing studies, this research considers all investment assets directly accessible to Chinese investors, thus offering new perspectives on the connectedness of green bonds. This study is particularly valuable in understanding the interactions between green bonds and traditional financial markets in a major emerging market and sheds light on how these relationships evolve during periods of significant market volatility.
  - This thesis contributes to the literature by applying the TVP-VAR frequency connectedness approach to investigate the return connectedness between green bonds and a range of investment assets available to Chinese investors. This innovative

method helps to identify the impact of shocks on both short-term and long-term behaviors.

– This thesis analyzes the dynamic connectedness between green bonds and key implied volatility indices across different frequency domains in various financial markets. The primary advantage of this approach lies in its ability to decompose connectedness into short-term and long-term frequencies. Since investors have varying investment horizons, identifying the transmission patterns of connectedness between green bonds and major financial markets at different frequencies is crucial for better understanding effective risk management and investment strategies. For instance, short-term investors may be more concerned with the connectedness mechanisms at short-term frequencies, which often reflect rapid information transmission and result in market effects lasting less than a week. Conversely, for long-term investors, analyzing the connectedness mechanisms at long-term frequencies is more critical. When long-term frequencies are the primary drivers of connectedness, the resulting shocks can profoundly affect investor expectations and the overall market environment. By examining the variations in connectedness across different frequency domains, this study provides a more comprehensive analysis of the complex volatility transmission between green bonds and other financial markets. Using a frequency-domain connectedness approach, our analysis offers more precise guidance for green investors with varying investment horizons, particularly when sudden events lead to discrepancies between short-term and long-term frequencies. Furthermore, our analysis leverages the recently developed frequency connectedness method, enabling us to assess how investors with different investment expectations respond to macroeconomic and geopolitical shocks.

– Furthermore, this thesis contributes to the literature by investigating the dynamic transmission between green bonds and various implied volatility indices, including the VIX, OVX, GVZ, EVZ, and CVI. Given the importance of implied volatility indices as forward-looking measures of market risk and key indicators for portfolio management, understanding the linkages between green bonds and risks in various financial markets is essential. This understanding helps green investors identify the major risk transmitters in the financial system concerning green bond markets, enhancing their ability to adjust asset allocation strategies in a timely manner. Consequently, our findings not only address a research gap regarding the interconnectedness between green bonds and the cryptocurrency market but also reveal the broader connectedness characteristics between green bonds and various financial markets.

- Third, this thesis highlights the performance of green investment portfolios and constructs an optimal portfolio strategy, offering new investment insights for green investors.
  - This thesis introduces a novel perspective by assessing the performance of ESG leaders' equity markets across various regions, employing six major ESG leaders' index ETFs from developed and developing markets. The analysis spans regions such as Global, EAFE (Europe, Australasia, and the Far East), the US, Canada, China, and India.
  - This thesis is the first to investigate return connectedness and the differential behavior among regional ESG ETFs. By examining spillover effects between January 2020 and February 2023—encompassing significant global events such as COVID-19 and the Russia-Ukraine war—this thesis sheds light on the return transmission mechanisms in global ESG markets. The findings underscore the importance of monitoring return connectedness to promote the stability and resilience of these markets.
  - This thesis contributes to the existing literature by incorporating ESG ETFs into portfolio construction strategies. Specifically, it evaluates the minimum connectedness portfolio strategy alongside minimum variance, minimum correlation, and risk-parity portfolios. The comparative analysis of these four models provides a detailed understanding of portfolio management strategies in ESG ETF markets, offering valuable guidance for global ESG investors and hedge fund managers.
  - Finally, this thesis breaks new ground by assessing the hedging effectiveness of

sustainable investments within portfolios—an area previously unexplored. Using the hedging effectiveness ratio, this thesis evaluates the performance of individual ESG ETFs under various portfolio strategies. This metric serves as a benchmark for hedging performance, highlighting the critical role of different regional ESG ETFs in mitigating portfolio risk.

1.4 Thesis outline

This section presents an overview of the thesis structure, consisting of eight chapters, with a brief description of each chapter provided below.

Chapter 1 introduces the main content of the thesis, including the background of green finance, the research questions, and the key contributions of the study.

Chapter 2 provides a literature review focusing on studies of key green finance markets, including green bonds and the ESG market. It also reviews the econometric methodologies employed in this thesis, particularly the different connectedness approaches from the literature.

Chapter 3 examines the impact of two major risks—financial risks and climate risks—on green financial markets. It specifically explores the heterogeneity of these risks in influencing the returns and volatility of green financial markets. Additionally, this chapter investigates various relationships between different types of risks and green financial markets, including lagged effects, co-movement patterns, and causal links.

Chapters 4 and 5 explore the connectedness mechanisms between green bond markets in the United States and China and several other financial markets, including gold, oil, and Bitcoin. A particularly valuable finding is that, by examining the relationships between green bond markets (in both the U.S. and China) and other financial markets, it is revealed that green bonds in both regions exhibit characteristics of financial hedging and safe-haven assets.

Chapter 6 focuses on constructing sustainable investment portfolios using ESG ETFs. By applying the TVP-VAR model and portfolio analysis, it examines the return correlations of ESG

ETFs and portfolio performance. The findings reveal that, due to market size and maturity, European ETFs play a dominant role in the global ESG system.

Chapter 7 explores the dynamic connectedness between financial risk indicators and global ESG leaders' stock markets. The analysis categorizes ESG markets by factors such as global scope, level of economic development (developed countries vs. developing countries), and geographic region (Americas, Europe, Pacific, and Asia). This chapter further examines the interrelationships and dynamic connectedness between these ESG categories and a range of financial risk indicators.

Chapter 8 provides a comprehensive summary of the main findings of the thesis and discusses some key areas for future research.

1.5 Note on publications

A series of journal articles have been derived from this thesis.

1) Xu, D., Y. Hu, S. Corbet, Y. G. Hou, and L. Oxley (2024). Green bonds and traditional and emerging investments: Understanding connectedness during crises. ***The North American Journal of Economics and Finance***, 72, 102142.

   (This publication is presented as Chapter 4)

2) Xu, D., Y. Hu, S. Corbet, and C. Lang (2024). Return connectedness of green bonds and financial investment channels in China: Implications for hedging and regulation. ***Research in International Business and Finance***, 70, 102329

   (This publication is presented as Chapter 5)

3) Xu, D., S. Corbet, C. Lang, and Y. Hu (2024). Understanding dynamic return connectedness and portfolio strategies among international sustainable exchange-traded funds. ***Economic Modelling***, 141, 106864.

   (This publication is presented as Chapter 6)

4) Xu, D., Hu, Y., Oxley, L., Lin, B., & He, Y. (2024). Exploring the Connectedness Between Major Volatility Indices and Worldwide Sustainable Investments. ***International Review of Financial Analysis***, 97, 103862.

(This publication is presented as Chapter 7)

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Chapter 2

Literature review

2.1 Previous studies on green finance

2.1.1 Green bond market

In recent years, green bonds, as a critical instrument for the transition to a green economy and a key component of portfolio allocation, have garnered significant attention from both investors and researchers. When considering the development of green bonds and the broader scope of green investments, dynamic co-movement and market connectedness have remained central themes. Pham (2016) is among the earliest studies to examine the connectedness between green bonds and traditional bonds, highlighting the benefits of incorporating green bonds into investment portfolios. Similarly, Reboredo (2018) employed a copula-based approach to uncover evidence of weak relationships between green bonds and the stock and energy markets, supporting the view that green bonds can serve as effective diversification tools.

To extend the understanding of green bonds in risk management, hedging, and diversification, a number of studies have explored the connectedness between green bonds and other financial markets, including oil (Lee et al., 2021; Wang et al., 2022), gold (Dutta et al., 2021), the U.S. dollar (Kocaarslan, 2021; Yan et al., 2022), and cryptocurrencies (Hassan et al., 2022; Huynh et al., 2020).

Recently, with the growing impact of systemic crises on financial markets, a significant body of literature has focused on the effects of specific shocks on the risk transmission between green bonds and other financial markets. These studies aim to investigate the role of green bonds under both normal and extreme financial conditions. For example, Gao et al. (2021) combined the DCC-GJR-GARCH model with the network connectedness methods of Diebold and Yilmaz (2012) and Diebold and Yilmaz (2015) to examine the risk spillovers between green bonds and traditional financial market volatility indices during periods such as the US-China trade war and COVID-19. They found that international crises significantly increased the volatility of green bonds, primarily driven by heightened risk-averse sentiment among investors, which led to greater capital inflows into the green bond market. Similarly, Pham (2021) examined the connectedness between green bonds and green stock markets under normal and extreme market conditions. Specifically, they observed that the connectedness between green bonds and green stocks was higher during periods of elevated volatility and weaker under normal market conditions. Additionally, this study highlighted that during the COVID-19 outbreak, the green stock market exerted substantial spillover effects on the green bond market.

Dutta et al. (2021) showed that climate bonds, a similar form of green bonds focused on addressing climate change, provided better hedging opportunities against risks associated with oil, gold, and stocks, especially during the pandemic. Similarly, Pham and Do (2022) and Lin and Su (2023) examined the connectedness between green bonds and various implied market volatilities to evaluate the hedging effectiveness of green bonds during critical events. Specifically, Pham and Do (2022) used the global green bond index alongside the implied volatilities of major stock markets (the US, Europe, China, and emerging markets), oil, and gold, concluding that the low correlation between these variables allows global green bonds to serve as a diversification asset in times of crisis. Lin and Su (2023), on the other hand, explored the connectedness between green bonds and three uncertainty factors—VIX, OVX, and EPU—associated with the US and Chinese markets. Their findings indicated that, due to the safe-haven properties of green bonds in investor sentiment, green bonds in both markets experienced significant risk contagion from the VIX and OVX during periods of financial turmoil.

2.1.2 ESG market

When analyzing the interaction effects between ESG-based financial products and financial shocks, several research areas provide a foundation for further investigation. For instance, Luo et al. (2023) demonstrated that ESG ambiguity significantly influences the perceptions of ESG-sensitive agents, while Zou et al. (2023) showed that discrepancies in ESG ratings contributed to widened bond spreads. Similarly, the results of Trinh et al. (2023) indicated that banks with higher social capital or CSR intensity tend to exhibit lower idiosyncratic and systemic tail risks and a lower possibility of severe suffering from market downturns. During the early stages of the COVID-19 pandemic, firms with higher ESG scores outperformed their counterparts, though Eisenkopf et al. (2023) described this advantage as short-lived. In terms of portfolio performance, Dumitrescu et al. (2023) observed that equally weighted Socially Responsible Investment (SRI) ETF portfolios underperformed their benchmark indices over the long term. However, recent evidence suggests a reversal of this trend.

Furthermore, an expanding body of literature focuses on the spillover effects of cross-different ESG markets. Umar et al. (2020) examined spillovers among ESG markets in 10 major countries using the spillover index method. Their findings highlight significant volatility transmission globally, with developed ESG markets acting as shock transmitters to emerging ESG markets. Likewise, Iqbal et al. (2022) investigated asymmetric spillover effects among sustainability indices of 14 countries, finding that spillover intensity between sustainable markets tends to increase during financial crises. Chen and Lin (2022) further identified strong spillover effects across eight ESG equity markets. They note that the US and Canada have the strongest inter-market links and are major shock transmitters in the global ESG equity market. To deepen understanding of the mechanisms behind global ESG connectedness and its asymmetric effects, Gao et al. (2021) and Naeem et al. (2023c) explored risk contagion in inter-regional ESG markets. Gao et al. (2021) analyzed risk transmission using the ESG yield indices of eight global regions, while Naeem et al. (2023c) assessed price asymmetry in four regional ESG markets—Americas, Europe, Asia, and the Pacific—through MSCI leader ESG indices. Both studies confirmed clear evidence of risk contagion across ESG regions, with the asymmetric effects becoming more pronounced during financial crises.

2.2 Methodology

2.2.1 Connectedness approach

There are two main approaches commonly used to analyze linkage among financial markets: the TVP-VAR connectedness approach and wavelet-based approaches. The TVP-VAR model, in particular, is extensively utilized to assess the connectedness within specific systems or networks. For instance, several studies investigate the connectedness within broad commodity markets (Balcilar et al., 2021; Corbet et al., 2021; Hu et al., 2023), cryptocurrencies (Okorie & Lin, 2023), crude oil (Hu et al., 2023; Naeem et al., 2023a), the investor fear index (Xu et al., 2023, 2024), precious metals (Uddin et al., 2019) and clean versus dirty cryptocurrency markets (Ren & Lucey, 2022). In addition, some studies focus on the connectedness between various uncertainty indices and financial markets. For example, Kang et al. (2019) explore the financial connectedness between VIX and a series of financial markets, including stock, bonds and commodities. Lin and Su (2020) and Urom et al. (2022) investigate the connectedness between OVX and various financial assets. Additionally, Ding et al. (2021) analyze the spillover effects of GVZ on financial markets. Further work focuses on the relationship between global uncertainty and sustainable finance. For example, Pham and Do (2022) use the TVP-VAR model to assess the connectedness between global uncertainty indicators (VIX, OVX, and GVZ) and green bonds, revealing substantial time-varying spillover effects. Similarly, Cepni et al. (2023) explore the impact of climate uncertainty on spillover dynamics between European conventional and ESG markets, concluding that ESG assets can serve as a diversification tool against climate uncertainty. Lu et al. (2023) explore return and volatility connectedness across green markets such as green bonds, clean energy markets, and socially responsible stocks, reporting a significant rise in the total connectedness index during the pandemic. Similarly, Tiwari et al. (2022) analyze the connectedness of green finance markets and highlight that the total connectedness index is strongly influenced by bearish, normal, and bullish market conditions. Liang et al. (2024) examine the impact of the carbon market and climate policy uncertainty on the stability of US financial markets.

A number of studies have used the TVP-VAR model and its various extensions to meet a variety of needs in the analysis of connectedness. For instance, Adekoya et al. (2022) introduce the asymmetric connectedness approach to investigate the asymmetric transmission of return spillovers across financial markets. Similarly, Baruník and Křehlík (2018) propose the frequency connectedness approach to analyze connectedness across different frequency domains. Recently developed various connectedness methodologies, such as the wavelet connectedness approach (Antonakakis et al., 2018), the DCC-GARCH connectedness approach (Gabauer, 2020), the joint connectedness approach (Lastrapes & Wiesen, 2021), the quantile connectedness approach (Chatziantoniou et al., 2021), and the TVP-VAR frequency connectedness approach (Chatziantoniou et al., 2023) have also gained significant attention. These approaches have been widely applied to estimate the connectedness mechanisms in financial markets. For example, the quantile connectedness approach proposed by Ando et al. (2022) has been utilized in studies such as Bouri et al. (2021) and Yousaf et al. (2023) to explore its applications in various contexts. Xu et al. (2024c) focus on the return connectedness of green bonds with major investment markets in China using the novel TVP-VAR frequency connectedness approach.

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Chapter 3

Dynamic co-movement between financial risk, climate risk and green finance: Evidence from wavelet approaches

Dynamic co-movement between financial risk, climate risk and green finance: Evidence from wavelet approaches

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Abstract

This paper examines the co-movement of two risk factors (financial risk of COVOL from Engle and Campos-Martins [2023] and climate risk (physical risk and transition risk) from Bua et al. [2024]) on the return and volatility connectedness of green assets for the period of 14 October 2014 to 30 December 2022 using the two wavelet approaches (wavelet multi-scale decomposition and wavelet coherence). Our main findings show that the return and volatility connectedness of green finance markets are more sensitive to financial risk than climate risk. Specifically, we find that the influence of financial risks on the return connectedness of green finance markets is more persistent than on the volatility connectedness. Furthermore, in categorizing climate risk, our analysis reveal that the impact of physical risk on the connectedness of green assets is more pronounced compared to that of transition risk. These empirical findings have important implications for assessing the impact of different risk factors on green finance in risk management and regulatory decisions.

Keywords: Green assets; Financial risk; Climate risk; Co-movement; Wavelet.

1. Introduction

As a global leader in the development of green finance, Europe has pioneered this progress earlier than other regions. Since the European Investment Bank (EIB) issued the first green bond in 2007, the green finance market in Europe has grown steadily, and the growth of the green finance sector has further spurred the emergence of various financial products, including ESG assets, sustainable investments, and green equities [Long et al., 2022]. These financial instruments have provided diverse investment channels for green finance, attracting both public and private capital towards sustainable development projects and accelerating Europe's transition from traditional finance to green finance [Zhang et al., 2023]. The continued expansion of green finance in Europe has also attracted considerable attention, particularly with regard to the relationship between green financial products and different types of risk.

Green finance is a critical channel for the transition to a low-carbon economy. However, the green finance market is subject to a wide range of risks, and these risks have varying degrees of impact on the stability of the financial system. Among these risks, financial and climate risks have been widely identified by previous studies as the two major risk factors influencing green finance system [Flammer, 2021, Hoepner et al., 2023, Campos-Martins and Hendry, 2024]. For example, it has been found that financial risk has substantial impact on the return and volatility connectedness of green finance markets, see Tiwari et al. [2022] and Ren et al. [2023]. Not only does financial risk have a significant impact on green finance, but also the impact of climate risk on green finance should not be underestimated. Pástor et al. [2021] and Ardia et al. [2023] show that investors will shift their investments from brown assets to green assets as climate risks increase, thereby leading to better performance in the green finance markets. Theoretically, during periods of heightened climate risk uncertainty, investors tend to move from conventional equity markets to green investment markets [Cepni et al., 2023]. Typically, climate risk can be divided into two categories: physical risks and transition risks. Physical risks can result in financial losses or increased costs due to chronic or acute physical events or extreme events. On the other hand, transition risk is the cost of adjustments that firms make to comply with altered climate regulations or to transition towards a low-carbon economy. More importantly, the categorisation of climate risks into physical and transient risks certainly helps to differentiate the unique impact of these specific climate risks on the green finance market.

In response to the complex and diverse nature of financial and climate uncertainty, Engle and Campos-Martins [2023] and Bua et al. [2024] develop novel metrics to effectively measure and quantify the financial and climate risks, respectively. We utilise these novel financial and climate risks to examine, for the first time, the co-movement and connectedness with green finance markets. It is generally accepted in the literature that the volatility of asset returns tends to move together.

Hence, Engle and Campos-Martins [2023] develop a new index to measure the size of the shocks that have the largest impact on asset prices across regions and asset classes, which they call the global common volatility (COVOL). Consequently, COVOL is often interpreted as a broad measure of risk. In addition, the impact of global COVOL is driven by political, financial, economic and terrorist events. The importance of the COVOL index is its potential as a tool for understanding the nature of financial risk. Examining the relationship between COVOL and various green assets can provide insights into how financial risk changes over time and is transmitted across green finance markets. It can also shed light on how external factors, such as economic events, geopolitical events, or policy decisions, may influence these processes. In terms of climate risk, Bua et al. [2024] presents an innovative measurement framework which measures the variation of climate-related risks through physical and transition channels. Using textual analysis techniques, Bua et al. [2024] have developed two new measures: Physical Risk Index (PRI) and Transition Risk Index (TRI). The main advantages of choosing these two measures as suitable proxies for climate risk in this paper lies not only in their use of more advanced climate vocabularies to capture climate risk, but also in their ability to capture different dimensions of climate risk, thereby creating a comprehensive set of climate risk indicators.

It is noteworthy that the distinction between the impacts of financial risks and climate risks on green finance markets, as well as whether these two types of risks exert differential effects on the return and volatility of green finance markets, remains an unresolved question. Against this backdrop, this study proposes the following hypotheses. First, we hypothesize that financial risks and climate risks have distinct impacts on green finance markets. This hypothesis is grounded in the unique characteristics of green finance markets, particularly their differing responses to financial market fluctuations and extreme climate events. Second, we hypothesize that the linkage between green finance markets' return and volatility varies heterogeneously across different sources of risk, such as financial risks and climate risks. This is because different risks are transmitted through distinct mechanisms, which in turn influence the market performance of green finance markets. Furthermore, the attitudes and behaviours of those investing in environmentally-focused initiatives may differ according to the type of risk involved, resulting in fluctuations in the return and volatility of green finance markets. Last, we hypothesize that different climate risks, such as physical risk and transition risk, exert varying impacts on the return and volatility system of green finance markets. This distinction reflects the fundamental differences between the two types of climate risk. Physical risks are primarily concerned with the direct effects of extreme climate events, whereas transition risks are closely linked to policy support or regulatory changes. Investors are likely to exhibit different responses when faced with extreme climate disasters versus green policy incentives.

In particular, the distinction between the impact of financial and climate risks on the green finance market, as well as whether these two risks affect the return and volatility of green finance markets differently, remain unresolved issues. Based on the discussion above, this paper will focus on exploring the following questions: 1) What is the major factor driving the connectedness among green equity markets, financial risk, or climate risk? 2) Is there heterogeneity in return/volatility connectedness of green finance across different sources of risk? 3) Do physical and transition risks have the same impact on the return and volatility connectedness to green assets?

This study contributes to the literature in a number of important ways. First, we extend the existing literature by distinguishing between the impact of financial risk and climate risk on green financial markets. In the existing literature, there are a large number of studies exploring the impact of a single risk factor on the performance of green financial, such as climate risk or climate concern [Engle et al., 2020, Bouri et al., 2023], financial crisis or uncertainty [Banerjee et al., 2024, Zhao et al., 2022], oil price shocks [Xu et al., 2024] and geopolitical risk [Zhang et al., 2023]. However, we believe it is necessary to explore and compare the influence of different risk factors to determine which is the primary driver of green finance. In particular, our research reports strong evidence that financial risk - not climate risk - is the primary driver of the dynamics of connectedness in green finance markets. This crucial finding contributes to the study of the impact of risk factors on green finance, advancing the understanding of the determinants of green finance and adding to the relevant literature.

Second, we extend the literature on green finance in Europe by demonstrating the heterogeneous influence of specific risk factors on the return and volatility connectedness of European green assets. It is now well-established that return and volatility connectedness among green finance markets typically display different patterns. For example, return connectedness reflects return spillovers within a given system, capturing the dynamic interplay of returns between different markets [Lu et al., 2023], while volatility connectedness shows the volatility spillover effect within a system, indicating variations in information transmission or investor sentiment [Yarovaya et al., 2022]. In this paper, we show that, in European financial markets, financial risk has a more pronounced impact on the return connectedness of green finance than on its volatility connectedness, whereas climate risk has a stronger effect on the volatility connectedness of green finance than on its return connectedness. These findings not only extend related research on the impact of different sources of risk on green finance [Zhao et al., 2022, Bouri et al., 2023], but also offer a novel and comprehensive perspective on European green finance research.

Third, by employing two different wavelet approaches, this paper provides new evidence of a causal relationship between COVOL, PRI and TRI to the connectedness of green finance markets at different time horizons, as well as the co-movement relationship between two major risk factors and green assets. In particular, we adopt a novel multi-step framework to analyze the co-movement between risk factors and green finance, building on the work of Naeem et al. [2023] and Jiang and Yoon [2020]. Furthermore, we combine the time-varying parameter vector autoregressions connectedness approach of Antonakakis et al. [2020] and two types of wavelet transforms: the maximal overlap discrete wavelet transform (MODWT) approach of Percival and Walden [2000]. This allows us to obtain the multi-scale decomposition and the continuous wavelet transform (CWT) approach of Torrence and Compo [1998] and Torrence and Webster [1999] for obtaining the wavelet coherence measure. In the first stage, we calculate the total return and volatility connectedness of all green assets based on the connectedness approach. In the second stage, we examine the co-movement between different risks as well as the total connectedness of green finance, using both the MODWT and CWT techniques simultaneously. These two wavelet techniques can reveal distinct characteristics of the relationship between risk indicators and green finance assets. In particular, the wavelet multi-scale decomposition approach reveals the behaviour of the series across different time scales, enabling further analysis for each time decomposition, while the wavelet coherence approach highlights the frequency, period, and intensity of the relationship between two time series. The empirical findings of this paper attempt to fill the gap in the literature on the impact of climate risk on green finance markets.

The rest of this paper is structured as follows: Section 2 provides an overview of the existing literature. Section 3 discusses the econometric methodologies employed in this paper and Section 4 provides a thorough explanation of the data used in the analysis. Section 5 presents the empirical findings, while Section 6 concludes.

2. Literature Review

2.1. The influencing factors on green finance

Assessing the impact of various influencing factors on green-related markets has always been a prominent research topic in the green finance literature. For instance, Zhang et al. [2023] focus on the impact of geopolitical risk on green assets, including clean energy, green bonds, and renewable energy. Similarly, Bouri et al. [2024] examine the impact of climate policy uncertainty and economic policy uncertainty on green bonds. However, the majority of studies in this field have primarily analyzed the relationship between green bonds and different financial markets, such as conventional bonds [Pham, 2016, Reboredo et al., 2020], stock markets [Reboredo, 2018, Xu et al., 2024], and oil markets [Lee et al., 2021]. Among the various risk factors, financial risk and climate risk are regarded as two critical drivers of the green finance market [Naeem et al., 2023], and they can influence the market in distinct ways.

Financial crises, such as the outbreak of COVID-19, have caused significant disruption to global equity markets, leading to negative economic impacts and increased volatility in the green finance sector [Ren et al., 2023]. In particular, the green finance market has experienced notable risk spillovers from commodity markets during the pandemic [Dutta et al., 2021], and energy market volatility tends to influence green investments more during periods of heightened uncertainty. Furthermore, black swan events such as Brexit, the European sovereign debt crisis and the COVID-19 pandemic have also been associated with increased volatility in green investment markets [Tiwari et al., 2022]. A recent study by Karim et al. [2024] shows that the COVID-19 pandemic has reshaped the spillover effects between green bonds and financial markets.

With regard to climate risk, several studies highlight that growing concerns over climate change have increased investors' preference for green investments, driving higher capital flows into green finance markets [Pástor et al., 2021, Ardia et al., 2023]. Moreover, green bonds have been found to provide credible safe haven benefits against climate uncertainty, even surpassing traditional assets like gold [Cepni et al., 2022]. In examining the asymmetric effects of climate risk on connectedness among carbon, energy, and metals markets, Zhou et al. [2023] suggest that green finance offers multiple benefits due to its central role in the transition to a low-carbon economy. This transition may increase insolvency risks for commercial banks, although greener portfolios could benefit from the shift toward sustainable investments [Zhang et al., 2024]. Additionally, assets with ESG features have become more attractive to investors during extreme climate events [Fiordelisi et al., 2023], and the rising demand for alternative energy in response to climate risks has driven further investment in green energy [Dutta et al., 2023]. Although the impacts of financial risk and climate risk on green finance markets have been extensively studied individually, there remains a gap in the literature that directly and comprehensively compares these two global risk factors and identifies which one serves as the primary driver of returns and volatility in green finance markets.

2.2. Econometric methodologies

This section provides an overview of the econometric methods commonly used in the literature. In terms of the existing research, two primary methods have been widely employed to analyze connectedness among financial markets: the TVP-VAR connectedness approach and wavelet-based techniques. For example, a substantial body of existing research adopts the TVP-VAR connectedness approach to estimate the dynamic connectedness in equity markets [Yousaf et al., 2023, Corbet et al., 2021], investor's fear index [Xu et al., 2023, 2024], crude oils [Hu et al., 2023, Naeem et al., 2023], cryptocurrencies [Ren and Lucey, 2022, Long et al., 2024], precious metals [Uddin et al., 2019]. Regarding green finance markets, Chatziantoniou et al. [2022] employ the TVP-VAR connectedness approach, capturing the return connectedness among green-related investment markets. Lu et al. [2023] examine the return and volatility connectedness of several green markets, including green bonds, clean energy markets and socially responsible stocks. They find that the total connectedness index of the green finance market notably increased during the pandemic period. Similarly, Tiwari et al. [2022] study the connectedness of green finance markets and suggest that the total connectedness index of green finance markets is highly dependent on the bearish, normal and bullish market states. Xu et al. [2024] investigate the return connectedness of green bonds with several major investment markets in China using a novel TVP-VAR frequency connectedness approach. Finally, Liang et al. [2024] investigate whether the carbon market and climate policy uncertainty affect the stability of the US financial markets.

On the other hand, wavelet-based techniques, such as maximal overlap discrete wavelet transform (MODWT) and continuous wavelet transform (CWT), have been widely used in the literature to model the linkages among different series into time and frequency domains. For example, some studies have applied the MODWT to capture the relationship between various financial markets, such as Alzahrani et al. [2014], Mensi et al. [2017], and Bouoiyour et al. [2023]. Several studies also employ the CWT approach to study dynamic co-movement in financial markets, see Tiwari et al. [2019], Goodell and Goutte [2021], Goodell et al. [2022], Goodell et al. [2023]. Recently, Naeem et al. [2023] pioneered the combination of the TVP-VAR connectedness model and wavelet analysis, offering a more detailed examination of the impact of individual risk factors on financial market connectedness. In this study, we follow the idea of Naeem et al. [2023], integrating these two models, which allows us to observe the impact of specific risks on the connectedness of the green finance market across both time and frequency domains. By combining these methods, we aim to fill the gap in the existing literature and offer a more in-depth understanding of the impact of global risk factors on green finance markets.

Our paper differs from the above studies in terms of the methodology employed and the research questions considered. We attempt to fill the gaps in the field of green finance by combining the connectedness approach and two types of wavelet approaches to show whether financial and climate risk affect the connectedness of green finance markets and which is the main risk factor affecting the return and volatility connectedness of green finance.

3. Methodology

3.1. TVP-VAR connectedness approach

We apply a two-stage modelling approach in order to capture the impact of financial and climate risks on the return and volatility connectedness across a range of green assets. In the first stage, we estimate the total connectedness index of selected green finance markets using the Time-Varying Parameter Vector Autoregressions (TVP-VAR) approach. The TVP-VAR connectedness approach of Antonakakis et al. [2020] has become a popular method in the literature for estimating the connectedness among various markets due to several advantages.

The TVP-VAR(p) model can be written by the following expressions:

$$x_t = \Phi_{1t}x_{t-1} + \Phi_{2t}x_{t-2} + ...\Phi_{pt}x_{t-p} + \epsilon_t \qquad \epsilon_t \sim \mathrm{N}(0, \Sigma_t) \tag{1}$$

where x_t, x_{t-1} are $N\times$ 1 dimensional vectors and Σ_t denotes time-varying variance-covariance matrix, Φ_{it} indicate the time-varying VAR coefficient.

The generalised impulse response function (GIRF) and the generalised prediction error decomposition (GFEVD) according to Koop et al. [1996] and Pesaran and Shin [1998] are used to compute time-varying coefficients and time-varying variance-covariance matrices. More specifically, the GFEVD can be defined as the impact of a shock to variable j on variable i and can be expressed as:

$$\theta_{ijt}(H) = \frac{(\boldsymbol{\Sigma}_t)_{jj}^{-1} \sum_{h=0}^{H} \left((\boldsymbol{\Psi}_h \boldsymbol{\Sigma}_t)_{ijt} \right)^2}{\sum_{h=0}^{H} \left(\boldsymbol{\Psi}_h \boldsymbol{\Sigma_t} \boldsymbol{\Psi}_h' \right)_{ii}}, \tag{2}$$

$$\tilde{\theta}_{ijt}(H) = \frac{\theta_{ijt}(H)}{\sum_{k=1}^{N} \theta_{ijt}(H)}, \tag{3}$$

where $\tilde{\theta}_{ijt}(H)$ indicates the contribution of the variable j to the variance of the forecast error of the variable i at horizon H.

Next, the direction of the connectedness index is provided below:

$$TO_{it}(H) = \sum_{i=1, i\neq j}^{N} \tilde{\theta}_{jit}(H), \tag{4}$$

$$FROM_{it}(H) = \sum_{j=1, i\neq j}^{N} \tilde{\theta}_{ijt}(H), \tag{5}$$

where $TO_{it}(H)$ and $FROM_{it}(H)$ are the directional connectedness index, while $TO_{it}(H)$ represents the value of the variable it transmitting the shocks to all others. In contrast, $FROM_{it}(H)$ indicates the value of the variable it receiving the impact from all others.

$$TCI_t(H) = N^{-1} \sum_{i=1}^{N} TO_{it}(H) = N^{-1} \sum_{i=1}^{N} FROM_{it}(H), \tag{6}$$

where $TCI_t(H)$ indicates the total connectedness index, which measures the degree of interconnectedness of the network.

3.2. Wavelet analysis

In the second stage, we use the maximum overlap discrete wavelet transform (MODWT) and continuous wavelet transform (CWT) techniques to examine the co-movement between financial risk, climate risk and green finance markets.

Ramsey [2002] introduced the concept of "father" and "mother" wavelets. They define the father wavelet as describing a very long-term scale and smooth component of the time series. Therefore, the father wavelet is known as a scaling coefficient. They also specify that the mother wavelet represents the smoothed component deviation. The mother wavelet is known as a difference coefficient.

The father wavelet and mother wavelet are defined as:

$$\phi_{j,k} = 2^{-j/2}\phi\left(\frac{t-2^j k}{2^j}\right), \int \phi(t)dt = 1 \tag{7}$$

$$\psi_{j,k} = 2^{-j/2}\psi\left(\frac{t-2^j k}{2^j}\right), j = 1, \cdots, J, \int \psi(t)dt = 0 \tag{8}$$

The function F$(\cdot)$ is defined as:

$$F(t) = \sum_k s_{J,k}\phi_{J,k}(t) + \sum_k d_{J,k}\psi_{J,k}(t) + \cdots + \sum_k d_{j,k}\psi_{j,k}(t) + \cdots + \sum_k d_{1,k}\psi_{1,k}(t) \tag{9}$$

If we represent the detail coefficients and smooth coefficients as below,

$$D_j = \sum_k d_{j,k}\psi_{j,k}(t), \quad S_J = \sum_k S_{J,k}\phi_{J,k}(t) \tag{10}$$

F$(\cdot)$ can be simplified as:

$$F(t) = \sum_{j=1}^{\bar{J}} D_j + S_J \tag{11}$$

The resulting multi-horizon decomposition of $F(t)$ is D_J, D_{J-1}, $\ldots$, D_1, and S_J. D_j defines the jth level of wavelet detail that is associated with a series of changes at the scale of λ_j. S_J is the cumulative sum of the variations in each scale, which becomes smoother as the j value is increased.

The MODWT approach, which has many advantages over the other techniques, is used in this analysis.

Based on Percival and Walden [2000], wavelet and scaling coefficients can be calculated using:

$$\tilde{W}_{j,t} = \sum_{t=0}^{N-1} \tilde{h}_{j,l} X_{t-l \bmod N}, \tilde{V}_{j,t} = \sum_{t=0}^{N-1} \tilde{g}_{j,l} X_{t-l \bmod N} \tag{12}$$

The jth level of wavelet detail and smooth coefficients are as follows:

$$\tilde{D}_{j,t} = \sum_{t=0}^{N-1} \tilde{h}_{j,l} W_{t+l \bmod N}, \tilde{S}_{j,t} = \sum_{t=0}^{N-1} \tilde{g}_{j,l} V_{t+l \bmod N} \tag{13}$$

F$(\cdot)$ is then simplified to

$$F(t) = \sum_{j=1}^{J_0} \tilde{D}_j + \tilde{S}_{J_0} \tag{14}$$

where J_0 is the decomposed level.

The series is decomposed into wavelet coefficients from D_1 to D_7 in our study. The wavelet series D_1, D_2, ..., D_7 represent the short-term deviations from the long-term movement.

Coherence, which ranges from zero to one, measures the correlation between two variables in the frequency domain. As suggested by Madaleno and Pinho [2012], the correlation may not occur simultaneously, but it may have a lead or lag, the magnitude of which is measured by the phase lead. This study measures the wavelet coherence using the CWT method to characterise the degree of co-movement between financial/climate risks and the connectedness of green finance. The wavelet coherence generalises traditional correlations in both frequency and time by combining the wavelet transform and cross-spectral techniques to provide a three-dimensional view.

The cross-wavelet spectrum of two time series $x_(t)$ and $y_(t)$ with the continuous wavelet transforms $W_x(\tau, s)$ and $W_y(\tau, s)$ are defined by Torrence and Compo [1998] as follows:

$$W_{x,y}(\tau, s) = W_z(\tau, s) W_y^*(\tau, s) \tag{15}$$

with τ the location parameter and ss the scale parameter. The symbol $*$ represents the complex conjugate of $W_y(\tau, s)$.

The cross-wavelet power of two-time series can be written as $W_{x,y}(\tau, s)$, which describes the local covariance between the two series at each frequency or scale. Using this measure, the wavelet squared coherence of a two-time series is now written as:

$$R^2(\tau, s) = \frac{\left| S\left(s^{-1} W_{*v}(\tau, s)\right)\right|^2}{S\left(s^{-1} \left|W_\mu(\tau, s)\right|^2\right) S\left(s^{-1} \left|W_y(\tau, s)\right|^2\right)} \tag{16}$$

where S is viewed as a smoothing operator over time and scale, with $0 \leq R^2(\tau, s) \leq 1$. The wavelet squared coherence graph shows the areas of co-movement between two series in both the frequency and time domains. The result would indicate a higher degree of dependence between two series if the measured wavelet squared coherence has a high value close to one, and vice versa. However, this approach does not allow us to distinguish between positive and negative correlations.

Torrence and Webster [1999] propose the wavelet coherence phase difference in the following way to solve the issue:

$$\theta_{xy}(\tau, s) = \tan^{-1}\left(\frac{I\left\{S\left(s^{-1}W_{ry}(\tau, s)\right)\right\}}{R\left\{S\left(s^{-1}W_{sy}(\tau, s)\right)\right\}}\right), \tag{17}$$

where R and I represent the real and imaginary parts. The black arrow indicates the phase difference in the wavelet coherence plots. Zero phase difference implies that the two series are linked to each other in a specified frequency. When two series are in-phase (anti-phase) or positively (negatively) correlated, the arrow points to the direction $\rightarrow$ ($\leftarrow$). As discussed in Torrence and Webster [1999], the arrow pointing in the direction of $\nearrow$ and $\swarrow$ means that x is leading y, while the arrow pointing in the direction of $\searrow$ and $\nwarrow$ means that y is leading x.

The TVP-VAR connectedness approach and the wavelet approach are two techniques that are widely recognised in the literature and are valued for their unique strengths. The TVP-VAR connectedness method is particularly effective in detecting and monitoring interconnectedness within specific markets [Chatziantoniou et al., 2022, Yousaf et al., 2023, Lu et al., 2023], whereas wavelet approaches excel at capturing lead-lag relationships and co-movements across different markets [Jiang and Yoon, 2020, Goodell and Goutte, 2021, Bouoiyour et al., 2023]. For example, the TVP-VAR approach provides evidence on the transmission mechanism within specific sectors or markets. Such a framework allows to monitor and evaluate spillovers in a given network in order to mitigate adverse effects that may have been caused by economic and policy strategies. In addition, this approach allows the calculation of the overall connectedness index, which helps researchers to analyse cross-market linkages under certain conditions. This provides a deeper understanding of how shocks affect the relationships between specific financial assets or systems. In addition, the advantages of the wavelet approach can be summarized as follows: First, it effectively reveals the interactions between two variables, such as coherence and phase relationships. Coherence measures the degree of association between two variables, ranging from weak (completely incoherent) to strong (completely coherent). Typically, the co-movement between two variables does not occur simultaneously, but may exhibit lead-lag relationships, which are captured by phase lead. Second, by employing both the MODWT and CWT approaches, the analyses exploit the complementary strengths of these two techniques. For instance, the MODWT is highly effective at decomposing time series into distinct frequency bands, enabling the clear separation of short-term, medium-term, and long-term components. This facilitates a detailed examination of connectedness within specific frequency ranges, offering precise insights into the impact of various risks on green financial markets across different frequency domains. Additionally, the CWT enables time-domain analysis and is particularly suitable for capturing the dynamic interactions between two financial time series. Specifically, it provides an intuitive visualization of how specific patterns of co-movement evolve, thereby deepening the understanding of temporal interactions between different financial series. By integrating these complementary methodologies, the two-step process used in this study reveals the linkages between financial/climate risks and green financial markets from multiple perspectives, revealing patterns and relationships that may remain hidden when using a single methodology alone.

3.3. Granger causality tests

We also perform the classic Granger causality tests in this study. In the following, a brief overview of the Granger causality tests for Granger [1969] is given. Granger causality testing is the most common and popular approach to determining the causal validity of the variables of interest. A variable, x, is said to Granger cause another variable, y, if its past values help predict the current value of y, in the presence of all other relevant information, and vice versa.

The simplest test of Granger causality requires estimating the bivariate VAR:

$$y_t = \beta_{1,0} + \sum_{i=1}^{p} \beta_{1,i} y_{t-i} + \sum_{i=1}^{p} \beta_{1,p+i} x_{t-i} + \varepsilon_{1t} \tag{18}$$

$$x_t = \beta_{2,0} + \sum_{i=1}^{p} \beta_{2,i} y_{t-i} + \sum_{i=1}^{p} \beta_{2,p+i} x_{t-i} + \varepsilon_{2t} \tag{19}$$

where p is the number of lags that adequately models the dynamic structure so that the coefficients of further lags of variables are not statistically significant. The error terms ε are an approximation of white noise processes. If the p parameters $\beta_{1,p+1}$ to $\beta_{1,2p}$ are jointly significant, then we can reject the null hypothesis that x does not Granger cause y. On the other hand, if the p parameters $\beta_{2,1}$ to $\beta_{2,p}$ are jointly significant, we can reject the null hypothesis that y does not Granger cause x.

4. Data

Our analysis utilises two distinct datasets, one encompassing financial and climate risks and the other comprising green assets. The first dataset comprises two different risk measures for financial and climate risks, which are sourced from Engle and Campos-Martins [2023] and Bua et al. [2024], respectively. The daily country-level ETF-based global common volatility (COVOL) data is obtained from Engle and Campos-Martins [2023] to provide a broad measure of all types of financial risk. Engle and Campos-Martins [2023] use daily closing prices of 47 individual country ETFs traded on the New York Stock Exchange (NYSE) to construct the global COVOL index. Furthermore, this new indicator provides a more accurate representation of the significance of financial risks compared to other text-based indicators, such as the geopolitical risk index (GPR).

Since then, several studies have adopted COVOL to represent financial risks, see Xu et al. [2023], Zhang et al. [2023], Oxley et al. [2023] and Campos-Martins and Hendry [2024]. In addition, to capture the variation in climate risk, Bua et al. [2024] develop two novel climate risk measures - Physical Risk Index (PRI) and Transition Risk Index (TRI) based on textual and narrative analysis of Reuters News. These two climate risk indicators reflect innovations in the two facets of climate change risk. Climate-related risks can affect the financial system through physical and transition risks, especially financial markets [Bua et al., 2024]. Notably, these two proxies have quickly attracted considerable attention from the literature, for example, see Bouri et al. [2023], Cepni et al. [2022, 2023] and Zhou et al. [2023].

The second dataset comprises several important green assets. In accordance with Cepni et al. [2022], we select a wide range of green assets that provide a comprehensive overview of green finance across various sectors. The majority of the selected green assets in this paper are based in Europe due to its importance and dominant role in the green finance market [Ren et al., 2023, Karim et al., 2024]. Specifically, the following green assets are selected for the analysis in this paper: Bloomberg Barclays MSCI Euro Green Bond Index (green bond), MSCI Europe ESG Leaders Index (ESG), NASDAQ OMX Green Economy Europe Index (green economy), Solactive Eurozone Sustainability Index (sustainability), S&P Clean Energy Index (clean energy). In addition, we also consider green technology companies by incorporating the Wilderhill New Energy Global Innovation Index (green innovation).[1] In short, previous studies have widely recognised these six different green finance markets selected in this study as appropriate indicators to represent various segments of the green finance market, see Cepni et al. [2022], Zhang et al. [2023], Goodell et al. [2022] and Chatziantoniou et al. [2022].

Insert Figure 1 about here

The sample period of the analysis is determined by data availability. The reason for choosing October 2014 as the starting point for the analysis is that data on European green bonds only became available after this period. Thus, we select the daily data that spans from 14 October 2014 to 30 December 2022. This selection encompasses several major global events related to both financial and climate risks. The financial risk events include the oil price crash, Brexit, the US-China trade war, and the outbreak of COVID-19. On the climate risk side, key events include the adoption of the Paris Agreement at the end of 2015, the US's withdrawal from the Paris Agreement in 2017, and the 2019 Climate Action Summit.

[1] The Wilderhill New Energy Global Innovation Index comprises companies that concentrate on innovative technologies in the areas of clean energy, renewable, decarbonization, and efficiency.

Figure 1 shows the raw time series for all variables, showing the variation of financial risk (COVOL) and climate risks (TRI and PRI), as well as the dynamic prices of each green asset. As required for the subsequent analysis, the return and volatility series of each green asset are estimated. The return series of each green asset is computed as $100 * ln(P_t/P_{t-1})$, in which P_t denotes the closing price. The volatilities of each green asset are calculated using the absolute return method as we follow Antonakakis and Kizys [2015], Antonakakis et al. [2018] and Lang et al. [2024]. The absolute return method is adopted in our study due to its unique advantages, including greater persistence, better sampling error behaviour, and immunity to jumps [Forsberg and Ghysels, 2007, Antonakakis and Kizys, 2015][2]. The return and volatility series of each green asset are shown in Figure 2 and Figure 3, respectively.

Insert Figures 2 to 3 about here

Table 1 presents the summary statistics of the return and volatility of various green assets, as well as financial and climate risks in their original scales. Note that all the variables are stationary at the 1% level based on the results of ERS unit-root test of Elliott et al. [1996]. The results of the weighted portmanteau test of Fisher and Gallagher [2012] indicate that all sample variables are auto-correlated. This suggests that the TVP-VAR approach is a suitable econometric technique for modelling the selection of the variables [Chatziantoniou et al., 2023, Tiwari et al., 2022].

Insert Table 1 about here

5. Results

Section 5.1 and Section 5.2 present the results of dynamic connectedness and wavelet analysis, respectively. Section 5.3 discusses the implication of our findings and Section 5.4 presents robustness checks.

To gain a comprehensive understanding of financial and climate risks on green financial markets, we consider a network of various green assets, such as green bonds, ESG, green economy,

[2] As discussed in the prior literature, the volatility estimate derived from the absolute return measure shows substantive proximity to those gauged from some well-known alternative measures such as Generalized Autoregressive Conditional Heteroscedasticity (GARCH) model and integrated volatility (IV) [Khalifa et al., 2011]. Furthermore, the absolute return measure provides a superior forecasting capability for volatility than the GARCH counterpart due to the relative outlier resistance of the former [Bollerslev and Wright, 2001]. The absolute return is also deemed to be a sensible indicator for implied volatility since it has a closer relationship with the VIX than the alternative volatility measures [Engle and Gallo, 2006]. These reasons support our choice to utilize the absolute return as a main proxy of volatility instead of the alternative measures based on the GARCH model and integrated volatility.

sustainability, clean energy, and new energy innovation indexes in this paper. We then estimate the dynamic total return and volatility connectedness of all six green assets, employing the TVP-VAR connectedness approach as outlined in Antonakakis et al. [2020]. The total return connectedness index captures the dynamic variation of the return spillover in this specific network, while the total volatility connectedness index shows the dynamic evaluation risk transmission among sub-segments in green markets. This broader perspective can provide valuable insights into how different risk factors relate to and interact with the green finance market. It also offers a new approach to comprehensively evaluating the dynamics and resilience of the entire green finance market. Several studies in the literature adopt a similar approach to capture the evolution of the asset market using both total return and volatility connectedness within the sample period, see Bouri et al. [2021], Lu et al. [2023] and Naeem et al. [2023]. Therefore, our research focuses on the return and volatility connectedness results based on the Total Connectedness Index.

To further investigate the impact of global risk and climate risk on the return and volatility connectedness of green assets, we sequentially employ two wavelet analysis techniques: MODWT and CWT techniques. These two complementary techniques are commonly used in the literature and can be used to gain insight into the relationship between financial/climate risks and green assets. In short, the results of the two wavelet analyses underscore a key finding that financial and climate risks have distinctly different relationships with green assets, and the relationship is also heterogeneous for the return and volatility connectedness among green finance markets. Such findings are particularly important for the researcher, investor or portfolio manager interested in green investments.

5.1. Total return and volatility connectedness of green finance

Figure 4 provides the dynamic total return and volatility connectedness of green assets during the sample period considered in this paper. In particular, Figure 4a illustrates the dynamic total return connectedness of green assets, where the connectedness is time-varying and event-dependent. As can be seen from Figure 4a, the dynamic total return connectedness index fluctuates from 50% to 85%, indicating a strong return spillover effect across the various green markets. Specifically, we observe a strong spillover effect in the return connectedness index during three distinct episodes: 2014-2016, early 2019, and 2020. From 2014 to 2016, financial market uncertainty increased dramatically, driven by events such as the plunge in oil prices (from $115 per barrel in 2014 to $35 per barrel in 2016), the European government debt crisis, and Brexit. Coinciding with this period, the adoption of the Paris Climate Agreement by 196 countries at the end of 2015 is an indication of the increasing focus of policymakers and other stakeholders on the development of green markets. Consequently, we observe a notable upward trend in green return connectedness under the dual influences of financial and climate policy uncertainties. Following President Donald Trump's announcement in mid-2017 that the US intended to withdraw from the Paris Agreement, the return connectedness index subsequently decreased until the onset of the China-US trade war in early 2018. A particularly noteworthy finding is that there was an increasing trend in the connectedness index in 2019, which may be linked to the convening of the Climate Action Summit at that time. The summit, organized by the United Nations, once again raised the ambitions of policymakers for the development of green markets and accelerated the investment community's focus on the growth of these markets [3].

Insert Figure 4 about here

At the beginning of 2020, we observe a substantial increase in return connectedness across green assets, triggered by the unprecedented shock to the global financial system from the outbreak of COVID-19 and the concomitant rise in climate policy concerns triggered by the COVID-19 pandemic. The increase in return connectedness among green financial markets over this period is consistent with existing research. See Lin and Su [2023] and Su et al. [2022]. In addition, Ardia et al. [2023] show that green investments generally perform better as climate concerns increase.

In terms of the total volatility connectedness index of green assets, which is displayed in Figure 4b a comparable trend is evident in the total volatility connectedness index when compared to the total return connectedness index. The volatility connectedness index of green assets fluctuates between 50% and 92%. Similar to the return connectedness index, a large increase in the total volatility connectedness index is observed in the years 2014, 2018 and 2020. In particular, the total volatility connectedness index of green assets peaked during the COVID-19 pandemic period in early 2020. As pointed out by Naeem et al. [2023], the outbreak of the COVID-19 pandemic induced extreme instability in financial markets, which accelerated the spillover effect between various green financial markets. On the other hand, the second peak of the total volatility connectedness index is observed at the onset of the sample period in October 2014, reflecting the impact of extreme occurrences in financial markets as aforementioned, such as the oil price collapse [Ren et al., 2023]. Note that the total volatility connectedness index is much higher than its counterpart for total return connectedness at the beginning of 2014. Furthermore, the total volatility index exhibits a trend opposite in comparison to the total connectedness of return between 2017 and 2018, which can be seen by comparing Figure 4a and Figure 4b. In particular, we observe a consistent upward trend in the total volatility connectedness of green asset markets. The upward trend in total connectedness of volatility could be attributed to investor climate change concerns raised by the announcement that the United States will withdraw from the Paris Agreement [Ardia et al., 2023]

[3]https://www.un.org/en/climatechange/2019-climate-action-summit

and increased financial market uncertainty, driven by the escalation of trade conflicts between the US and China [Zhang et al., 2023].

Overall, we find that green market connectedness fluctuates dramatically during periods of high financial and climate policy uncertainty. It would be interesting to examine the impact of these two types of risk on total return and volatility connectedness to see if they differ.

5.2. Wavelet analysis

To explore the linkage between financial risk (COVOL), climate risk (PRI and TRI), and the return and volatility connectedness of green financial markets, this section presents the empirical results based on two wavelet approaches, namely MODWT and CWT approaches [4].

5.2.1. MODWT analysis

Insert Figure 5 about here

To distinguish the effect of frequency variation, Figure 5 shows the results of the wavelet multi-scale decomposition based on total return and volatility connectedness of green assets and two key risk indicators using the MODWT approach.[5] The short-term fluctuations (or high-frequency band) are captured in Figures 5a, 5b, and 5c, which represent the changes due to shocks occurring over 2-4 days, 4-8 days and 8-16 days, respectively. Mid-term variations are presented in Figures 5d and 5e, corresponding to the 16-32 and 32-64 day scales. In addition, the long-term movements (or low-frequency band) are shown in Figure 5f and 5g, capturing changes due to shocks occurring over 64-128 days and beyond 128 days, respectively.

Insert Table 2 and Table 3 about here

Table 2 and Table 3 report the results of the MODWT wavelet decomposition-based VAR Granger causality test between financial risk, climate risk, and total connectedness of return and volatility of green finance. All decomposed series are stationary at the 1% level.[6] In terms of

[4]Referring to the work of Campos-Martins and Hendry [2024], Xu et al. [2023], Cepni et al. [2022], Bouri et al. [2023] and Lang et al. [2024], these risk indices are suitable measures to capture the dynamic variation of financial and climate risks in the literature.

[5]The series are decomposed into seven frequency domains from D1 to D7 based on the MODWT approach with time horizons of 2-4 days, 4-8 days, 8-16 days, 16-32 days, 32-64 days, 64-128 days and 128-256 days, respectively.

[6]We perform several unit root tests to check if decomposed series are stationary, including the augmented Dickey-Fuller, Phillips-Perron, and ERS unit-root tests. All tests confirm that all decomposed series are stationary.

Granger causality results for the return connectedness of green finance as shown in Table 2, it is observed that significant Granger causality is detected from the COVOL to return connectedness of green finance across all cases. All causal relationships are significant at the 1% level, except for D5, where the causal relationship is significant at the 10% level. The Granger causality results also reveal that the null hypothesis, which posits no Granger causality from two climate risks (PRI and TRI) to return connectedness of green finance, is rejected at D5, D6, and D7 decomposition. This suggests significant causality from climate risk to the return connectedness of green finance over long-term horizons.

Turning to the Granger causality results related to volatility connectedness of green finance, the findings are generally in line with those observed for return connectedness. Significant Granger causality is identified from COVOL to the volatility of green finance at the 1% level for almost all frequencies. In addition, the PRI Granger-causes the volatility connectedness of green finance for most cases. TRI exhibits significant Granger causality with the volatility connectedness of green finance in the case of D5 and D7.

In summary, the empirical results for the MODWT wavelet-based VAR Granger causality test clearly show distinct differences in Granger causality relationships among financial risk, climate risk, and total connectedness of green finance regarding both return and volatility. Specifically, financial risk appears to have a significant impact on the connectedness of green finance across seven different frequency ranges, whereas the impact of climate risk is more evident in the long-term horizon (D5, D6, D7). PRI is found to significantly Granger-cause the volatility connectedness of green finance markets across almost all decompositions.

Based on the VAR Granger causality test results, we can identify several interesting results. First, financial risk has a much greater impact on the return and volatility connectedness in green finance markets than climate risk regarding the Granger causal relationship. The connectedness of green financial markets seems more sensitive to financial shocks than climate change shocks. This finding can be explained by the fact that financial indicators and events, such as the increase in inflation or the consumer price index (CPI) rate, financial crises, and policy uncertainty or exchange rate fluctuations, immediately affect market sentiment and investor behavior [Hoffmann et al., 2013], thereby directly and rapidly influencing the performance of green finance [Zhao et al., 2022]. Conversely, information about climate change, such as the rise in global temperatures, loss of biodiversity, and carbon emission allowances, often represents a long-term process with a more gradual and indirect impact on the green market. For example, it may take years or even decades for the impacts of climate policies to fully materialise in the market [Lee et al., 2024]. Intuitively, green investors are more likely to focus on financial risk and overlook climate risk when both financial and climate risks are present. This result is similar to a survey by Krueger et al. [2020], which ranks the six major risks in institutional investor beliefs. In their ranking, financial risk is considered the most important, taking first place, while climate risks are ranked fifth.

Second, climate risk has a stronger impact on the volatility connectedness than the return connectedness across green finance markets. In particular, we observe that when PRI is used as the proxy for the physical risk of climate change significantly Granger causes the volatility connectedness of green finance across almost all frequencies, indicating the occurrence of climatic events or natural disasters will significantly influence the volatility of the green market. This finding is particularly interesting because it suggests that physical risks have a more direct impact on investor sentiment. For example, Jha et al. [2021] reveal the impact of the occurrence of natural disasters, such as epidemics, earthquakes, floods, and landslides, on financial investor sentiment. Furthermore, as stated by Lin and Wu [2023], investors will only recognise the significance of climate risks when they become evident. Taken as a whole, the Granger causality tests facilitate a comprehensive understanding of the causal relationship between the connectedness of green finance and prominent risk factors.

5.2.2. CWT analysis

The results based on the MODWT method only display two-dimensional views, ignoring the influence of unknown change points, such as specific times or events. The wavelet coherence approach offers a three-dimensional perspective on co-movement. Therefore, when we focus on wavelet coherence using the CWT method, we can show how the two major risks co-move with the total return and volatility connectedness of green finance over time and across frequencies. We will use the decomposed series from the MODWT approach for the following analysis.

Insert Figure 6 about here

Figure 6 shows the wavelet coherence and phase difference among total connectedness of green finance, financial risk, and climate risks based on the CWT method. It is important to clarify that, unlike the MODWT method analysis from the previous section, wavelet coherence results are expressed in three dimensions: frequency (vertical axis), time (horizontal axis), and the strength of co-movement. The colour spectrum represents the intensity of co-movement between each pair of variables, with warmer colours (red) indicating strong co-movement and colder ones (blue) representing weak co-movement. The black contours demarcate areas of significance at the 5% level, as determined through estimation via Monte Carlo simulation. Moreover, the direction of the arrow depicts the interdependence and phase relationship of each pair. Arrows pointing right $\rightarrow$ (left $\leftarrow$) signify that the risk is positively (negatively) correlated with the total connectedness of green finance. Arrows pointing up ↑ (down ↓) indicate that the risk is leading (lagging) the total connectedness of green finance.

The wavelet coherence and phase diagrams in Figures 6a, 6c, and 6e illustrate the co-movement between green finance return it can be seen that return connectedness has a stronger dependence on financial risk compared to climate risk (PRI and TRI). Notably, a significant level of high co-movement between green finance return connectedness and financial risk is observed at the mid-term level of decomposition during several key periods, including early 2016, 2018, and around 2020. These periods coincide with major financial events, such as the oil price collapse, the US-China trade war, and the outbreak of the COVID-19 pandemic. Furthermore, we also find that the dependence between finance risk and green finance return connectedness is much stronger in the long run of the 256-512 days over all the sample periods. Moreover, from the diagonally upward direction of arrows in Figure 6a, we conclude that financial risk is positively correlated with green finance return connectedness. Moreover, financial risk leads to a variation of connectedness among green finance markets in both the mid and long term. In contrast, we identify a relatively weak co-movement between return connectedness and climate risks, as evidenced in Figures 6c and 6e.

The co-movement between the volatility connectedness of green finance and various risks is presented in Figures 6b, 6d and 6f. Similar to the results based on return connectedness, it can be seen that there is a strong dependence between financial risk and volatility connectedness of green finance in the mid-term (32-64 days and 64-128 days) during early 2016, 2018, 2020 and around 2022 corresponds to the timeline of occurrence of extreme events mentioned above. Notably, the upward and right directions of the arrows indicate a positive correlation between financial risk and the volatility connectedness of green finance. Furthermore, these arrows also reveal that COVOL leads to the volatility connectedness of green finance. In comparison, the wavelet coherence results in Figures 6d and 6f show a strong dependence between climate risks and green finance volatility connectedness, especially over the 256-512 days band during the sample period, in comparison with the wavelet coherence of the return connectedness results.

5.3. Findings discussion

Combining all the sets of results, several are presented below. First, consistent with the empirical results obtained using MODWT methods, financial risk emerges as the primary driver for the return and volatility connectedness of green finance markets. Specifically, we observe a positive co-movement and a leading relationship between financial risk and the green asset market. The co-movement between financial risk and the return and volatility connectedness of green finance at intermediate frequencies may be attributed to the occurrence of financial crises. These crises severely impact the green finance market and the sentiment of green investors, leading to substantial changes in the return and volatility connectedness of green finance [Yarovaya et al., 2022, Banerjee et al., 2024]. In the long-term, there is a strong co-movement between financial risk and green finance return connectedness. This suggests that the financial crisis has had a sustained impact on the returns of green finance markets [Markwat et al., 2009].

Next, climate risks (PRI and TRI) pose heterogeneous impacts on green finance's return and volatility connectedness. It can be observed that there is a stronger co-movement between climate risk and the volatility connectedness of green finance and a weaker co-movement relation with return connectedness. This finding is particularly interesting due to its implications for the relationship between green assets and climate risks. The high level of co-movement suggests that the variation of volatility connectedness across green assets is more sensitive to climate risks [Wu and Wan, 2023]. The underlying logic behind this economic phenomenon may be attributed to the following factors. When climate risk increases (e.g. due to the occurrence of major natural disasters or the implementation of relevant green policies by governments), investors' green sentiment is affected, leading to increased attention on green financial assets, which in turn drives volatility in the green financial market [Lin and Wu, 2023]. In addition, climate risk may change the expectations of non-green investors and make them more aware of the importance of the green finance market. As a result, they may shift their capital from traditional markets to green finance markets in an attempt to hedge against climate risk [Pástor et al., 2021, Ardia et al., 2023].

In comparison, the low level of co-movement indicates that the impact of climate risk on the return system of green finance is relatively small. In other words, climate risk shocks may not have a substantial impact on the returns in the green finance market. This phenomenon may be attributed to the specific nature of green companies in Europe and the preference for green investments among European investors. As climate risk increases, investors tend to favour green companies [Pástor et al., 2021]. Consequently, investors tend to hold green investments for the long term, making the green financial market's return system resilient to the significant impacts of climate change [Ardia et al., 2023]. Furthermore, these findings are consistent with empirical analysis using the MODWT methods. Therefore, it can be concluded that the green finance market is a viable investment option to mitigate climate risks, including physical and transition climate risks.

Overall, the empirical results from the two complementary wavelet techniques (MODWT and CWT) are interesting. Specifically, financial risk is the main driver of the return and volatility connectedness of the European green financial market system, exerting a notably pronounced influence on the return mechanism in comparison to its effect on the risk mechanism. Furthermore, climate risk exerts a more substantial influence on the volatility connectedness of green finance, surpassing its impact on the return connectedness. In summary, these two complementary wavelet approaches present several important findings and contribute to a more effective, comprehensive and in-depth understanding of the relationship between financial risk, climate risk and the emerging green finance markets.

5.4. Robustness check

Insert Table 4 and Table 5 about here

To further validate the robustness of our main findings, we conduct two additional empirical analyses, each using a different proxy index. In particular, we consider using alternative financial risk and green finance indexes. First, we apply the asset-based COVOL as an alternative measure to the COVOL to represent the global financial risk. Similar to the COVOL, asset-based common volatility, an asset class version of COVOL as constructed by Engle and Campos-Martins [2023], measures the common volatility across a broad range of twenty-three assets [7]. Table 4 and Table 5 present the results of the MODWT wavelet-based VAR Granger causality analysis, which examines the causal relationship from asset-based COVOL to both return and volatility connectedness of green finance. Particularly, it can be found that the asset-based COVOL Granger causes both the return and volatility connectedness of green finance across almost all frequency decomposition, consistent with the results obtained using the COVOL as reported in Table 2 and Table 3.

Insert Figure 7 about here

Figure 7 presents wavelet coherence results between asset-based COVOL and the return and volatility connectedness of green finance markets. It can be seen that the asset-based COVOL, as an alternative financial risk indicator, exhibits significant co-movement with the return and volatility connectedness of green finance during three intervals: 2014-2016, 2018 and early 2020. This finding is consistent with the results obtained using the COVOL in Section 5.2, further substantiating the robustness of the observed relationships. Furthermore, the above results confirm the dominance of financial risk over climate risk in the connectedness of green finance markets, a conclusion that holds even when a different indicator of financial risk is used.

Insert Table 6 and Table 7 about here

[7] The asset-based COVOL is different from the country-level ETF base COVOL in terms of data construction, please see Engle and Campos-Martins [2023] for details.

The second robustness check is to use European clean energy index to replace S&P clean energy index. The corresponding total return and volatility connectedness indexes among green finance markets are shown in Figure 8. Subsequently, we further confirm the robustness of our main findings by adopting the same wavelet approaches, including MODWT and CWT. The results of MODWT wavelet-based VAR Granger causality analysis between financial, climate risks and connectedness of green finance markets are shown in Table 6 and Table 7, respectively. Meanwhile, the wavelet coherence results are displayed in Figure 9. It can be found that these results are consistent with the main results in section 5.2, further illustrating the robustness of our findings [8]

Insert Figure 8 and Figure 9 about here

6. Conclusion and implications

Green financial products and instruments, including green bonds, green equity, and various green industries, represent an emerging financial system with the explicit goal of financing green industries and accelerating the transition towards a green economy. However, green finance markets are susceptible to financial and climate risks (physical and transition risks). More specifically, a series of major global events such as Brexit, the collapse in oil prices, the COVID-19 pandemic and the Russia-Ukraine conflict have led to an increase in financial risk. This has increased the attractiveness of green assets and led to the fragmentation of efforts to transition from a traditional to a green economy. In addition, the stability of the green financial system is directly or indirectly affected by escalating climate risks, including physical factors such as rising global temperatures and the frequency of various natural disasters, as well as transition risks related to policy and regulatory risks associated with carbon emissions. Therefore, identifying the specific impact of different risk shocks on green finance and its main drivers has become a crucial issue in the field of research on green finance [Zhang et al., 2023, Long et al., 2022].

This paper specifically examines the impact of two dominant risk factors (financial and climate risks) on the return and volatility connectedness of green finance markets using wavelet techniques from a time and frequency perspective. To do so, we first estimate the total return and volatility connectedness among six different green finance markets, encompassing green bonds, ESG assets, green economy, sustainability, clean energy, and new energy innovation indexes. Then, we further investigate the impact of financial and climate risks on the return and volatility connectedness of green finance markets by employing two popular wavelet methods the MODWT and CWT.

[8] In addition, we also try additional Granger causality tests with different lag lengths and reach consistent conclusions. Due to space limitations, these results are not reported here. Results are available on request.

Additionally, to capture accurately the impacts of financial and climate risks on green finance, we apply the novel global financial risk index of Engle and Campos-Martins [2023] and climate risk index of Bua et al. [2024] as suitable measures for these risks, respectively. In particular, Bua et al. [2024] classify climate risks into physical risks and transition risks, which contributes to a deeper and more nuanced understanding of the different impacts of different types of climate risks on green markets. Using daily data from 2014 to 2022, this paper aims to investigate the impact of a wide range of extreme events, including the US-China trade war, the COVID-19 pandemic and the Russia-Ukraine war, as well as a series of climate-related events, such as the EPA's climate change initiative, the Paris Agreement, Trump's withdrawal from the Paris Agreement and the recent COP26 climate conference.

The key findings of this paper can be summarised as follows. First, based upon the MODWT based-VAR Granger causality test results, which identify the linkage between financial, climate risk and green finance in the frequency domains (low and high frequency), we find that financial risk significantly Granger-causes both return and volatility connectedness among green finance across all decomposition series. Furthermore, we also detect that there is heterogeneity in the causal relationships between climate risks (PRI and TRI) and green finance. Specifically, physical climate risk has a more pronounced impact on the volatility connectedness of green finance than return connectedness. This result established across almost all frequencies where there is a significant Granger causality relationship between physical climate risks and volatility connectedness of green finance. In contrast, the Granger causality relationship with return connectedness exists only at lower frequencies (mid- and long-term). There is no significant Granger causality relationship between transition climate risks and both return and volatility connectedness among green finance in the short term. However, there is a significant Granger causality relationship between transition climate risks and both return and volatility connectedness among green finance based upon a long-term decomposition.

The wavelet coherence results indicate that the financial risk and connectedness of green finance have a high co-movement compared to climate risks during the sample period. Notably, there are three periods where financial risk and green finance exhibit strong co-movement: 2015-2016, 2017-2018, and 2020. These periods corresponded with the onset of extreme financial events, including the oil price collapse, Brexit, the US-China trade war, and the COVID-19 pandemic. Moreover, we find that financial risk is positively correlated and leads to connectedness among green assets. Regarding climate risk, the empirical results show that physical and transition climate risks strongly co-move with the volatility connectedness of green finance but weakly co-move with the return connectedness of green assets.

Overall, this study offers a number of valuable insights to stakeholders, including investors, enterprises, as well as regulators and policymakers. For regulators, it is crucial to focus on targeted financial risk detection. This is especially important given recent research findings that suggest financial risks have a greater impact on green financial markets than climate risks. It is also important to gain a deeper understanding of the relationship between climate risk and the volatility correlation of green financial markets, especially to identify different types of climate risk to effectively mitigate risk spillovers in green markets under various climate-related events. For environmentally conscious companies, it is vital to remain aware of the impact of various risks to ensure they continue to grow and develop. Consequently, companies need to remain vigilant about the impact of the various risks on the green finance markets and formulate tailored responses accordingly, drawing on the results of our research. Finally, for green investors, it is worth noting that the return connectedness in green finance markets shows greater resilience to climate risk but relatively weaker resilience to financial risk. Therefore, investors can use our research findings to evaluate the impact of different risks and adjust their investment strategies to improve portfolio diversification. Future research could examine sub-segments within green finance markets to investigate the impact of different risk factors on specific green assets, such as green bonds or ESG assets, in greater detail. Future research could also focus on other major international economies, such as the US and China, which exhibit distinct climate concerns and green investment preferences.

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Table 1: Descriptive statistics for all variables

	Returns					
	Green Bond	ESG	Green Economy	Sustainability	Clean Energy	New Energy Innovation
Min	-1.964048	-11.58538	-14.69854	-15.32604	-12.49767	-12.50827
Max	1.736472	7.35687	7.99326	11.19976	11.03462	9.4009
Mean	-0.004	0.016	0.015	0.014	0.035	0.03
Variance	0.086	1.077	1.478	2.205	2.473	2.162
Skewness	-0.376***	-0.958***	-1.122***	-0.760***	-0.405***	-0.479***
Ex.Kurtosis	5.678***	11.583***	14.338***	11.926***	7.991***	7.417***
JB	2803.579***	11778.969***	17998.524***	12351.522***	5513.266***	4779.691***
ERS	-7.230***	-3.181***	-5.297***	-5.247***	-17.101***	-19.082***
Q(20)	45.469***	23.086***	38.373***	24.099***	88.089***	98.678***
Q2(20)	1310.174***	603.820***	378.470***	400.201***	1265.935***	752.492***
	Volatilities					
	Green Bond	ESG	Green Economy	Sustainability	Clean Energy	New Energy Innovation
Min	0.000	0.000	0.000	0.000	0.000	0.000
Max	0.0196405	0.115854	0.146985	1.53E-01	1.25E-01	0.125083
Mean	0.002	0.007	0.008	0.01	0.011	0.01
Variance	0.000	0.000	0.000	0.000	0.000	0.000
Skewness	2.717***	3.514***	3.996***	3.756***	3.138***	2.861***
Ex.Kurtosis	10.811***	28.236***	38.799***	28.495***	17.269***	14.294***
JB	12511.424***	72356.745***	134104.584***	74210.154***	28850.221***	20258.134***
ERS	-8.270***	-2.685***	-5.338***	-5.623***	-8.282***	-7.341***
Q(20)	1790.866***	1116.157***	1017.492***	733.511***	1421.813***	1376.770***
Q2(20)	1310.174***	603.820***	378.470***	400.201***	1265.935***	752.492***
	Financial and climate risks					
			COVOL	TRI	PRI	
Min			0.0417	-0.078206	-0.055995	
Max			2.8582	0.137991	0.122507	
Mean			0.555	-0.004	-0.002	
Variance			0.098	0.000	0.000	
Skewness			2.241***	0.686***	0.842***	
Ex.Kurtosis			10.893***	2.398***	2.001***	
JB			11861.725***	652.756***	585.006***	
ERS			-5.595***	-6.294***	-11.758***	
Q(20)			12313.352***	134.159***	88.557***	
Q2(20)			11736.505***	93.134***	45.778***	

Note: This table reports the summary statistics for all variables, including the return and volatilities of green finance markets, as well as financial risk (COVOL), transition climate risk index (TRI) and physical climate risk index (PRI). The above table also reports the estimation results of the Skewness test, the Kurtosis test, the normality test, and the ERS unit root test, where *,**,*** indicate significance at 10%, 5%, and 1%, respectively. $Q(20)$ and $Q^2(20)$ represent weighted portmanteau test statistics.

Table 2: MODWT wavelet-based VAR Granger causality test between COVOL, PRI, TRI, and return connectedness

Null Hypothesis:	D1	D2	D3	D4	D5	D6	D7
COVOL does not Granger cause return connectedness of green finance	**27.153*** **	**32.068*** **	**29.576*** **	**31.421*** **	**2.831* **	**181.390*** **	**602.000*** **
PRI does not Granger cause return connectedness of green finance	1.808	0.387	0.147	**13.183*** **	**45.341*** **	**17.571*** **	**21.124*** **
TRI does not Granger cause return connectedness of green finance	0.044	1.298	**4.827** **	0.859	**6.176** **	**16.195*** **	**9.189*** **

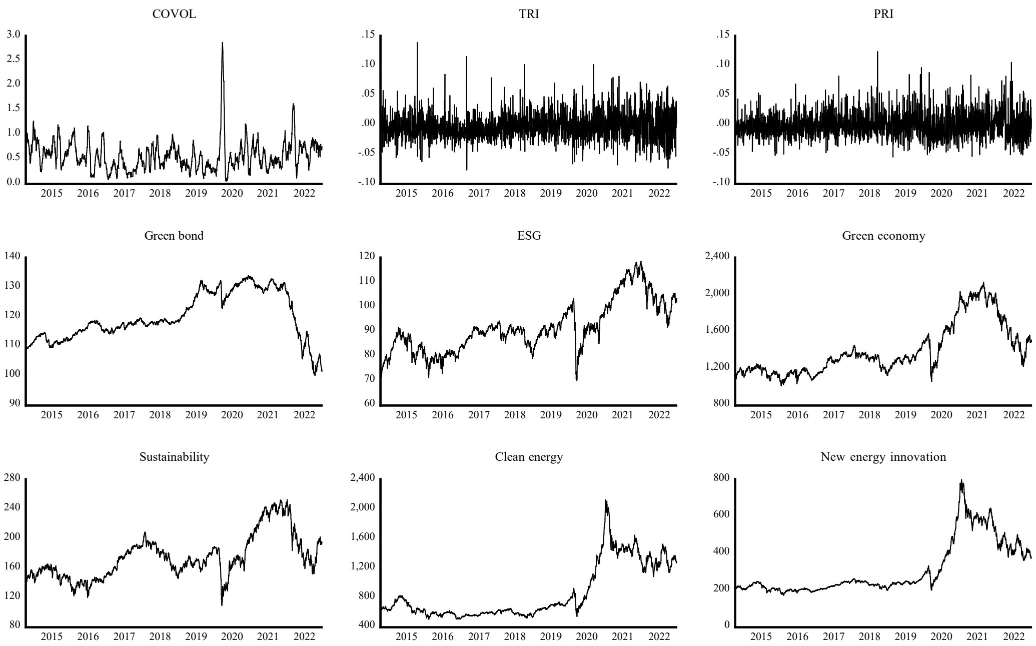
Note: where *,**,*** indicate significance at the 10%, 5%, and 1% levels, respectively. The lags are determined as 1, based on the result of the Schwarz information criterion (SIC).

Table 3: MODWT wavelet-based VAR Granger causality test between COVOL, PRI, TRI, and volatility connectedness

Null Hypothesis:	D1	D2	D3	D4	D5	D6	D7
COVOL does not Granger cause volatility connectedness of green finance	**10.538*** **	0.978	**9.900*** **	**39.954*** **	**27.516*** **	**611.950*** **	**280.160*** **
PRI does not Granger cause volatility connectedness of green finance	**4.358** **	**11.813*** **	**8.294*** **	**33.849*** **	**28.379*** **	1.828	**18.382*** **
TRI does not Granger cause volatility connectedness of green finance	0.122	1.859	1.730	1.105	**29.602*** **	0.274	**72.294*** **

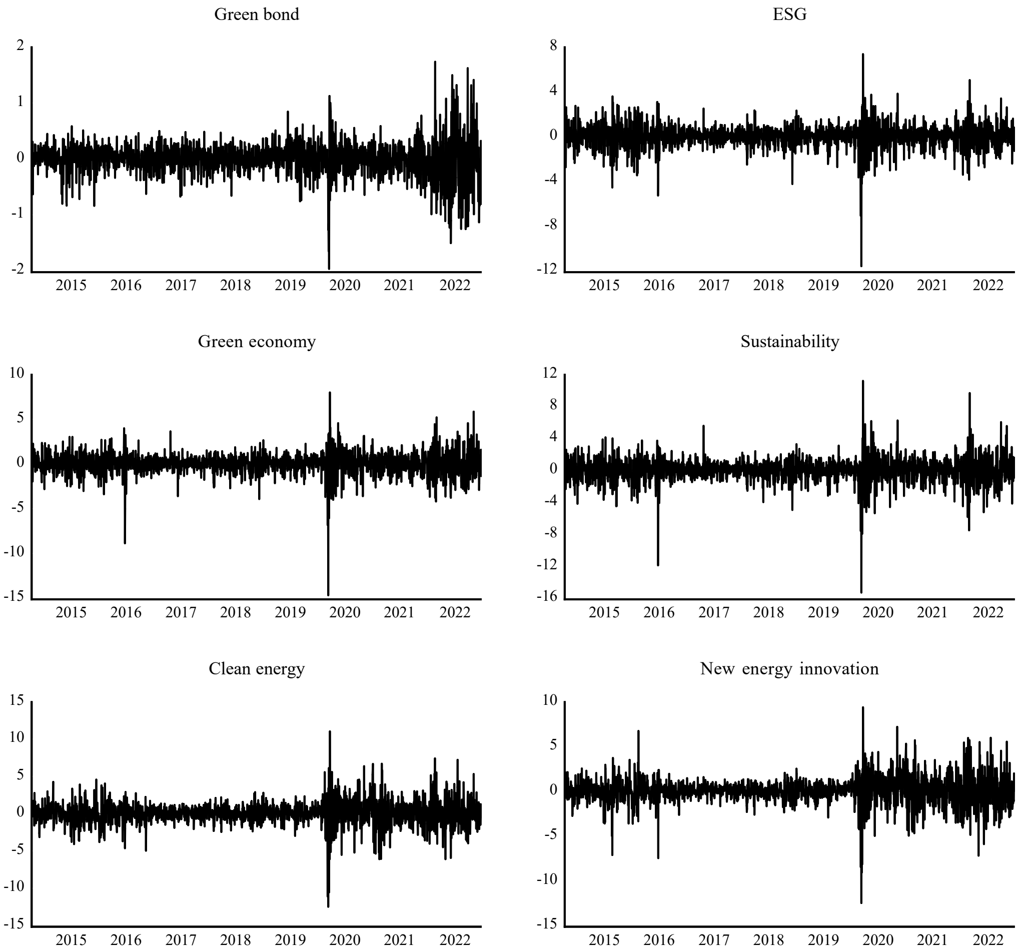
Note: where *,**,*** indicate significance at the 10%, 5%, and 1% levels, respectively. The lags are determined as 1, based on the result of the Schwarz information criterion (SIC).

Figure 1: Raw time series of all variables



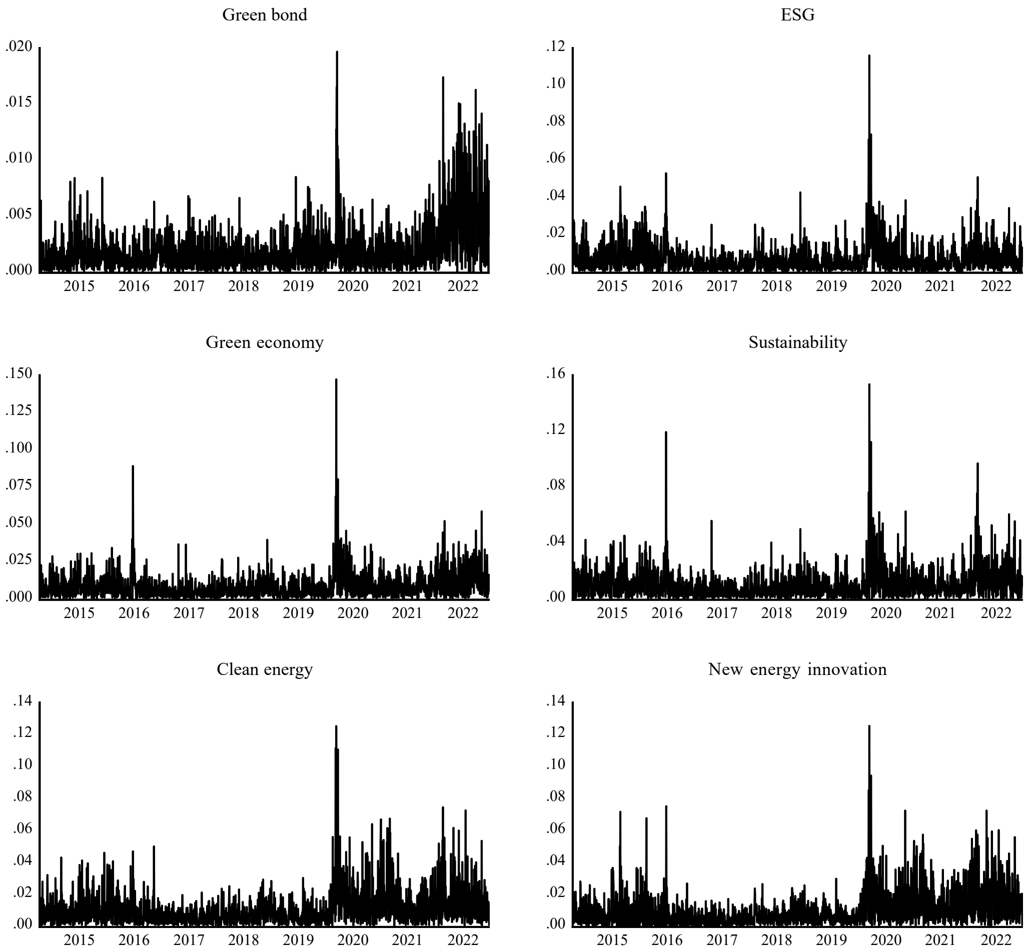
Note: This figure shows the time series of COVOL, transition climate risk index, physical climate risk index and the selected six green assets from 14 October 2014 to 30 December 2022.

Figure 2: Return series of selected green assets



Note: This figure shows the dynamic return series of each green finance market from 14 October 2014 to 30 December 2022.

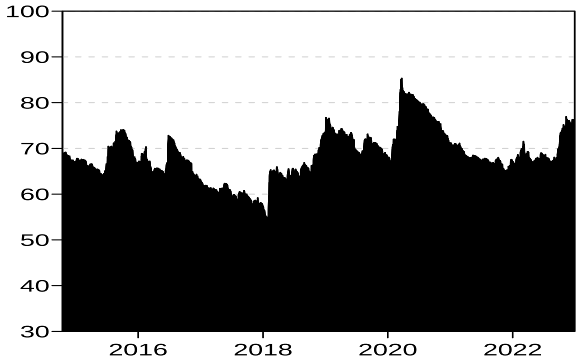
Figure 3: Volatility series of selected green assets



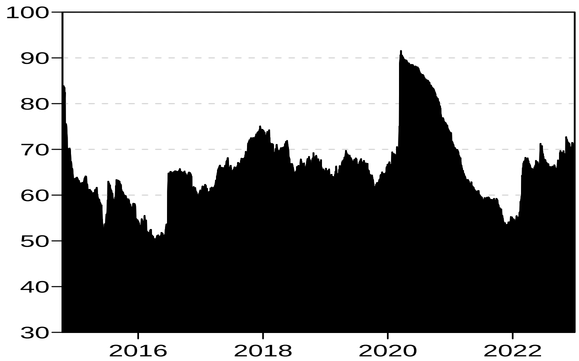
Note: This figure plots the dynamic volatility series of each green finance market from 14 October 2014 to 30 December 2022.

Figure 4: Total return and volatility connectedness across green finance markets

(a) Total return connectedness index



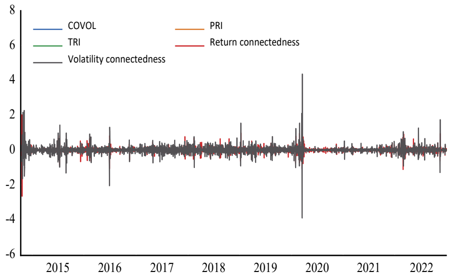
(b) Total volatility connectedness index



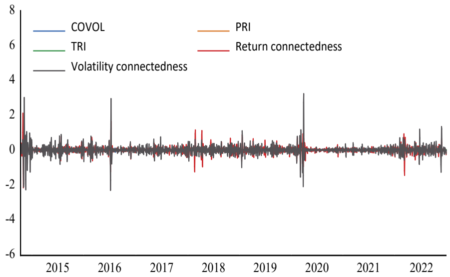
Note: Figure shows the total return and volatility connectedness of green finance, respectively. The results are based on TVP-VAR model with lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition.

Figure 5: Plot of wavelet decomposed series for the total connectedness of green finance (return, volatility) and two systemic risks (financial risk, climate risk)

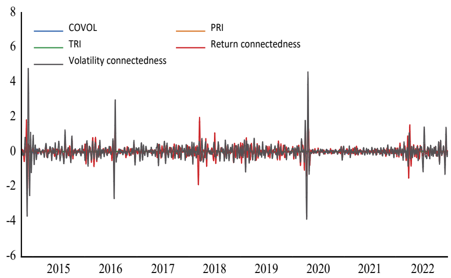
(a) D1



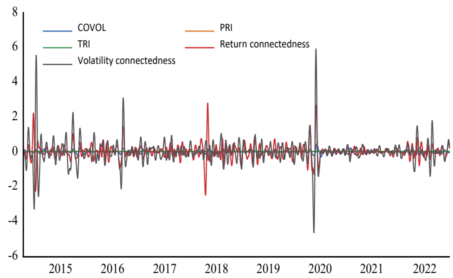
(b) D2



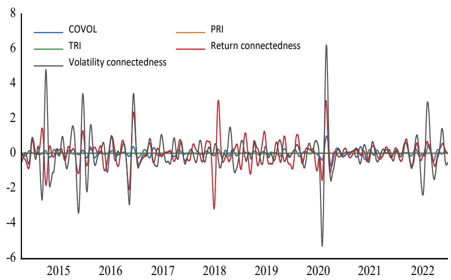
(c) D3



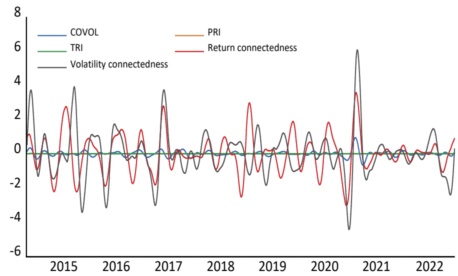
(d) D4



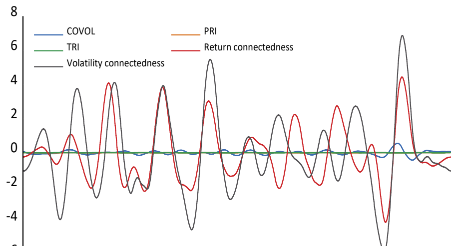
(e) D5



(f) D6



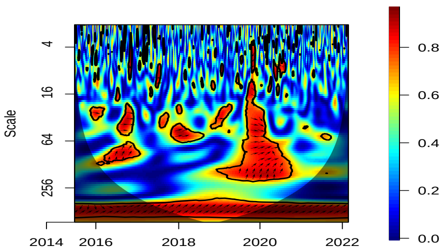
(g) D7



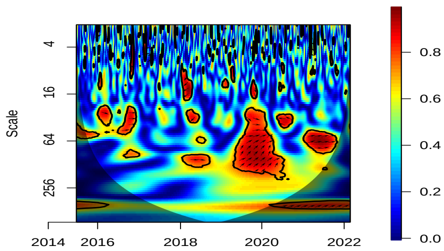
Note: This figure presents seven distinct frequency decomposition series for COVOL, physical climate risk index, transition climate risk index, total return connectedness index, and total volatility connectedness index, all obtained using the MOWDT approach. The decomposed series are available from the authors upon request.

Figure 6: Wavelet coherence

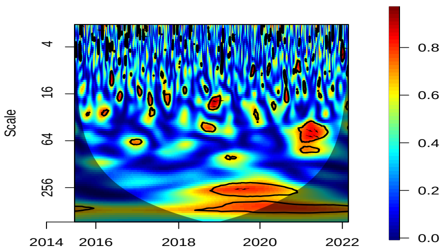
(a) COVOL and return connectedness



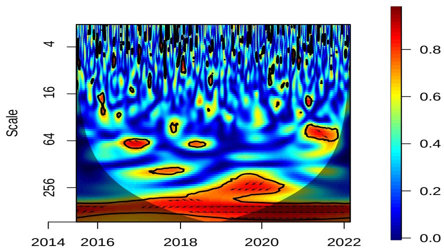
(b) COVOL and volatility connectedness



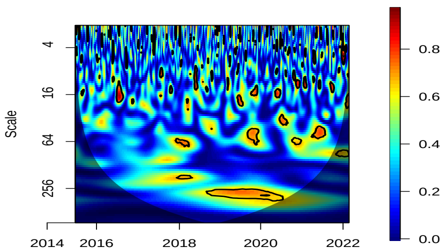
(c) PRI and return connectedness



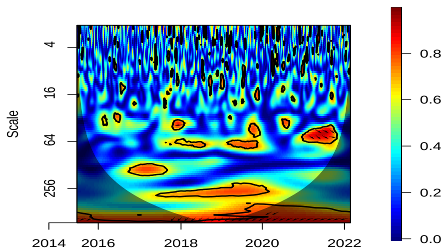
(d) PRI and volatility connectedness



(e) TRI and return connectedness



(f) TRI and volatility connectedness



Note: The figure illustrates the pairwise wavelet coherence and phase plots between the total return and volatility connectedness indices and COVOL, physical climate risk index and transition climate risk index.

Table 4: MODWT wavelet-based VAR Granger causality test with return connectedness (robustness check using asset class COVOL)

Null Hypothesis:	D1	D2	D3	D4	D5	D6	D7
Asset-based common volatility does not Granger cause return connectedness of green finance	**3.833***	**6.797*****	**4.278****	**11.517*****	2.605	**181.190*****	**625.480*****
PRI does not Granger cause return connectedness of green finance	1.3065	1.1581	0.087007	**10.506*****	**36.71*****	**9.3944*****	**1.041*****
TRI does not Granger cause return connectedness of green finance	0.032488	1.869	**10.106*****	0.82354	**2.5473***	**9.1658*****	**21.631*****

Note: where *,**,*** indicate significance at the 10%, 5%, and 1% levels, respectively. The lag order is determined to be 1.

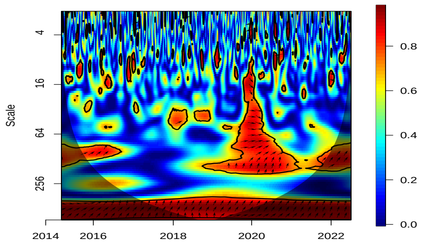
Table 5: MODWT wavelet-based VAR Granger causality test with volatility connectedness (robustness check using asset class COVOL)

Null Hypothesis:	D1	D2	D3	D4	D5	D6	D7
Asset-based common volatility does not Granger cause volatility connectedness of green finance	**4.974****	**2.855***	0.355	**22.919*****	**3.834***	**260.74*****	**197.97*****
PRI does not Granger cause volatility connectedness of green finance	**3.3674****	**13.552*****	**5.6333*****	**21.52*****	**3.7481****	**3.9086****	**24.462*****
TRI does not Granger cause volatility connectedness of green finance	0.11588	2.6544	0.9567	**2.8456***	0.55092	**7.0862*****	**54.98*****

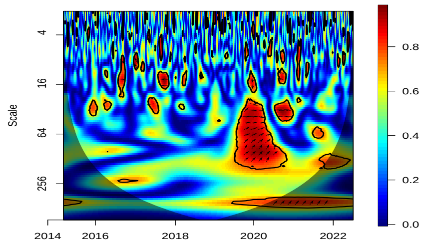
Note: where *,**,*** indicate significance at the 10%, 5%, and 1% levels, respectively. The lag order is determined to be 1.

Figure 7: Wavelet coherence (robustness check using asset class COVOL)

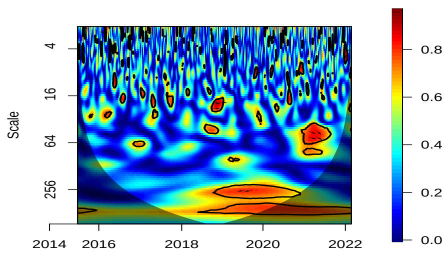
(a) Asset class COVOL and return connectedness



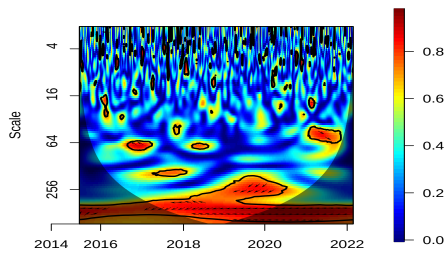
(b) Asset class COVOL and volatility connectedness



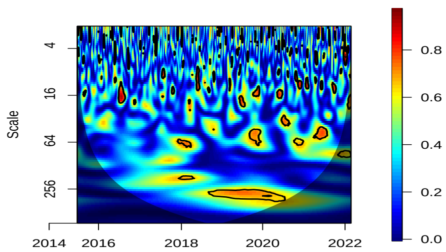
(c) PRI and return connectedness



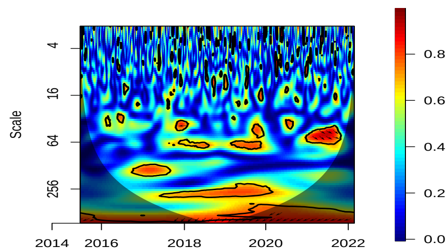
(d) PRI and volatility connectedness



(e) TRI and return connectedness



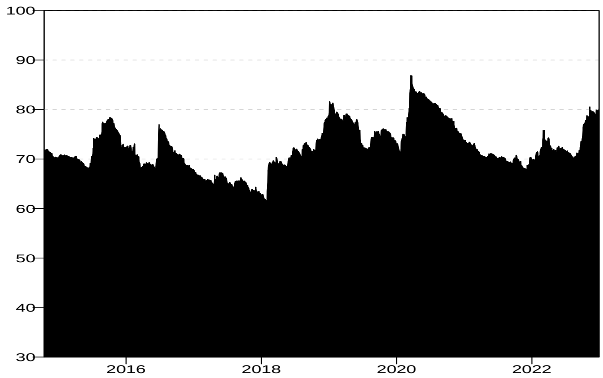
(f) TRI and volatility connectedness



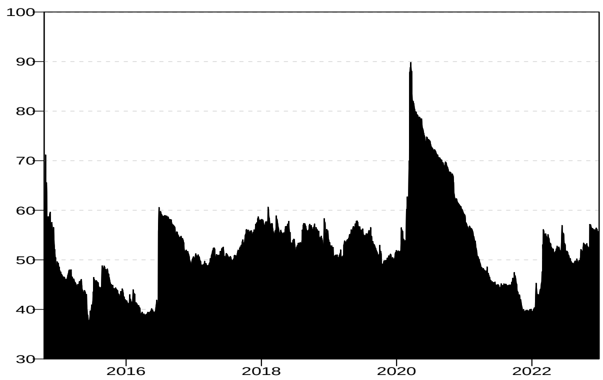
Note: The figure illustrates the pairwise wavelet coherence and phase plots between the total return and volatility connectedness indices and asset class COVOL, physical climate risk index and transition climate risk index.

Figure 8: Total return and volatility connectedness across green finance markets (robustness check using European clean energy index)

(a) Total return connectedness index



(b) Total volatility connectedness index



Note: Figure shows the total return and volatility connectedness of green finance, respectively. The results are based on TVP-VAR model with lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition.

Table 6: MODWT wavelet-based VAR Granger causality test with return connectedness (robustness check using European clean energy index)

Null Hypothesis:	D1	D2	D3	D4	D5	D6	D7
COVOL does not Granger cause return connectedness of green finance	**24.235*** **	**29.451*** **	**29.271*** **	**20.623*** **	1.9481	**208.18*** **	**435.92*** **
PRI does not Granger cause return connectedness of green finance	1.3065	1.1581	0.087007	**10.506*** **	**36.71*** **	**9.3944*** **	**1.041*** **
TRI does not Granger cause return connectedness of green finance	0.032488	1.869	**10.106*** **	0.82354	**2.5473* **	**9.1658*** **	**21.631*** **

Note: where *,**,*** indicate significance at the 10%, 5%, and 1% levels, respectively. The lags are determined as 1 for the robustness check purpose.

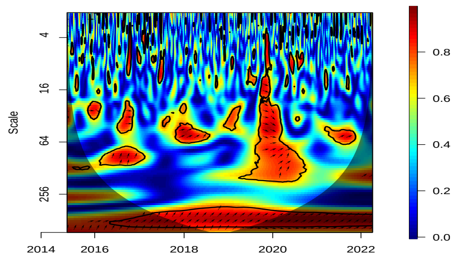
Table 7: MODWT wavelet-based VAR Granger causality test with volatility connectedness (robustness check using European clean energy index)

Null Hypothesis:	D1	D2	D3	D4	D5	D6	D7
COVOL does not Granger cause volatility connectedness of green finance	**30.559*** **	**24.133*** **	**51.362*** **	**105.71*** **	**12.951*** **	**531.93*** **	**309.01*** **
PRI does not Granger cause volatility connectedness of green finance	**3.3674** **	**13.552*** **	**5.6333*** **	**21.52*** **	**3.7481** **	**3.9086** **	**24.462*** **
TRI does not Granger cause volatility connectedness of green finance	0.11588	2.6544	0.9567	**2.8456* **	0.55092	**7.0862*** **	**54.98*** **

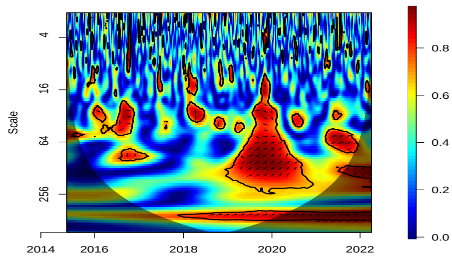
Note: where *,**,*** indicate significance at the 10%, 5%, and 1% levels, respectively. The lags are determined as 1 for the robustness check purpose.

Figure 9: Wavelet coherence (robustness check using European clean energy index)

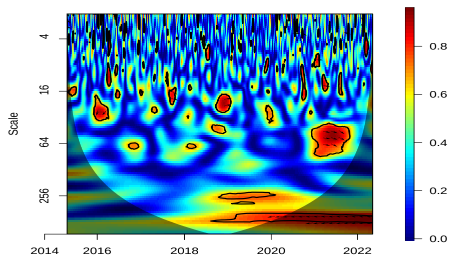
(a) COVOL and return connectedness



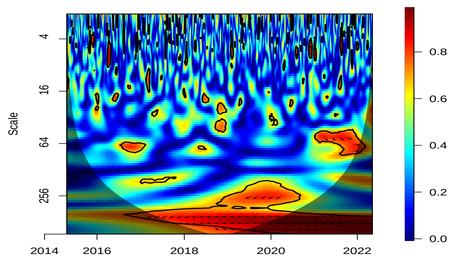
(b) COVOL and volatility connectedness



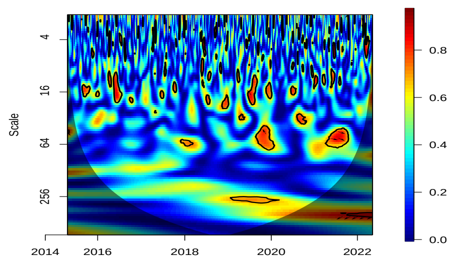
(c) PRI and return connectedness



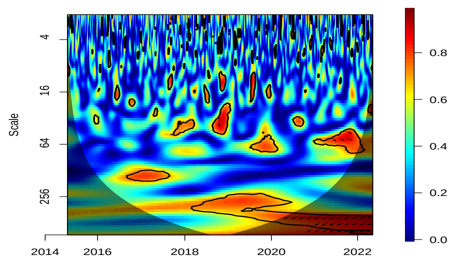
(d) PRI and volatility connectedness



(e) TRI and return connectedness



(f) TRI and volatility connectedness



Note: Wavelet coherence between the total return and volatility connectedness among green finance, COVOL, physical climate risk index and transition climate risk index.

Chapter 4

Green bonds and traditional and emerging investments: Understanding connectedness during crises

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Green bonds and traditional and emerging investments: Understanding connectedness during crises

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A R T I C L E I N F O

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A B S T R A C T

This paper investigates dynamic connectedness between US green bonds and major implied volatility indices from stock, crude oil, gold, exchange rate and cryptocurrency markets through the application of a novel TVP-VAR frequency connectedness approach of Chatziantoniou et al. (2023) for the first time. The specific goal of this paper is to explore how uncertainty from different financial markets could affect the US green bonds during three major events that resulted in substantial financial market instability, such as the US–China trade war, the COVID-19 pandemic, and the Russia–Ukraine conflict. Firstly, there is a relatively low connectedness between green bonds and all implied volatility indices. Secondly, the degree of transmission is notably influenced by such extreme events. Thirdly, the US green bond market is a receiver of each of the analysed stock, oil, and gold markets, while it is a transmitter of exchange rate and cryptocurrency markets. Fourthly, the US green bond functioned as the primary shock transmitter for the cryptocurrency market during the COVID-19 outbreak, but it shifted to being a receiver of shocks during the Russia–Ukraine conflict. Lastly, connectedness between the green bond market and other financial markets is predominantly driven by short-term frequencies. Our results are crucial for understanding the evolution of green bonds, especially during turbulent periods, and assessing green bonds' classification as safe assets. Such findings also show that black swan events have been deeply disruptive to the green transition, with specific relevance to policymakers and market participants.

1. Introduction

Green bonds, as an emerging asset class and a crucial component of the transition to a low-carbon economy, have attracted significant interest from investors, researchers, and policymakers, where proceeds are predominantly used to finance environmentally friendly projects. The market experienced unexpected growth from 2019 to 2021 (Bhutta et al., 2022), presenting evidence of resilience when considering several economic shocks that generated substantial headwinds.[1] However, throughout 2022, green bond issuance fell sharply. The total amount of green bond issuance fell 34.63% in the first quarter of 2022. In particular, the US dropped to fourth place in the ranking countries' issue in 2022 from the top in the past years, with evidence of significant sectoral pressures being experienced due to the broad uncertainty generated within the Russia–Ukraine conflict (Conlon et al., 2024, 2022; Neely, 2022). The recent sharp decline in green bond issuance in the US market in the context of substantial economic turmoil

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[1] According to the Climate Bonds Initiative (CBI), the amount of green bond issuance has been explosive, from around $250 billion in 2019 to $532 billion in 2021, in which the United States contributed the largest amount of green bond issuance.

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presents an opportunity to examine shifts in dynamic connectedness with other traditional financial market volatility indices. This paper examines such dynamic changes and the growing importance of green bonds within the international financial system.

Green bonds have rapidly emerged as a distinctive instrument in investment markets, characterised by their explicit commitment to financing environmentally sustainable initiatives. At their core, these bonds signal a dual intention: to achieve a financial return and to advance environmental goals. Unlike traditional financial instruments, the proceeds from green bonds are earmarked for projects with a positive environmental impact, such as renewable energy development, pollution control, or sustainable water management. This allocation amplifies an issuer's environmental stewardship and introduces a layer of accountability, often reinforced through third-party verification processes that ensure funds are deployed as intended. Furthermore, green bonds resonate with a growing pool of environmentally conscious investors, creating a unique demand dynamic in the financial market. This distinctive demand, coupled with the inherent accountability mechanisms, often results in these bonds exhibiting different risk-return characteristics than their conventional counterparts. The green bond market's growth, driven by investor appetite and organisational commitments to sustainability, highlights the pressing need to understand its financial nuances. While they share many features with traditional bonds, the environmental commitment and the increasing interest from institutional and individual investors set green bonds apart, making them an indispensable subject of contemporary financial research.

Recently, the emergence of green bonds as a mainstream investment market has sparked considerable attention among researchers exploring its relationship with other predominant financial markets. For instance, Reboredo (2018) investigates the co-movement between green bonds, stocks, and energy commodity markets, finding that green bonds can provide substantial diversification benefits for investors in the stock and energy markets. Similarly, Dutta et al. (2021) examines the time-varying correlation between climate bonds and various financial markets, including equities, oil, and gold. The evidence suggests climate bonds offer significant hedging benefits for stock and gold investors while providing some marginal hedging benefits for oil investors. Likewise, the study by Arif et al. (2022) focuses on exploring the connections between green bonds and conventional financial markets, including equity, fixed income, commodity, and foreign exchange markets. This research emphasises investigating the potential of green bonds to act as safe havens in these diverse financial contexts. While substantial research has been conducted on the link between green bonds and key financial markets (Kocaarslan, 2021; Pham & Nguyen, 2021; Reboredo & Ugolini, 2020; Tiwari et al., 2022), the relation with the cryptocurrency market remains largely unexplored.

Cryptocurrencies represent an emerging investment market widely regarded as offering investors diversification opportunities and the potential to hedge against other assets (Corbet et al., 2019; Shahzad et al., 2019). Given its unique characteristics, the cryptocurrency market has become an indispensable component of the financial investment landscape, attracting increasing attention from investors. However, this shift in investor attention inevitably impacts the standing of green bonds in the financial markets. For example, Hassan et al. (2022) finds a negative relationship between the green bond and cryptocurrency environmental attention index. Similarly, Kamal and Hassan (2022) find that environmental-related attention in the cryptocurrency market could negatively impact the green market.

Furthermore, although a substantial body of literature (Billah et al., 2023; Pham & Do, 2022; Pham & Nguyen, 2022) has demonstrated the significant impact of financial market implied volatilities such as VIX, OVX and GVZ on green bonds, research exploring the relationship between green bonds and cryptocurrency implied volatilities remains scarce. Implied volatility not only provides market participants and policymakers with important information about market uncertainty but also reflects anticipated forward-looking market risks (Jiang & Tian, 2005). Therefore, research into the volatility of the cryptocurrency market and its relationship with the volatility of the green bond market has become crucial, given that both are widely regarded as safe havens, see Shahzad et al. (2019) and Guesmi et al. (2019). Understanding how risk is transferred between green bonds and cryptocurrency markets is essential for investors seeking to make informed decisions.

Building upon the aforementioned context, this paper attempts to address the following questions. First, what is the specific role of the US green bond in the financial system? Secondly, has the dynamic connectedness of the US green bond and traditional and emerging financial markets differed in facing various episodes of crisis? Thirdly, does the connectedness differ under the various frequency bands? Finally, is the investor expectation of the US green bond influenced by the turmoil?

The contribution of this paper to the growing area of green bond research is threefold. First, this paper analyses the dynamic connectedness between green bonds and major implied volatility indices from a range of financial markets across different frequency domains using a novel approach as recently proposed by Chatziantoniou et al. (2023). The overwhelming advantage of this method is that it allows the decomposition of connectedness into short-term and long-term frequencies. It is crucial to identify the patterns of connectedness transmission between green bonds and major financial markets across different frequencies to better understand effective risk management and investment strategies due to the diverse investment horizons of investors. For instance, short-term investors may focus on understanding the connectedness mechanisms with other financial markets at short-term frequencies, which typically exhibit rapid information transmission and result in market effects that last less than a week. Conversely, for long-term investors, it is even more important to analyse the connectedness mechanism of long-term frequencies. When long-term frequencies are the main driver of connectedness, the resulting shocks can profoundly affect investor expectations and market conditions overall. Analysing variations in connectedness across different frequency domains allows for a more comprehensive analysis of the complex transmission of volatility between green bonds and other financial markets. Our analysis, utilising the frequency connectedness approach, provides more precise guidance for green investors with varying investment cycles. This is particularly consequential when unexpected events cause discrepancies between short-term and long-term frequencies. In addition, our analysis, based on a recently developed frequency correlation methodology, allows us to assess the responsiveness of investors with different investment expectations in the face of macroeconomic and geopolitical shocks.

Second, this paper is the first to use the Cryptocurrency Volatility Index (CVI), which is the first of its kind decentralised VIX in cryptocurrency markets, to provide a proper estimate of the risk measurement of the cryptocurrency market. Green bonds and cryptocurrencies possess numerous common characteristics in investors' portfolios. They can be regarded by investors as novel types of haven assets in times of financial instability, hedges in ordinary times or diversifying portfolios. Given these shared features, it seems natural to examine the connectedness transmission between both emerging markets. In this paper, we consider a recently proposed CVI to represent the emerging cryptocurrency market.[2]

Third, our research contributes to the literature by investigating the dynamic transmission between green bonds and various implied volatility indices, including VIX, OVX, GVZ, EVZ, and CVI. Given the importance of implied volatility indices, which represent forward-looking market risks and serve as significant indicators for portfolio management, understanding the linkage between green bonds and various financial market risks is crucial. This understanding will help green investors identify key risk transmitters of the green bond market in the financial system, thereby enhancing the feasibility for investors to adjust their asset allocation strategies in a timely manner. Consequently, our results not only fill the research gap regarding the interconnection between green bonds and cryptocurrency markets but also unveil the characteristics of green bonds in relation to various financial markets.

Our main empirical results emphasise that the total connectedness between the US green bond and selected financial markets is time-varying, and the averaged total connectedness is around 26%, which indicates that green bonds present significant and substantial portfolio diversification opportunities. Furthermore, results indicate that the variation of connectedness among green bonds and selected traditional financial market volatility indices are highly dependent upon market conditions in which connectedness increases significantly at each turmoil. Specifically, green bonds and cryptocurrencies are the main receivers of shocks, while stocks, gold, and exchange rates function as net shock transmitters. Focusing on pairwise relationships, both short- and long-term dynamic connectedness is found to constantly co-move between green bonds and stocks, oil, and gold markets, but not with analysed exchange rates and cryptocurrency pairs, indicating differential time-varying behavioural differentials for currency products. Some relationships are found to present dynamic behavioural differentials. At the same time, the Russian-Ukraine conflict is identified as the most disruptive international event that generated substantial external influence on green bond markets. Robustness testing procedures provide further verification. Overall, our study presents some supportive evidence that changing investor expectations surrounding the implicit characteristics of the analysed crises could be a key contributor to the recent decline of investor interest in green bonds, potentially softening the urgency surrounding the green transition.

The paper proceeds as follows: Section 2 summarises the related literature. Further, Sections 3 and 4 describes the data and methodology employed in the paper, respectively. Section 5 provides the empirical findings with associated discussion. Finally, Section 6 concludes.

2. Literature review

The advantages of risk management and hedging are heavily emphasised in the current green bond literature. Pham (2016) was among the first to focus on the interlinkages between green and conventional bonds, specifically presenting evidence of the benefits of incorporating green bonds in portfolios. Similarly, Reboredo (2018) found evidence of a weak relationship between green bonds and both stock and energy markets using a copula methodological structure, supporting the view that green bonds can be used as an effective diversification tool. To extend the research of green bonds in risk management, hedging and diversification, several studies have started to examine the linkage between green bonds and other financial markets, such as oil (Lee et al., 2021; Wang et al., 2022), gold (Dutta et al., 2021), US dollar (Kocaarslan, 2021; Yan et al., 2022) and cryptocurrency (Hassan et al., 2022; Huynh et al., 2020).

More recently, in the context of an increasing number of crises and broad shocks to the financial system, considerable literature has started aiming at the impact of specific event shocks on the risk transmission of green bonds with other financial markets, trying to explore the role of green bonds under both normal and extreme financial conditions. For example, Gao et al. (2021) investigated the impact of event shocks such as the US–China trade war and COVID-19 on the risk spillover between green bonds and traditional financial market volatility indices by combining the DCC-GJR-GARCH model and the network connectedness approach from Diebold and Yilmaz (2012, 2015). They find that international emergencies significantly enhance the volatility level of green bonds, which is mainly driven by the risk aversion sentiment of investors and results in a larger capital inflow to the green bond market. Likewise, Pham (2021) compares the connectedness between green bonds and green stock markets in normal and extreme market conditions. Specifically, they indicate a high level of connectedness between the green bond and green equity markets during high-volatility periods and a weak connectedness during normal market conditions. Furthermore, the study demonstrates that the green stock market has strong spillovers to the green bond market around the COVID-19 outbreak. Dutta et al. (2021) emphasise that the climate bond, which is a similar form of the green bond but with a greater focus on the solution to the climate change issue, provides a better hedge opportunity against the risk of oil, gold, and stocks in an investor's portfolio, especially during the pandemic. In the same vein, Pham and Do (2022) and Lin and Su (2023) the relationship between green bonds and various implied volatility of the markets, to explore the hedge effectiveness of green bonds under crucial events. In particular, Pham and Do (2022)

[2] Similar to the VIX index, the CVI is designed to capture the risk of the cryptocurrency market, offering researchers an opportunity to explore risk transmission within the financial system. To the best of the author's knowledge, this research is the first to examine the dynamic connectedness between green bonds and the cryptocurrency volatility index. Hence, this paper also contributes to understanding the dynamic connectedness between green bonds and the cryptocurrency market.

use the global green bond index and the implied volatilities of major stock markets (US, Europe, China, and emerging markets), oil, and gold markets to find that the global green bond can serve as a diversification asset during the crisis due to the low connectedness among variables. Whilst (Lin & Su, 2023) explore the linkage between green bonds and three uncertainties, including VIX, OVX, and EPU in the US and China. The findings highlight that green bonds in both markets experience significant risk contagion from VIX and OVX during financial turmoil due to the safe haven properties of green bonds in investor sentiment.

Regarding the methodological processes used to analyse the effectiveness of the hedge of green bonds, Pham (2016) uses the GARCH model to explore the dynamic volatility spillover between the labelled green bond market and the conventional bond market. Similarly, Jin et al. (2020) examine the connectedness among green bonds, carbon credits, and each of the stock, commodity, and energy markets using the dynamic connectedness method of Diebold and Yılmaz (2014). In addition, they found that green bonds can provide the best hedge against carbon market risk, especially during a crisis, after applying the three dynamic hedge models, including the DCC-APGARCH, DCC-T-GARCH, and DCC-GJR-GARCH models, as well as the constant hedge ratio model. On the other hand, the connectedness framework developed by Diebold and Yilmaz (2012), Diebold and Yılmaz (2014), who propose a framework to characterise cross-market connectedness by using variance decompositions from approximating models, and Baruník and Křehlík (2018) further improve the connectedness analysis by looking at different frequency domains to estimate the impact of shocks on different duration investors. Further, Reboredo et al. (2020) examined such dynamic connectedness in both EU and US markets, while Ferrer et al. (2021) used the frequency connectedness analysis to evaluate the linkage between green bonds and several mainstream financial markets, identifying a strong connectedness between green bonds and Treasury and corporate bonds. In the same vein, Arif et al. (2021) uses the network connectedness analysis to investigate the network of green bonds and debt, equity, and energy markets to explore the impact of COVID-19. They observe an enhanced connectedness among green bonds and other sample variables during the pandemic. Pham and Do (2022) apply the connectedness analysis to examine the dynamic relationship between green bonds and other implied volatility indexes.

Taken together, these studies support the notion that the green bond can be treated as a hedging or diversification asset in many cases. The sudden fall of the US green bond, however, in 2022 is still inexplicable. Therefore, the following research presents a specific novelty by focusing on the connectedness variation of the US green bond to explore the fundamental driving forces of the growth and decline of the US green bond. In particular, this study is closely related to that of Pham and Do (2022) as both works assess the dynamic connectedness between green bonds and the volatility of various markets at different investment horizons.

3. Data

To analyse the volatility performance of green bonds in the US, we follow Reboredo et al. (2020) and Lin and Su (2023), which use the Bloomberg Barclays MSCI US Green Bond Index (USGB) as a key measurable indicator. This index contains the green bonds labelled in the United States whose proceeds are only used to finance green projects (such as energy efficiency and environmental sustainability) and are issued by corporations and governments in US dollars. On the other hand, to capture the volatility performance of the stock, oil, exchange rate, and gold in the US, we apply the four well-known volatility indexes published by CBOE, including the stock market volatility index (VIX), the crude oil volatility index (OVX), the foreign exchange rate volatility index (EVZ) and the gold price volatility index (GVZ). We also use the cryptocurrency volatility index (CVI) to depict the volatility dynamics of the cryptocurrency market.[3] The sample period selected in this research spans 2 April 2019 through 10 August 2022 due to data availability.[4] Thus, our data sample contains 848 daily observations and spans the timeline of crucial events such as the US–China trade war, the pandemic, and the Russia–Ukraine war.[5]

Fig. 1 presents the time series of the daily closing price of each variable. It is observed that the US green bond market has experienced periods of enormous growth and decline throughout the sample period. Looking at the other volatility indexes, there exist periods of substantial escalation of volatility in each market at the beginning of 2020, corresponding to the time of significant contagion of the COVID-19 pandemic, where the OVX shows the largest upward among the sample variables.[6] Furthermore, we also note that the magnitude of each volatility index has increased around the beginning of 2022, consistent with the timeline of the Russian-Ukraine conflict.

Following Antonakakis et al. (2018), Antonakakis and Kizys (2015), Forsberg and Ghysels (2007), we use the absolute return method to calculate the volatility of the US green bond. According to Forsberg and Ghysels (2007), the advantages of the absolute return method include greater persistence, better sampling error behaviour, and immunity to jumps. The literature has substantially discussed whether the absolute return is an appropriate indicator for volatility dynamics. Specifically, a question has been addressed about how good the representative of the absolute return for volatility is, compared to the model-based measure such as the Generalised Autoregressive Conditional Heteroscedasticity (GARCH) model and some alternative ones. To the best of our knowledge, although the competition among those measures for the best proxy of volatility may remain unresolved, it has been revealed that

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3 Consistent with the market fear index such as VIX and GVZ, the CVI is designed by Prof. Dan Galai, the creator of the original VIX, to measure the market fear for the crypto market. The purpose of this index is to analyse the market expectation of future volatility by computing a decentralised volatility index from cryptocurrency options prices.

4 CVI is unavailable before April 2019.

5 The data on the US green bond index is downloaded from Bloomberg Terminal, and the market volatility indexes are from the St. Louis FRED. Regarding the volatility index of cryptocurrency, we obtain the CVI data from here.

6 An explainable reason for the phenomenon is that the oil market experiences double pressure of negative oil prices caused by the Russia-Saudi Arabia oil price war and sharply reduced consumption due to the pandemic (Ahonen et al., 2022; Corbet et al., 2021a, 2021b).

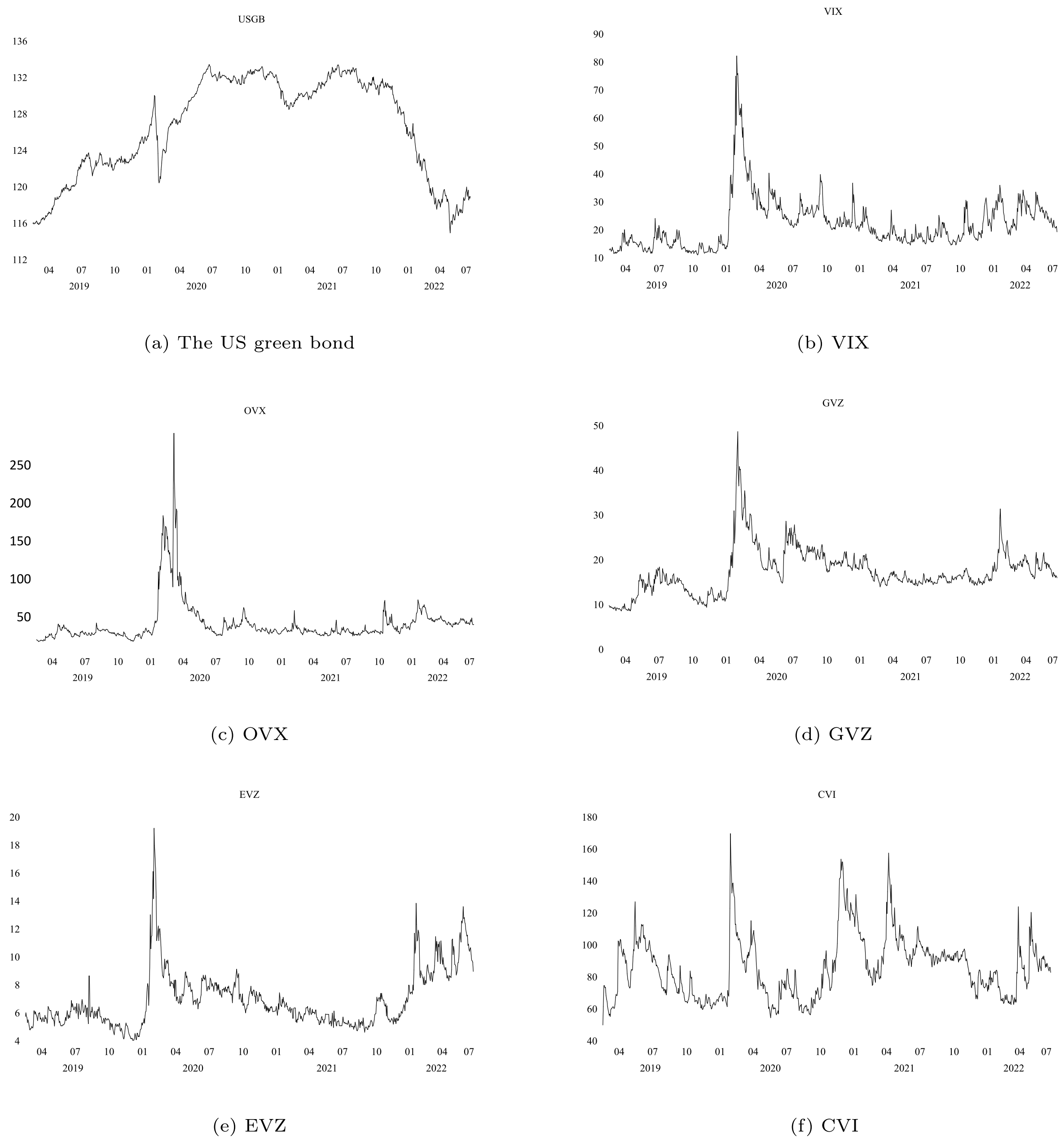
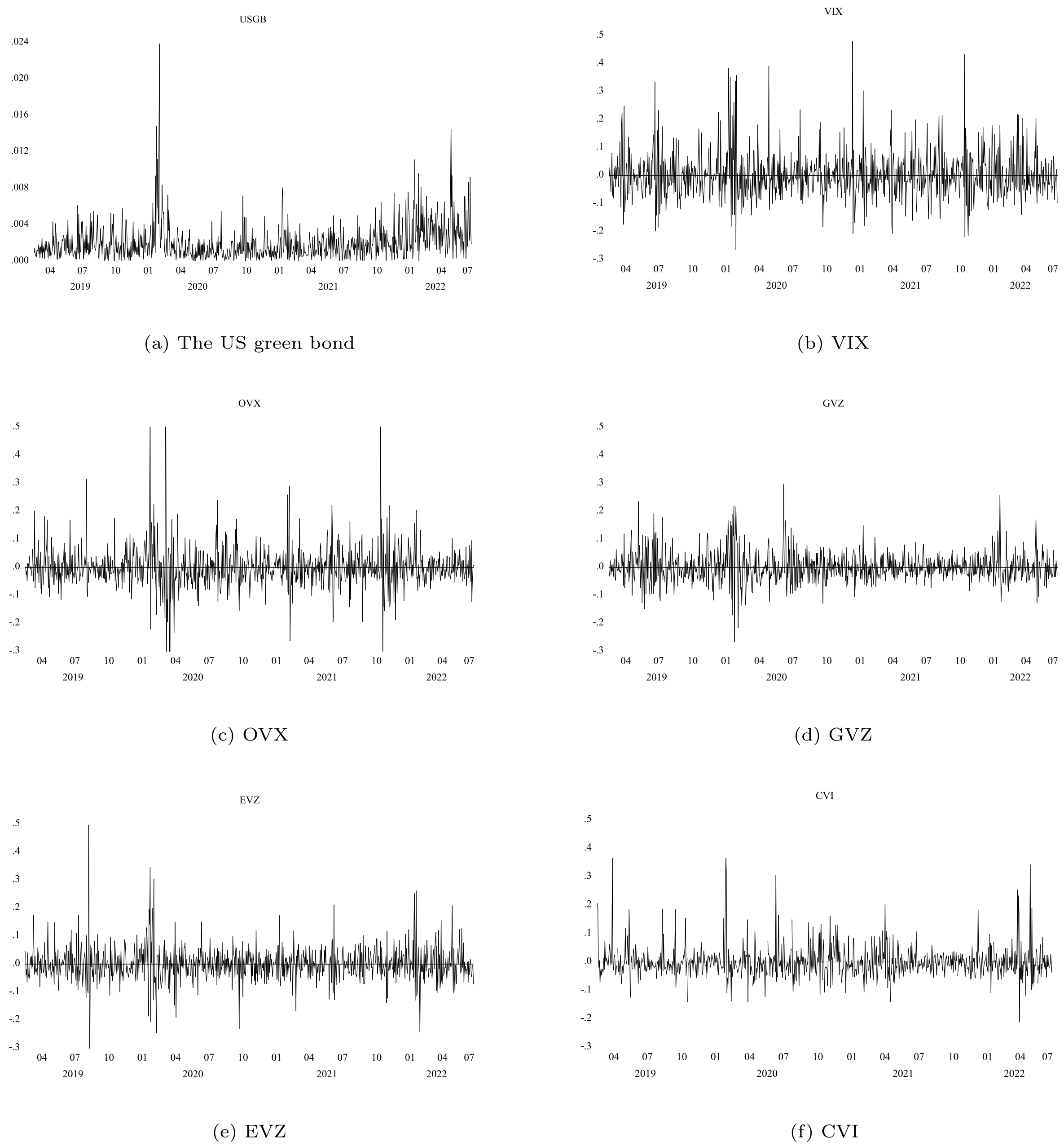


Fig. 1. Time Series of raw variables.
Note: This figure displays the daily values of green bonds (US), VIX, OVX, GVZ, EVZ, and CVI from 02 April 2019 to 10 August 2022.

the absolute return-based measure presents evidence of proximity to the GARCH-based measure to a substantive extent. On some occasions, the former may even possess a superior feature regarding volatility forecasting compared to the latter. Khalifa et al. (2011) show no substantive difference between the absolute return and the GARCH(1,1) model in terms of the average annualised volatility based on estimated daily standard deviation. Further, they document evidence of proximity between those two measures by unveiling that the forecasted volatility from the GARCH model is reasonably close to the measure by the absolute return in light of a relatively low loss function value equivalent to mean squared error (MSE). Some similarities between the GARCH volatility estimates and the absolute return are evidenced in such circumstances.

Moreover, Bollerslev and Wright (2001) rigorously evaluated how far the forecasted volatility by the GARCH model deviates from the forecast of integrated variance derived from the absolute return. Testing the significance of the difference in the mean square prediction error (MSPE) between the GARCH forecast and the absolute return one reveals that the latter provides a better performance as its MSPE is 20% below that of the GARCH counterpart. The result is attributed to the absolute return being relatively outlier-resistant. Finally, the literature has detected that the absolute return has a substantive relation with the market-based volatility dynamics. Engle and Gallo (2006) find that the absolute return significantly contributes to VIX, which is the implied volatility of the S&P 500 index. It has a tighter positive relation with VIX than alternative volatility measures such as daily range-based and realised volatility. In such a vein, it is implied that the absolute return may be a sensible indicator for the model-free



(a) The US green bond (b) VIX

(c) OVX (d) GVZ

(e) EVZ (f) CVI

Fig. 2. Volatility series of each index.
Note: Our sample data range from April 2019 to August 2022.

volatility. In sum, the prior literature has found evidence supporting our choice to employ the absolute return as a proxy of volatility dynamics instead of the GARCH model-based measure. The evidence points to some crucial reasons that, firstly, substantive similarities exist between the absolute return and GARCH-based measures; secondly, the former measure may be superior to the latter on the occasion that integrated volatility is forecasted. Also, as the raw volatility indexes are non-stationary according to the result of the unit root test of the ADF test (Dickey & Fuller, 1981), we take the first difference for all volatility indexes to ensure that all volatility indexes are stationary. All re-scaled volatility indices are illustrated in Fig. 2.

In Table 1, we present the summary statistics for each series of market volatility. All the indexes have a positive mean value, where specifically, the mean value of the US green bond index is higher than those of other financial market volatility indexes. These results suggest that the average performance of the US green bond is higher than that of other variables during the sampler period. In contrast, the volatility index of US green bonds has the smallest variance, whereas the VIX and OVX indexes have the largest variance. Furthermore, all volatility series have significantly right skewed and significantly excess kurtosis. Finally, we confirm that all series are non-normally distributed and significantly stationary through the J.B. normality test (Jarque & Bera, 1980). The non-parametric Kendall rank correlation coefficients show that the US green bond positively correlates with all other volatility indexes except for the CVI, in which the VIX strongly correlates with the green bond index. Furthermore, all the volatility series are stationary according to the ADF and ERS unit root tests.

Table 1
Summary statistics.

	USGB	VIX	OVX	GVZ	EVZ	CVI
Mean	0.002	0.000	0.001	0.001	0.001	0.001
Variance	0.000	0.007	0.007	0.003	0.004	0.003
Skewness	3.390***	1.190***	1.954***	0.678***	0.786***	2.046***
Ex.Kurtosis	22.158***	4.002***	24.406***	3.401***	9.462***	9.811***
JB	18927.092***	764.353***	21535.942***	472.496***	3243.115***	3983.325***
Q(20)	420.630***	22.582***	18.932**	17.788**	42.273***	16.891*
Q2(20)	231.391***	76.713***	79.868***	373.310***	128.173***	76.253***
	USGB	VIX	OVX	GVZ	EVZ	CVI
USGB	1.000	0.074	0.067	0.065	0.032	−0.02
VIX	0.074	1.000	0.240	0.265	0.240	0.107
OVX	0.067	0.240	1.000	0.213	0.139	0.057
GVZ	0.065	0.265	0.213	1.000	0.220	0.091
EVZ	0.032	0.240	0.139	0.220	1.000	0.114
CVI	−0.02	0.107	0.057	0.091	0.114	1.000

Note: The above table reports the estimation results of the Skewness test (D'Agostino, 1970); the Kurtosis test (Anscombe & Glynn, 1983); the JB normality test (Jarque & Bera, 1980); and the ADF test (Dickey & Fuller, 1981).

* Indicate significance at 10%.

** Indicate significance at 5%.

*** Indicate significance at 1%.

4. Methodology

4.1. Connectedness techniques

Work based on dynamic connectedness builds direction up that of Diebold and Yilmaz (2012), Diebold and Yılmaz (2014), who first creates a connectedness index to capture the nexus of various markets based on the generalised forecast error variance decomposition from a vector autoregressive (VAR) model. Subsequently, a growing number of techniques have developed based on the connectedness approach (Diebold & Yilmaz, 2012; Diebold & Yılmaz, 2014), such as the wavelet connectedness approach (Reboredo et al., 2020), Lasso connectedness approach (Tiwari et al., 2022), DCC-GARCH connectedness approach (Gabauer, 2020), asymmetric connectedness approach (Adekoya et al., 2022) and frequency connectedness approach (Baruník & Křehlík, 2018). Despite the increasing number of approaches developed to impulse the connectedness method evolution, most approaches built upon the rolling-window VAR approach, which led to several shortcomings, such as the discrepant set window size and the loss of observations. To overcome those disadvantages, Antonakakis et al. (2020) propose the time-varying parameter (TVP)-VAR-based connectedness approach, which does not need to set a rolling-window size and no observation loss. Subsequently, the TVP-VAR-based method is fast becoming a key instrument in exploring the connectedness among financial variables (see, for example, Bouri et al. (2021), Corbet et al. (2021), and Adekoya and Oliyide (2021)). However, the TVP-VAR-based method considers only the variation of connectedness among variables and ignores frequency consideration, which is crucial in risk management. Therefore, this paper considers the relationship between the US green bond and other volatility indexes by employing a fresh method of Chatziantoniou et al. (2023), which displays dynamic connectedness and shows information with different frequency domains.

4.2. TVP-VAR based frequency connectedness approach

To capture the variation of connectedness in different frequency bands among variables, we apply a novel TVP-VAR-based frequency connectedness approach of Chatziantoniou et al. (2023). This method is built upon by combining the frequency connectedness of Baruník and Křehlík (2018) and the TVP-VAR-based connectedness approach (Antonakakis et al., 2020). Thus, the TVP-VAR(p) model is defined by the following mathematical expression:

$$x_t = \Phi_{1t}x_{t-1} + \Phi_{2t}x_{t-2} + \cdots \Phi_{pt}x_{t-p} + \epsilon_t \qquad \epsilon_t \sim \mathrm{N}(0, \Sigma_t) \tag{1}$$

where x_t, x_{t-1} are $N \times 1$ dimensional vectors and Σ_t denotes time-varying variance–covariance matrix, Φ_{it} indicate the time-varying VAR coefficient.

Next, we calculate the core of the connectedness approach, which is the generalised forecast error variance decomposition (GFEVD) from Koop et al. (1996) and Pesaran and Shin (1998). According to Wiesen et al. (2018), the GFEVD method is appropriate to assess variables that do not have a particular variable ordering in economic theory. To the best of our knowledge, there is a lack of economic theory that emphasises variable ordering between the US green bond and other volatility indexes. In more detail, the GFEVD can be interpreted as the impact of a shock on variable j on variable i and can be calculated as:

$$\theta_{ijt}(H) = \frac{(\boldsymbol{\Sigma}_t)^{-1}_{jj} \sum_{h=0}^{H} \left((\boldsymbol{\Psi}_h \boldsymbol{\Sigma}_t)_{ijt} \right)^2}{\sum_{h=0}^{H} (\boldsymbol{\Psi}_h \boldsymbol{\Sigma}_t \boldsymbol{\Psi}'_h)_{ii}} \tag{2}$$

$$\tilde{\theta}_{ijt}(H) = \frac{\theta_{ijt}(H)}{\sum_{k=1}^{N} \theta_{ijt}(H)} \tag{3}$$

where $\tilde{\theta}_{ijt}(H)$ indicates the contribution of the variable j to the variance of the forecast error of the variable i at horizon H. Next, to further estimate the direction of connectedness among variables, we apply the TVP-VAR-based connectedness approach, which is given by:

$$TO_{it}(H) = \sum_{i=1, i\neq j}^{N} \tilde{\theta}_{jit}(H) \tag{4}$$

$$FROM_{it}(H) = \sum_{j=1, i\neq j}^{N} \tilde{\theta}_{ijt}(H) \tag{5}$$

$$NET_{it}(H) = TO_{it}(H) - FROM_{it}(H) \tag{6}$$

$$NPDC_{ijt}(H) = \tilde{\theta}_{ijt}(H) - \tilde{\theta}_{jit}(H). \tag{7}$$

$$TCI_{t}(H) = N^{-1} \sum_{i=1}^{N} TO_{it}(H) = N^{-1} \sum_{i=1}^{N} FROM_{it}(H) \tag{8}$$

where $TO_{it}(H)$ and $FROM_{it}(H)$ are the directional connectedness index, while the first represents the value of the variable it transmitting the shocks to all others. In contrast, the latter indicates the value of the variable it receiving the impact from all others. The $NET_{it}(H)$ indicates the net directional connectedness, which is the difference between the $TO_{it}(H)$ directional connectedness and the $FROM_{it}(H)$ directional connectedness. Thus, if $NET_{it}(H) > 0$ or $NET_{it}(H) < 0$, generally, it refers to the variable it being a net transmitter or receiver of shocks in the network. The $NPDC_{ijt}(H)$ denote the net pairwise connectedness, which demonstrates the connectedness information at the bilateral level. If the $NPDC_{ijt}(H) > 0$ or $NPDC_{ijt}(H) < 0$, it means that the variable j influences variable i or the variable j impacted by the variable I. Finally, the $TCI_{t}(H)$ indicate the total connectedness index that measures the network's interconnectedness level. At this point, the higher value of $TCI_{t}(H)$ refers to the higher level of market risk. The main advantage of the TVP-VAR frequency connectedness approach over other ordinary connectedness methods is the frequency domain method that decomposes the connectedness into different frequency domains. First, considering the spectral decomposition method of Stiassny (1996), the spectral density of x_t at the frequency ω can be defined as the Fourier transformation of TVP-VMA (Chatziantoniou et al., 2023). This can be formulated as follows:

$$\boldsymbol{S}_x(\omega) = \sum_{h=-\infty}^{\infty} E\left(\boldsymbol{x}_t \boldsymbol{x}'_{t-h}\right) e^{-i\omega h} = \boldsymbol{\Psi}\left(e^{-i\omega h}\right) \boldsymbol{\Sigma}_t \boldsymbol{\Psi}'\left(e^{+i\omega h}\right) \tag{9}$$

Next, the frequency GFEVD can be computed by,

$$\theta_{ijt}(\omega) = \frac{\left(\boldsymbol{\Sigma}_t\right)_{jj}^{-1} \left|\sum_{h=0}^{\infty} \left(\boldsymbol{\Psi}\left(e^{-i\omega h}\right) \boldsymbol{\Sigma}_t\right)_{ijt}\right|^2}{\sum_{h=0}^{\infty} \left(\boldsymbol{\Psi}\left(e^{-i\omega h}\right) \boldsymbol{\Sigma}_t \boldsymbol{\Psi}\left(e^{i\omega h}\right)\right)_{ii}} \tag{10}$$

$$\tilde{\theta}_{ijt}(\omega) = \frac{\theta_{ijt}(\omega)}{\sum_{k=1}^{N} \theta_{ijt}(\omega)} \tag{11}$$

where $\tilde{\theta}_{ijt}(\omega)$ indicates the percentage of the spectrum of the market i at a specific frequency ω.

To estimate the connectedness at different frequency bands, we set a specific range for all frequencies, where $d = (a, b), a, b, \epsilon(-\pi, \pi), a < b$.

$$\tilde{\theta}_{ijt}(d) = \int_{a}^{b} \tilde{\theta}_{ijt}(\omega) d\omega \tag{12}$$

Finally, the DY time-domain connectedness (Diebold & Yilmaz, 2012; Diebold & Yılmaz, 2014) and the BK frequency-dependent connectedness (Baruník & Křehlík, 2018) are presented respectively as follows.

$$TO_{it}(d) = \sum_{i=1, i\neq j}^{N} \tilde{\theta}_{jit}(d) \tag{13}$$

$$FROM_{it}(d) = \sum_{i=1, i\neq j}^{N} \tilde{\theta}_{ijt}(d) \tag{14}$$

$$NET_{it}(d) = TO_{it}(d) - FROM_{it}(d) \tag{15}$$

$$NPDC_{ijt}(d) = \tilde{\theta}_{ijt}(d) - \tilde{\theta}_{jit}(d) \tag{16}$$

$$TCI_{t}(d) = N^{-1} \sum_{i=1}^{N} TO_{it}(d) = N^{-1} \sum_{i=1}^{N} FROM_{it}(d) \tag{17}$$

Table 2
Averaged connectedness table (US).

	USGB	VIX	OVX	GVZ	EVZ	CVI	FROM
USGB	87.61	3.9	2.56	2.73	1.75	1.45	12.39
	(67.04, 20.57)	(2.92, 0.98)	(1.72, 0.84)	(2.09, 0.64)	(1.44, 0.31)	(1.19, 0.26)	(9.36, 3.03)
VIX	2.78	64.35	10.16	11.43	8.72	2.54	35.64
	(2.63, 0.15)	(56.82, 7.53)	(8.86, 1.3)	(10.11, 1.32)	(7.76, 0.96)	(2.26, 0.28)	(31.63, 4.01)
OVX	1.61	11.46	72.28	7.67	5.72	1.27	27.72
	(1.25, 0.36)	(9.65, 1.81)	(62.59, 9.69)	(6.69, 0.98)	(4.99, 0.73)	(1.21, 0.06)	(23.79, 3.93)
GVZ	1.92	11.32	6.96	64.38	11.86	3.58	35.63
	(1.64, 0.28)	(9.83, 1.49)	(5.96, 1)	(56.36, 8.02)	(10.55, 1.31)	(2.92, 0.66)	(30.89, 4.74)
EVZ	1.89	8.9	5.43	12.14	69.53	2.12	30.48
	(1.43, 0.46)	(7.53, 1.37)	(4.36, 1.07)	(10.1, 2.04)	(61.79, 7.74)	(1.83, 0.29)	(25.25,5.23)
CVI	2.27	3.5	1.74	4.81	3.1	84.57	15.43
	(1.81, 0.46)	(2.89, 0.61)	(1.24, 0.5)	(3.75, 1.06)	(2.47, 0.63)	(69.34, 15.23)	(12.16, 3.27)
TO	10.48	39.08	26.85	38.78	31.15	10.95	
	(8.76, 1.72)	(32.82, 6.26)	(22.14, 4.71)	(32.74, 6.04)	(27.21, 3.94)	(9.41, 1.54)	TCI
Net	−1.91	3.44	−0.87	3.15	0.67	−4.48	26.22
	(−0.6, −1.31)	(1.19, 2.25)	(−1.65, 0.78)	(1.85, 1.3)	(1.96, −1.29)	(−2.75, −1.73)	(22.18, 4.04)

Note: Averaged connectedness results are based on the TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead forecast. The values on the left and right of the parentheses represent the results of the short- and long-term frequency connectedness measures, respectively.

where $TO_{it}(d)$, $FROM_{it}(d)$, $NET_{it}(d)$, $NPDC_{ijt}(d)$ and $TCI_t(d)$ illustrate exactly the same connectedness measures of Diebold and Yilmaz (2012), Diebold and Yılmaz (2014), in the given frequency range d. $TO_{it}(d)$ denotes the total dynamic directional connectedness transmitted from market i TO all other markets; $FROM_{it}(d)$ represents the total dynamic directional connectedness received $FROM$ all other markets to market i; $NET_{it}(d)$ and $NPDC_{ijt}(d)$ signify the net directional connectedness of market i and the specific net-pairwise connectedness between market i and market j, respectively. $TCI_t(d)$ shows the results of the total connectedness of the whole network.

5. Empirical results

In this section, we reveal the main results of the transmission mechanism between green bonds and several major volatility indices in stock, oil, gold, currency, and cryptocurrency markets, based on a time-varying parameter frequency connectedness approach of Chatziantoniou et al. (2023).

5.1. Averaged dynamic connectedness

We first present the results of the averaged connectedness that are presented in Table 2. The results display the connectedness (on average) among variables throughout the period without considering the impact of events occurring at specific points in time. In addition, the connectedness tables contain not only the full-period connectedness but also the short-term band (high frequency), which corresponds to the first value in parentheses, and long-term band connectedness (low frequency), which corresponds to the second value in parentheses.

The amount of connectedness of the US green bond markets transmitted to the other uncertainty indexes is estimated to be 10.48%.[7] In contrast, the US green bond market receives a 12.39% volatility shock from the other five uncertainty indexes. The net connectedness is, therefore, −1.91%, indicating that the green bond is a net recipient in the system during the sample period. Combining the results of Table 2, we derive several findings. Firstly, consistent with previous studies (Elsayed et al., 2022; Reboredo, 2018), we find that the total connectedness (on average) between the US green bond and other financial markets is remarkably small when considering the cryptocurrency market, which is only 26.22% throughout the sample period. This result implies a very weak interdependence within this network of variables. Furthermore, by decomposing the total connectedness into different frequency bands, 22.18% is found to result from short-term connectedness, and 4.04% resulting from long-term connectedness, indicating that short-term connectedness is predominantly the largest driver of overall connectedness amongst the selected variables, adding further support to the empirical results of Pham (2021), who found that the transmission of forceful connectedness between the US green bond and other financial markets occurs only in short-term frequency and dissipates in the relatively high-frequency bands.

Secondly, by investigating the net directional connectedness (on average), which identifies the position of assets within the network, we find that VIX, GVZ, and EVZ each function as net transmitters and that CVI, the US green bond and OVX are a net receiver of shocks during the sample period. Specifically, we observe that VIX is the dominant net transmitter of shocks and the net volatility spillover is 3.44%, decomposed into 1.19% in the short-term frequency and 2.25% in the long-term frequency, followed

[7] It is worth illustrating that the value in the "to row" indicates the contribution of each market to the system at the averaged level when all other variables are considered together. Moreover, the "from column" value denotes the volatility of a single market received from the system. Furthermore, the value of the "Net row", which is calculated by the To values of each market minus the From values of each market according to Eq. (6), shows the net spillover role of the market in the system, in which the negative value means that the market plays a risk-receiver role, and vice versa.

by GVZ (3.15%) and EVZ (0.67%). In terms of net recipients, the CVI is the largest net shock receiver in the system (−4.48%), and the US green bond is the second largest net receiver among the markets (−1.91%) and is followed by OVX (−0.87%).

Finally, we observe that own-variable shocks are relatively high, and off-diagonal elements, which capture the interaction between the variables in the network, are relatively low. For example, in Table 2, we observe that the highest own variation spillover is presented by the green bond index (based on the estimated average value), 87.61% of connectedness, of which 67.04% contributes to the short-term spillover of the own variation and 20.57% contributes to the long-term spillover of the own variation. This result indicates that 87.61% of the US green bond can be considered a self-internal shock. The remaining 12.39% is sourced from the entire network when all other variables are considered together. Similarly, we observe that the CVI index has a comparatively high variance on the average value, with 84.57%, which breaks down into 69.34% attributed to the short run and 15.23% attributed to the long run.

Taken together, the lower degree of total connectedness index (on average) indicates the existence of a weak interaction effect within the network, further confirming the findings of Reboredo (2018), who found evidence of co-movement between green bonds and other financial markets, including the stock and energy markets, which is a fundamental factor in investigating the safe haven property of the green bond. Furthermore, the results of the averaged connectedness tables highlight that the US green bond, CVI, and OVX, as net recipients within the network, can serve as safe-haven assets and diversification assets within investors' portfolios. In particular, the CVI seems to provide the best performance against the risk of other financial markets, followed by the US green bond. In the case of OVX, the smallest receiver of connectedness spillover implies that it can serve as a weak safe-haven asset and diversifier during the sample period. Meanwhile, when looking at the net transmitter, it can be seen that VIX, GVZ, and EVZ are the main transmitters within the network during the sample period. However, the average connectedness table emphasises the average behaviour of variables in the network and ignores the dynamic linkage between variables after the occurrence of unique events.[8]

5.2. Total dynamic connectedness

Fig. 3 shows the dynamic variation in the Total Connectedness Index (TCI) during the entire sample period. As illustrated in the Figure, the black area indicates the time dynamic connectedness values, while the red and green areas illustrate the short- and long-term frequency connectedness.[9] In general, we observe a low degree of connectedness between green bonds and other uncertainty indices.[10]However, the TCI exhibits substantial increases during three distinct periods: from March to May 2019, from January to March 2020, and from February 2022 onwards.

Specifically, it is observed that there is a sharp increase in the total connectedness index occurring in early 2019, which corresponds to the time of the US announcement that raised its tariff rates on the product list from 10% to 25% due to the US–China trade war. The deterioration of China-US relations further heightened interconnectedness among various financial investment markets globally (Hou et al., 2022; Song et al., 2022). This result indicates that policy changes related to the Sino-U.S. trade conflict have had a notable impact on various US financial markets, leading to a marked increase in the interconnectedness of the network.

More importantly, we find a notable increase in TCI during the COVID-19 period, where the connectedness reaches approximately 45%, and the peak place corresponds to the time of the official outbreak of the epidemic. Meanwhile, the results also corroborate the results presented by Costa et al. (2022), Lin and Su (2021) and Chen et al. (2022), that the dynamic connectedness presented among financial variables has changed enormously during the pandemic period. Furthermore, we find that the change in connectedness is mainly driven by the short-term frequency rather than the long-term frequency, which implies that COVID-19 has shocked investor expectations in the short term. These expectations guide investors to transmit to their investment portfolios to surrounding assets.

Regarding the third exception that occurred around February 2022, corresponding to the time of the Russia–Ukraine conflict, the TCI shows a distinct level of elevation after the beginning of the conflict, which is quite different from the trend observed during the period of epidemic development. In comparison, the result reveals that the shock of the investor's belief is more persistent than the shock of COVID-19. A rational explanation for this phenomenon is that investor fear has been constantly expanded during the conflict period by the several substantial crises arising from the war, such as the energy crunch (Nerlinger & Utz, 2022), currency issues (Chortane & Pandey, 2022). In terms of the COVID-19 period, although the pandemic outbreak has been considered a once-in-a-century pandemic (Gates, 2020) that generated a tremendous loss of economics, investor sentiment recovered rapidly due to the positive fiscal policy announced by the government.[11] The differential trend of the TCI in two periods presents evidence of the unique responses of investors' expectations in the face of varied market conditions that could generate a different variation of connectedness within the network. In other words, it is important to determine the driving forces of the turmoil when investors are searching for a safe haven asset.

[8] Therefore, it cannot reveal the influence on the evolution of connectedness under a specific event. In short, the information from the averaged connectedness table is static and hardly records the risk contagion among variables during the turmoil period we are interested in. Thus, for a deep understanding of the interaction among variables under major political and economic events, the latter investigation would be particularly meaningful, focusing on the dynamic interrelationship through the dynamic volatility connectedness approach, which can reflect both event-specific and time-varying effects.

[9] According to Baruník and Křehlík (2018), the essence of the variation in dynamic connectedness is mainly driven by the fundamental change in investor expectations. In this way, an increased level of connectedness in the framework of this study implies that: (1) the investor's expectations have been tremendously changed by the event's shock; (2) there is increased risk transmission among markets.

[10] The trend of the total dynamic network is highly dependent on occurrence and policy. A possible reason is that when investors' expectations are shocked by the recent occurrence, which could accelerate (decelerate) the behaviour of investors in searching for a haven asset, resulting in the connectedness of the network showing a climbing (declining) posture (Baur & McDermott, 2016).

[11] For example, the US government announced the Coronavirus Aid, Relief and Economy Security Act (CARES Act), which injects US$ 2.3 trillion (around 11% of GDP) into the market to support business operations, causing a decrease in investor sentiment anxiety even in the middle of the pandemic (Sharif et al., 2020).

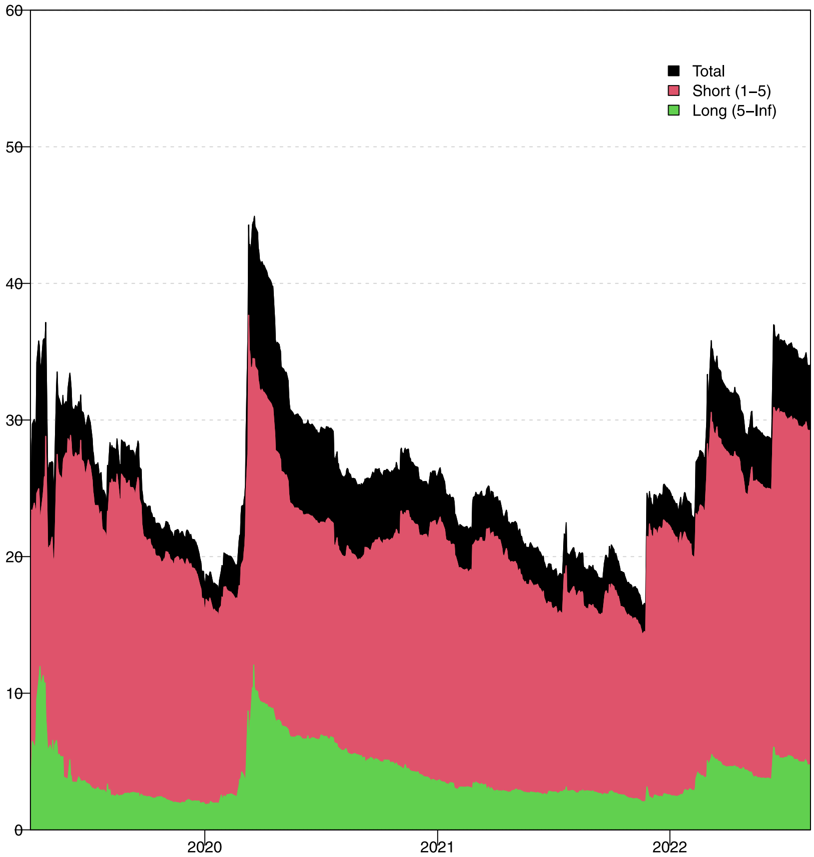


Fig. 3. Dynamic total connectedness.
Note: This figure presents the time–frequency dynamics of total connectedness between green bonds(US) and the rest of the variables over the entire sample period. The results are obtained using a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead forecast. The black area indicates the time dynamic connectedness values, while the red and green areas illustrate the short- and long-term frequency connectedness, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.3. Net total directional connectedness

In this section, we display the results of the dynamic net directional connectedness of individual variables within the system during the sample period, as shown in Fig. 4. It is worth noting that the net direction connectedness index is calculated by subtracting the received risk from all other markets from the transmitted risk to all other markets. Therefore, the connectedness index's positive (negative) value implies that the variable plays a transmitting (receiving) role in the overall network. Several interesting findings from Fig. 4 are presented as follows.

Focusing on the US green bond, it can be observed that the net connectedness index of green bonds remains negative for most of the sample period, indicating that green bonds generally function as receivers. Notably, there are sharp declines in the net directional connectedness index during the beginning of 2020 and early 2022. These periods correspond to two extreme events: the outbreak of the COVID-19 pandemic and the Russia–Ukraine conflict. A considerable drop in the net directional connectedness index shows that (1) there is a significant transmission of risk among variables, and (2) the variable is a receiver of shocks in the system, as the values of the shocks received are higher than those transmitted to all other variables. It is also noteworthy that the US green bond functioned as a transmitter of shocks during an initial period, possibly related to the market-stimulating policies implemented by the US government at that time. For instance, the Federal Reserve's injection of billions of dollars into the market to stabilise interest rates in 2019 helped maintain investor confidence, alleviating concerns about funding liquidity and high inflation expectations (Chen et al., 2022). Due to these policies' impact, investors gained significant confidence in the market, becoming more inclined to opt for relatively riskier investments over low-risk assets like green bonds (Pham & Do, 2022).

The aforementioned results are particularly interesting. It can be seen that the net directional connectedness of US green bonds shifts significantly under various market conditions. Specifically, green bonds function as a receiver during market turbulence and as a transmitter during normal market conditions. Such results can be linked to the flight-to-quality or flight-to-safety phenomenon in the financial markets (Baele et al., 2020; Baur & Lucey, 2009). When major external events impact the investment market environment, investors shift their funds from high-risk markets (such as stocks) to relatively safer markets (like green bonds). This transfer of risk capital leads to a notable risk transmission in the green bond market. Consequently, the green bond market can be considered an effective hedge and safe asset in an extreme market (Kuang, 2021; Lin & Su, 2023). On the other hand, the US green bond will shift towards being a transmitter in the network when financial market conditions stabilise due to policy support.

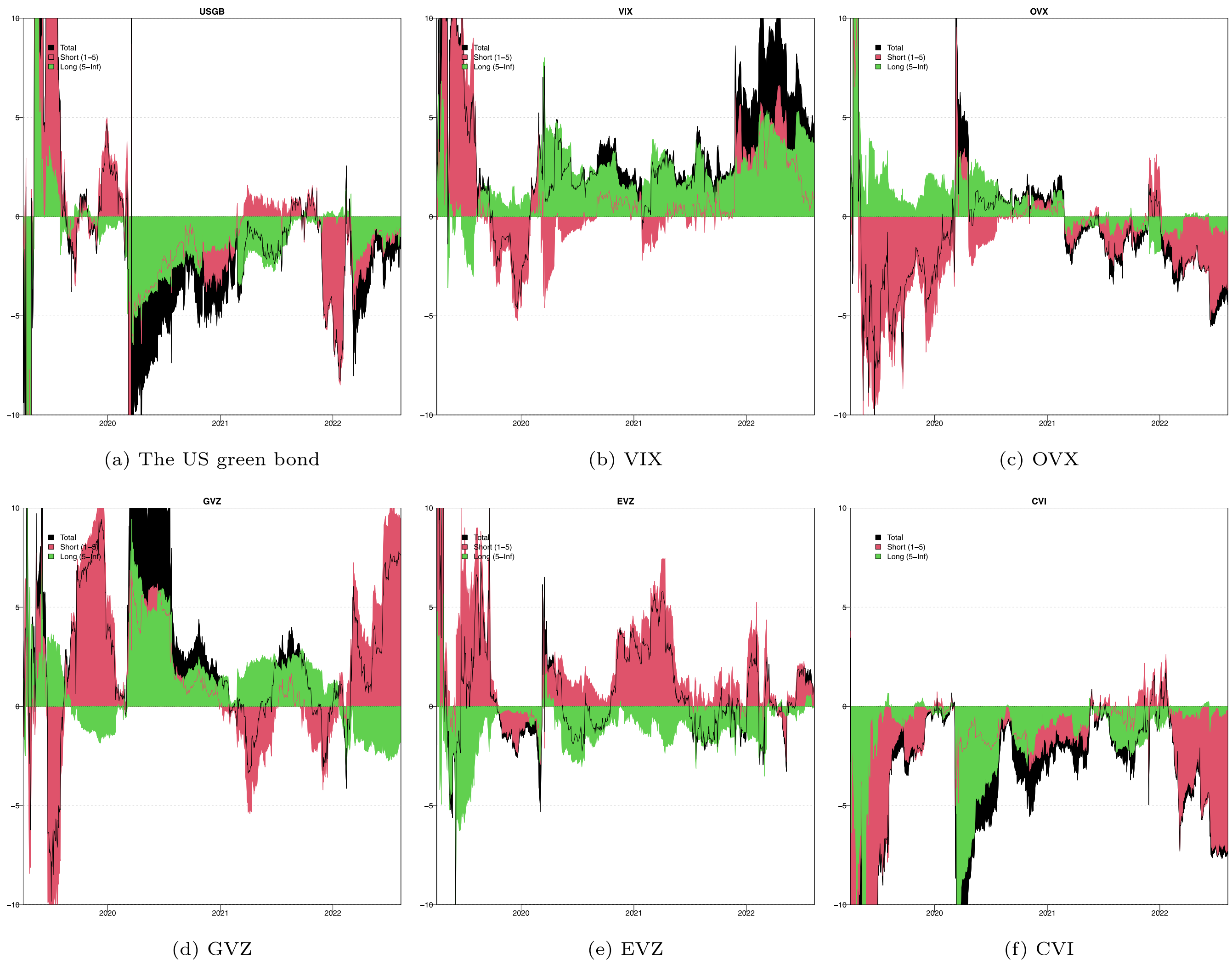


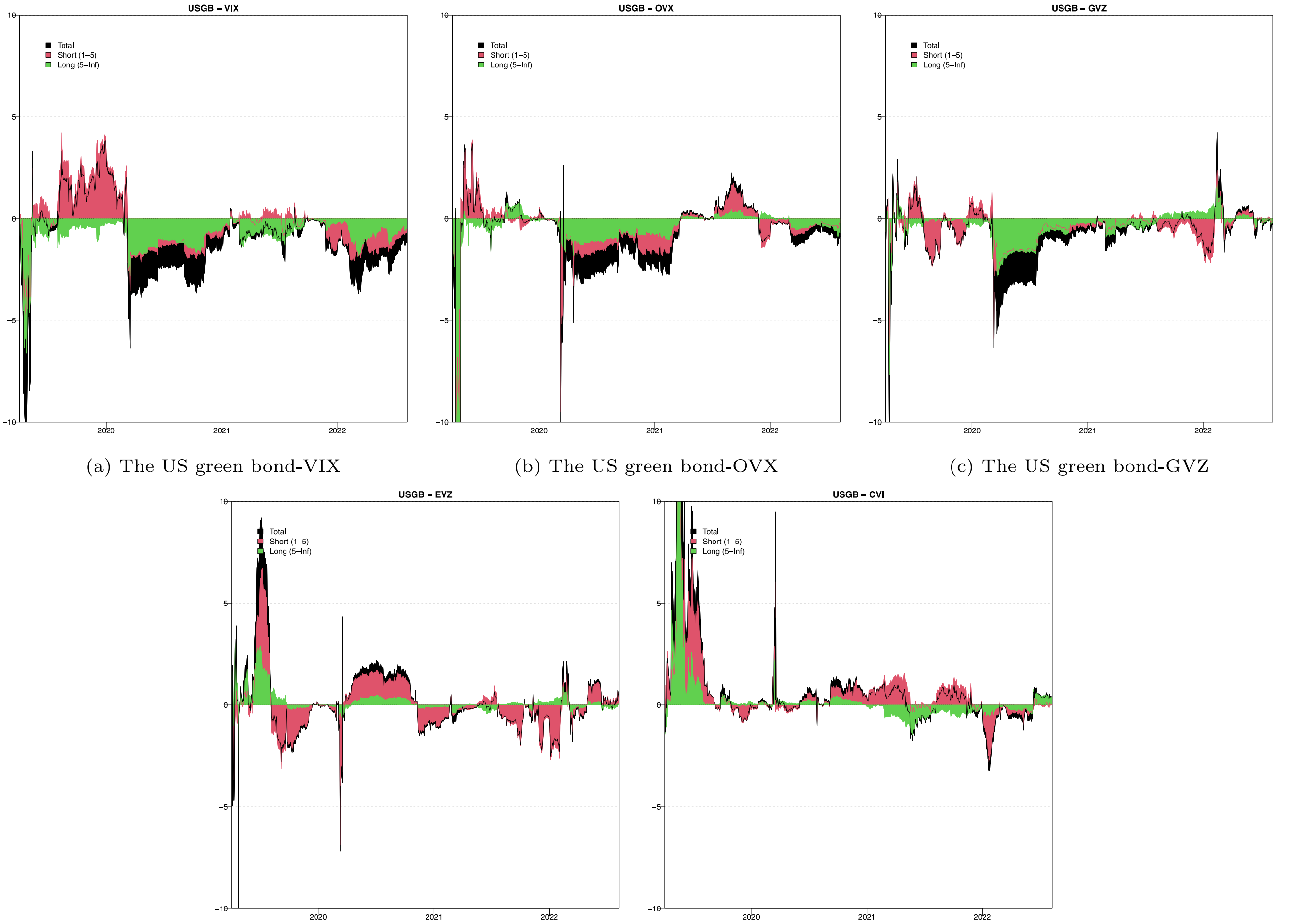
Fig. 4. Net total directional connectedness.
Note: This figure shows time–frequency dynamics of net total directional connectedness of each variable. The results are obtained using a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead forecast. The black area indicates the time dynamic connectedness values, while the red and green areas illustrate the short- and long-term frequency connectedness, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A reasonable explanation of this fact is that as the green bond is a fixed-income and lower-risk asset, it generally cannot meet investors' expectations in return. Therefore, investors may shift their funds to other markets to pursue higher returns when market conditions stabilise.

Similarly, the OVX and CVI also function as receivers of shocks in the system. The net directional connectedness of those indexes consistently remains negative during most of the sample period. These correspond to the timeline of the increase in the total connectedness index. Interestingly, looking at the OVX, the connectedness index has suddenly turned to a positive position during such times, indicating that the OVX has shifted from being a receiver of shocks to a transmitter of shocks. Furthermore, the variation of connectedness is dominated by the short-term frequency band.

In the same vein, VIX, GVZ, and EVZ assume the main net transmitter role within the network, as the direction of connectedness consistently remains positive in most of the samples. In more detail, we notice that the connectedness of VIX shows three spikes in May 2019, March 2020, and early 2022, which aligns with the aforementioned timeline. The results suggest that VIX transmitted strong shocks to the system during the turmoil. In addition, turning to GVZ, the connectedness of GVZ is similar to that of VIX. We observe that the connectedness of GVZ has been dropping since March 2020, showing that the GVZ continually receives shocks from the system during 2020 and 2021. This could be related to the diversification and hedging roles of gold (Akhtaruzzaman et al., 2021).

Focusing on the results relating to EVZ, the net connectedness consistently remains positive in most samples, indicating the role of EVZ as a shock transmitter in the system. However, focusing on the frequency domain, the short- and long-term frequency connectedness display exactly different directions, where the short-term frequency connectedness consistently remains positive and the long-term frequency consistently remains negative. The results suggest that the EVZ is a transmitter of shocks in the short band but acts as a receiver in the long band. One possible explanation for this outcome for EVZ could be related to the



(a) The US green bond-VIX (b) The US green bond-OVX (c) The US green bond-GVZ

(d) The US green bond-EVZ (e) The US green bond-CVI

Fig. 5. Net pairwise connectedness of the US green bond.
Note: This figure shows time–frequency dynamics of net pairwise directional connectedness of the US green bond by applying a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead forecast. The black area indicates the time dynamic connectedness values, while the red and green areas illustrate the short- and long-term frequency connectedness, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

unique characteristics of the US dollar, that it is not only an essential currency in the world but also a crucial safe asset for risk sharing (Maggiori, 2017).

5.4. Net pairwise connectedness

Fig. 5 depicts the pairwise connectedness mechanism between the volatility of the US green bond and other crucial investment markets volatility indices. It should be noted that the positive pairwise connectedness indicates that the US green bond is a transmitter of shocks from the paired market, and the negative one means that the green bond is a receiver of shocks in a paired relation.

In this regard, we first focus on the pairwise connectedness between the US green bond and VIX, as the previous results suggest that VIX is a primary volatility transmitter in the system. Intuitively, VIX consistently acts as a shock transmitter to green bonds, with the pairwise connectedness index remaining negative for most of the sample period (except for a certain period before 2020). In particular, we observe significant fluctuations in the connectedness index between the US green bond and VIX during May 2019, March 2020, and February 2022, corresponding to the timeline of the China-US trade war, the COVID-19 epidemic, and the Russia–Ukraine conflict, respectively. These results indicate that the VIX transmits enormous shocks to green bonds during the time period of high uncertainty. Furthermore, we observe that changes in the pairwise connectedness index during the China-US trade war were driven by the long-term frequency band, while during the COVID-19 outbreak and the Russia–Ukraine conflict, it is predominantly affected by the short-term frequency band.

Upon examining the interconnectedness between the US green bonds and OVX, it appears that the transmission mechanism from OVX to green bonds displays a similar pattern to that from VIX, particularly during three extreme events: the US–China trade war, the outbreak of COVID-19, and the Russia–Ukraine conflict. In each instance, the US green bond receives substantial connectedness transmissions from OVX, as indicated by the negative values of the pairwise connectedness index during these periods. In early 2020, it was identified that there was a strong spillover effect from OVX to the US green bond market. This is likely correlated with the unprecedented negative pricing event in the WTI crude oil market. Although the negative oil pricing is a transient market anomaly, it unequivocally transmits substantial shocks from OVX to the green bond market. As identified by Lee et al. (2022), who note the intricate interplay between oil prices and green bond prices, fluctuations in oil prices invariably lead to discernible changes in green bond prices. Our analysis concludes that OVX has a significant impact on green bonds, transmitting strong shocks not only during extreme events but also amidst severe disruptions in oil prices, such as the negative pricing event.

Next, we examine the transmission mechanism between US green bonds and GVZ during the sample period. It is evident that the outbreak of COVID-19 had a profound impact on the volatility transmission relationship between US green bonds and GVZ. The pairwise connectedness index sharply declined from a positive to a negative value, indicating that GVZ has transmitted substantial shocks to US green bonds throughout the COVID-19 pandemic. This finding aligns with the results of Pham and Do (2022), who observed that significant changes in gold volatility affect the performance of US green bonds.

It is worth noting that the shifting of investor beliefs among different markets mainly depends on the risk characteristics of assets and the main driving uncertainty factors (Maggiori, 2017). For example, with regard to EVZ, we find that the connectedness index dropped at the start of the COVID-19 outbreak but suddenly turned positive. The US green bond became a major transmitter of shocks to the EVZ during the outbreak, except for a short interval at the beginning of the epidemic. This observation indicates that, compared to the safeness of green bonds, investors prefer to hold the US dollar to avoid the high uncertainty, which could be related to the fact that the US dollar is considered the safest instrument in the financial market and the best tool for securing risky assets during market downturns (Kocaarslan & Soytas, 2019; Maggiori, 2017). Also, in a particularly interesting observation, we notice that during the conflict period, the positive connectedness of both GVZ and EVZ illustrate that the US green bond is a transmitter in each network, and the investor expectation has shifted from green assets to traditional safe-haven assets due to the Russian-Ukraine conflict shocks.

Focusing on the US green bond-CVI pairing, results vary in that the connectedness maintains a positive position for most of the sample period, indicating that the US green bond is a major net transmitter in the paired network, especially during the trade war and COVID-19 period. More specifically, we observed a significant spike in May and July 2019, corresponding to the trade war.[12] These results are of particular interest as they further support the results presented by Hou et al. (2022) and Bouri et al. (2020), that the trade war has impacted the connectedness of cryptocurrency with other financial markets. Our results highlight that the influence of the trade war also increases the connectedness between US green bonds and cryptocurrency.

Another interesting finding surrounding the connectedness index suddenly turning sharply negative during the Russia–Ukraine conflict period from January 2022 to March 2022. The lowest point corresponds to the start of the conflict. The result suggests that the green bond turns from a transmitter into a receiver and that investors shift their attention from cryptocurrency to the green bond market due to conflict shocks. This result further confirms the findings of Khalfaoui et al. (2023), cryptocurrency investors' attention has been heavily impacted due to a series of sanctions against Russia by the US.[13] Furthermore, focusing on the frequency band, the short-term frequency is the main driver of the dynamic connectedness, suggesting that conflict mainly impacts investors in the short term. In addition, it reflects the confidence of investors that shocks have a less persistent influence on the cryptocurrency system. Meanwhile, the results highlight that green bonds can be a safe option for investor decision-making when the cryptocurrency market is highly volatile. In general, the connectedness of the US green bond and cryptocurrency increased during the Russian-Ukraine conflict, in which the US green bond played a receiver role.[14]

5.5. *Robustness testing procedures*

Finally, we complete several robustness checks by employing two alternative volatility indexes to replace the CVI index in our sample, namely BitVol Index and Royalton VCRIX Crypto Index (VCRIX).[15] We are particularly interested in the variation of connectedness between the US green bond and other financial markets, specifically, whether the main results are still robust by employing the different cryptocurrency volatility indexes. Therefore, we mainly focus on the net pairwise directional connectedness results of each alternative volatility index, which are presented in Figs. 6 and 7.

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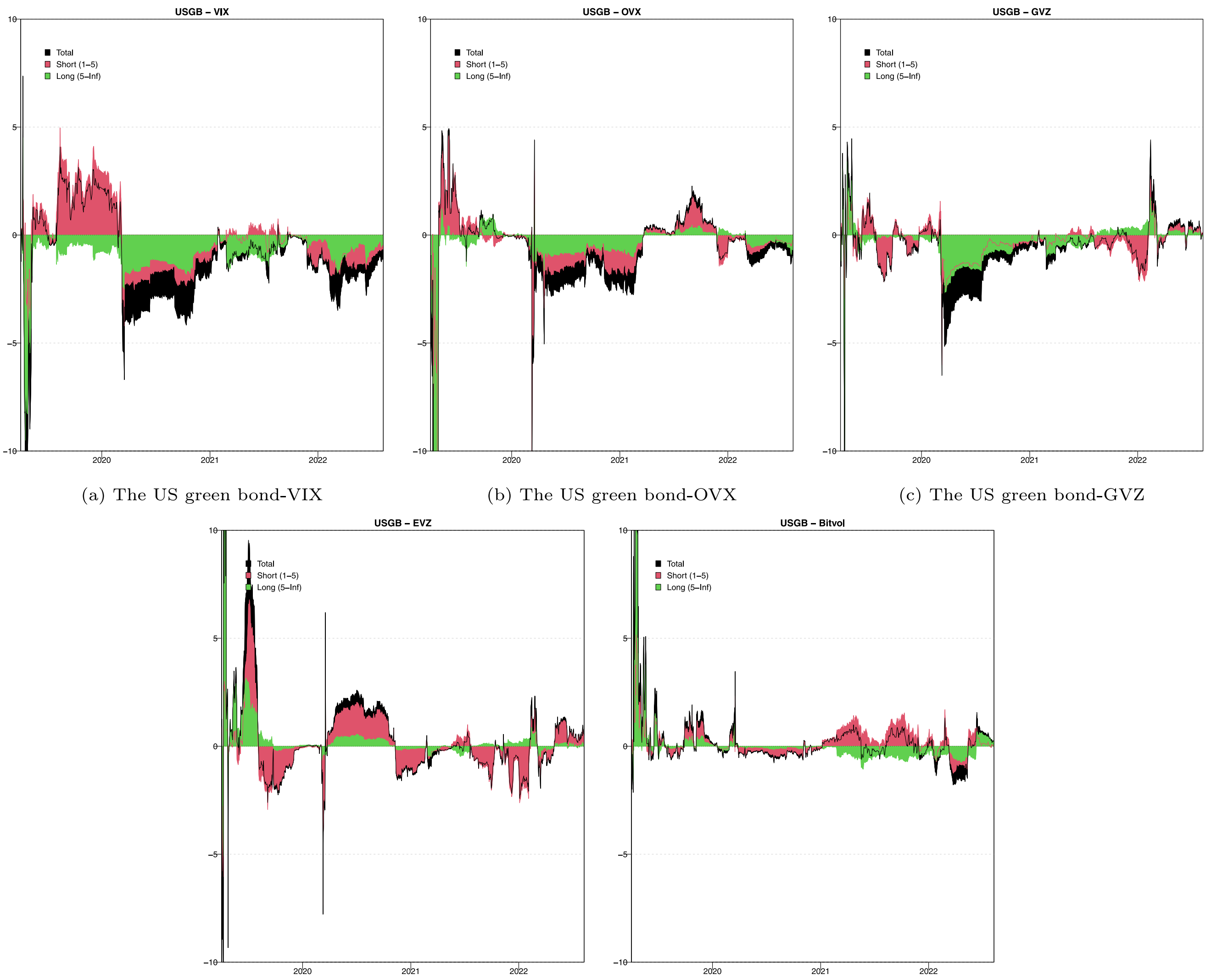
[12] The upward movement trend, which is dominated by the long-term frequency connectedness, can be interpreted as the structural change of investors' expectations within the network by shocks of the trade war and raises concerns about long-term market stability. Therefore, investors may shift their investment decisions from green bonds to cryptocurrency, thereby increasing connectedness in the long term.

[13] For example, Coinbase, a famous online trading platform in the world, announced that they had blocked more than 25,000 crypto users who are from Russia.

[14] We thank an anonymous reviewer for suggesting performing sensitivity checks to ensure that any outlier estimated points are not due to the model's specifications. We perform two additional sensitivity checks by using alternative mode specifications, and the results we present confirm that these outlier estimation points still exist. We first use a lag length of order one (BIC) with a 10-step-ahead forecast. We then consider an alternative model specification using a lag length of order two with a 20-step-ahead forecast. The results for pairwise connectedness in the above-mentioned models are displayed in Fig. 8 and Fig. 9, respectively. When comparing Fig. 5 with Fig. 8 and Fig. 9, it is evident that the outlier estimated points persist. Therefore, these findings indicate that the presence of outliers in the estimation points is attributed to the characteristics of our data rather than a model specification issue.

[15] The BitVol Index is constructed to measure the implied volatility of Bitcoin and is developed by T3 Index, a well-known financial indexing firm. They use a similar methodology to the Chicago Board of Trade's (CBOE) VIX Index to reflect the investor fear sentiment of the Bitcoin markets. We obtained the data from https://t3index.com/indices/bit-vol/ Regarding the VCRIX, this index was recently published by Kim et al. (2021), the same as the VIX for US stock, the VCRIX aims at the cryptocurrency market condition. It is worth noting that, compared to Bitvol, VCRIX emphasises the diversity of liquid cryptocurrencies in the market. The VCRIX index covers cryptocurrency volatility, not only Bitcoin but also Ether, Binance Coin, and Ripple. And we obtain the official data from here.



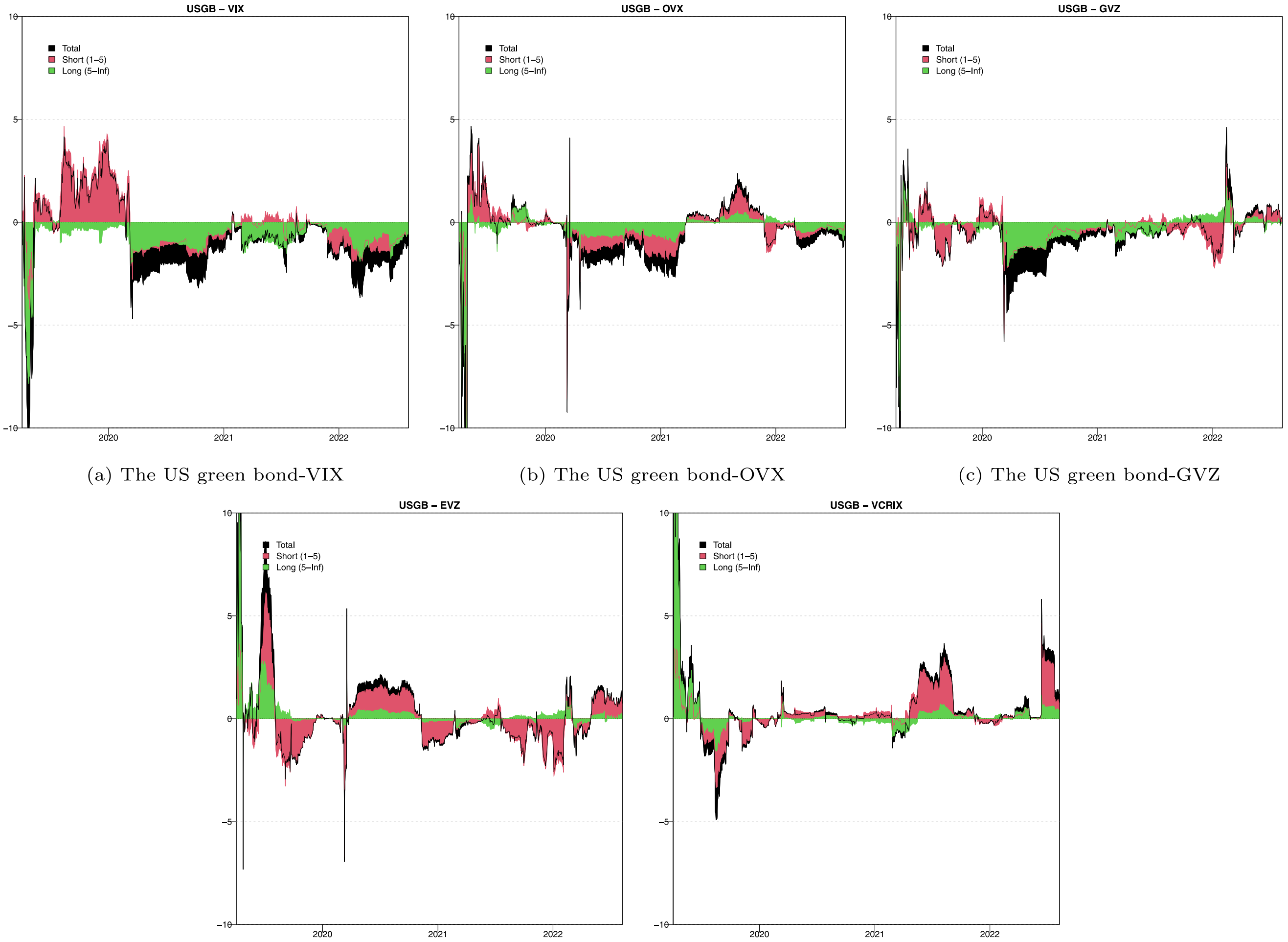
(a) The US green bond-VIX (b) The US green bond-OVX (c) The US green bond-GVZ

(d) The US green bond-EVZ (e) The US green bond-Bitvol

Fig. 6. Net pairwise connectedness of the US green bond (Robustness check using Bitvol).
Note: This figure displays the robustness check results. We select the Bitvol index as an alternative proxy for the CVI index here. Consistent with the above experimentation, the results are based on the TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead forecast. The black area indicates the time dynamic connectedness values, while the red and green areas illustrate the short- and long-term frequency connectedness, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As Figs. 6 and 7 show, the main results are still robust with two different crypto fear sentiment indexes; that is, the green bond is a major net transmitter of shocks to the cryptocurrency market by focusing on the results of the connectedness of the US green bond-BitVol and US green bond-VCRIX pair. In particular, paying attention to the economic downturn and highly uncertain periods, such as the US–China trade war and the COVID-19 outbreak, the connectedness of the two results maintains a positive position, reflecting that investor expectations have shifted from the green bond to the cryptocurrency markets. Such results confirm that the cryptocurrency is treated as a safe haven or hedge asset for the green bond investor. Furthermore, we notice that the variation of connectedness between the US green bond and VCRIX during the Russian-Ukraine period is smaller than the BitVol pair. It could be related to the difference in the proportion of Bitcoin in each index. In more detail, the VCRIX covers more than five types of cryptocurrencies, and BitVol mainly aims at Bitcoin. Thus, by comparing the influence of different types of cryptocurrency fear indexes on the results, we conclude that the Russian-Ukraine war significantly impacts cryptocurrency investor beliefs that shift their expectation from the cryptocurrency market to the US green bond, which is more apparent in the Bitcoin market.

In addition, to further verify the robustness of our main results, we follow Su et al. (2022) and Lin and Su (2023) and estimate an alternate measure of volatility using the GARCH (1,1) model. The GARCH-based volatility series are then used to estimate the connectedness. The purpose of this additional check is to validate the consistency and reliability of our results under different methodological contexts. The main results, which show the net pairwise connectedness of US green bonds, are presented in Fig. 10. It can be seen that our main findings remain relatively consistent when employing the alternate volatility estimator. Under the context of the GARCH-based volatility, there are more time episodes where large estimates of connectedness are evident, which



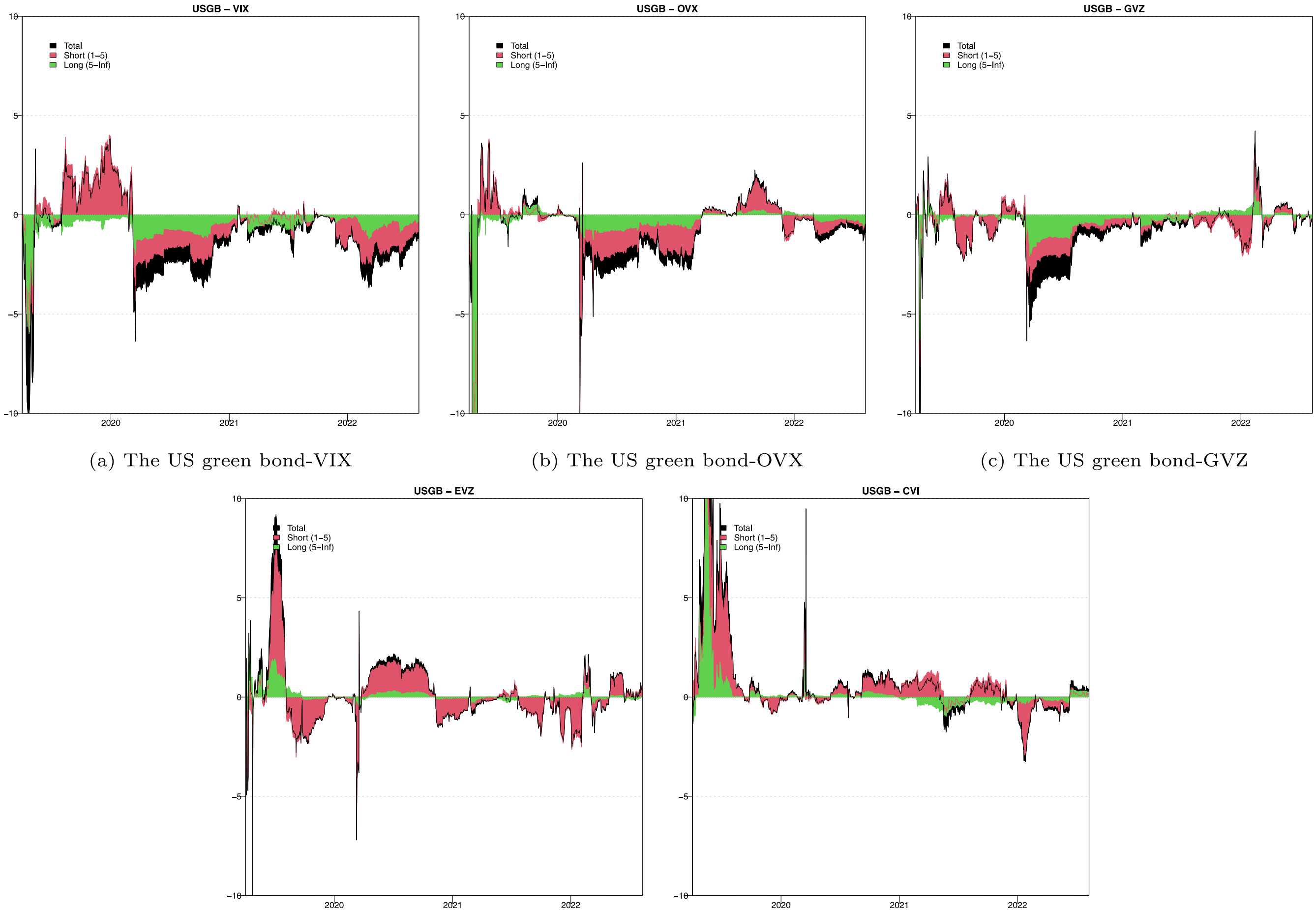
(a) The US green bond-VIX (b) The US green bond-OVX (c) The US green bond-GVZ

(d) The US green bond-EVZ (e) The US green bond-VCRIX

Fig. 7. Net pairwise connectedness of the US green bond (Robustness check using VCRIX).
Note: This figure displays the second robustness check results. We select the VCRIX index as an alternative proxy for the CVI index here. Consistent with the above experimentation, the results are based on the TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead forecast. The black area indicates the time dynamic connectedness values, while the red and green areas illustrate the short- and long-term frequency connectedness, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

complements the main results under the measure of absolute returns. More importantly, it is still found that the US green bond continues to act as a shock receiver in each paired relationship, with the VIX still being the largest shock transmitter, followed by the OVX and the GVZ. The characteristics of the two-way risk transmission channel between green bonds and cryptocurrencies become more evident under the alternate measurement of volatility. Moreover, the time episodes in Fig. 10, where outliers are envisaged under the GARCH-based volatility measure, are relatively in line with those in Figs. 8 and 9 under the absolute return measure. This further highlights that the outliers are due to the characteristics of our data, regardless of the estimation model. Overall, the result in Fig. 10 confirms the robustness of our main results in terms of volatility measure.

Overall, several interesting findings can be summarised from the pairwise connectedness results. First, substantial evidence indicates that green bonds exhibit pronounced shock transmission with other investment markets, and transmission strength remarkably increases during the financial crisis. In other words, extremely unexpected events enhance the risk contagion capabilities across all financial markets through various pathways, thereby significantly affecting the connectedness of green bonds. This phenomenon is particularly evident during the COVID-19 outbreak. Second, a further investigation shows that there is a noticeable one-way connectedness transmission relationship from the VIX, OVX and GVZ to the green bond, in which the VIX appears to be the main driving force for the connectedness variation of green bonds, followed by the OVX and GVZ markets. Third, we find strong evidence of two-way risk transmission channels among the green bond, EVZ and CVI. Also, it is worth mentioning that the direction of risk transmission between the green bond market, exchange rate, and cryptocurrency is closely related to the nature of crises. For example, during the outbreak of COVID-19, the green bond market transmitted strong shocks to the cryptocurrency market. At the same time, it received risk transmission from the cryptocurrency market during the Russia–Ukraine conflict. Last, under the context of the GARCH-based volatility measure, the connectedness estimates are similar to those obtained using the measure of absolute returns but also complementary to the latter results. Therefore, our main results based on the absolute return measure are robust to different methodological measurements of volatility metrics.



(a) The US green bond-VIX (b) The US green bond-OVX (c) The US green bond-GVZ

(d) The US green bond-EVZ (e) The US green bond-CVI

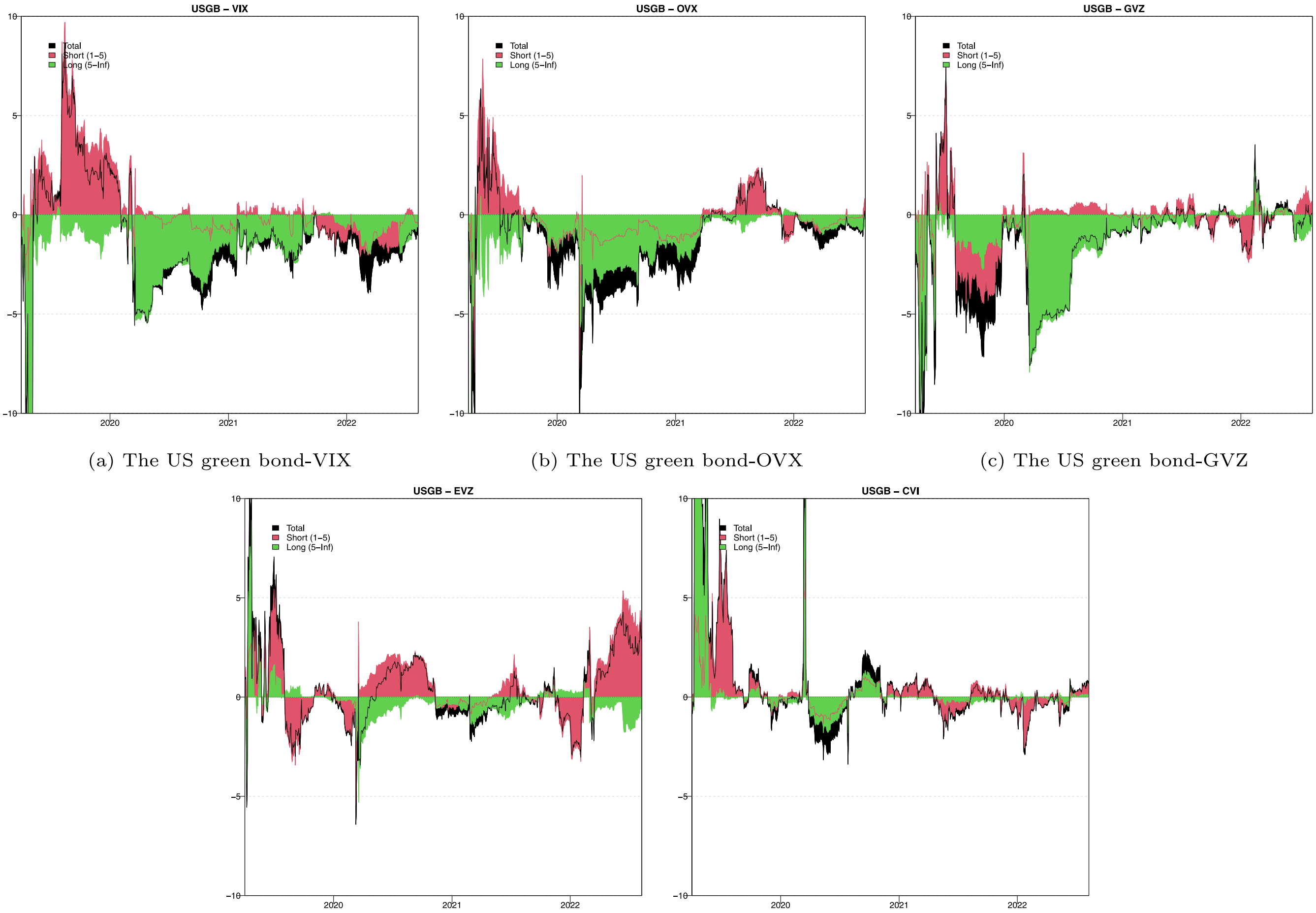
Fig. 8. Net pairwise connectedness of the US green bond (Robustness check using alternative step ahead forecast).
Note: We select the CVI index here. The results are based on the TVP-VAR model with a lag length of order one (BIC) and a 10-step-ahead forecast. The black area indicates the time dynamic connectedness values, while the red and green areas illustrate the short- and long-term frequency connectedness, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6. Conclusion

This study set out to examine the transmission channel between US green bonds and the implied volatility of several mainstream investment financial markets, including stock, oil, gold, currency, and cryptocurrency markets. In addition, we use a novel TVP-VAR frequency connectedness approach to estimate the connectedness variation among financial markets across different frequency domains during extreme events.

The key findings of this study are summarised as follows. We find that the connectedness between green bonds and other financial market volatility indices is relatively low, with short-term frequencies playing a dominant role in the variation of connectedness. Moreover, financial turmoil significantly exacerbates the spillover effects between green bonds and other investment market volatilities. This feature is particularly evident during the outbreak of COVID-19. Notably, the stock, oil, and gold markets are the primary transmitters of shocks to the US green bonds, while currencies and cryptocurrencies are the main receivers of shocks from the US green bond. The last and most crucial point is that the variation in the connectedness mechanism between green bonds and the cryptocurrency market is strongly associated with factors that trigger financial turbulence. For instance, we find that the US green bond has functioned as the primary shock transmitter to the cryptocurrency market during the COVID-19 outbreak, whereas it has shifted to being a receiver of shocks during the Russia–Ukraine war.

Based on the aforementioned conclusions, our research has several important implications and provides insights for investors, financial institutions, policymakers and regulators. Firstly, for green investors, the market for green bonds is highly responsive to market sentiment. Therefore, it is crucial to accurately evaluate this sentiment when incorporating green bonds into a diversified portfolio for optimal returns. Green bonds can be a valuable addition to portfolios, especially for investors who invest in the equity, oil, and gold markets, as they offer a reliable tool against spillover effects caused by extreme events in financial markets. Secondly, as our results demonstrate that US green bonds and cryptocurrencies can function as safe havens during market instability, further effort should be made to integrate such assets into investment portfolios. When constructing a diversified investment portfolio, investors and hedge fund managers must consider the dynamic connectedness between green bonds and the implied volatility of various

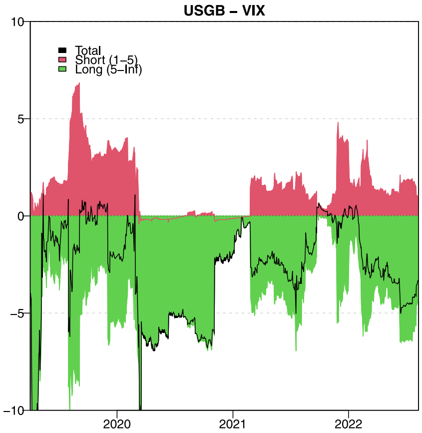


(a) The US green bond-VIX (b) The US green bond-OVX (c) The US green bond-GVZ

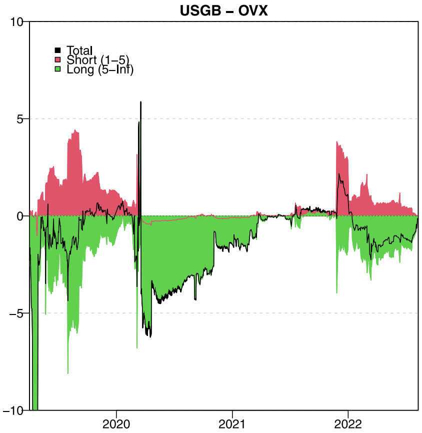
(d) The US green bond-EVZ (e) The US green bond-CVI

Fig. 9. Net pairwise connectedness of the US green bond (Robustness check using alternative lag order).
Note: We select the CVI index here. The results are based on the TVP-VAR model with a lag length of order two (BIC) and a 20-step-ahead forecast. The black area indicates the time dynamic connectedness values, while the red and green areas illustrate the short- and long-term frequency connectedness, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

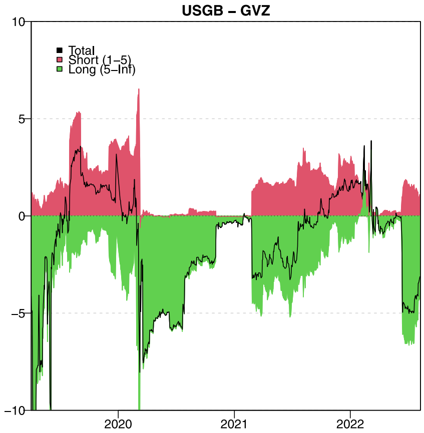
financial markets. This ensures that the investment portfolio is optimised for diversification purposes. Thirdly, those regulatory bodies must remain cognisant of the evolving financial landscape, particularly the roles and influences of emerging asset classes like cryptocurrencies and green bonds. For policymakers, the hedging capacity of the green bond market and its prominent role in risk mitigation underscore the benefits of a green economy. They must formulate more initiative-taking and comprehensive stimulus policies to develop the green bond market. Institutions may consider propagating the issuance and acquisition of green bonds as a strategic risk-mitigation tactic. This becomes particularly relevant in light of the bonds' observed performance during periods of significant volatility. Promoting green bonds can concurrently catalyse the transition to a low-carbon, sustainable economy, thus amplifying the environmental benefits accrued from this policy direction. Moreover, the announcement of fiscal policies could significantly impact the green bond market. Therefore, when formulating policies for economic development, it is essential to comprehensively consider the spillover effects between the green bond market and other financial markets to achieve the goal of transitioning to a green economy. Finally, our study underscores the need for regulatory bodies to acknowledge the pronounced impact of geopolitical events on the cryptocurrency market. It becomes incumbent upon these entities to develop regulatory frameworks that mitigate the risks associated with sudden market sentiment shifts towards cryptocurrencies, especially during times of geopolitical instability. Moreover, these regulatory bodies must remain cognisant of the evolving financial landscape, particularly the roles and influences of emerging asset classes like cryptocurrencies and green bonds. Collectively, these findings contribute to the extant literature on the volatility connectedness between green bonds and other financial markets. They underscore the importance of these burgeoning asset classes in the spheres of risk management and portfolio diversification, especially during periods of crisis and uncertainty. For future research, additional variables and factors can be incorporated into the model that shares similar characteristics with green bonds, for example, green energy ETFs or green stock ETFs. Moreover, our ideas can provide a reference for further research into the risks associated with the cryptocurrency market. Additionally, future research can employ our findings to examine hedge ratios and optimal portfolio strategies from the perspective of portfolio models.



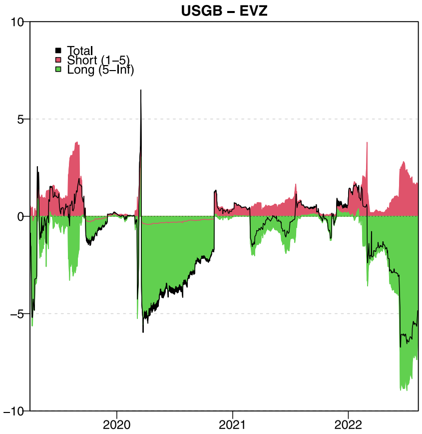
(a) The US green bond-VIX



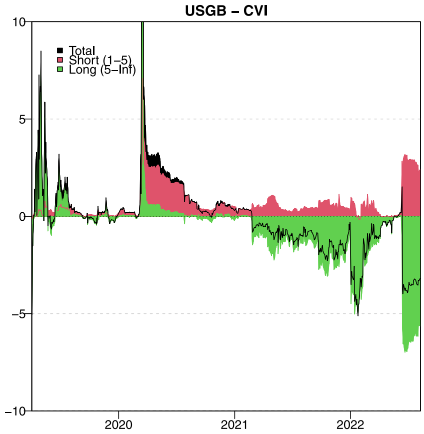
(b) The US green bond-OVX



(c) The US green bond-GVZ



(d) The US green bond-EVZ



(e) The US green bond-CVI

Fig. 10. Net pairwise connectedness of the US green bond(Robustness check using GARCH model).
Note: This figure shows time–frequency dynamics of net pairwise directional connectedness of the US green bond based on GARCH volatilities. The black area indicates the time dynamic connectedness values, while the red and green areas illustrate the short- and long-term frequency connectedness, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

CRediT authorship contribution statement

Danyang Xu: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yang Hu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shaen Corbet:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yang (Greg) Hou:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Les Oxley:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Investigation.

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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Chapter 5

Return connectedness of green bonds and financial investment channels in China: Implications for hedging and regulation

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Return connectedness of green bonds and financial investment channels in China: Implications for hedging and regulation

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ABSTRACT

Using a TVP-VAR frequency connectedness approach, this study examines the return connectedness of green bonds with several major investment markets (e.g. index exchange-traded funds, oil, gold and currency) from the perspective of Chinese investors. The main results indicate that the connectedness of green bonds with other assets is relatively low and typically serves as a receiver in the network. However, during the epidemic period, the connectedness has obviously fluctuated, and green bonds briefly acted as a shock transmitter. This study also employs portfolio construction methods, and the portfolio analysis also demonstrates that green bonds can act as an efficient hedging tool. Our portfolio results can help market participants and policymakers better understand different Chinese financial markets and develop strategies to mitigate market risks.

1. Introduction

Green finance, such as green bonds, is rapidly gaining more attention as economies worldwide strive to balance growth and sustainability. Green bonds have emerged as a crucial instrument for raising capital for environmentally friendly projects, allowing investors to align their portfolios with environmental sustainability goals while potentially enhancing their risk-return profile (Pham, 2016; Reboredo, 2018; Reboredo et al., 2020; Abakah et al., 2022). However, the interaction of green bonds with major asset markets in emerging markets, particularly during periods of geopolitical and economic volatility, remains a relatively under-explored area. This is the gap that our research aims to fill by investigating dynamic return connectedness and portfolio analysis between green bonds and major investment markets in China. Our study focuses on the Chinese market, which offers a unique context given its growing green bond market, its economic significance on the global stage, and the significant events impacting it over the study period, such as the US–China trade war, the COVID-19 pandemic, and the Russia–Ukraine conflict. The evolving dynamics of the Chinese market provide a unique environment to facilitate a thorough examination of green bonds' interactions with traditional financial markets and their performance as a hedge. In recent years, the growth of China's green bond market has been remarkable, with the issuance of green bonds continuously increasing since 2015 (Wang et al., 2020; Tang and Zhang, 2020). The sustained growth in green bond issuance indicates a significant interest in environmental investment among Chinese investors (Su et al., 2022). However, despite the increasing popularity of green bonds, little research has been conducted on the specific role of green bonds in Chinese investors' investment portfolios and their connectedness with other financial markets.

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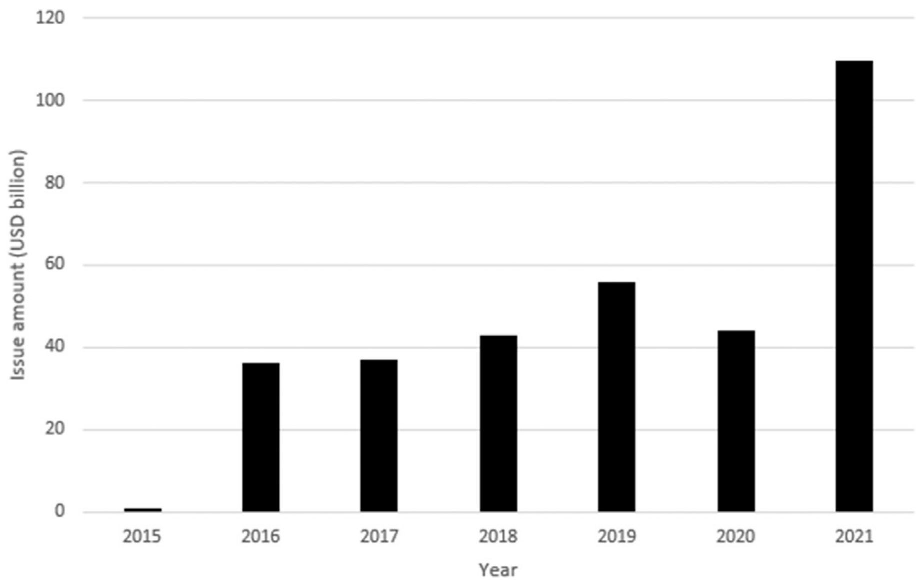

Fig. 1. China's green bond issuance. Note: The figure displays the amount of China's green bond issuance between 2015 and 2021. The figure is constructed based on data from the Climate Bond Initiatives (CBI) database.

The importance of green bonds in Chinese markets and the global economy cannot be overstated. As the world grapples with the immense challenges of climate change, green bonds have emerged as a crucial financial instrument to channel investments into projects with a positive environmental impact. They offer a concrete way for the financial sector to contribute to the global sustainability agenda, aligning capital allocation with climate mitigation and adaptation goals. In the Chinese context, green bonds hold particular significance. As one of the world's largest economies and a significant emitter of greenhouse gases, China's transition to a more sustainable growth path is paramount for global climate goals. Recognizing this, China has been at the forefront of developing the green finance market, where, specifically, green bonds have become an integral part of the financial landscape in China, aiding its transition to a low-carbon economy.

Specifically, this research attempts to investigate the role of the green bond among several financial investment channels of Chinese investors. Our paper considers the main investment channels for Chinese investors through index exchange-traded funds (ETFs), oil, gold and currency markets. Several research hypotheses are developed in this paper. Firstly, we hypothesize that green bonds exhibit a relatively low level of connectedness with traditional financial assets due to their unique nature and objectives. Secondly, we posit that significant geopolitical and economic events, such as the COVID-19 pandemic and other recent geopolitical events, increase this connectedness due to heightened investor uncertainty and risk aversion. Lastly, we hypothesize that green bonds can be an effective hedging tool in investment portfolios, given their distinct performance characteristics and growing investor interest in sustainable finance. Such research is particularly important when considering the evidence presented in Fig. 1, which displays the issue amount of China's green bonds between 2015 and 2021. As observed, the issuance of green bonds has been continuously increasing, especially presenting evidence of pronounced, sustained growth between 2016 and 2021. It is worth noting that there was a decline in the issuance of green bonds in 2020 in comparison to the previous year, which may be attributed to the 2020 outbreak in China, but after accounting for this brief period of decline, sectoral growth has remained persistent.

This paper contributes to the existing literature in several important aspects. First, this paper examines the return connectedness between green bonds and several important investment channels based on the Chinese investor's perspective by applying frequency connectedness of Chatziantoniou et al. (2021) and different investment portfolio construction methods. Unlike existing studies, this research considers all investment assets available for direct investment by Chinese investors, thereby providing novel insights into the connectedness of green bonds. This research particularly contributes to understanding the interaction between green bonds and traditional financial markets in a major emerging market, providing insights into how this relationship changes during periods of significant volatility. Second, this paper contributes to the existing literature by applying a novel TVP-VAR frequency connectedness approach of Chatziantoniou et al. (2021) to study return connectedness between green bonds and several investment assets for Chinese investors. This new approach allows for identifying the impact of shocks in the short- or long-run behaviours. Third, our research contributes to the understanding of the influence of major global events on the connectedness among financial assets, highlighting the importance of contextual factors in financial decision-making. Our study spans 2018 to 2022, covering major events such as the US–China trade conflict, the COVID-19 pandemic, and the Russia–Ukraine conflict in 2022. This temporal scope enables us to analyse how the interconnectedness between green bonds and other financial markets changes under diverse economic and market conditions. Therefore, our findings provide fresh empirical evidence on green bond connectedness and are particularly pertinent for investment decision-makers and market participants. As portfolio management is inherently sensitive to market conditions, investors' behaviour, market outlook, and risk tolerance can fluctuate significantly under normal and abnormal markets. Third, this paper contributes to the literature by examining the optimal investment strategies and potential portfolio diversification benefits of green bonds and major assets in China. In addition, the hedge effectiveness method is used to compare the hedging performance of green bonds in different portfolios. Our research identifies the role of green bonds as a hedging tool, providing practical implications for investors who consider incorporating green bonds into their portfolios while managing risk. Our analysis, based on the combination of several portfolio models, offers a comprehensive analysis of portfolio management strategies in green bond markets in China for the first time. This analysis is particularly valuable for informing the decision-making processes of both Chinese investors and hedge fund managers. Last, our study also incorporates considerations of Chinese investment markets such as index ETFs, cross-border country index ETFs, gold, oil, and forex, offering new insights for investors in constructing their investment portfolios. Hence, this analysis offers valuable insights for Chinese investors seeking to invest in green bonds across various assets.

Our main results are as follows. Firstly, the connectedness between green bonds and selected investment channels (e.g., HS300 ETF, S&P500 ETF, INE oil, SHFE gold and onshore RMB exchange rates) is quite low, and the variation of the connectedness index is time and event-related. Specifically, the transmission of connectedness among variables is not pronounced under normal economic market conditions, while the connectedness transmission among markets increases sharply during extreme market conditions. Secondly, we find that green bonds evolved from being receivers of shocks to shock transmitters during the pandemic period. Although the spillover effect is short-lived, Chinese investors' expectations of green bonds are certainly affected by the epidemic. Next, the HS300 ETF and S&P500 ETF are the primary sources of risk in the network, with the HS300 ETF having a greater impact on the system than the S&P500 ETF. Finally, through the creation of four portfolio strategies, we find that green bonds can be added to investors' portfolios as an effective hedging tool, but the weights of green bonds in the investment portfolio should be adjusted per the expectations and risk tolerance of investors.

Further, this research has important policy and regulatory implications for green bonds. Firstly, green bonds can be a reliable hedging instrument, and regulators can encourage their development to provide investors with more risk management tools. However, the weight of green bonds in portfolios should be adjusted based on investors' preferences and expected returns. Secondly, regulatory frameworks are needed to govern the issuance and trading of green bonds to protect investors from market risks and potential spillover effects during exceptional market circumstances. Thirdly, monitoring the connectedness of different investment channels during critical periods is crucial to identifying potential systemic risks and taking preemptive actions to prevent market instability. Additionally, increasing transparency and information disclosure requirements for green bond issuers can enhance market efficiency. Finally, policymakers can promote sustainable finance and mitigate climate change risks by leveraging investors' green inclinations through regulatory frameworks that provide tax incentives, promote green finance standards, and encourage green bond issuances.

The paper is organized as follows: Section 2 reviews the related literature. Section 3 describe the data and methodologies employed in the following research. Empirical findings are presented in Section 4, along with associated discussion. Finally, Section 5 concludes.

2. Literature review

Green bonds, as a key instrument in green economic transition and an important component of portfolio allocation, have attracted considerable attention from investors and researchers in recent years. Dynamic co-movement and market interconnectedness have been central themes when considering the development of green bonds and, to a larger extent, green investment. Pham (2016) investigates the volatility spillover between conventional and global green bond markets. This study concludes that the conventional bond market transmits the shocks to the green bond market. Reboredo (2018) find that green bond markets are strongly connected with corporate and treasury bond markets; however, they weakly co-move with stock and energy commodity markets. Reboredo et al. (2020) examine the connectedness between green bonds and asset classes for the EU and US markets and present empirical evidence that shows a strong connectedness between green bonds and treasury and corporate bonds in the short and long term and in both the EU and the US. Le et al. (2021) investigate the spillover effects between Fintech, green bonds, and cryptocurrencies, and the findings indicate that green bonds act as shock receptors in an international asset portfolio. Saeed et al. (2021) find that return connectedness across clean energy stocks, global green bonds, crude oil, and energy ETF is larger at both left and right tails. Pham (2021) identifies that after controlling for international stock movements and those of energy and fixed-income markets, the dependence between green bonds and green equities during normal market conditions is relatively small. Naeem et al. (2021a) examine the asymmetric connectedness among green bonds and commodities (e.g., gold, silver, crude oil, natural gas, wheat, and corn). Overall, this study demonstrates the importance of green bonds in mitigating risk in other commodity markets (excluding precious metals) at different frequencies. Elsayed et al. (2022) show that the dynamic connectedness between green bonds and financial markets is volatile over time and peaks in 2020 due to the COVID-19 pandemic. Chatziantoniou et al. (2022) examine dynamic connectedness among a set of environmental financial indices, including the S&P Green Bond Index, MSCI Global Environment, Dow Jones Sustainability Index World, and S&P Global Clean Energy and S&P Green Bond Index is found to be a receiver for both short-term and long-term. Tiwari et al. (2022b) examine the return connectedness between green bonds, carbon prices and renewable energy stocks and find that green bonds receive more shocks from other markets. Moreover, various portfolio techniques can significantly reduce the risk of investing in a single asset, with the exception of green bonds. Tiwari et al. (2023b) investigate the co-movement between green bonds and green stocks, using three measures from the MSCI Global Environment Index: alternative energy, pollution prevention, and green building. Empirical results suggest that the dependency between green bonds and green stocks is relatively weak. This is particularly evident during market downturn periods in the short- to medium-term dynamics. Tiwari et al. (2023a) conduct a quantile coherency analysis that reveals a negative spillover effect from green bonds to Islamic stocks in the long run. The cross-quantilogram correlation indicates that the dependency between green bonds and other asset returns is concentrated in the lower quantiles. Billah et al. (2023) identify that Sukuk is effective when hedging the risks of green bonds and global factors. Umar et al. (2023) also explore the dynamic linkages between oil shocks, conventional bonds, Islamic bonds (sukuks) and green bonds. Further significant influence is identified upon green bond markets when considering the role of pro-environmental preference (Zerbib, 2019), green bond financing (Tolliver et al., 2020), institutional ownership (Tang and Zhang, 2020), investor sentiment (Piñeiro-Chousa et al., 2022, 2021), corporate signalling (Flammer, 2021), market efficiency (Adekoya et al., 2021), external shocks (Corbet et al., 2020, 2021b), geopolitical risk (Sohag et al., 2022; Lee et al., 2021; Billah et al., 2023) and financial uncertainty (Pham and Nguyen, 2022).

While the dynamic connectedness between green bonds and various financial markets has been extensively researched, the dynamic connectedness between green bonds and ETFs has rarely been explored. ETFs, characterized by their unique features such as low management fees, a wide selection of underlying assets, and convenient trading, have attracted substantial attention from both individual and institutional investors over the past few years (Naeem et al., 2022; Xu et al., 2020). Jin et al. (2020) illustrate that the global industrial ETF can serve as an effective hedging tool, particularly during an economic downturn. Additionally, cross-border country index ETFs can significantly improve portfolio diversification benefits (Lee and Chen, 2021; Miffre, 2007). Thus, examining the dynamic connectedness and portfolio analysis between green bonds and ETFs has the potential to greatly improve portfolio efficiency and enhance the utility of portfolio diversification benefits.

Various multivariate portfolio construction and hedge effectiveness methods are used to evaluate the role of green bonds in investment portfolios. Broadstock et al. (2022) have recently developed a novel minimum connectedness portfolio (MCoP) strategy by using all pairwise connectedness indices rather than the variance or correlation matrix. As a result, this new portfolio technique has the feature of being less affected by network shocks. This strategy focuses on constructing portfolios that minimise the connectedness between assets, with the aim of reducing overall portfolio risk and volatility. Several studies apply this portfolio technique to seek an optimal diversified asset allocation. Tiwari et al. (2022a) apply the MCoP portfolio strategy in the context of energy and agricultural investments, finding that such a portfolio composition could effectively reduce overall portfolio volatility. This suggests that the MCoP strategy can be particularly beneficial in sectors where asset prices are highly volatile. Umar et al. (2022a) investigate the performance of MCoP with other portfolio strategies, such as the minimum variance portfolio (MVP) and minimum correlation portfolio (MCP) approaches for cryptocurrencies, DeFi tokens, and NFTs. The findings indicate that the MCP and MCoP investment portfolio strategies offer greater diversification than the MVP approach. Similarly, Tiwari et al. (2022c) also examines the investment performance among international commodity prices and the Australian industry stocks returns, using various portfolio techniques, including the minimum variance portfolio, the minimum correlation portfolio and the minimum connectedness portfolio to test portfolio performance. The portfolio analysis shows potential diversification benefits. In particular, Australian stocks generally have the lowest portfolio weights under all portfolios examined, highlighting their role as a hedge for a commodity investment portfolio.

Naeem et al. (2021b) investigate extreme tail dependence between five energy markets (crude oil, natural gas, heating oil, gasoline, and coal) and green bonds using a time-varying optimal copula (TVOC) model. The analysis of hedging effectiveness indicates that green bonds are an effective hedge for most energy commodities. Tiwari et al. (2022b) employ various portfolio techniques, including MVP, MCP and MCoP, to assess the hedging effectiveness of green bonds among energy commodities. Portfolio performance results show that including green bonds in the portfolio can effectively reduce portfolio volatility and thus improve the risk-hedging effectiveness of the portfolio. Tiwari et al. (2022a) investigate the time-varying volatility spillovers and connectedness among agricultural markets, energy markets and biofuel markets. They also undertake portfolio analysis by applying the MCoP approach to all the assets under consideration.

A growing body of literature, including the works of Han and Li (2022), Tiwari et al. (2022b) and Broadstock et al. (2022), has used green bond markets in developed countries to examine the benefits of green investment for portfolio diversification. In contrast, the green investment market in developing countries, including China, has received comparatively less attention in the literature. The green bond market in China is still in its early stages of development, and Chinese investors have low awareness of and demand for sustainable investments (Wang et al., 2020). This divergence is likely to lead Chinese investors to view green bonds differently from investors in developed countries. Currently, the existing literature on green bonds in China primarily falls into two categories: one focuses on the green premium and issuance motivations (e.g., Lin and Su (2022) and Hu et al. (2022)), while the other investigates the spillover effects between green bonds and other financial markets (e.g., Gao et al. (2021) and Lee et al. (2022), Su et al. (2022)). Guo and Zhou (2021) also study the dependence between the green bond market and the bond market, stock market, energy market, and forex market in the United States and China. They find that the hedging effectiveness of green bonds as hedging assets decreased during the pandemic. However, green bonds boost the hedging effectiveness in forex markets.

With the increasing interest of investors in green bond markets, it is necessary to identify the return transmission mechanisms between green bonds and major asset markets. Our research examines the return connectedness and portfolio analysis between green bonds and major asset markets in China for the first time in the literature. This study has been motivated by a number of research gaps in the existing literature, as follows. To the best of the author's knowledge, no previous studies have attempted to examine the dynamic return connectedness between green bonds and various investment markets (e.g. index ETFs, oil, gold and currency) in China. By examining the dynamic connectedness between green bonds and various investment markets, we obtain the estimated time-varying variance–covariance matrix of the TVP-VAR model to construct multiple portfolio strategies. We then construct portfolio strategies using both the traditional approaches (e.g., the minimum variance portfolio procedure, minimum correlation portfolio procedure and risk-parity portfolio procedure) and a recently developed minimum connectedness portfolio procedure.

This paper also fills the gap in the literature on the impact of green bond portfolio construction in developing country markets. To the best of our knowledge, no prior study has specifically investigated the optimal allocation of portfolios between China's green bonds and its asset markets. Hence, it is necessary to explore optimal investment strategies to uncover potential advantages in portfolio diversification when investing in China's green bonds. Therefore, analysing green bonds through a portfolio management lens provides valuable insights for environmentally conscious investors. This portfolio analysis helps them grasp the potential advantages of diversification offered by green bonds while also maximizing the expected value of their portfolios. In addition, our study also addresses the research gap by examining the connectedness and portfolio strategies between green bonds and Chinese index ETFs, as well as cross-border country index ETFs.

3. Data and methodology

3.1. Data

To explore the connectedness among mainstream financial markets in China from the perspective of a Chinese investor, we first follow the work of Su et al. (2022), Qi and Zhang (2022) and Gao et al. (2021), that utilize the ChinaBond green bond index (Green bond) as a suitable proxy to track the performance of the Chinese green bond market. In addition, regarding the equity ETFs, we use the China Shanghai Shenzhen 300 exchange-traded fund, known as the HS300 ETF (Ticker code: 510300.SH), and the S&P 500 ETF (Ticker code: 513500.SH) as measurable indicators to capture the performance of mainland Chinese investors who invest in equity ETFs for both China and the US.[1] For the oil, gold, and currency markets, consistent with previous studies focusing on the commodity market in China (Zhao et al., 2021; Corbet et al., 2021a; Hu et al., 2023), that use the daily price of the Chinese Shanghai crude oil futures (INE oil), the Shanghai Futures Exchange gold futures (SHFE gold) and the onshore RMB exchange rates (RMB) are used to measure the performance of each market and are obtained from the WIND database. Our sample period is from 27 March 2018 to 2 November 2022 (INE oil is available after 26 March 2018) and contains 1119 daily observations and covers major international events (e.g., the trade conflict between China and the US, the COVID-19 pandemic and the Russia–Ukraine war). We estimate the return of selected variables by taking the first log differences. The log-transformed return series are presented in Fig. 2.

Table 1 displays the summary statistical results of the green bond, HS300 ETF, S&P500 ETF, INE oil, SHFE gold, and RMB. It can be seen that all of the selected variables have a positive return during the sample period based on the positive value of the mean. In addition, the HS300 ETF has the smallest variance among the selected variables, whereas the SHFE gold has the largest variance.

Focusing on the skewness coefficient results, all variables are negatively skewed except for the Green bond, which is positively skewed, and the kurtosis coefficient indicates that all variables are peaked distribution except for INE oil. Finally, we ensure that all variables are non-normally distributed and significantly stationary based on the consequences of the Jarque–Bera statistical test (JB) and the modified ADF test of Elliott, Rothenberg and Stock (ERS).

From unconditional correlation results, we observe that there is a weak correlation between green bonds and other assets with a range of correlation coefficients between −0.048 and 0.074. In addition, the highest correlation coefficient is found between HS300 ETF and S&P500 ETF at 0.25, followed by the correlation between S&P500 ETF and INE oil, which is 0.202. Furthermore, an interesting observation is that the green bond is negatively correlated with most variables, except the SHFE gold and RMB, while the RMB has a negative correlation coefficient with other selected markets.

3.2. Methodology

In this section, we briefly introduce the modelling framework adopted in this paper, including a novel TVP-VAR-based frequency connectedness approach of Chatziantoniou et al. (2021) and four alternative portfolio methods. Finally, we evaluate the effectiveness of each financial market using the hedge effectiveness approach of Ederington (1979).

[1] The rationale for employing the HS300 ETF in our research, as opposed to the China Shanghai Shenzhen 300 Stock Index (CSI300), Shanghai Securities Composite Index (SSEC), and Shenzhen Component Index (SZC), is the fact that these indices are not financial products and therefore, the investor does not invest directly. The HS300 ETF is designed to mirror the performance of the HS300 index, which comprises the top 300 stocks based on market capitalization traded on the Shanghai Stock Exchange and Shenzhen Stock Exchange. Additionally, investors can invest directly. For further information, please refer to Qiao and Dam (2020). On the other hand, regarding the S&P500 ETF, the data collected in this paper is not from SPDR S&P 500 ETF (Ticker: SPY) or iShares Core S&P500 ETF (IVV), which are designed for international investors by US mutual fund companies, but from S&P 500 ETF (Ticker code: 513500.SH) constructed by Bosera Asset Management Company, one of the largest mutual fund companies in China, aiming to correspond to the performance of Standard & Poors 500 ETF (S&P 500). For further information about Bosera Asset Management Company, see Firth et al. (2010). Consistent with the role of the iShares MSCI China ETF for international investors who want to invest in the Chinese market, S&P500 ETF (Ticker code: 513500.SH) provides a way for Chinese investors who want to invest in the US stock market. The main reason for using S&P 500 ETF (Ticker code: 513500.SH) is that due to foreign exchange control and Qualified Domestic Institutional Investor (QDII) policy restrictions, Chinese domestic investors are not allowed to invest in the US stock market directly and must invest through related QDII products, such as China's S&P 500 ETF.

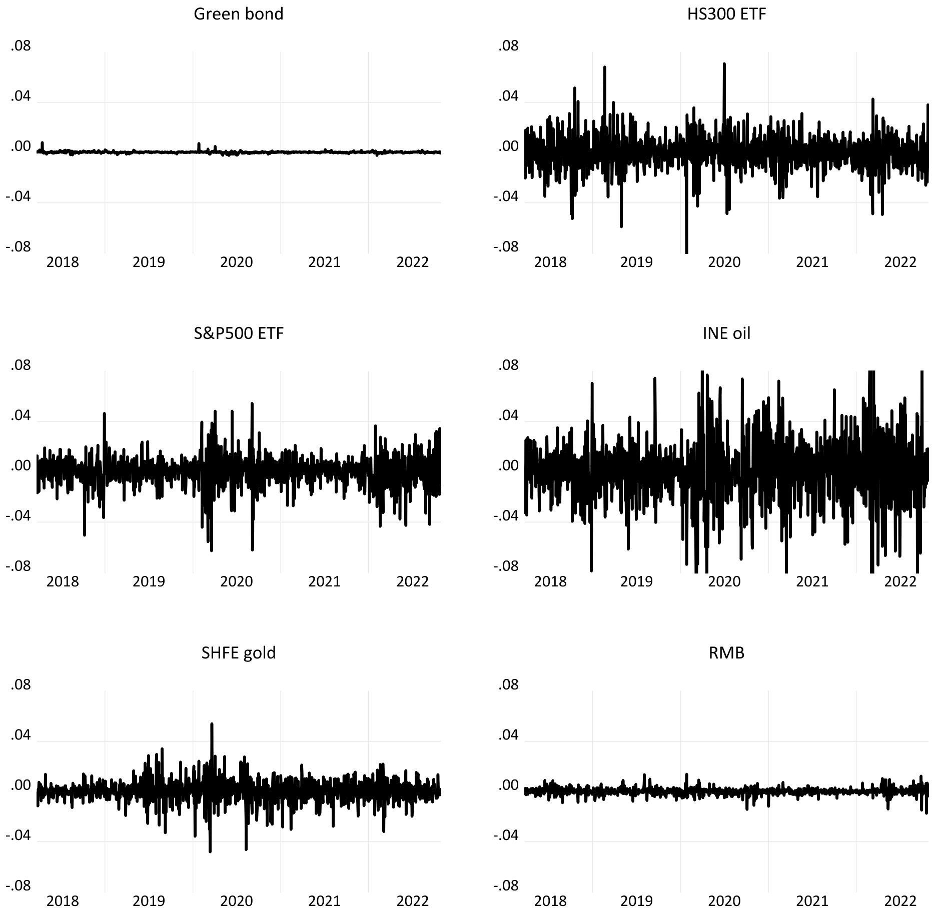

Fig. 2. Return series plot for each asset. Note: The figure shows the time series of the log return of selected variables, including China green bond (Green bond), HS300 ETF, S&P500 ETF, INE oil, SHFE gold and RMB, over the period from March 2018 to November 2022.

Table 1
Summary statistics.

	Green bond	HS300 ETF	S&P500 ETF	INE oil	SHFE gold	RMB
Mean	0.0002	0.0002	0.0004	0.0004	0.0003	0.0001
Variance	0.0004	0.0001	0.0001	0.0006	0.0007	0.0007
Skewness	2.777***	−0.237***	−0.489***	−0.227***	−0.235***	−0.214***
Ex.Kurtosis	33.819***	4.062***	3.607***	2.724***	4.556***	5.498***
JB	54 714.286***	779.061***	650.688***	355.304***	977.308***	1416.715***
ERS	−10.938***	−8.165***	−5.715***	−9.116***	−15.458***	−6.751***
Unconditional Corr	Green bond	HS300 ETF	S&P500 ETF	INE oil	SHFE gold	RMB
Green bond	1.000	−0.048	−0.017	−0.021	0.074	0.058
HS300 ETF	−0.048	1.000	0.250	0.119	0.009	−0.242
S&P500 ETF	−0.017	0.250	1.000	0.202	−0.045	−0.129
INE oil	−0.021	0.119	0.202	1.000	0.04	−0.069
SHFE gold	0.074	0.009	−0.045	0.04	1.000	−0.061
RMB	0.058	−0.242	−0.129	−0.069	−0.061	1.000

Note: This table reports the descriptive statistics for each asset and the estimation results of the Skewness test (D'Agostino, 1970); the Kurtosis test (Anscombe and Glynn, 1983); the JB normality test (Jarque and Bera, 1980); and the ERS unit roof test (Elliott et al., 1996). *, **, *** indicate significance at 10%, 5%, and 1%, respectively. Unconditional correlation results are reported in the lower panel of the table.

3.3. TVP-VAR based frequency connectedness approach

We start with the TVP-VAR-based frequency connectedness approach of Chatziantoniou et al. (2021), that extended based on the traditional spillover approach of Diebold and Yilmaz (2012), Diebold and Yılmaz (2014), and combined the frequency approach of Baruník and Křehlík (2018). Many researchers have utilized the TVP-VAR-related approach to measure connectedness among variables due to its unique features, such as not needing to set the rolling window size and no loss of observations (Qiao et al., 2022; Furuoka et al., 2023; Umar et al., 2022b; Cui and Maghyereh, 2023).

Regarding the TVP-VAR-based frequency connectedness approach of Chatziantoniou et al. (2021), we first calculate the TVP-VAR(p) model which is given by the following mathematical expression:

$$x_t = \Phi_{1t} x_{t-1} + \Phi_{2t} x_{t-2} + \cdots \Phi_{pt} x_{t-p} + \epsilon_t \qquad \epsilon_t \sim \mathrm{N}(0, \Sigma_t) \tag{1}$$

where x_t, x_{t-1} are $N \times 1$ dimensional vectors and Σ_t denotes time-varying variance–covariance matrix, Φ_{it} indicate the time-varying VAR coefficient.[2]

Next, we calculate the core of the connectedness approach, which is the generalized forecast error variance decomposition (GFEVD), showing the response of shocks from all variables j on a shock in variable i and can be written as:

$$\theta_{ijt}(H) = \frac{\left(\Sigma_t\right)_{jj}^{-1} \sum_{h=0}^{H} \left(\left(\Psi_h \Sigma_t \right)_{ijt} \right)^2}{\sum_{h=0}^{H} \left(\Psi_h \Sigma_t \Psi'_h \right)_{ii}}, \tag{2}$$

$$\tilde{\theta}_{ijt}(H) = \frac{\theta_{ijt}(H)}{\sum_{k=1}^{N} \theta_{ijt}(H)}, \tag{3}$$

where $\tilde{\theta}_{ijt}(H)$ shows the total contribution of the j to the variance of the forecast error of the variable i at forecast horizon H. Next, in a deep estimate of the direction of connectedness among variables, we apply the TVP-VAR-based connectedness approach, which is given by:

$$TO_{it}(H) = \sum_{i=1, i \neq j}^{N} \tilde{\theta}_{jit}(H), \tag{4}$$

$$FROM_{it}(H) = \sum_{j=1, i \neq j}^{N} \tilde{\theta}_{ijt}(H), \tag{5}$$

$$NET_{it}(H) = TO_{it}(H) - FROM_{it}(H), \tag{6}$$

$$NPDC_{ijt}(H) = \tilde{\theta}_{ijt}(H) - \tilde{\theta}_{jit}(H), \tag{7}$$

$$TCI_t(H) = N^{-1} \sum_{i=1}^{N} TO_{it}(H) = N^{-1} \sum_{i=1}^{N} FROM_{it}(H), \tag{8}$$

where $TO_{it}(H)$ and $FROM_{it}(H)$ denote the directional connectedness index, of which the $TO_{it}(H)$ display the shock transmission from the variable it to all others, and the $FROM_{it}(H)$ indicates the shock acceptance from all others. The $NET_{it}(H)$ indicates the net directional connectedness, which is the difference between variable $TO_{it}(H)$ and variable $FROM_{it}(H)$, showing the specific role of the variable in the network. Hence, if the value of $NET_{it}(H) > 0$ or $NET_{it}(H) < 0$, it means the transmitter or receiver role of the variable among the network. Further, the value of $NPDC_{ijt}(H)$ shows the net connectedness results with specific pair; for instance, if the $NPDC_{ijt}(H) > 0$ or $NPDC_{ijt}(H) < 0$, it indicates that the variable j transmit the shocks to the variable j or receive the shocks from the variable$i$. Finally, the value of $TCI_t(H)$ represents the results of the total connectedness index, which shows the degree of all variable interconnectedness in the network.

Next, we estimate the different frequency connectedness among variables by applying the approach of Baruník and Křehlík (2018), which decomposes the connectedness into short-run and long-run. The frequency decomposition expression of the Fourier transformation of TVP-VMA (Chatziantoniou et al., 2021) can be formulated as follows:

$$S_x(\omega) = \sum_{h=-\infty}^{\infty} E\left(x_t x'_{t-h}\right) e^{-i\omega h} = \Psi\left(e^{-i\omega h}\right) \Sigma_t \Psi'\left(e^{+i\omega h}\right), \tag{9}$$

where the frequency GFEVD is estimated as:

$$\theta_{ijt}(\omega) = \frac{\left(\Sigma_t\right)_{jj}^{-1} \left| \sum_{h=0}^{\infty} \left(\Psi\left(e^{-i\omega h}\right) \Sigma_t \right)_{ijt} \right|^2}{\sum_{h=0}^{\infty} \left(\Psi\left(e^{-i\omega h}\right) \Sigma_t \Psi\left(e^{i\omega h}\right) \right)_{ii}}, \tag{10}$$

$$\tilde{\theta}_{ijt}(\omega) = \frac{\theta_{ijt}(\omega)}{\sum_{k=1}^{N} \theta_{ijt}(\omega)}, \tag{11}$$

[2] The choice of the Time-Varying Parameter Vector Autoregression (TVP-VAR) frequency connectedness method was motivated by its capability to account for evolving market conditions, which is highly pertinent given the turbulent period the study focuses on. This method allows us to capture the dynamic and possibly non-linear relationships between the green bond market and other major financial markets, which might not be accurately reflected using a static methodology. Regarding the choice of priors, our selection was influenced by the desire to balance model complexity and the risk of over-fitting. Priors used in our TVP-VAR model contribute to its adaptability in handling many different scenarios and offer a sensible regularization to the estimation problem (Xu et al., 2023b; Chan et al., 2020; Akyildirim et al., 2023; Xu et al., 2023a).

where $\tilde{\theta}_{ijt}(\omega)$ indicates the part of the spectrum of variable i at the frequency ω. Therefore, all frequencies can be set within a specified range, $d = (a, b), a, b, \epsilon(-\pi, \pi), a < b$. as,

$$\tilde{\theta}_{ijt}(d) = \int_{a}^{b} \tilde{\theta}_{ijt}(\omega)d\omega. \tag{12}$$

Finally, the TVP-VAR connectedness based on the frequency approach of Baruník and Křehlík (2018) can be presented as follows:

$$T\tilde{O}_{it}(d) = \Gamma(d) \cdot TO_{it}(d), \tag{13}$$

$$FRO\tilde{M}_{it}(d) = \Gamma(d) \cdot FROM_{it}(d), \tag{14}$$

$$NE\tilde{T}_{it}(d) = \Gamma(d) \cdot NET_{it}(d), \tag{15}$$

$$NPD\tilde{C}_{ijt}(d) = \Gamma(d) \cdot NPDC_{ijt}(d), \tag{16}$$

$$TC\tilde{I}_{t}(d) = \Gamma(d) \cdot TCI_{t}(d), \tag{17}$$

where $T\tilde{O}_{it}(d)$, $FR\tilde{M}_{it}(d)$, $FRO\tilde{M}_{it}(d)$, $NE\tilde{T}_{it}(d)$, $NPD\tilde{C}_{ijt}(d)$ and $TC\tilde{I}_{t}(d)$ denote the connectedness measurement under the different frequencies.

3.4. Portfolio methodologies employed

Subsequently, the selected assets are incorporated into four different portfolio strategies, namely the Minimum Variance Portfolio (MVP), the Minimum Correlation Portfolio (MCP), the Minimum Connectedness Portfolio (MCOP), and the Risk-Parity Portfolio (RPP), developed to analyse the returns of the investment portfolios during sample periods. It is worth noting that the selected assets must be readily investable or directly accessible for purchase by investors to estimate investment portfolio returns. The aim of this paper is to explore the risk-hedging effect of green assets in Chinese investor portfolios. Thus, Chinese investors can directly invest all variables selected in this research to mitigate market risk or establish a low-risk investment portfolio.

The first portfolio method is the Minimum Variance portfolio, which generates a portfolio with the aim of minimizing variance among multiple assets, from Durand (1960) and the weights of this portfolio can be calculated using the following equation:

$$w_t = \frac{H_t^{-1} I}{I H_t^{-1} I}, \tag{18}$$

where w_t denotes the portfolio weight vector, H_t depicts the conditional variance–covariance matrix.

The second portfolio method is the Minimum Correlation Portfolio, which is introduced by Christoffersen et al. (2014). Similar to MVP, the portfolio of MCP is constructed by minimizing the conditional correlations and not the conditional co-variances. The formula for calculating the portfolio weights is as follows:

$$R_t = \text{diag}\left(H_t\right)^{-0.5} H_t \,\text{diag}\left(H_t\right)^{-0.5}, \tag{19}$$

$$w_t = \frac{R_t^{-1} I}{I R_t^{-1} I}, \tag{20}$$

where R_t is a dimensional matrix and w_t is the minimum correlation portfolio weight.

The Minimum Connectedness Portfolio technique was recently developed by Broadstock et al. (2022), which creates a portfolio with the aim of the minimum connectedness among the weight of variables. The portfolio weights can be computed using the following mathematical expression:

$$w_t = \frac{PCI_t^{-1} I}{I PCI_t^{-1} I}, \tag{21}$$

where PCI_t denotes the connectedness index matrix and I is the identity matrix.

We next utilize the Risk-Parity Portfolio, which obtains the portfolio's weight based on the same share of risk contribution. The calculation of the portfolio weights is through the following formula:

$$\min \sum_{i,j=1}^{N} \left(w_{it}\left(H_t w_t\right)_i - w_{jt}\left(H_t w_t\right)_j\right)^2. \tag{22}$$

Furthermore, to test the performance of each market in the portfolio, we apply the hedge effectiveness approach of Ederington (1979), and the equation is given by:

$$HE = 1 - \frac{\text{Var}\left(y_p\right)}{\text{Var}\left(y_{\text{unhedged}}\right)}, \tag{23}$$

where $\text{Var}\left(y_p\right)$ is the variance of the portfolio returns, $\text{Var}\left(y_{\text{unhedged}}\right)$ indicate the variance of the unhedged asset, HE show the hedge efficiency of assets. The high value of HE means a large risk reduction.

Table 2
Averaged connectedness table.

	Green bond	HS300 ETF	S&P500 ETF	INE oil	SHFE gold	RMB	FROM
Green.bond	86.58	4.64	1.57	0.98	3.23	2.99	13.42
	(57.84,28.74)	(3,1.64)	(1.19,0.38)	(0.64,0.34)	(2.03,1.2)	(2.03,0.96)	(8.9,4.52)
HS300.ETF	2.57	69.5	10.38	3.25	2.03	12.27	30.49
	(2.25,0.32)	(59.62,9.88)	(9.06,1.32)	(2.84,0.41)	(1.66,0.37)	(10.42,1.85)	(26.23,4.26)
S&P500.ETF	0.88	11.43	73.36	8.59	2.07	3.66	26.64
	(0.78,0.1)	(10.27,1.16)	(63.65,9.71)	(7.06,1.53)	(1.81,0.26)	(3.31,0.35)	(23.24,3.4)
INE oil	1.16	3.69	9.4	80.05	3.61	2.09	19.94
	(0.79,0.37)	(2.9,0.79)	(7.69,1.71)	(67.35,12.7)	(3.23,0.38)	(1.59,0.5)	(16.2,3.74)
SHFE gold	2.63	2.28	2.38	3.53	86.2	2.99	13.8
	(2.04,0.59)	(1.95,0.33)	(2.02,0.36)	(2.89,0.64)	(72.85,13.35)	(2.46,0.53)	(11.36,2.44)
RMB	2.37	12.68	3.49	1.8	3.24	76.41	23.59
	(1.89,0.48)	(10.95,1.73)	(3.14,0.35)	(1.53,0.27)	(2.62,0.62)	(64.64,11.77)	(20.13,3.46)
TO	9.62	34.73	27.24	18.15	14.17	23.98	
	(7.76,1.86)	(29.07,5.66)	(23.11,4.13)	(14.97,3.18)	(11.35,2.82)	(19.8,4.18)	TCI
Net	−3.8	4.23	0.6	−1.8	0.37	0.39	21.32
	(−1.14,−2.66)	(2.84,1.39)	(−0.13,0.73)	(−1.24,−0.56)	(−0.01,0.38)	(−0.33,0.72)	(17.68,3.64)

Note: The results of the average connectedness are derived from a TVP-VAR model with a lag of 1 (as determined by the BIC criterion) and a 20-step-ahead prediction. The value in the parentheses denotes the average short-term and long-term connectedness, respectively.

4. Empirical results

4.1. Averaged dynamic connectedness

Table 2 presents the results of the averaged return connectedness between selected variables, specifically green bonds, HS300 ETF, S&P 500 ETF, INE oil, SHFE gold and RMB during the sample period. It is important to note that the values in the table are averaged over the entire sample period and do not consider the dynamic impact of events that occurred at specific points in time.[3]

The TCI value, which measures the overall connectedness of the network among green bonds and other financial assets during the sample period, is found to be relatively low at an average of 21.32%. Of this, 17.68% is estimated to result from the short-term connectedness band, and 3.64% results from the long-term band, indicating the variation of total connectedness of the network is mainly driven by the shock transmissions in short-term connectedness. In addition, 21.32% of the forecast error variance in this network between the green bond and selected sample variables can be attributed to interactions within the network, while the remaining 78.68% can be attributed to unique causes for each individual variable.

Focusing on the net connectedness value (estimated as the average), which is calculated by the difference between the transmission (denoted as "To") and reception (denoted as "From") of shocks, that illustrate the position of assets within the network.[4] Green bonds are the dominant receiver of shocks in the system during the sample period, with −3.8% of net values. More specifically, by separating the connectedness into different frequency bands, of which −1.14% are contributed by the short-term connectedness bands, −2.66% resulted from the long-term connectedness bands. In comparison, HS300 ETF and S&P500 ETF assume the major net transmitter in the network, of which the HS300 ETF is the largest net shock transmitter with 4.23% of values, and the S&P500 ETF is the second largest net transmitter with 0.6%.

It is evident that the main diagonal value in Table 2 for each variable, which denotes the own-variable shocks, is notably high, and the off-diagonal elements, which refer to the interactions of each variable in the particular network, are relatively low. For example, the highest percentage of its own variance is found in the case of green bonds with 86.58%. Out of the 86.58%, 57.84% is contributed to the short-term own-variance share spillover, and 28.74% is contributed to the long-term. Turning to the off-diagonal of the green bond, it can be seen that the HS300 ETF has the highest effect on the green bond index variation, which is 4.64%, followed by SHFE gold, RMB, S&P500 ETF, and INE oil.

Overall, Table 2 emphasizes a very weak interdependence between the green bond and selected financial investment channels during the sample period, further supporting the findings of Dai et al. (2023) and Reboredo (2018) research, which investigated a lower degree of co-movement between the green bond and other financial markets, such as stock, oil, and the energy market from both the China and US markets. However, the results of Table 2 only display the static connectedness, masking the specific impacts of time and events, which are particularly important for understanding the specific role of green bonds in the field of investment assets.

[3] Additionally, the values in the table not only contain the time-domain results obtained from the TVP-VAR model but also display the frequency domain results (short-term and long-term) that are based on the Baruník and Křehlík (2018) approach. The short-term and long-term band connectedness results correspond to the left and right values in parentheses, respectively.

[4] The positive net value of asset implies that the asset acts a transmitter of shocks in the network, while the negative net value means the asset acting the receiver of shocks.

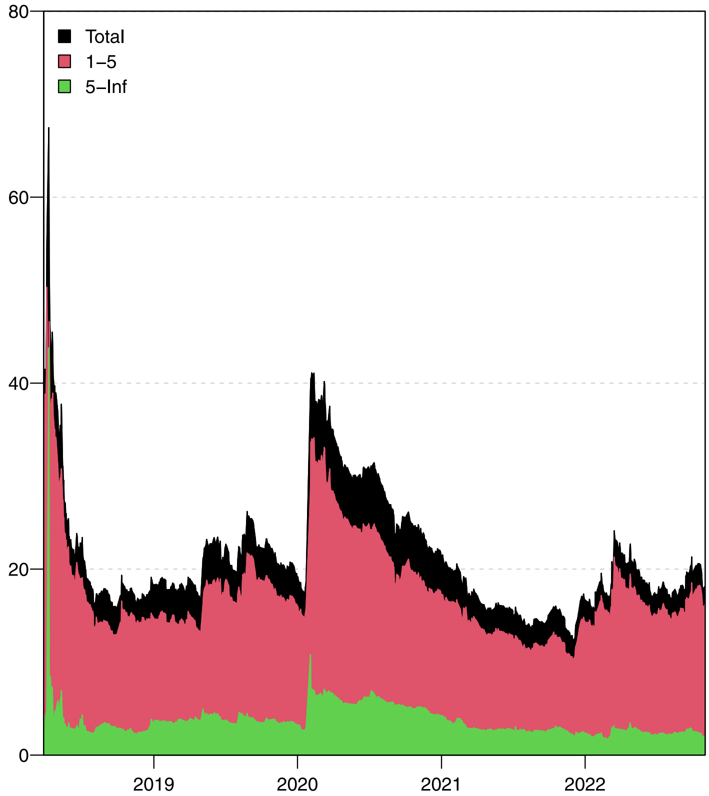

Fig. 3. Dynamic total connectedness. Note: This figure depicts the total dynamic connectedness across all markets between 27 March 2018 and 1 November 2022. The results are obtained using a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead forecast. Total dynamic connectedness is also decomposed into short-connectedness (red areas) and long-run connectedness (green areas). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Total dynamic connectedness

Next, we focus on the dynamic results of connectedness among sample variables. Fig. 3 presents the dynamic variation of the total connectedness index during the whole sample period, which not only displays the total connectedness index (represented by the black area), based on the approach proposed by Chatziantoniou et al. (2021), but also includes the results of the decomposed short-term connectedness (represented by the red areas) and long-term connectedness (represented by the green areas), which is based on the approach proposed by Baruník and Křehlík (2018).

From Fig. 3, it can be observed that the total connectedness of green bonds with selected financial investment channels is relatively low, with most fluctuations staying below 20%. However, the variations of the connectedness index are still time and event-related. Specifically, we observe two significant spikes that occurred in early 2018 and February 2020, corresponding to the timeline of two extreme events: the trade conflict between China and the US and the COVID-19 pandemic. The implication of these results is that the connectedness between the green bond and other financial channels has a dramatic increase under extreme market conditions, which is in line with existing research (Su et al., 2022; Mensi et al., 2021; Dai et al., 2022, 2023). It is worth noting that the total connectedness index has a slight upward trend in early 2022, reflecting the influence of the Russian–Ukrainian war on the network.

Specifically, our study focuses on the differential behaviour between short-term and long-term connectedness in the examined financial markets. Focusing on the dynamic connectedness at different frequencies provides insight into how market shocks influence investor expectations (Baruník and Křehlík, 2018). Notably, as depicted in Fig. 3, the total connectedness is primarily driven by short-term connectedness, which is approximately five times greater than long-term connectedness. This finding implies that the relevant information is being processed quickly by the market. Additionally, the findings indicate that the overall dynamic connectedness is highly responsive to major economic and political shocks that transpire within the examined period. Furthermore, short-term connectedness can effectively capture the prompt reaction of the financial market to substantial political and economic occurrences.

In a broad sense, the results of the total connectedness index show that the Chinese green bond market is relatively weakly connected to other major investment markets, offering potential diversification benefits to investors. Notably, the degree of connectedness intensifies during extreme periods, such as the US–China trade conflict and the COVID-19 pandemic. The occurrence of extreme events, which trigger investor behaviour in search of safe assets (Su et al., 2022), leads to an increased spillover effect across different markets. This finding is consistent with previous literature (Mensi et al., 2021; Dai et al., 2022, 2023), identifying an increased spillover effect between green bond markets and other financial markets in developed countries during extreme events. Our

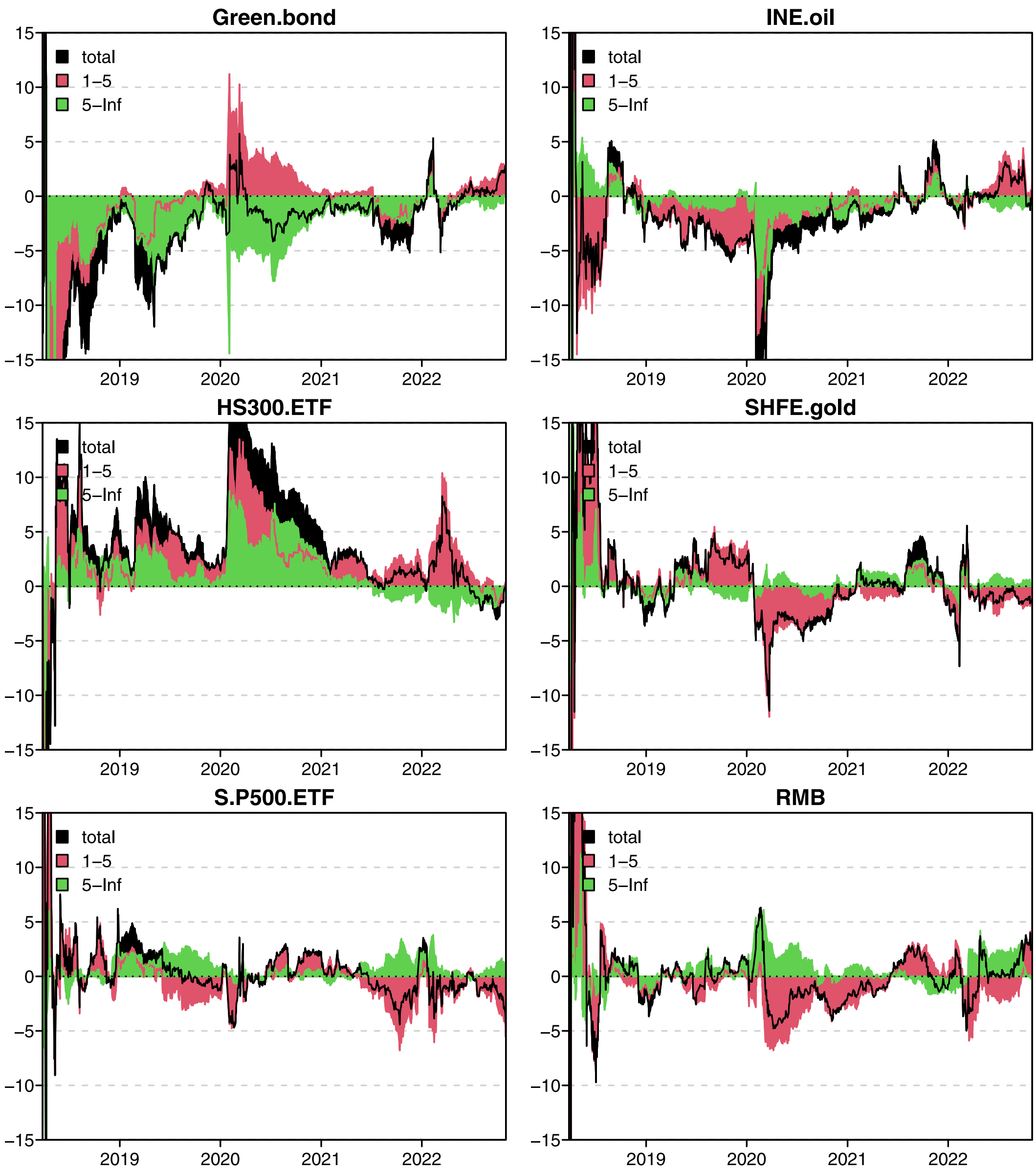

Fig. 4. Dynamic net total directional connectedness. Note: This figure displays the dynamic net connectedness index of each variable. The results are obtained using a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead forecast. Connectedness is further decomposed into short-connectedness (red areas) and long-run connectedness (green areas). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

results also confirm that China's green bond market, as a major green finance market in developing countries, is also experiencing increased interconnectedness with other financial markets driven by extreme events.

Overall, the results presented in Fig. 3 are noteworthy, revealing that the network connectedness among selected financial markets is relatively low during most of the sample period. Additionally, our findings indicate that the impact of the US–China trade war and the COVID-19 pandemic, particularly on China-based investors, is comparatively strong, which aligns with previous survey results (Dai et al., 2023; Lin and Su, 2021).

4.3. Net total directional connectedness

Fig. 4 displays the results of the dynamics of net directional connectedness. This presents the specific role of the asset over the sample period. It is worth noting that when the net directional connectedness is at a negative position, it implies that the asset is acting as a receiver of shocks, while a positive value of connectedness implies that the asset acts as a transmitter of shocks.

We first focus on the net recipients of the network. It can clearly be found that the green bond, INE oil, SHFE gold, and RMB are the major recipients of shocks in the network, especially the green bond and INE oil, maintaining a negative position over most of the sample period. Individually, we noticed that the green bonds exhibited a complex temporal variation, and the connectedness index of green bonds experienced a huge variation in two periods, including the China–US trade war between 2018 and 2019 and the pandemic in 2020. An interesting finding is that focusing on the COVID-19 period, the green bond turns rapidly into shock transmitters from a receiver position in the short term while remaining the shock receiver under the long-term frequency domain.

There are several reasons to explain the switch in the role of green bonds between the COVID period and the non-COVID-19 period. The role of green bonds as a transmitter in the short-term frequency during the COVID-19 period can be attributed to the different investment horizons of investors. Those with shorter investment horizons tend to be more risk-taking (Gaspar et al., 2005). During periods of heightened market risk, such as the outbreak of COVID-19, investors seeking higher returns often shift away from fixed-income assets like green bonds and redirect their funds into products such as oil and gold. Therefore, it may be explained that the net connectedness index of green bonds becomes a transmitter of shocks in short-term frequencies during the crisis. This result is similar to the findings of Su et al. (2022), who find that during the crisis, the Chinese green bond acts as a transmitter to conventional financial markets, such as corporate bonds or energy assets, in the short term, while acting as a recipient in the long term. As a result, China's green bond markets may be more susceptible to systemic risk in times of stress, which are increasingly integrated into wider financial markets. As China's green market develops and matures, it will become less isolated and more integrated with other financial markets, making it more vulnerable to shock transmission in times of turbulence. Therefore, our results highlight the heterogeneity of green investors in different market states, in contrast to previous research by Khalfaoui et al. (2023) and Tiwari et al. (2022b), who identify green bonds in developed countries as a recipient role during the crisis. In addition, the high level of uncertainty during COVID-19 could lead to a significant reallocation of resources and even green bonds are affected. Green bonds appeal to ESG-oriented investors, who might demonstrate unique investment behaviours during periods of high market stress, triggering increased interconnectedness in the green bond market.

On the other hand, we observe a sharp decline in the connectedness index of INE oil and SHFE gold, implying that gold and oil received a strong shock from the network during the COVID-19 period. In more detail, in terms of INE Oil, the short-term and long-term connectedness display the same direction of dropping trend, indicating the COVID-19 outbreak expands the spillover effect from the network to the INE oil market. Turning to the RMB result, we can see that the short-term connectedness and long-term connectedness of RMB are in opposite directions. In particular, it is worth mentioning that RMB played the role of risk transmission in the system during the early COVID-19, which was driven by the long-term connectedness, indicating the expectation of Chinese investors in the RMB underwent a fundamental change under the shocks of COVID-19.

When taking the perspective of the shock transmitter, HS300 ETF and S&P500 ETF, which remain in a positive position for the most sample period, assume the major risk transmission role in the network. Specifically, in the case of HS300 ETF, we find that the connectedness index sharply rises during the occurrence of each event. For example, looking at the COVID-19 period, the connectedness of HS300 ETF transmits the strongest shock among the variables to the network, in which the dynamic of connectedness variation is mainly driven by short-term connectedness. In comparison, the risk spillover of S&P 500 EFT for the network is smaller than HS300 ETF, with most of the connectedness index fluctuating between 5% and −5%.

Taken together, through the results of net directional connectedness, we accurately point out the specific role of each variable in the network and the variation connectedness during both normal and extreme market conditions. In general, the net connectedness indices remain relatively stable during normal market conditions but experience significant changes during periods of extreme market conditions.

4.4. Net pairwise total connectedness

We next focus on the net pairwise directional connectedness results, which clearly illustrate the specific connectedness between individual markets and each other during the sample period. The main results are presented in Fig. 5.

Empirically, it can be observed that the Chinese green bond consistently acts as a shock receiver in each pair, with the HS300 ETF being the primary shock transmitter, followed by INE oil, SHFE gold and the SP500 ETF. Such findings suggest that the index ETF is more closely linked to the green bond market than other investment markets. Furthermore, it is worth noting that the return spillover from the HS300 ETF to Chinese green bonds is most pronounced in three different periods: 2018, 2020 and 2021. These periods correspond to three representative observational events: the US–China trade war, the outbreak of COVID-19, and the release of a white paper titled "Energy in China's New Era". This white paper aims to build a diversified clean energy supply system, as discussed in Li et al. (2022). As a result, there has been an accelerated shift of investor capital from the equity market to the green bond market due to the occurrence of extreme events and government support for the green economy. This has resulted in a remarkable spillover effect from the equity market to green bonds. The nature of this spillover effect may be attributed to a flight to quality behaviour of investors and financial contagion (Baur and Lucey, 2009). Lin and Su (2023) also note a similar finding that a significant increase in market risk can drive capital from riskier to safe-haven assets.

However, it is worth noting that during the COVID-19 outbreak, we observed a shift in the pairing of green bonds with INE oil, SHFE gold, and RMB markets to a transmitter. Among these, the INE oil market emerges as the largest recipient of spillovers, followed by SHFE gold and RMB. As pointed out by Su et al. (2022), investors in China may still view green bonds as traditional assets, largely overlooking their unique green characteristics. In other words, the proportion of investors in the Chinese market with a strong preference and belief in green investments is relatively small. Therefore, when significant arbitrage opportunities arise in the market, investors tend to reallocate their risk capital to other markets. For instance, it is observed that the spillover effect is enhanced from green bonds to the INE oil market during a negative oil price event in early 2020. The unprecedented plunge of WTI prices into negative territory has created massive arbitrage opportunities in the oil market, which has fundamentally altered the market perceptions of green bond investors in China.

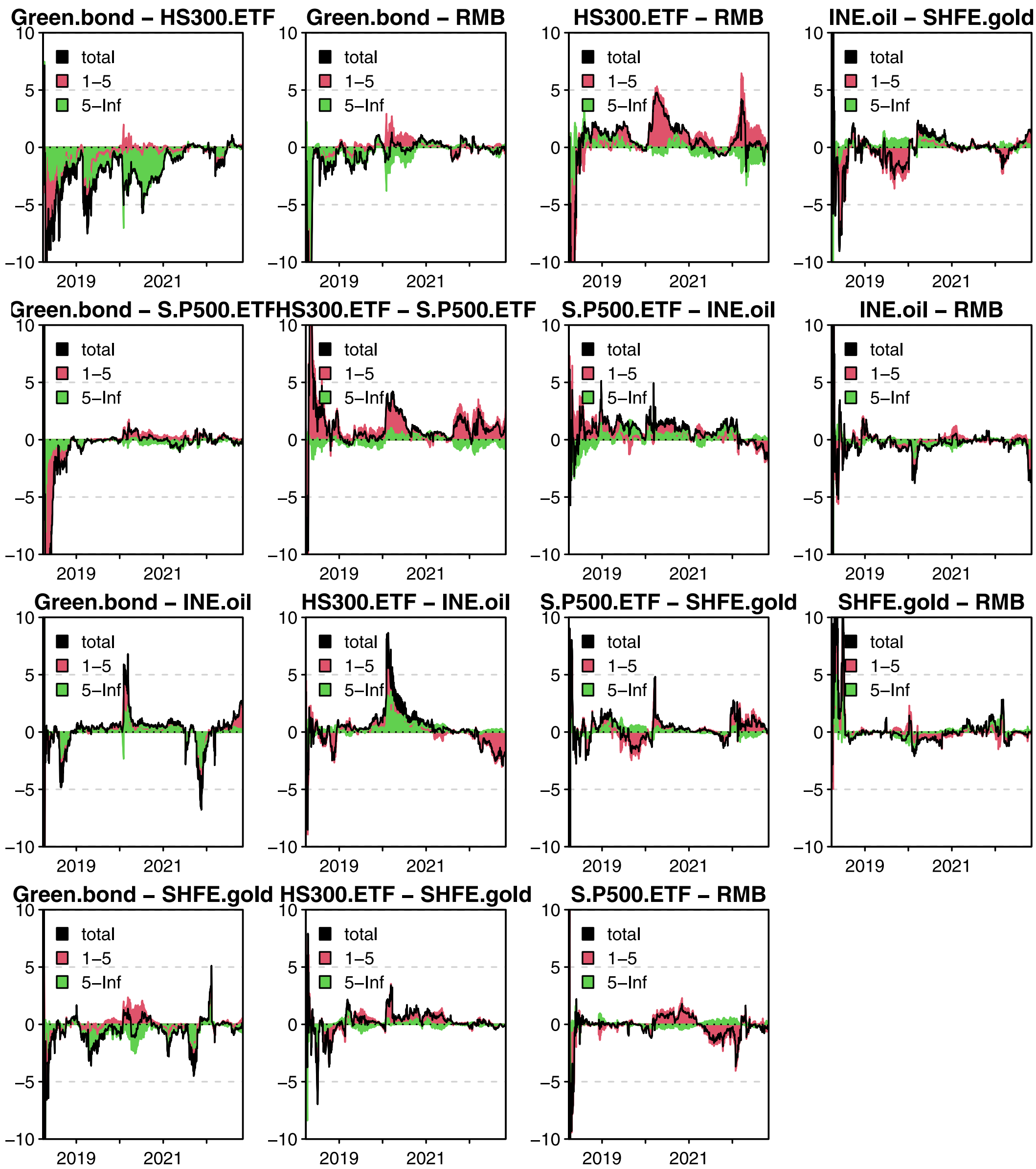

Fig. 5. Dynamic net pairwise directional connectedness. Note: This figure shows the dynamic net pairwise direction connectedness for each pair. The results are obtained using a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead forecast. Connectedness is further decomposed into short-connectedness (red areas) and long-run connectedness (green areas). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Focusing on the net pairwise results of the INE oil market, we notice that the INE oil market received a strong connectedness transmitted from each market during the pandemic, of which the HS300 ETF is a major transmitter of shocks to the oil market, followed by green bonds, S&P500 ETF, SHFE gold and RMB. These results further confirmed the idea of Kang et al. (2017), Umar et al. (2019) and Cui and Maghyereh (2023) that the connectedness between the oil market and other financial assets has been enhanced by the major crisis events. Additionally, we observed a significant alteration in the interdependence between INE oil and other financial markets during the Russian–Ukrainian conflict, particularly INE oil transitioning from a recipient of green bonds to a transmitter of shocks. This is demonstrated by the abrupt decrease in the pairwise connectedness index between green bonds and INE oil in early 2022.

With regards to the HS300 ETF and S&P500 ETF, which are identified to be the main transmitters in the network, with a positive connectedness index for each pair during most of the sample period. Further, it can be clearly seen that when the market is under extreme conditions, such as the pandemic and the Russian–Ukraine War period, the HS300 ETF and S&P500 ETF have a significant spillover effect on other financial investment channels, where the connectedness transmission of HS300 ETF to green bonds, INE oil, and RMB is much greater than that of S&P500 ETF, but the spillover of S&P500 ETF to the SHFE gold market is higher than that of HS300 ETF. Additionally, another interesting finding surrounds the net pairwise result of the HS300 ETF and S&P500 ETF, where we find that the connectedness index is in a positive position in most sample periods, and especially, the fluctuations of the

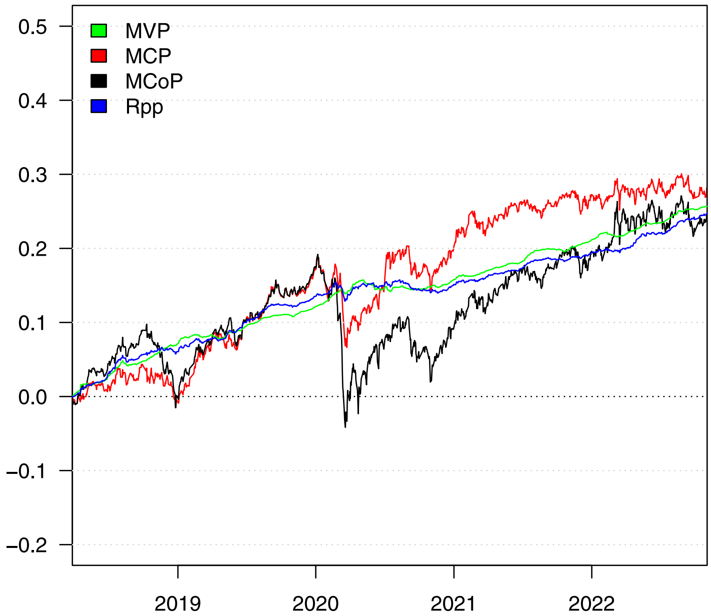

Fig. 6. Cumulative portfolio returns. Note: This figure displays the cumulative returns of each portfolio based on four investment portfolio strategies, including minimum variance portfolios (MVP), minimum correlation portfolios (MCP), minimum connectedness portfolios (MCoP), and risk-parity portfolios (RPP).

index present a dramatic increase in both COVID-19 and Russian–Ukrainian conflict, indicating that the HS300 ETF transmit strong shocks to the S&P500 ETF in that time.

To conclude, the aforementioned results illustrate the disparities in interconnectedness among financial assets in China and the distinctive role each market serves within the network. Notably, our findings indicate that the connectedness of selected assets experiences a substantial increase during extreme market conditions. Therefore, it is crucial for Chinese investors to construct a judicious portfolio and evaluate the hedging capabilities of each asset.

4.5. Portfolios strategies

Four investment portfolio strategies are used to construct multivariate investment portfolios for the selected data. Table 3 provides the results of hedge effectiveness, which evaluates the hedging performance of each asset in the portfolio. It is worth noting that among those competing portfolio construction approaches, the aim of the MVP approach is ensuring the minimized volatility of the portfolio; based on Durand (1960), the MCP technique focuses on the reduction of correlation among the assets, from Christoffersen et al. (2014), the MCoP procedure minimizes connectedness across assets, according to Broadstock et al. (2022) and the RPP approach emphasizes the minimized risk contribution of each asset, based on Maillard et al. (2010).

Fig. 6 shows the cumulative return performance of each portfolio approach over the sample period. The MVP and RPP portfolios show a similar dynamic pattern of sustained increase over the sample period, while the MCP and MCoP portfolios have greater volatility. For example, both the MCP and MCoP portfolios had a distinct downturn in early 2020, corresponding to the effects of the COVID-19 pandemic. Although the trends of the four portfolios show distinct differences over the sample period, the returns of all four portfolios are positive and consistently rising, with the MCP portfolio having slightly higher returns than the other three portfolios.

To obtain a deeper insight into the composition of each portfolio, we analyse the results of the dynamic portfolio weights, as shown in Fig. 7. This figure displays the dynamic weighting of individual assets in different investment portfolios over the sample period. As can be seen, the MCP and MCoP have a similar distribution of dynamic portfolio weights, with each asset almost equally weighted, while the MVP and RPP have a more concentrated weighting to a single asset, green bonds. Additionally, Table 3 presents the average multivariate portfolio weights and their corresponding hedging effectiveness for each portfolio. As mentioned above, green bonds have a significant presence in MVP and RPP, with average proportions of 94% and 65%, respectively. Another key finding is that green bonds and RMB have a substantial contribution to the construction of portfolios in the Chinese market, with green bonds and RMB accounting for a significant proportion of each portfolio at 99% in MVP, 41% in MCP, 36% in MCoP and 86% in RPP. Moreover, it is evident from the minimum and maximum columns that the MVP and RPP portfolio strategies exhibit a higher emphasis on allocating assets to green bonds. In both portfolios, the minimum and maximum values of the weights of the green bond are substantially greater than those observed in MCP and MCoP.

Combining the results from Figs. 6 and 7, we can observe that the portfolios with a high weighting in green bonds, such as MVP and RPP, show a consistent upward trend in returns during the sample period. In contrast, portfolios with a lower weighting in green bonds, like MCP and MCoP, demonstrate greater volatility in the trend of return, especially during crisis periods. Consequently, we can conclude that incorporating green bonds into a portfolio could help investors achieve a more stable return trend. This is

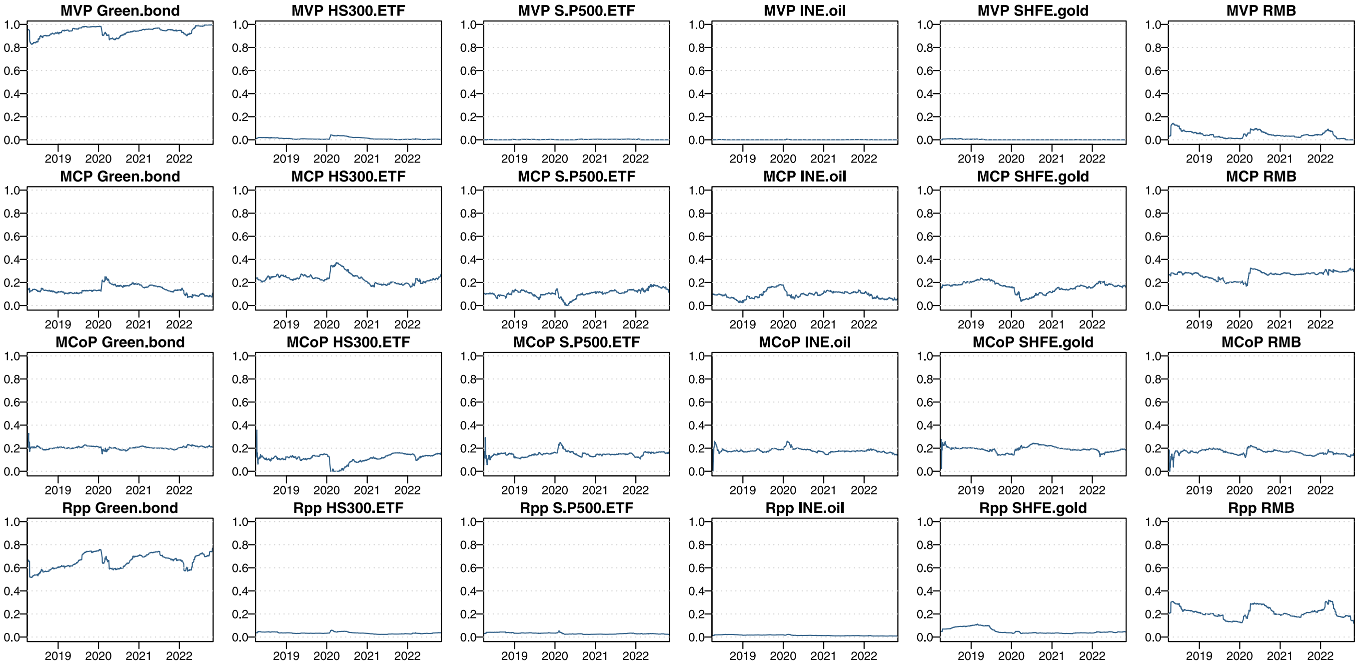

Fig. 7. Dynamic multivariate portfolio weights. Note: This figure shows the dynamic portfolio weights based on four investment portfolio strategies, including minimum variance portfolios (MVP), minimum correlation portfolios (MCP), minimum connectedness portfolios (MCoP), and risk-parity portfolios (RPP).

particularly important for investors, as in the early stages of the pandemic, the cumulative returns of MVP and RPP outperformed those of MCP and MCoP, suggesting that the portfolio with a high weighting in green bonds could generate the extra return for the investor in the context of the onset of the crisis. Hence, Chinese green bonds could be considered a safe haven during crises. However, in the aftermath of the outbreak, the cumulative returns of MCP and MCoP have generally trended sharply upwards, outperforming those of MVPs and RPPs. Therefore, to build an optimal portfolio strategy, investors should not only increase the proportion of green bonds in their portfolio during economic downturns or periods of heightened risk, but also incorporate more diverse assets from other markets (e.g., oil and gold) during periods of economic prosperity to improve portfolio returns and investment diversification.

Furthermore, regarding the hedge effectiveness ratios (HE value) in Table 3, it can be observed that the green bond and RMB are indeed effective risk-hedging tools in the Chinese financial market. More precisely, the HE of green bonds and RMB are only positive in the MVP, in which the portfolio contains a large weight of green bonds and RMB, 94% and 5%, and statistically significantly reduce volatility by 14% from green bonds and 95% from RMB, respectively. In the case of the negative HE of green bonds and RMB, such as MCP, MCoP, and RPP approaches, investing in the green bond and RMB can statistically significantly reduce the volatility of other assets, for example, in the case of MCP, if investing 14% in green bonds, 23% in HS300 ETF, 11% in S&P500 ETF, 10% in INE oil, 16% in SHFE gold, and 27% in RMB, can statistically significantly reduce the volatility of each asset, as indicated in HE column with 87% for HS300 ETF, 84% for S&P500 ETF, 96% for INE oil, and 68% for SHFE gold.

By comparison, it could be noted that the inclusion of Chinese green bonds would significantly reduce the volatility of other assets in the portfolio, with all these reductions being significant at the 1% level. Furthermore, our findings indicate that the inclusion of any asset results in an increase in volatility for green bonds within the portfolio. In other words, our analysis does not support the notion that adding any asset reduces the risk associated with Chinese green bonds. Our findings align with the work of Tiwari et al. (2022b), which examines the portfolio performance of green bonds in developed countries, yielding a similar conclusion. From this perspective, we observe similarities in the portfolio management strategies applied to green bonds across both developing and developed nations. The phenomenon in the Chinese financial market may be related to the consistent upward trend in the price of Chinese green bonds over the past few years. As pointed out by Broadstock et al. (2022), due to the consistently positive returns of the Chinese green bond market in recent years, combining it with any other market can significantly reduce the overall risk of the portfolio. It is imperative to note that the results of the HE ratios once again highlight the importance of including green bonds in a diversified investment portfolio.

5. Conclusions

This paper examines return connectedness between the green bond and major financial markets (e.g. index ETFs, oil, gold and currency) from the viewpoint of Chinese investors, utilizing a novel TVP-VAR-frequency connectedness method. This paper also constructs multivariate investment portfolios for the selected data by applying the MVP, MCP, MCoP and RPP strategies and to provide insightful implications of green bonds with portfolio management. A key difference between our study and others lies in the context where we focus on the Chinese market, which is uniquely affected by several significant events, such as the US–China

Table 3
Multivariate portfolio weights.

	Mean	Std.Dev.	Minimum	Maximum	HE	*p*-value
Minimum variance portfolio (MVP)						
Green bond	0.94	0.04	0.83	1.00	0.14	0.01
HS300 ETF	0.01	0.01	0.00	0.04	1.00	0.00
S&P500 ETF	0.00	0.00	0.00	0.01	1.00	0.00
INE oil	0.00	0.00	0.00	0.01	1.00	0.00
SHFE gold	0.00	0.00	0.00	0.01	1.00	0.00
RMB	0.05	0.03	0.00	0.14	0.95	0.00
Minimum correlation portfolio (MCP)						
Green bond	0.14	0.04	0.07	0.25	−55.07	0.00
HS300 ETF	0.23	0.04	0.16	0.37	0.87	0.00
S&P500 ETF	0.11	0.03	0.00	0.18	0.84	0.00
INE oil	0.10	0.03	0.02	0.18	0.96	0.00
SHFE gold	0.16	0.04	0.04	0.24	0.68	0.00
RMB	0.27	0.03	0.17	0.32	−2.00	0.00
Minimum connectedness portfolio (MCoP)						
Green bond	0.20	0.01	0.15	0.33	−88.39	0.00
HS300 ETF	0.11	0.04	0.00	0.36	0.79	0.00
S&P500 ETF	0.15	0.02	0.05	0.29	0.74	0.00
INE oil	0.18	0.02	0.00	0.26	0.94	0.00
SHFE gold	0.19	0.02	0.02	0.28	0.49	0.00
RMB	0.16	0.02	0.00	0.22	−3.79	0.00
Risk-parity portfolio (RPP)						
Green bond	0.65	0.06	0.52	0.77	−1.47	0.00
HS300 ETF	0.03	0.01	0.02	0.06	0.99	0.00
S&P500 ETF	0.03	0.01	0.02	0.05	0.99	0.00
INE oil	0.01	0.00	0.01	0.02	1.00	0.00
SHFE gold	0.05	0.02	0.03	0.11	0.99	0.00
RMB	0.21	0.05	0.12	0.32	0.87	0.00

Note: This table reports the average portfolio weights, standard deviation and the minimum of the portfolio weights and maximum of the portfolio weights, and the hedging effectiveness (HE) for each asset. The *p*-value indicates whether the HE ratio is significant or not.

trade war, the COVID-19 pandemic, and the Russia–Ukraine conflict. These unique contextual factors may account for any deviations in our results from those of studies conducted in different regions or during different time frames.

The connectedness analysis reveals several important findings as follows. First, we find that there is a low level of connectedness between green bonds and other investment markets, highlighting the potential diversification benefits of Chinese green bonds for investors. Second, among all selected markets, the HS300 ETF emerges as a major transmitter to the Chinese green bond market, indicating a stronger linkage between Chinese green bonds and the stock index ETFs than with other investment markets. Third, green bonds typically serve as receivers. However, during the epidemic period, the connectedness fluctuated, and green bonds briefly acted as a shock transmitter. This distinct nature of green bonds was particularly highlighted during the COVID-19 pandemic, where we observed a transition in the role of green bonds from shock receivers to shock transmitters. More precisely, the variation in connectedness is mainly driven by short-term frequency. Fourth, the pairwise results show that during this period, INE oil was the primary recipient of spillovers from the Chinese green bond market, followed by SHFE gold and the RMB.

Regarding the performance of constructing portfolios with green bonds through four different approaches, we note several interesting results. First, we find that portfolios with high weightings in green bonds, such as MVP and RPP, tend to perform better during economic downturns, whereas portfolios like MCP and MCoP offer more substantial returns in stable economic conditions. Second, regarding the dynamic portfolio weights, MVP and RPP allocate a larger share to Chinese green bonds, while MCP and MCoP place greater emphasis on investment diversification. Third, by combining the results of cumulative returns and portfolio weights, we find that portfolios with higher portfolio weights for green bonds tend to offer a stable trend in returns, especially during economic downturns, suggesting that Chinese green bonds can act as a safe asset in hedging risks and portfolio management. Fourth, concerning the results of hedging effectiveness, it is observed that the inclusion of Chinese green bonds in a portfolio significantly reduces the risk of other assets. However, no combination is found to help mitigate the risk of green bond investments. Last, our analysis provides compelling evidence that green bonds should be an integral part of a diversified investment portfolio strategy.

From a policy perspective, our findings have several implications. First, regulators should consider the role of green bonds as a potential hedging tool in investors' portfolios; therefore, it could be vital for broadening the risk management tools available to investors. Regulators could introduce measures to bolster investor confidence, such as developing robust regulatory frameworks for issuing and trading green bonds and mechanisms for increased transparency and information disclosure. This would improve market participants' understanding and, hence, market efficiency. Second, given the spillover effects of green bonds observed during exceptional market circumstances, regulators could consider implementing additional prudential measures to mitigate potential contagion risks. This might involve developing stress-testing mechanisms for investment portfolios involving green bonds and devising prudent investment guidelines for green bond investors. Third, policymakers should exploit the observed trend towards green investment, leveraging this momentum to foster sustainable finance and mitigate climate risks. Initiatives such as tax incentives, standards promotion, and encouragement of green bond issuances can stimulate growth in the green bond market and contribute towards sustainability goals.

An unexpected finding in our study is the significant spillover from green bonds to the INE oil market during the pandemic. This may suggest a heightened investor interest in sustainable alternatives in the face of oil market volatility. This finding opens up new avenues for research into the interactions between traditional and sustainable financial assets during times of crisis. With regard to further directions for future research, there are a number of significant opportunities. The influence of investors' green inclinations on the demand for green bonds and the subsequent impact on portfolio management warrants further examination. Exploring the behavioural aspect of green investment could also yield valuable insights into investor sentiment and decision-making processes, adding a new dimension to the understanding of green bond markets. In addition, future research could delve into a more detailed analysis of the risk-return trade-off for different weights of green bonds in portfolios. Considering investors' diverse risk appetites and return expectations, a more nuanced understanding of this relationship would be beneficial. Finally, given the dynamic nature of financial markets, continual monitoring of the connectedness between green bonds and other financial markets is paramount. Studies examining this interconnectedness during different economic conditions or events, using a wider array of economic variables and financial assets, would further enrich the discourse on the role of green bonds within the financial ecosystem.

CRediT authorship contribution statement

Danyang Xu: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Yang Hu:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Shaen Corbet:** Investigation, Writing – original draft, Writing – review & editing. **Chunlin Lang:** Investigation, Writing – original draft.

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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Chapter 6

Understanding dynamic return connectedness and portfolio strategies among international sustainable exchange-traded funds

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Understanding dynamic return connectedness and portfolio strategies among international sustainable exchange-traded funds ☆

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ABSTRACT

The rapid growth of sustainable investing has led to the global expansion of environmental, social, and governance (ESG) investment products. Existing literature on sustainable investing focuses primarily on corporate social responsibility theory and risk assessment, with relatively little research on ESG investment value and portfolio strategies. Using data from six worldwide ESG exchange-traded funds (ETFs) between 2020 and 2023, we examine return connectedness and portfolio performance by employing a time-varying parameter vector autoregressive (TVP-VAR) and portfolio approaches. The findings reveal that European ETF plays a dominant role in the worldwide ESG system due to the market size and market maturity. Specifically, the European ETF can substantially reduce portfolio volatility. Moreover, the results show that minimum variance and risk-parity portfolios outperform the other portfolio strategies during periods of geopolitical turmoil. These results provide valuable insights for improving the resilience of ESG markets and enhancing sustainable investment strategies.

1. Introduction

With a dual focus on generating long-term financial returns and addressing pressing environmental, social, and governance (ESG) issues, ESG investments are reshaping the financial market landscape. However, recent global crises have raised concerns about the ability of ESG investments to maintain operational stability and serve as effective hedges against financial risks. These concerns underscore the importance of understanding underlying market resilience, the potential benefits of ESG investments, and the limitations and challenges they face in navigating uncertain financial environments, much of which can be furthered through our understanding of market connectedness, which can vary because of several factors. For example, integrating ESG criteria leads to differences in market behaviour compared to traditional financial markets. Investors' motivations in ESG markets often extend beyond financial returns to include ethical considerations and long-term sustainability goals, resulting in unique investment patterns and connectedness.

In recent years, there has been a significant growth in ESG adoption, driven by investors' recognition of the critical role of these non-financial factors in assessing risk and investment opportunities (Linnenluecke et al., 2016; Pástor et al., 2021; Avramov et al., 2022; Pástor et al., 2022). ESG markets inherently exhibit patterns and unique characteristics that differ from those of conventional capital markets. In recent years, the global ESG equity market has demonstrated significant growth, as shown in Fig. 1. Valued at $22 trillion in 2016, it grew to $37.8 trillion by 2021. Furthermore, ESG investment, particularly that within ESG funds, has generated substantial investor attention in recent years. For example, during 2020, a period widely recognised for its instability due to the pandemic outbreak, ESG funds attracted remarkable attention from global investors. The rapid growth of ESG capital and related financial derivatives in recent years has highlighted the importance of the ESG market and revealed significant differences between it and traditional investment markets. Different regions exhibit varying levels of ESG adoption and integration, influenced by local regulations, market maturity, and investor preferences. For instance,

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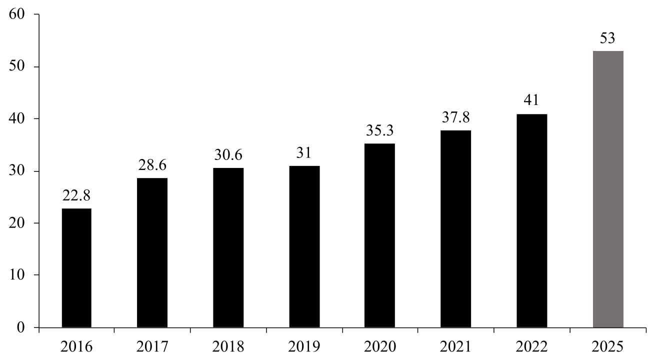

Fig. 1. ESG assets scale (trillion $).
Note: The figure displays the amount of worldwide ESG assets from 2016 to 2022. The data in this figure are taken from Bloomberg Intelligence.

the European market possesses a more mature and stringent regulatory framework for ESG investments, leading to higher degrees of connectedness and market stability. In contrast, emerging markets like China and India are still developing their ESG frameworks, resulting in lower connectedness and higher volatility. These differences in market maturity and regulatory environments could help to explain the varying degrees of connectedness observed among ESG investments globally.

ESG investors prioritise many criteria to guide investment decisions beyond financial returns (Hartzmark and Sussman, 2019; Pástor et al., 2021). For example, pro-social and pro-environmental performance influence their choices (Zerbib, 2019), while ESG indices screen based on social responsibility, enhancing transparency, reducing information asymmetry, and increasing market efficiency (Plastun et al., 2022). Further, ESG investing often yields superior returns with lower risk, especially during crises, due to comprehensive assessments of company quality (Chen and Lin, 2022).[1] More specifically, ETFs are ideal for tracking performance, offering efficient asset allocation, diversification, liquidity management, and hedging opportunities (Miralles-Quirós and Miralles-Quirós, 2019; Akhtaruzzaman et al., 2022a; Naeem et al., 2023a). This study explores return connectedness among ESG ETFs and their reactions to market turmoil driven by rapid ESG market growth. We investigate dynamic return connectedness and analyse portfolio strategies and hedging efficiency using four approaches. This research fills a gap in the literature, focusing on hedging efficiency and portfolio strategies among ESG ETFs.

Specifically, this study addresses the following research questions: (i) what is the interconnectedness among major ESG leaders' index ETFs worldwide? (ii) which region's ESG market drives the ESG leaders' ETF markets? (iii) what are the optimal investment portfolio strategies using ESG leaders' ETFs? (iv) how does the connectedness among ESG indices vary during the COVID-19 outbreak and the ongoing Russia-Ukraine conflict? and (v) how does the evolution of connectedness among ESG ETFs impact portfolio diversification benefits? Through our analysis, we aim to enhance understanding of the resilience and potential benefits of ESG investments while highlighting the limitations and challenges they face in a dynamic financial landscape, providing valuable insights for stakeholders making informed decisions regarding ESG investments in times of uncertainty and beyond. Specifically, our study builds on the work of Chen and Lin (2022) and Iqbal et al. (2022), who quantified spillovers and connectedness in sustainable investments using ESG leader indices from multiple countries. Their findings revealed significant risk contagion among ESG leader stock indices across different countries, emphasising the need for ESG investors to consider this factor when constructing their portfolios.[2]

Our research contributes to the literature in several important ways. First, we provide a novel perspective by evaluating the performance of ESG leaders' equity markets across different regions using six major ESG leaders' index ETFs from both developed and developing markets, including Global, EAFE (Europe, Australasia, and the Far East), US, Canada, China, and India. Unlike previous studies focusing on ESG leaders' equity indices, we select major ESG leaders' ETFs to represent sustainable equity markets globally. ESG ETFs offer cost-effectiveness, diversification, transparency, and suitability for socially responsible investing and tax-efficient investing, making our approach a significant addition to the literature on sustainable investments. Second, this paper is the first to examine the return connectedness and differential behaviour among regional ESG ETFs using the TVP-VAR connectedness approach of Antonakakis et al. (2020). We explore spillover effects from January 2020 to February 2023, covering major global events such as COVID-19 and the Russia-Ukraine war. This study provides new insights into the return transmission mechanisms of global ESG markets during such events, emphasising the importance of monitoring return connectedness to ensure the stability and resilience of these markets. Third, our study extends the existing literature by including portfolio construction strategies using ESG ETFs. While recent research has focused on the connectedness of ESG markets (Chen and Lin, 2022; Iqbal et al., 2022; Naeem et al., 2023b; Umar et al., 2020), optimal portfolio strategies for global ESG investments remain unexplored. We adopt the minimum connectedness portfolio strategy of Broadstock et al. (2022), along with minimum variance, minimum correlation, and risk-parity portfolios. Our analysis of these four models offers a comprehensive view of portfolio management strategies in ESG ETF markets, providing valuable insights for global ESG market investors and hedge fund managers. Fourth, this paper evaluates the hedging effectiveness of sustainable investments in portfolios, an unexplored area. We use the hedging effectiveness ratio of Ederington (1979) to test the performance of each ESG ETF in different portfolio strategies. This measurement, a benchmark for hedging performance, highlights the role and importance of different regional ESG ETFs in reducing portfolio risk. Understanding the hedging effectiveness of ESG investments is crucial for investors and portfolio managers when including ESG assets in investment portfolios. Finally, this paper makes significant contributions that will be cited for its innovative use of ESG ETFs to understand connectedness variations during the COVID-19 and Russia-Ukraine war and for its novel approach to constructing portfolio strategies. Applying the minimum connectedness portfolio approach of Broadstock et al. (2022) demonstrates its effectiveness in portfolio strategies by minimising the connectedness of different assets, assigning higher weights to less influential assets, and offering valuable insights for investment practitioners and policymakers.

Our empirical results indicate a high degree of interdependence among global ESG leaders' ETFs. The total connectedness index peaked in early 2020, reflecting the impact of the COVID-19 outbreak on the ESG market. The EAFE ETF, representing EU markets, emerged as a major transmitter of shocks, while China and the US were primary recipients. Additionally, the Russia-Ukraine conflict significantly affected global ESG markets, particularly in developed countries such as the US and Canada. We applied four investment portfolio strategies and found that the minimum correlation and minimum connectedness portfolios outperformed the benchmark from 2020 to 2021. Conversely,

[1] We also note that the interconnectedness in ESG investments underscores their broader importance (Iqbal et al., 2022). At the same time, economic globalisation has increased the interconnectedness of global equity markets, affecting investment decisions through cross-country contagion dynamics (Chen and Lin, 2022). ESG investors maintain internationally oriented portfolios, emphasising inter-country risk dynamics. Understanding return spillovers in global ESG equity markets is crucial for diversified portfolios (Chen and Lin, 2022).

[2] Our study differs from theirs in both analytical methodology and data used, and it specifically addresses unique research questions that set it apart.

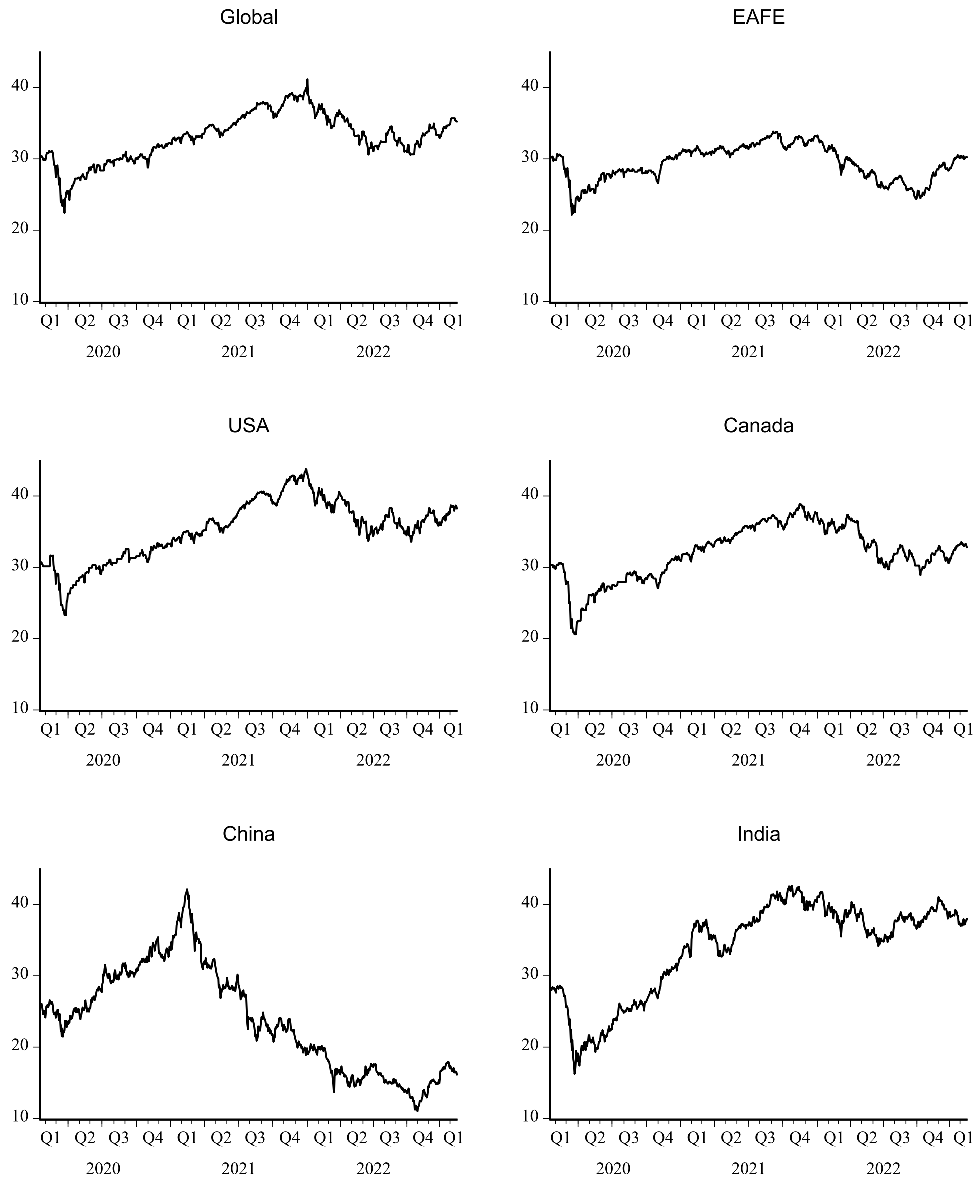

Fig. 2. Time series of ESG leaders' index ETFs.
Note: The above figure depicts the raw times series plot of six ESG Leaders Index ETFs between 21 January 2020 and 13 February 2023.

the minimum variance and risk-parity portfolios yielded better returns during the Russia-Ukraine conflict. The EAFE ETF notably improved hedging effectiveness and diversification opportunities across all strategies. These findings offer valuable insights into generating returns and managing risks in ESG markets under varying conditions. The economic rationale behind the observed connectedness in ESG investments is multifaceted. This interconnectedness is driven by a shared global commitment to sustainability, aligning investor behaviour and market responses across regions. Institutional investors' growing emphasis on ESG factors leads to synchronised investment patterns, amplifying market connectedness. Furthermore, integrating ESG criteria into investment decisions creates a feedback loop where positive ESG performance attracts more investment, reinforcing this interconnectedness.

The rest of this paper is structured as follows: Section 2 provides an overview of the related literature, while Section 3 summarises the utilised data and the econometric methodologies developed to examine the stated research questions. Section 4 presents the empirical findings, while Section 5 concludes.

2. Previous literature

When considering the interaction effects between ESG-based financial products and financial shocks, several research areas have been used as a foundation for the following research. Considering ESG performance, a complex network of factors and outcomes has emerged. Luo et al. (2023) identified that ESG ambiguity affected the perceptions of ESG-sensitive agents, while Zou et al. (2023) confirmed that ESG rating confusion widened the bond spread. Trinh et al. (2023) found a nuanced interaction between Corporate Social Responsibility (CSR) intensity and financial crises. At the same time, no protective effect was evident during the global financial crisis of 2007–2009, where banks with high social capital and trust, embodying socially responsible practices exhibited lower tail risks in other crises. The early stages of the COVID-19 pandemic saw firms with higher ESG scores outperforming their peers, an advantage that Eisenkopf et al. (2023) noted as transient. Considering portfolio performance, Dumitrescu et al. (2023) observed under-performance of equally weighted Socially Responsible Investment (SRI) ETF portfolios relative to their benchmark

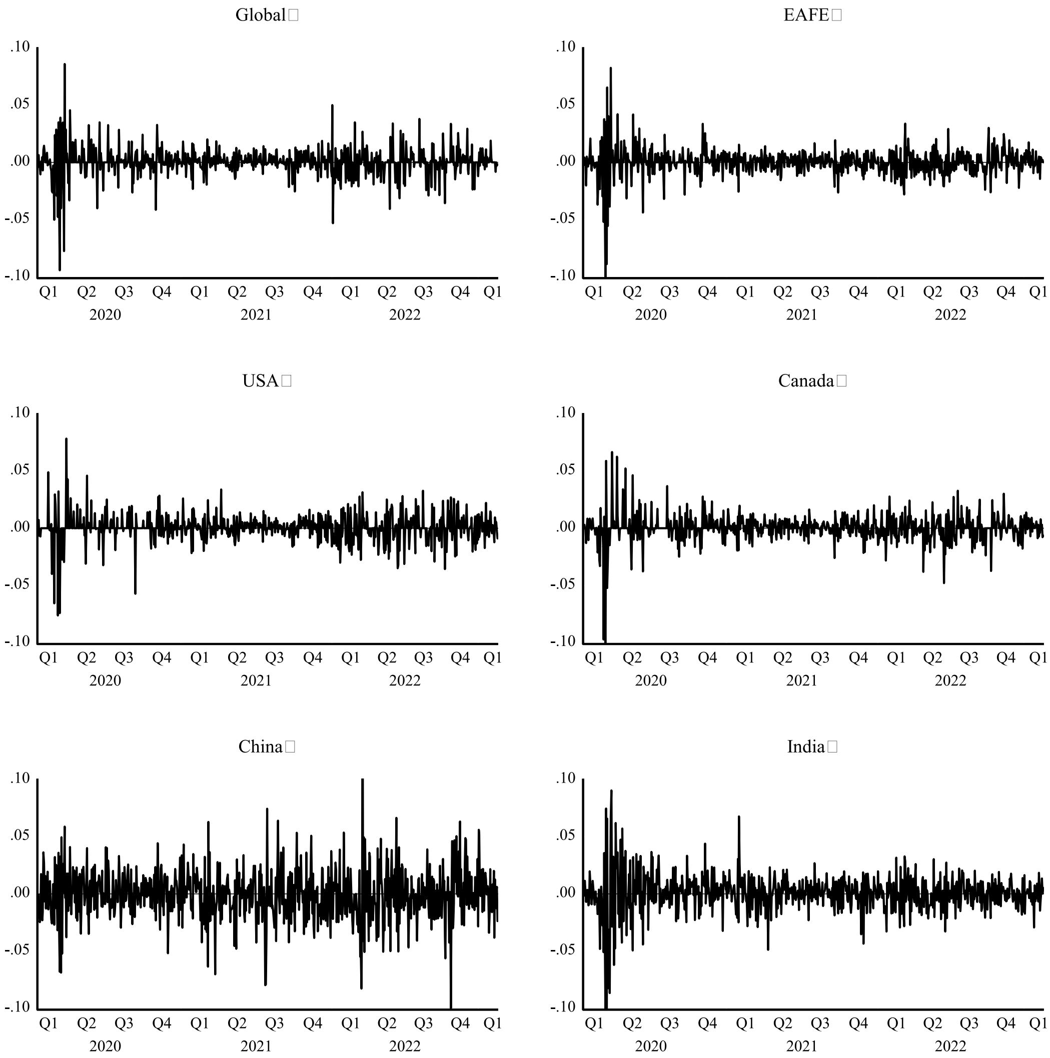

Fig. 3. Log return series plot of ESG leaders' index ETFs.
Note: The above figure depicts the log return series plot of six ESG Leaders Index ETFs between 21 January 2020 and 13 February 2023.

counterparts in the long term. However, recent times have seen a reversal of this trend. Lei et al. (2023) suggested palladium best represented a short-term safe haven for developed ESG markets in North America, Europe, and the Asia-Pacific, while gold provided weak protection over most of the analysed period.

The role of climate news in influencing market behaviour was quantified by Engle et al. (2020), who built hedge portfolios to effectively counter climate news innovations, demonstrating commendable performance when controlled for ESG factors. Investigating the interconnectedness of major global equity indices based on ESG performance, Umar et al. (2020) found significant transmission effects, underscoring the global influence of ESG factors. This global aspect is reinforced by Capelle-Blancard et al. (2019), who linked strong ESG performance to lower default risk and sovereign bond yield spreads across countries.

The growth of green finance has been significantly impacted by green bonds and regulations, according to Li et al. (2022), who noted their critical role in fostering investment in renewable energy sources. However, a nuanced view of ESG portfolio performance was presented by Beloskar and Rao (2023), who identified a trade-off between superior investment performance and the unsystematic risk of ESG portfolios. Chen and Lin (2022) found that the main risk transmitters to the global ESG investment market were the North American and EU markets.

Cepni et al. (2023) presented an interesting perspective on the resilience of ESG investments during periods of high climate uncertainty, with evidence suggesting lower shock transmissions between conventional and ESG assets, indicating potential diversification benefits. Further complexity in ESG performance was highlighted by Nofsinger and Varma (2014), who noted that asymmetric return patterns were predominantly driven by ESG-focused mutual funds, with the effect especially pronounced for funds using positive screening techniques.

Examining the Chinese context, Liu et al. (2023) highlighted the Chinese government's dual approach of advocating for ESG investment and green finance while stabilising the financial market. In contrast, Zhang et al. (2023) found a positive association between ESG performance and fund downside risk from July 2018 through March 2021. Further, Avramov et al. (2022) suggested that ESG uncertainty can impact the risk-return trade-off, social impact, and economic welfare, while Tsai and Wu (2022) found a general value enhancement associated with improved CSR incorporation. Other influential factors in explaining ESG performance were identified by Blomqvist and Stradi (2022), Anquetin et al. (2022), Nofsinger and Varma (2023), and Choy et al. (2023), who pointed to political views, carbon risk disclosures, and social capital as significant determinants.

Research based on the investigation of dynamic connectedness between financial markets has developed substantially over time. Focusing on energy commodities, Lovcha and Perez-Laborda (2020) identified long-lasting market transitions. In contrast, market interactions due

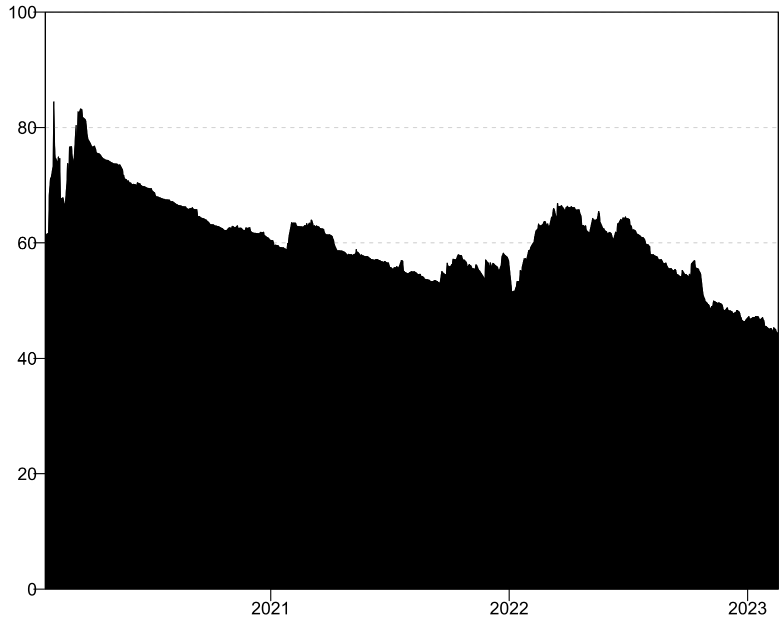

Fig. 4. Dynamic total connectedness.
Note: This figure presents the dynamic total connectedness index of the network from 2020 to 2023. The results are obtained using a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead forecast.

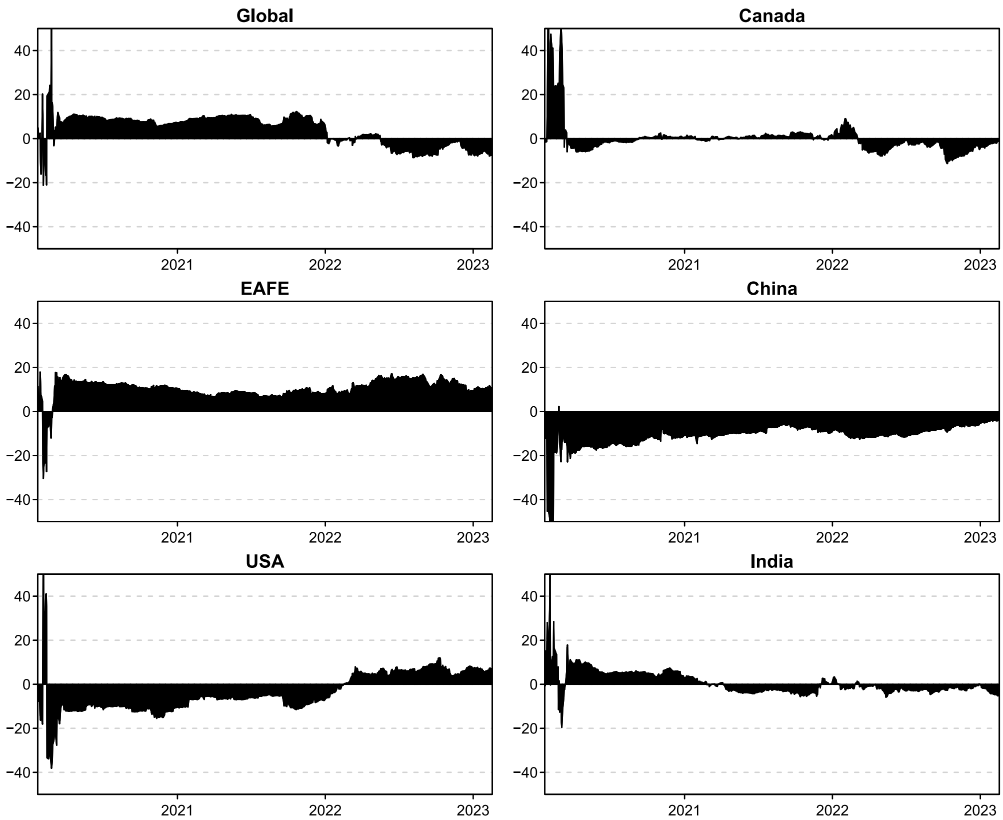

Fig. 5. Dynamic net total directional connectedness.
Note: This figure presents the dynamic net connectedness index of the network from 2020 to 2023. The results are obtained using a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead forecast. A positive value of the connectedness index indicates that the variable is a transmitter of the shock, while a negative value acts as a shock receiver in the system.

to economic policy uncertainty were investigated by Lien et al. (2022), where larger connectedness is identified in high-volatility states. Such behavioural differentials have also been examined across developing financial market products such as cryptocurrency (Zeng et al., 2020). When investigating the connectedness of the most significant global equity indices with corporate ESG performance, Umar et al. (2020) identify that dynamic connectedness patterns are exhibited during the European sovereign debt crisis, the systemic Greek problems, and the

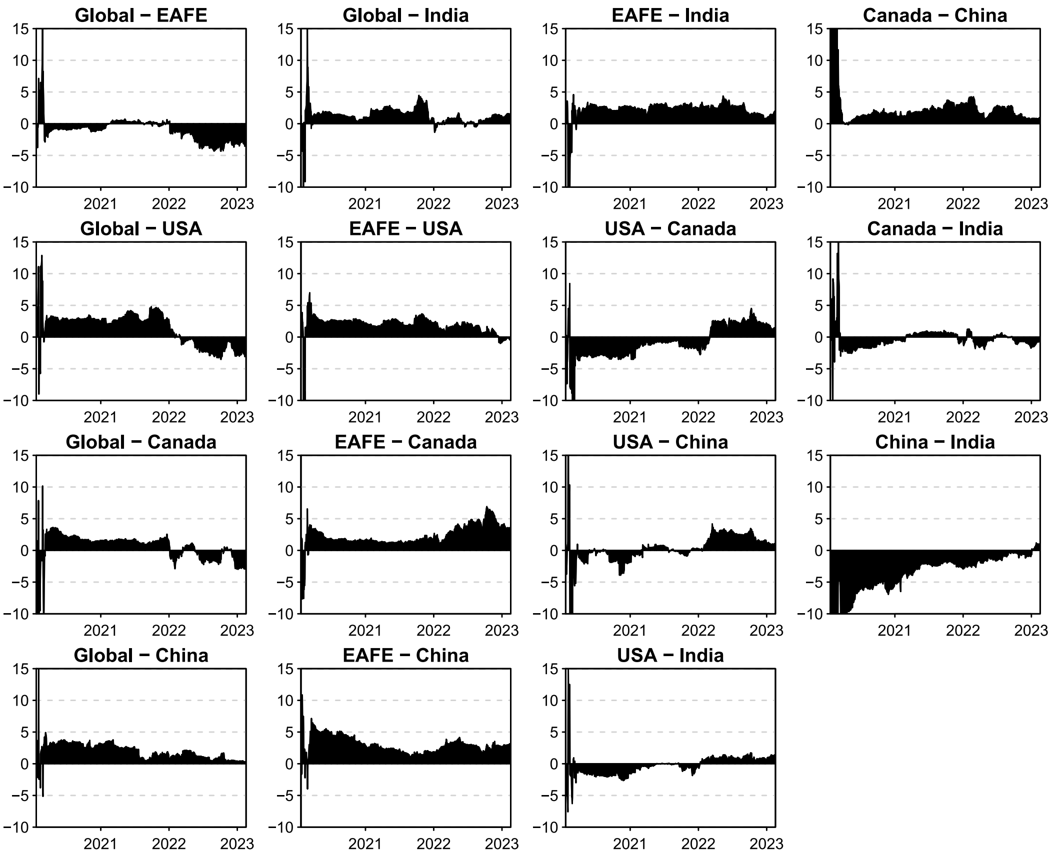

Fig. 6. Dynamic pairwise directional connectedness.
Note: This figure presents the dynamic pairwise connectedness index of the network from 2020 to 2023. The results are obtained using a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead forecast. A positive value of the pairwise connectedness index indicates that the first variable serves as a transmitter within the matched pair. In contrast, a negative value implies its role as a recipient.

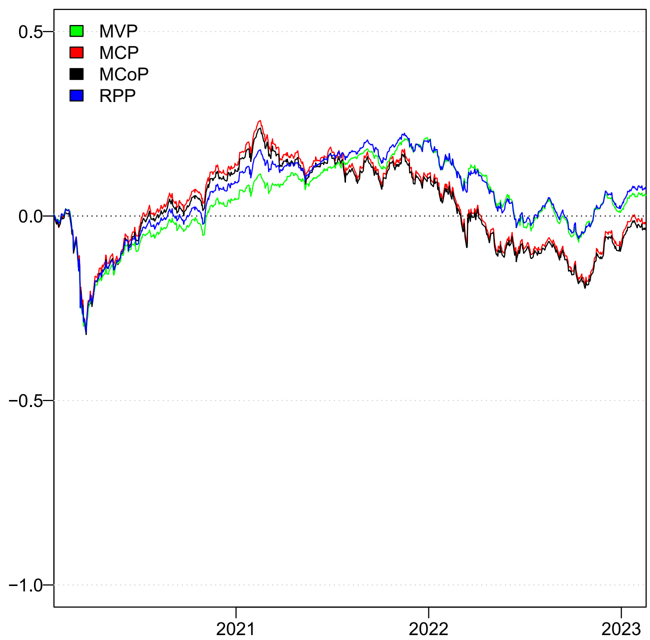

Fig. 7. Cumulative portfolio returns.
Note: This figure displays the cumulative returns of four different portfolios from 2020 to 2023. Four portfolio strategies are considered, including minimum variance portfolios (MVP), minimum correlation portfolios (MCP), minimum connectedness portfolios (MCoP), and risk-parity portfolios (RPP).

outbreak of the coronavirus pandemic. Dynamic behaviour due to black-swan events has also been considered (Aparicio et al., 2018; Irungu et al., 2020; Corbet et al., 2021b; Kyriazis et al., 2023b,a; Goodell et al., 2022; Gozgor et al., 2022; Akyildirim et al., 2023; Dai et al., 2023), including those resulting from the COVID-19 pandemic (Corbet et al., 2021a).

3. Data and methodology

3.1. Data

We collect data based on six distinct ESG leaders Index ETFs from the Eikon database, including BMO MSCI US ESG Leaders Index (US), BMO MSCI China ESG Leaders Index ETF (China), BMO MSCI India ESG Leaders Index ETF (India), BMO MSCI Canada ESG Leaders Index ETF (Canada), BMO MSCI EAFE ESG Leaders Index ETF (EAFE) and BMO MSCI Global ESG Leaders Index ETF (Global).[3] We select the major ESG Leaders Index ETFs for several reasons. First, as suggested by several studies (for example, Akhtaruzzaman et al. (2022b), Iqbal et al. (2022) and Umar et al. (2021)), the ESG leader's equity indices represent companies with the highest level of ESG risk management and thus serve as a proxy for the overall state of the ESG equity investment landscape. Understanding the dynamics of the ESG Index is critical to understanding how financial markets respond to sustainability factors. Second, ESG Leaders indices have been widely used in the literature as the proxy for ESG investments (Umar et al., 2020; Chen and Lin,

[3] BMO is a financial services company based in Canada that offers a range of banking, investment, and wealth management services.

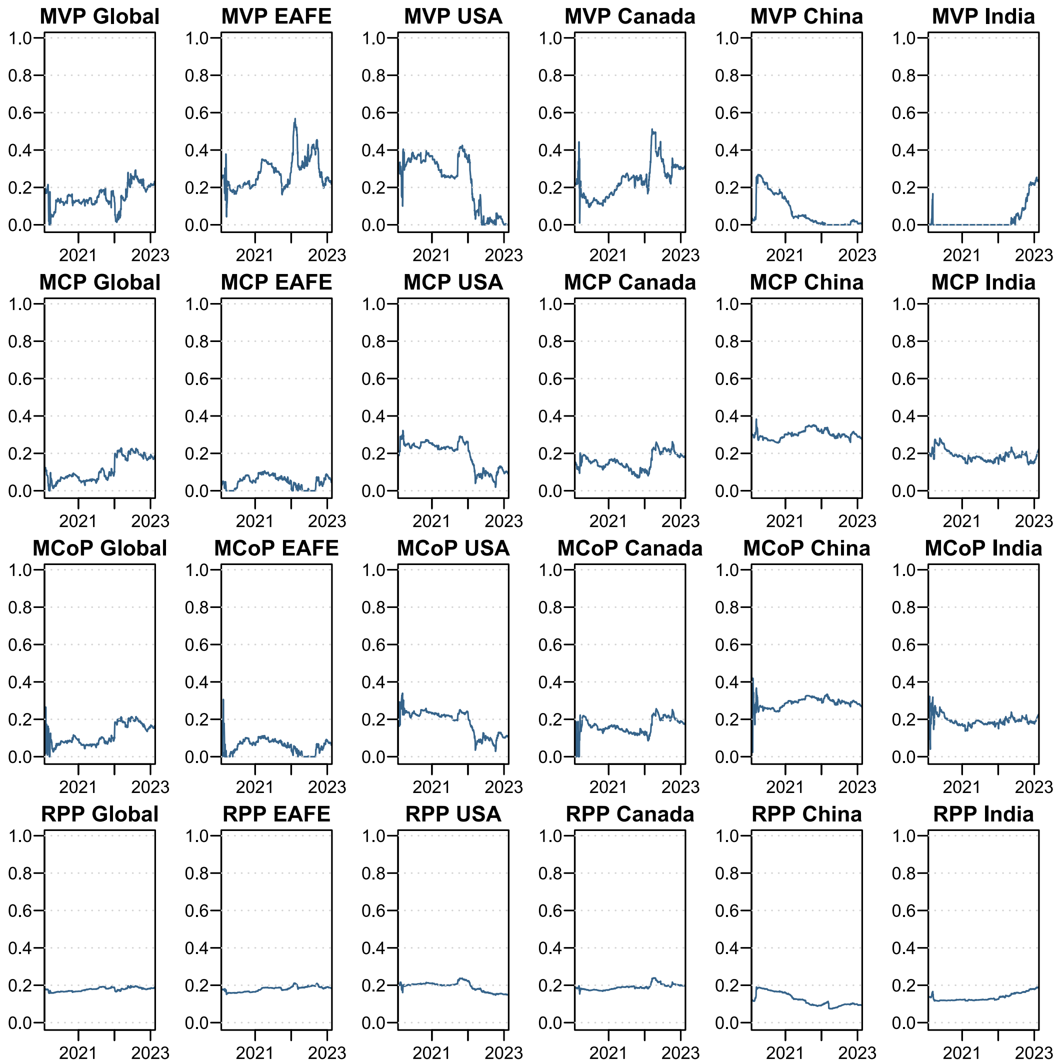

Fig. 8. Dynamic multivariate portfolio weights.
Note: This figure displays the dynamic portfolio weights based on four different investment portfolio strategies, including minimum variance portfolios (MVP), minimum correlation portfolios (MCP), minimum connectedness portfolios (MCoP), and risk-parity portfolios (RPP).

2022; Akhtaruzzaman et al., 2022b). Thirdly, according to Yan and Garcia (2017), the evaluation of an asset class can solely rely on the underlying financial instrument and not that of an index. As discussed in Miralles-Quirós and Miralles-Quirós (2019), the optimal method to monitor asset performance is trading ETFs. In this paper, the ESG Leaders Index ETF is designed to replicate, as closely as possible, the performance of the corresponding ESG Leaders Index.[4] Fourth, these ESG indices provide insights into the performance and risk exposure of those companies based on their environmental, social, and governance practices. Moreover, understanding these ESG ETFs helps investors assess the effectiveness of integrating ESG factors into making informed investment decisions. Fifth, these ESG indices include both developed and developing markets with a high level of investment in ESG in terms of both size and breadth.[5]

Analysed data spans[6] the period 21 January 2020 through 17 February 2023. Summary statistics for each ESG leader's index ETFs are presented in Table 1, presenting data for Global, EAFE, US, Canada, China, and India. The results reveal that all the ETFs exhibit a positive return, except for the Chinese ESG ETF, and each presents a relatively small variance. Furthermore, the skewness and kurtosis coefficients for all series suggest a negatively skewed and peaked distribution, except for the Chinese ETF, which presents evidence of a positively skewed and peaked distribution. The results of additional testing procedures show that all ETFs present evidence of stationarity, are autocorrelated, and exhibit ARCH/GARCH error at a significance at the 1% level. Furthermore, unconditional correlation analysis demonstrates that all ESG leaders' ETFs are positively correlated. Notably, the highest correlation coefficient is observed between EAFE and India, followed by EAFE and Global, while the lowest correlation is recorded between the US and China.

In Fig. 2, we observe the time series for each respective ESG index ETF. It is evident that all ESG leaders' index ETFs exhibit comparable patterns with weak upward trends from 2020 to early 2023, except for

[4] For example, the objective of the USA ESG Leaders Index ETF is to emulate the performance of the USA ESG Leaders Index closely.

[5] As ESG leaders' equity investors may prefer to construct a portfolio with a combination of international ESG assets, these ESG ETF indices are ideal candidates for exploring the connectedness and potential portfolio diversification benefits among major sustainable investments.

[6] This selection was made subject to data availability, as the inception date for these ESG Leaders Index ETFs was 21 January 2020.

Table 1
Summary statistics.

	Global	EAFE	US	Canada	China	India
Mean	0.000	0.000	0.000	0.000	−0.001	0.000
Variance	0.0001	0.0001	0.0001	0.0001	0.001	0.0002
Skewness	−0.648***	−0.955***	−0.546***	−1.659***	0.819***	−0.839***
Ex.Kurtosis	11.435***	16.690***	9.050***	23.401***	9.347***	10.070***
JB	4194.132***	8936.685***	2631.313***	17688.639***	2851.523***	3300.441***
ERS	−7.050***	−8.381***	−7.447***	−9.921***	−12.614***	−10.765***
Q2(20)	341.726***	616.104***	114.975***	192.390***	41.031***	921.655***
Uncond. corr.	Global	EAFE	US	Canada	China	India
Global	1.000	0.553	0.486	0.468	0.261	0.461
EAFE	0.553	1.000	0.431	0.494	0.328	0.596
US	0.486	0.431	1.000	0.529	0.203	0.318
Canada	0.468	0.494	0.529	1.000	0.258	0.352
China	0.261	0.328	0.203	0.258	1.000	0.309
India	0.461	0.596	0.318	0.352	0.309	1.000

Note: This table reports the descriptive statistics for each ETF and results of the skewness, kurtosis, JB normality and the ERS unit root tests. The lower panel of the table presents unconditional correlation results.

*** Indicates significance at the 1% level.

Table 2
Major BMO ESG leaders exchange-traded funds (ETFs).

Fund name	Inception date	Ticker	Top holdings
BMO MSCI US ESG Leaders Index ETF (This ETF is designed to measure the performance of the MSCI US ESG Leaders Index, net of expenses. This ETF invests in U.S. companies that have higher MSCI ESG ratings.)	January 2020	ESGY	MICROSOFT CORP (10.17%), NVIDIA CORP (3.32%), TESLA INC (3.15%), ALPHABET INC (3.11%), JOHNSON & JOHNSON (2.32%), VISA INC (2.07%), PROCTER & GAMBLE CO/THE (1.89%) MASTERCARD INC (1.76%), HOME DEPOT INC/THE (1.75%).
BMO MSCI China ESG Leaders Index ETF (This ETF is designed to measure the performance of the MSCI China ESG Leaders Index (Index). This ETF invests in Chinese companies that have higher MSCI ESG ratings.)	January 2010	ZCH	TENCENT HOLDINGS (26.45%), ALIBABA GROUP HOLDING (15.69%), MEITUAN (7.33%), CHINA CONSTRUCTION BANK CORP (5.66%), BAIDU INC (3.67%), NETEASE INC (2.95%), WUXI BIOLOGICS CAYMAN INC (2.43%), YUM CHINA HOLDINGS INC (2.37%), BYD CO LTD (2.13%), CHINA MERCHANTS BANK CO LTD (2.04%)
BMO MSCI India ESG Leaders Index ETF (This ETF is designed to measure performance of the MSCI India ESG Leaders Index (Index). The ETF invests in Indian companies that have higher MSCI ESG ratings.)	January 2010	ZID	RELIANCE INDUSTRIES LTD (19.67%), INFOSYS LTD (13.96%), HOUSING DEVELOPMENT FINANCE CORP (12.53%), TATA CONSULTANCY SERVICES (8.53%), HINDUSTAN UNILEVER LTD (5.71%), AXIS BANK LTD (5.40%), HCL TECHNOLOGIES LTD (3.36%), MAHINDRA & MAHINDRA LTD (3.18%), ASIAN PAINTS LTD (3.12%), KOTAK MAHINDRA BANK LTD (2.77%).

Note: BMO ETFs are managed by BMO Asset Management Inc., an investment fund manager and a portfolio manager and a separate legal entity from Bank of Montreal.

Table 3
Major BMO ESG leaders exchange-traded funds (ETFs).

Fund name	Inception date	Ticker	Top holdings
BMO MSCI Canada ESG Leaders Index ETF (This ETF is designed to measure the performance of the MSCI Canada ESG Leaders Index, net of expenses. The ETF invests in Canadian companies that have higher MSCI ESG ratings.)	January 2020	ESGA	TORONTO-DOMINION BANK/THE (13.54%), ENBRIDGE INC (8.49%), CANADIAN NATIONAL RAILWAY CO (7.48%), BANK OF MONTREAL (7.11%), BANK OF NOVA SCOTIA/THE (6.61%), SHOPIFY INC (5.46%), BROOKFIELD CORP (5.23%), NUTRIEN LTD (4.70%), ALIMENTATION COUCHE-TARD INC (4.29%), INTACT FINANCIAL CORP (2.82%)
BMO MSCI EAFE ESG Leaders Index ETF (This ETF is designed to measure the performance of the MSCI EAFE ESG Leaders Index, net of expenses. The ETF invests in companies with higher MSCI ESG ratings within developed equity markets, excluding Canada and the U.S.)	January 2020	ESGE	ASML HOLDING NV (3.25%), NOVO NORDISK A/S (3.03%), LVMH MOET HENNESSY LOUIS VUITTON SE (3.00%), ROCHE HOLDING AG (2.63%), ASTRAZENECA PLC (2.62%), TOTALENERGIES SE (1.99%), HSBC HOLDINGS PLC (1.97%), UNILEVER PLC (1.63%), AIA GROUP LTD (1.63%), SAP SE (1.53%).
BMO MSCI Global ESG Leaders Index ETF (This ETF is designed to measure the performance of the MSCI Global ESG Leaders Index, net of expenses. The ETF invests in companies with higher MSCI ESG ratings within global developed equity markets.)	January 2020	ESGG	BMO MSCI US ESG Leaders Index ETF (67.04%), BMO MSCI EAFE ESG Leaders Index ETF (29.54%), BMO MSCI Canada ESG Leaders Index ETF (3.39%), Cash (0.03%).

Note: BMO ETFs are managed by BMO Asset Management Inc., an investment fund manager and a portfolio manager and a separate legal entity from Bank of Montreal.

the China ESG leaders' ETFs. Moreover, it can be observed that each ETF has two distinct phases of decline, occurring at the beginning of both 2020 and 2022, reflecting the enormous impact of two global events, the COVID-19 pandemic and the Russia-Ukraine war, on the global ESG investment market. Further, Fig. 3 illustrates the log return series of each presented ETF.

Tables 2 and 3 provides an overview of the six distinct ESG leaders index ETFs with key associated information relating to the fund name,

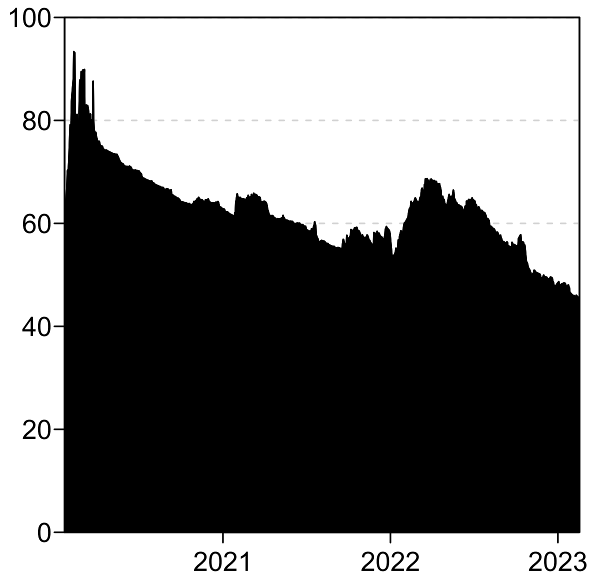

Fig. 9. Dynamic total connectedness- (robustness check 1).
Note: The robustness check results are obtained using a TVP-VAR model with a lag length of order two, a 20-step-ahead forecast horizon and a Minnesota prior.

the inception date, each respective ticker, and the top external holdings of each ETF, where such evidence allows for the comparison of the presented ETFs. As observed, the top holdings in each ETF are quite different. For example, US ESG Leaders Index ETF invests in US companies with higher ESG ratings while the Global index ETF invests in developed markets, including 67% in the US index ETF, around 30% EAFE index ETF and 3% in the Canada index ETF. On the other hand, the EAFE index ETF mainly invests in high-ESG score companies in Europe, which accounts for more than 50% of total holdings in EAFE.

3.2. Methodology

This paper adopts a two-stage modelling process to provide a thorough empirical analysis. In the first stage, we apply the Time-Varying Parameter Vector Autoregression (TVP-VAR) connectedness method (Antonakakis et al., 2020) to examine the connectedness and spillovers between various benchmark ESG ETFs. This study has chosen The TVP-VAR model over alternative models due to several distinct advantages. Firstly, with a time-varying covariance structure, the TVP-VAR model allows the investigation of dynamic interactions between variables, including the possibility of changing relationships over time, making it an ideal tool for examining financial market connectedness. Secondly, the TVP-VAR framework does not need to arbitrarily set up rolling-window size or a loss of observations, as no rolling-window analysis is needed for the TVP-VAR framework. In addition, this framework relies on a multivariate Kalman filter, which is less sensitive to outliers. Thirdly, it offers considerable flexibility, allowing us to incorporate time-varying structures into the autoregressive parameters and the variance–covariance matrix of the errors. This flexibility is crucial because financial data often shows changes in structure, regime shifts, and periods of high volatility. Fourthly and more importantly, following Broadstock et al. (2022), we obtain the estimated time-varying variance–covariance matrix of the TVP-VAR model for constructing multiple portfolio strategies.

In the second stage, we construct portfolio strategies using both the traditional approaches (e.g., the minimum variance portfolio procedure of Durand (1960), minimum correlation portfolio procedure of Christoffersen et al. (2014) and risk-parity portfolio procedure of Maillard et al. (2010) and a recently developed minimum connectedness portfolio approach of Broadstock et al. (2022). This paper considers the minimum connectedness portfolio procedure of Broadstock et al. (2022) as one of the main portfolio models in the portfolio strategies section.[7]

3.2.1. TVP-VAR-based connectedness approach

The TVP-VAR connectedness approach of Antonakakis et al. (2020) has become a popular method in the literature for estimating the interconnectedness among various markets. This can be attributed to its unique benefits, such as the ability to produce results not affected by the size of the rolling window and the absence of loss of observations. Moreover, the TVP-VAR approach can examine connectedness for low-frequency datasets, adding to its appeal as a valuable analytical tool. The TVP-VAR(p) model may be expressed as follows:

$$y_t = A_t z_{t-1} + \epsilon_t \quad \epsilon_t \mid \Omega_{t-1} \sim N\left(\mathbf{0}, \Sigma_t\right) \tag{1}$$

$$\text{vec}\left(A_t\right) = \text{vec}\left(A_{t-1}\right) + \xi_t \quad \xi_t \mid \Omega_{t-1} \sim N\left(\mathbf{0}, \Sigma_t\right) \tag{2}$$

where $z_{t-1} = [y_{t-1}, \dots, y_{t-p}]'$. Next, the Generalised Forecast Error Variance Decomposition (GFEVD) of Koop et al. (1996) and Pesaran and Shin (1998) can be interpreted as the effect a shock in variable j has on variable i in terms of its forecast error variance and can be expressed in the following manner:

$$\phi^g_{ij,t}(H) = \frac{S^{-1}_{ii,t} \sum_{t=1}^{H-1} \left(\iota_i' A_t S_t \iota_j\right)^2}{\sum_{j=1}^{k} \sum_{t=1}^{H-1} \left(\iota_i A_t S_t A_t' \iota_i\right)} \tag{3}$$

$$\tilde{\phi}^g_{ij,t}(H) = \frac{\phi^g_{ij,t}(H)}{\sum_{j=1}^{k} \phi^g_{ij,t}(H)} \tag{4}$$

where $\sum_{j=1}^{k} \tilde{\phi}^g_{ij,t}(H) = 1$, $\sum_{i,j=1}^{k} \tilde{\phi}^g_{ij,t}(H) = K$.

Further, the total connectedness index (TCI) can be constructed by:

$$C_t(H) = \frac{\sum_{i,j=1, i\neq j}^{m} \tilde{\phi}_{ij,t}(H)}{\sum_{i,j=1}^{m} \tilde{\phi}_{ij,t}(H)} * 100 = \frac{\sum_{i,j=1, i\neq j}^{m} \tilde{\phi}_{ij,t}(H)}{m} * 100 \tag{5}$$

The total directional connectedness to others measures how variable i transmits its shock to all other variables j and is defined as:

$$C_{i\to j,t}(H) = \frac{\sum_{j=1, i\neq j}^{m} \tilde{\phi}_{ji,t}(H)}{\sum_{j=1}^{m} \tilde{\phi}_{ji,t}(H)} * 100. \tag{6}$$

whereas, the total directional connectedness from others measures the directional connectedness variable i receives from variables j and can be calculated as:

$$C_{i\leftarrow j,t}(H) = \frac{\sum_{j=1, i\neq j}^{m} \tilde{\phi}_{ij,t}(H)}{\sum_{i=1}^{m} \tilde{\phi}_{ij,t}(H)} * 100. \tag{7}$$

Next, the net total directional connectedness can be calculated by subtracting total directional connectedness to others from total directional connectedness from others. The net total directional connectedness measures the influence that variable i has upon the entire network. The net total directional connectedness is defined as:

$$C_{i,t} = C_{i\to j,t}(H) - C_{i\leftarrow j,t}(H) \tag{8}$$

If $C_{i,t} > 0$, it means that variable i influences the network more than the opposite direction. On the other hand, if $C_{i,t} < 0$, then variable i is driven by the network. The net pairwise directional connectedness

[7] We are aware of alternative methodologies to analyse spillover, contagion, and connectedness, for example, dynamic copulas with and without regime-switching, asymmetric dynamic conditional correlation, non-parametric approaches, wavelet coherence analysis, etc. Overall, the TVP-VAR model has been selected for our analysis due to its capacity to strike an optimal balance between model complexity and interpretability, aligning with the specific research objectives of this study to perform a portfolio model analysis.

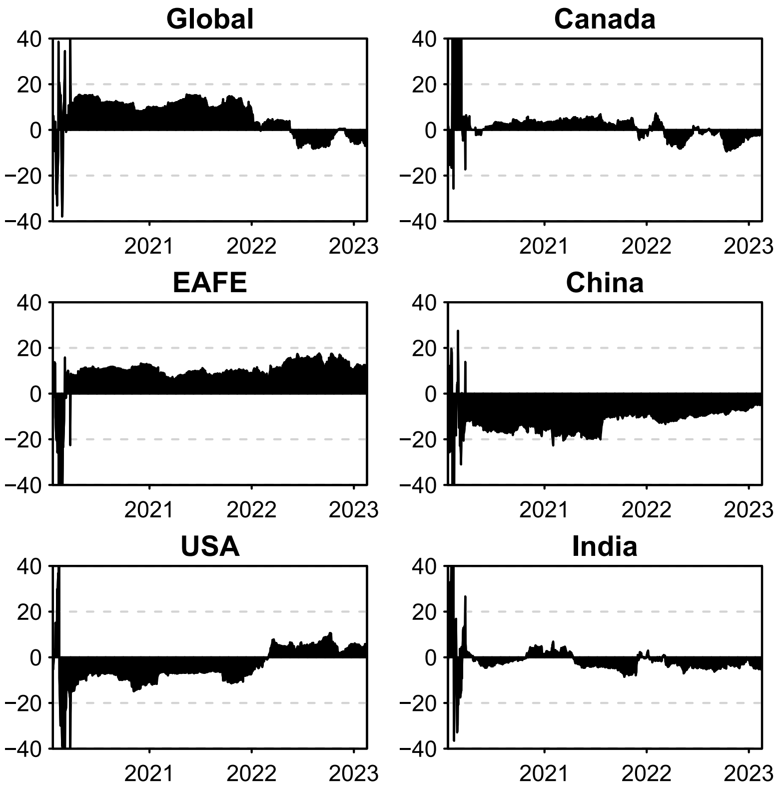

Fig. 10. Dynamic net total directional connectedness (robustness check 1).
Note: The robustness check results are obtained using a TVP-VAR model with a lag length of order two, a 20-step-ahead forecast horizon and a Minnesota prior.

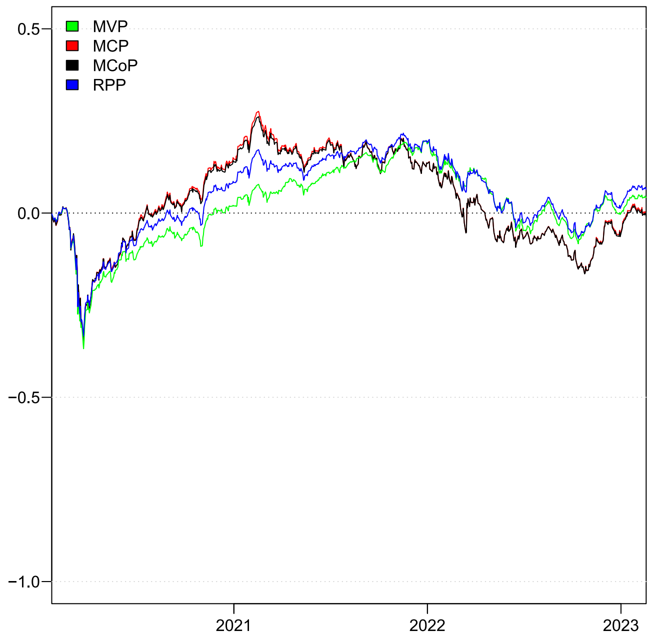

Fig. 11. Cumulative portfolio returns (Robustness check 1).
Note: (Robustness check 1) This figure displays the cumulative returns of four different portfolios for the period 2020 to 2023. Four portfolio strategies are considered, including minimum variance portfolios (MVP), minimum correlation portfolios (MCP), minimum connectedness portfolios (MCoP), and risk-parity portfolios (RPP).

can be used for examining bidirectional relationships between variable i and variable j:

$$NPDC_{ij}(H) = \left(\tilde{\phi}_{jit}(H) - \tilde{\phi}_{ijt}(H)\right) * 100 \tag{9}$$

If $NPDC_{ij}(H) > 0$, variable i dominates variable j. If $NPDC_{ij}(H) < 0$, variable i is dominated by the variable j. The net pairwise directional connectedness between variables i and j represents the difference between the gross shocks transmitted from variable i to variable j and those transmitted from variable j to variable i.

3.2.2. Estimated portfolio strategy approach

Subsequently, we employ four alternative portfolio strategies, namely the minimum variance portfolio, the minimum correlation portfolio, the minimum connectedness portfolio, and the risk-parity portfolio, to examine the profitability and hedging efficiency of major ESG-related ETFs. The minimum variance portfolio (MVP) approach of Durand (1960) is employed in this paper. The weights of the portfolio are calculated as follows:

$$w_t = \frac{H_t^{-1} I}{I H_t^{-1} I} \tag{10}$$

where w_t denotes the portfolio weight vector, H_t depicts the conditional variance–covariance matrix. The minimum correlation portfolio (MCP) of Christoffersen et al. (2014) is another popular approach. The MCP portfolio is constructed by minimising the assets' correlations with other assets. The formula for calculating the portfolio weights is as follows:

$$R_t = \text{diag}\left(H_t\right)^{-0.5} H_t \,\text{diag}\left(H_t\right)^{-0.5} \tag{11}$$

$$w_t = \frac{R_t^{-1} I}{I R_t^{-1} I} \tag{12}$$

where R_t is a dimensional matrix and w_t is the minimum correlation portfolio weight. The minimum connectedness portfolio (MCoP) was recently developed by Broadstock et al. (2022), which creates a portfolio with the aim of minimising bilateral interdependence among variables. This can be expressed as follows:

$$w_t = \frac{PCI_t^{-1} I}{I PCI_t^{-1} I} \tag{13}$$

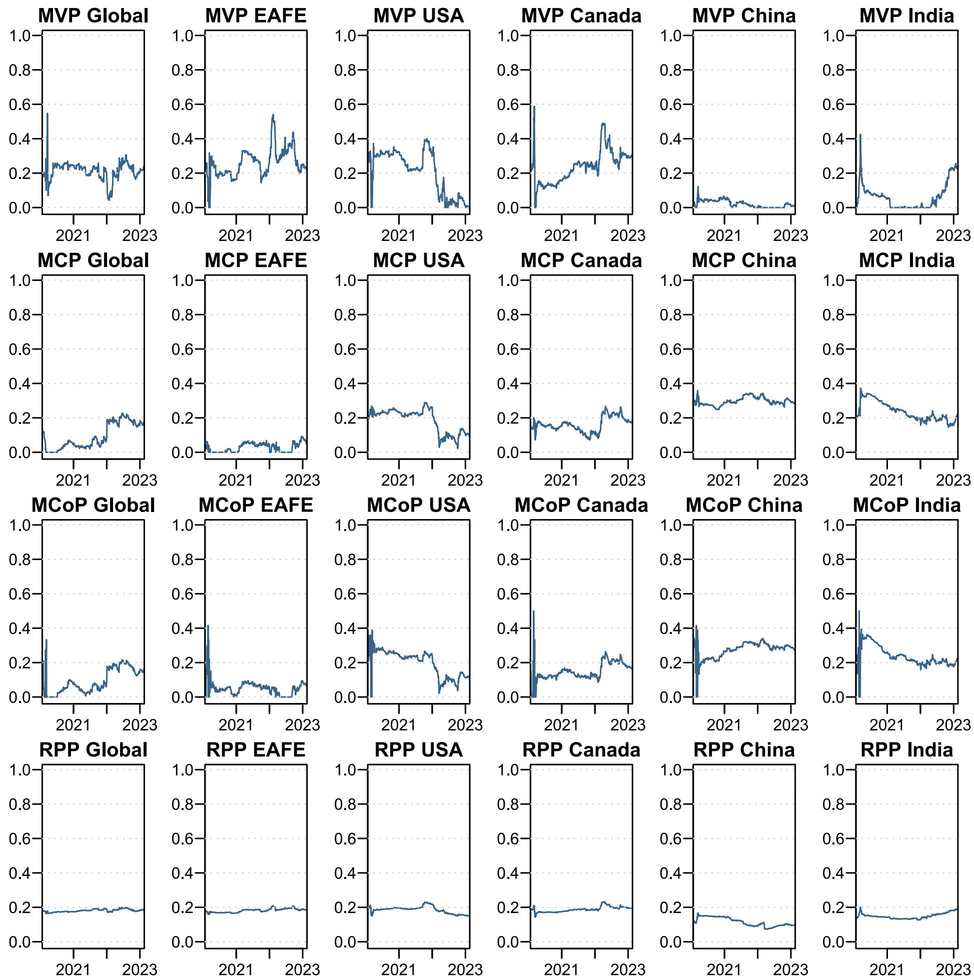

Fig. 12. Dynamic multivariate portfolio weights (Robustness check 1).
Note: (Robustness check 1) This figure displays the dynamic portfolio weights based on four different investment portfolio strategies, including minimum variance portfolios (MVP), minimum correlation portfolios (MCP), minimum connectedness portfolios (MCoP), and risk-parity portfolios (RPP).

where PCI_t denotes the connectedness index matrix and I is the identity matrix. The risk-parity portfolio (RPP) of Maillard et al. (2010) is also applied to portfolio constructions. The RPP approach obtains the portfolio's weight based on the same share of risk contribution. The optimal weight is specified as follows:

$$\min \sum_{i,j=1}^{N} \left(w_{it} \left(H_t w_t \right)_i - w_{jt} \left(H_t w_t \right)_j \right)^2. \quad (14)$$

In order to test the hedging performance of each ESG ETF in the portfolio, we apply the hedge effectiveness approach of Ederington (1979). The equation is given by:

$$HE = 1 - \frac{\text{Var}\left(y_p\right)}{\text{Var}\left(y_{\text{unhedged}}\right)} \quad (15)$$

where $\text{Var}\left(y_p\right)$ is the variance of the portfolio returns, $\text{Var}\left(y_{\text{unhedged}}\right)$ indicates the variance of the unhedged asset, HE shows the hedge efficiency of each ESG ETF.

4. Empirical results

4.1. Connectedness results

We begin by examining the average connectedness results presented in Table 4, illustrating the static connectedness among all ESG leaders' ETFs, excluding the impact of time-varying and extreme events on the global ESG leaders' equity system.

The estimated Total Connectedness Index (TCI), representing the overall network connectedness, stands at a relatively high average of 50.55%. This indicates a strong interdependence among the ESG leaders' index ETFs throughout the sample period, suggesting a high level of integration within the global ESG investment system. The NET value, derived from the difference between the TO and FROM values, illustrates the role of each ETF within the network. A positive NET value designates an ETF as a connectedness transmitter, whereas a negative value signifies it as a receiver. Detailed examination of the NET values reveals that the EAFE ETF is the leading net transmitter, with a net value of 10.5%, followed by the Global and India ETFs. Conversely, China, the US, and Canada emerge as the primary net receivers, with net values of −11.24%, −3.97%, and −0.05%, respectively. The TO and FROM values further reinforce EAFE's position as the largest transmitter and receiver of return connectedness within the system, receiving 57.97% of connectedness spillover and transmitting 68.47% on average. The Global ETF follows as the second largest, with TO and FROM values averaging 60.42% and 56.29%, respectively. The static connectedness results underscore a high degree of integration and pronounced spillover effects among the selected ESG ETFs, highlighting a tight-knit global ESG investment system (Chen and Lin, 2022). Notably, the European ESG ETF emerges as the principal transmitter within this network, likely due to the EU's substantial ESG market size, which exceeds that of other regions significantly. According to Iqbal et al. (2022), the EU has cemented its leading role in

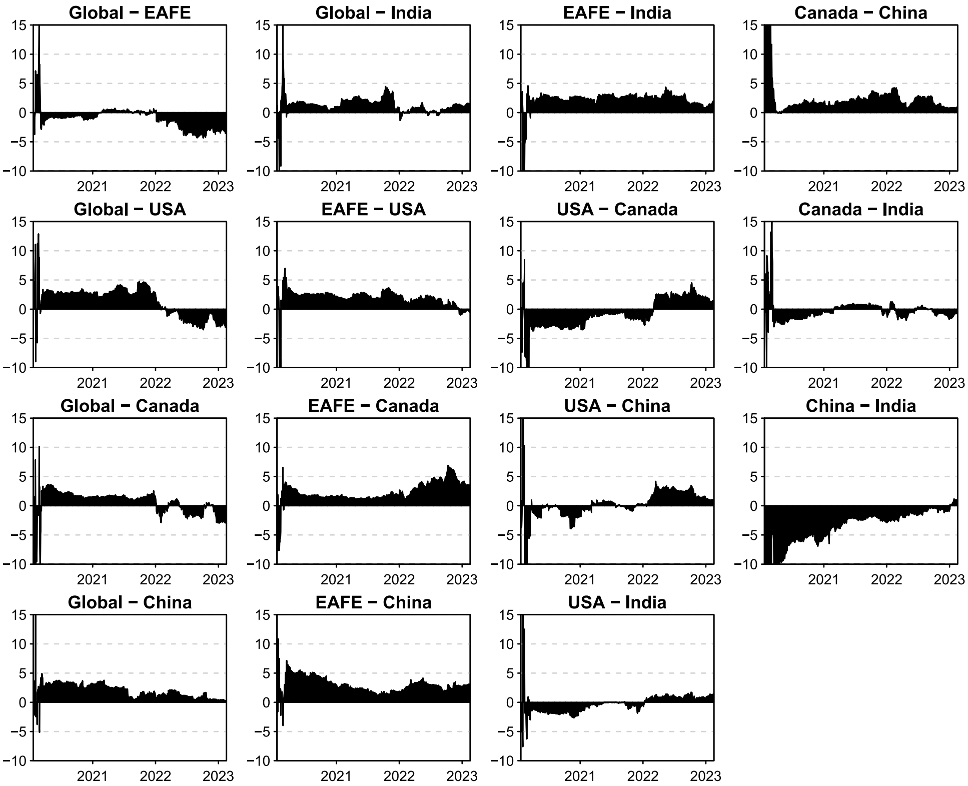

Fig. 13. Dynamic pairwise directional connectedness (robustness check 1).
Note: The robustness check results are obtained using a TVP-VAR model with a lag length of order two, a 20-step-ahead forecast horizon and a Minnesota prior.

Table 4
Averaged connectedness table.

	Global	EAFE	US	Canada	China	India	FROM
Global	43.71	16.76	13.00	11.73	4.37	10.44	56.29
EAFE	15.73	42.03	10.27	11.56	5.05	15.36	57.97
US	14.35	12.16	48.12	13.51	3.93	7.94	51.88
Canada	12.31	13.89	12.71	48.06	4.83	8.20	51.94
China	6.30	8.05	4.25	7.19	65.15	9.05	34.85
India	11.73	17.61	7.69	7.90	5.42	49.64	50.36
TO	60.42	68.47	47.91	51.89	23.61	50.99	TCI
NET	4.13	10.5	−3.97	−0.05	−11.24	0.63	50.55

Note: The results of the average connectedness are derived from a TVP-VAR model with a lag of 1 (as determined by the BIC criterion) and a 20-step-ahead prediction.

the global sustainable financial market, with its market scale surpassing $40 trillion, outstripping both the United States and China.[8]

On the other hand, countries like China, which are still developing their ESG markets, are predominantly net receivers of return connectedness. China's ESG investment market continues to develop, with institutional investors being less prevalent compared to developed markets, leading to a higher proportion of retail investor-driven ESG activities (Broadstock et al., 2021). This early stage of market development, coupled with limited institutional demand, explains China's reduced influence on the global ESG market despite its open financial system (Chen and Lin, 2022). To better understand the variations in interconnectedness within the global ETF investment system, especially under different market conditions and extreme events, we turn our focus to the dynamic connectedness results.

Fig. 4 depicts the variation of the dynamic total connectedness of the whole system over the sample period. It can be observed that there is a strong interconnectedness among major ESG leaders' indexes ETFs, ranging from 44% (lowest) to about 84% (highest). Also, the time- and events-varying features of TCI have further been confirmed from Fig. 4. Specifically, the peak of the index was observed on 4 February 2020 at 84%, corresponding to the occurrence of the COVID-19 outbreak spread worldwide. A notable increase in TCI implies that the interconnectedness of worldwide ESG networks has been greatly impacted by the shocks of COVID-19, leading to the TCI reaching the highest level of the whole sample period. Moreover, another notable finding is that we observe a gradual upward trend in the total connectedness index of the ESG leaders' ETFs system from early February 2022 to April 2022, rising from around 50% to approximately 66%, corresponding to the impact of the ongoing Russia-Ukraine conflict at that time.

Based on the results of TCI, it is evident that the dynamic connectedness among international ESG ETFs is highly dependent upon financial market conditions. Specifically, the dynamic total connectedness index tends to elevate significantly during episodes of extreme events, such as COVID-19 and the Russia-Ukraine conflict. A reasonable explanation for this phenomenon in ESG markets stems from the enormous

[8] This dominant position aligns with our findings, where the EAFE ETF, reflective of the European market, plays a central role in global ESG return transmission. This prominence can be attributed to its representation of the extensive and mature ESG investment markets within Europe.

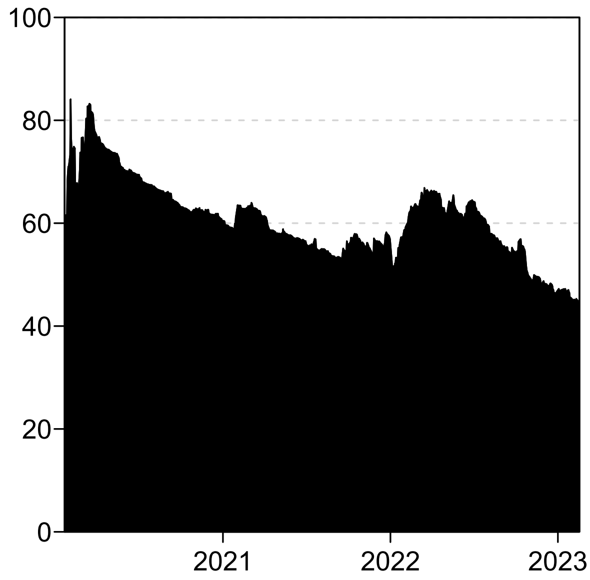

Fig. 14. Dynamic total connectedness- (robustness check 2).
Note: The robustness check results are obtained using a TVP-VAR model with a lag length of order one (BIC), a 10-step-ahead forecast horizon and a Minnesota prior.

market shocks induced by these extreme events, including precipitous declines in stock market indices, heightened economic uncertainty, and intensified market panic, leading to considerable shifts in investor expectations (Baruník and Křehlík, 2018). During periods of high uncertainty, investors typically prioritise short-term financial stability over longer-term sustainable investments. This leads to adjustments in investment strategies, resulting in a pronounced, short-term increase in market connectedness. Overall, the total connectedness among international sustainable investment has increased significantly during these extreme events, highlighting the fact that the shocks of extreme events hugely influence the connectedness of ESG ETF markets in the global landscape.

Next, to precisely identify and distinguish the specific role of each ESG leader's ETF within the entire system and the influence of extreme events on the different region's sustainable markets, we focus on the results of net directional connectedness, which are presented in Fig. 5.

Fig. 5 shows EAFE as the primary transmitter, with a consistently positive net connectedness index throughout the sample period.[9] Global ESG leaders' ETF also begins as a transmitter but changes to become a receiver in 2022. Conversely, China and the US are major receivers, with the US turning into a transmitter after 2022. These changes reflect the impact of specific external risks and economic factors (Chen and Lin, 2022). During early 2020, amid the COVID-19 pandemic, the US and Canada became substantial transmitters, with Canada's net connectedness index peaking at over 40%. China, EAFE, Global, and India acted as receivers during this period, with China's index dropping to −40%, highlighting the outbreak's impact on China's sustainable economic market (Corbet et al., 2021b; Jia et al., 2021). Notably, significant changes occurred in early 2022 during the Russia-Ukraine war. The net connectedness index for Global and Canada turned negative, indicating their roles as receivers, while the US shifted from a net receiver to a transmitter. These results underscore how the roles of sustainable investments in different countries change during unprecedented global crises.

The analysis of pairwise connectedness in Fig. 5 provides further insights. It highlights the dynamic relationships between ESG ETFs, particularly during market stress. For example, the EAFE and Global ETFs show significant volatility, with EAFE often acting as the transmitter. This underscores the influential role of the European market within the global ESG network. Understanding these dynamics is crucial for investors managing ESG investments during turbulent periods. To gain more detailed insights, we analyse the pairwise results shown in Fig. 6. A positive connectedness index indicates a shock transmitter, while a negative index indicates a receiver. For instance, the Global-EAFE results show EAFE as a major transmitter with increased transmission intensity in 2022 due to the Russia-Ukraine war. Global ETF's role shifts from a transmitter to a receiver post-2022. The net connectedness index for developed countries (US, Canada) changes significantly in 2022, while changes for emerging countries (China, India) are smaller. The US shifts from a shock recipient to a transmitter, particularly with Canada and China.

The first contribution of this paper is its exploration of dynamic market linkages, providing a comprehensive view of how different ESG markets interact over time. This analysis is crucial for understanding global ESG systems and interconnected ESG investing. It examines return transmission channels in different regions and identifies primary transmitters and recipients of shocks. European ESG markets are primary transmitters, while Asian markets are primary receivers, enriching the literature on financial contagion and market spillover effects on sustainable investments (Auer and Schuhmacher, 2016). Another contribution from such a result surrounds the improvement of risk management in ESG investing. Return spillovers between regions highlight the significance of geographical diversification. This analysis helps investors identify potential sources of market risk and respond to unexpected events effectively, enhancing portfolio stability (Levy and Lieberman, 2013). More specifically, pairwise dynamic connectedness results indicate EAFE as a dominant shock transmitter. The Russia-Ukraine war impacts developed markets (EAFE, US, Canada) more than emerging ones (China, India). The US ESG ETF notably shifted from a shock receiver to a transmitter post-conflict, emphasising the evolving roles of sustainable investments during global crises.

4.2. Portfolio strategies results

Next, we focus on the portfolio performance of four distinct strategies, MVP, MCP, MCoP, and RPP, to further understand how ESG investors can enhance investment efficiency and mitigate portfolio risk. The hedge effectiveness method of Ederington (1979) is applied to test the hedging performance of each asset in the portfolios.

Fig. 7 shows the cumulative returns of the four investment strategies over the sample period. All portfolios experienced significant declines early in the sample period due to the COVID-19 outbreak but exhibited sustained upward trends thereafter. Notably, MCP and MCoP outperformed MVP and RPP during the post-pandemic recovery, highlighting that ESG portfolios can generate substantial returns once market stability returns (Chen and Lin, 2022). However, during the Russia-Ukraine conflict, MVP and RPP strategies maintained positive returns, while MCP and MCoP showed a decline. This indicates that during crises, portfolios weighted towards developed markets, like MVP and RPP, perform better. This trend underscores the need for ESG investors to adapt strategies based on market conditions to optimise returns and hedge risks effectively (Boungou and Yatié, 2022; Jiang et al., 2023).

Fig. 8 and Table 5 present the dynamic and average portfolio weights. The MVP approach emphasises ESG investments in EAFE, US, and Canada, while MCP, MCoP, and RPP distribute weights more evenly. Notably, the US allocation decreases in 2022, except for RPP, where Canada's weight increases significantly, particularly in MVP.

The hedging effectiveness scores in Table 5 show that MVP and RPP have significant HE ratios for all ETFs. EAFE, US, and Canada dominate the MVP portfolio, reducing volatility by 50%, 46%, and

[9] It should be noted that the positive value of the net connectedness index in this paper indicates that the ESG leaders' ETF is a net transmitter of shocks in the system, and a negative direction implies that the ESG leaders' ETF acts as a receiver of shocks.

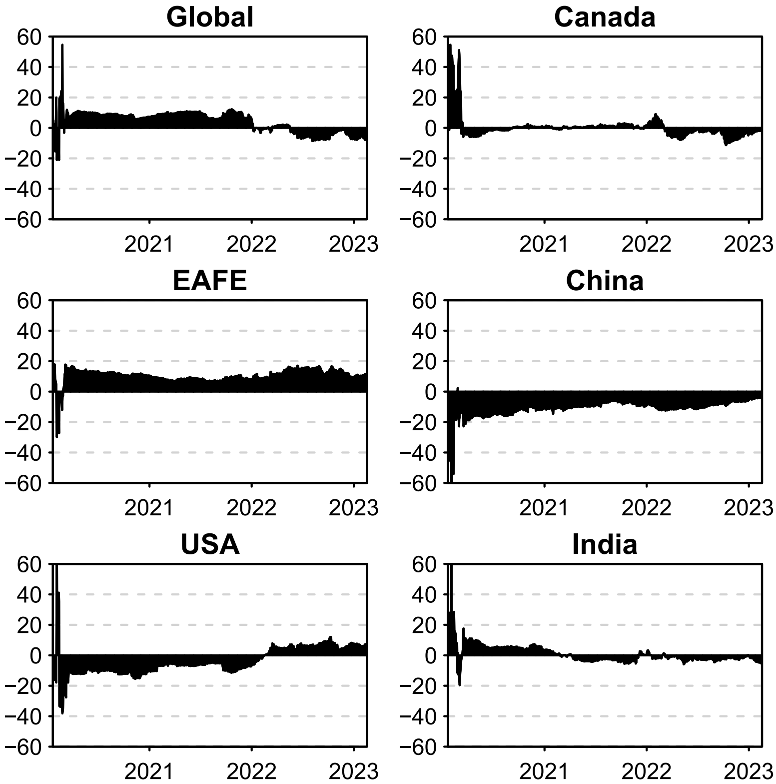

Fig. 15. Dynamic net total directional connectedness (robustness check 2).
Note: The robustness check results are obtained using a TVP-VAR model with a lag length of order one (BIC) and a 10-step-ahead forecast horizon and a Minnesota prior.

Table 5
Multivariate portfolio weights.

	Mean	S.Dev.	Max	Min	HE	p-val
MVP						
Global	0.15	0.06	0.29	0.00	0.50	0.00
EAFE	0.27	0.08	0.57	0.04	0.46	0.00
US	0.23	0.14	0.42	0.00	0.46	0.00
Canada	0.24	0.09	0.51	0.01	0.48	0.00
China	0.07	0.08	0.27	0.00	0.86	0.00
India	0.03	0.07	0.25	0.00	0.74	0.00
MCP						
Global	0.11	0.07	0.23	0.00	0.13	0.06
EAFE	0.05	0.03	0.11	0.00	0.06	0.42
US	0.19	0.07	0.30	0.02	0.07	0.34
Canada	0.16	0.04	0.26	0.07	0.09	0.21
China	0.30	0.02	0.38	0.26	0.75	0.00
India	0.19	0.03	0.29	0.14	0.55	0.00
MCoP						
Global	0.11	0.06	0.23	0.00	0.14	0.04
EAFE	0.06	0.04	0.11	0.00	0.07	0.34
US	0.19	0.07	0.30	0.02	0.08	0.27
Canada	0.16	0.04	0.26	0.07	0.10	0.16
China	0.29	0.03	0.38	0.26	0.75	0.00
India	0.19	0.03	0.29	0.14	0.55	0.00
RPP						
Global	0.18	0.01	0.20	0.16	0.39	0.00
EAFE	0.18	0.01	0.21	0.15	0.34	0.00
US	0.19	0.02	0.24	0.15	0.35	0.00
Canada	0.19	0.02	0.24	0.15	0.36	0.00
China	0.12	0.04	0.19	0.07	0.83	0.00
India	0.14	0.02	0.19	0.12	0.68	0.00

Note: This table reports the portfolio weights' average, standard deviation, minimum and maximum. The hedging effectiveness (HE) ratio for each asset and its *p*-value are also reported.

48%, respectively. MCP and MCoP show a similar pattern, with China holding the largest proportion and significantly reducing volatility by 75%. The RPP strategy evenly distributes weights, with notable reductions in volatility across all ETFs. Our results emphasise that the hedging effectiveness ratio of each ESG ETF within the portfolio is highly dependent on the EAFE allocation. MVP, with the highest EAFE weighting, shows the best hedging effectiveness, while reduced EAFE weights in MCP and MCoP correspond to lower hedging effectiveness. Thus, EAFE serves as an effective hedging instrument in ESG investment portfolios. These findings highlight the importance of dynamic market linkages and geographical diversification in ESG investing. Our analysis reveals that European ESG markets act as primary transmitters of shocks while emerging markets are receivers. Such dynamics influence portfolio performance during stable and volatile periods (Wan et al., 2024; Sherrill and Stark, 2018; Naeem et al., 2023a). Understanding these interactions is crucial for investors seeking to manage risk and optimise returns in global ESG portfolios.

In addition to portfolio construction, assessing the hedge effectiveness of various ESG ETFs is vital for risk management. Our study evaluates the effectiveness of ESG ETFs as hedges against regional ESG ETFs, offering insights into strategic allocation to improve overall portfolio stability in volatile markets. When examining ESG investor behaviour across regions provides insights into sustainability-focused investment strategies. Differences in national culture and market conditions affect ESG performance and investor behaviour. European ESG markets consistently act as shock transmitters, while emerging markets often receive shocks. These dynamics highlight the robust commitment to ESG principles in Europe and the importance of including European ESG ETFs to reduce portfolio volatility across regions (Campbell et al., 2012; Auer and Schuhmacher, 2016). Our analysis of dynamic connectedness among ESG ETFs reveals crucial insights into the resilience and interconnectedness of ESG investments during geopolitical conflicts and other shocks like the COVID-19 pandemic. EAFE consistently acts as a shock transmitter, with significant impacts observed during the Russia-Ukraine war. The effectiveness of different portfolio strategies varies with market conditions, with MVP excelling during geopolitical turmoil and MCP and MCoP performing better during stable periods. The hedging effectiveness of EAFE further supports its inclusion in diversified ESG portfolios.

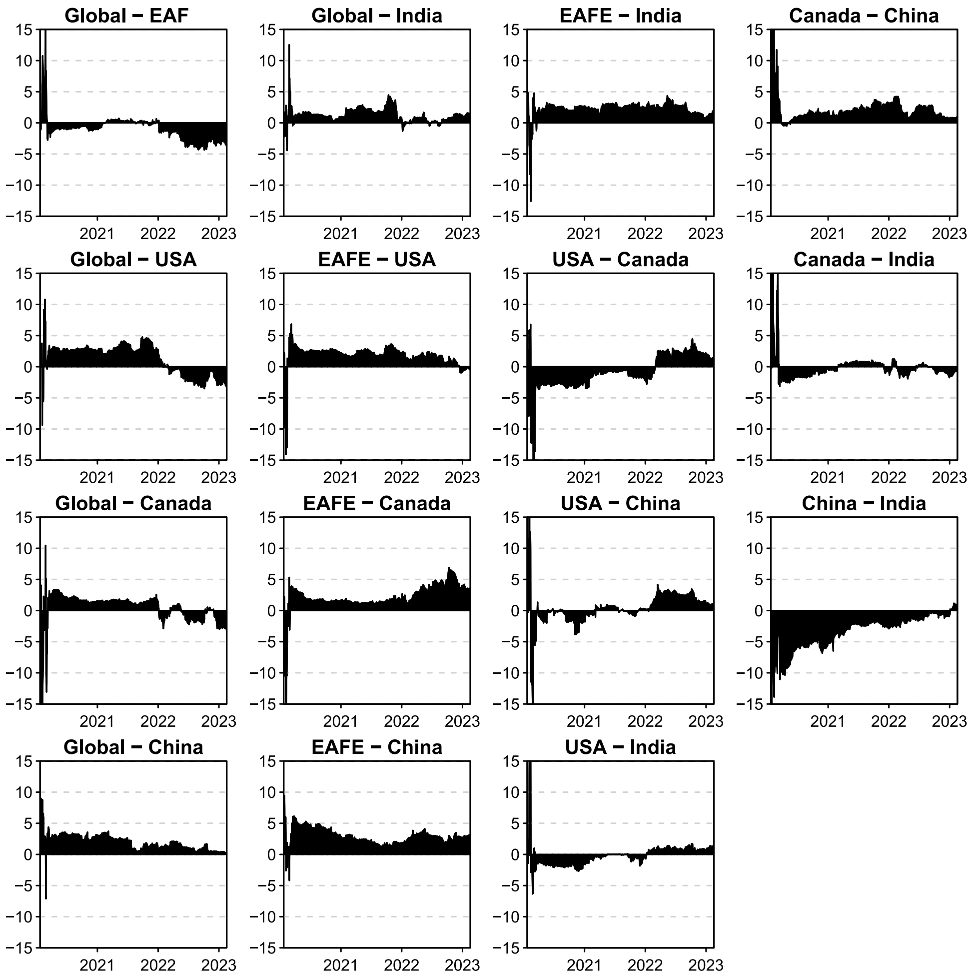

Fig. 16. Dynamic pairwise directional connectedness (robustness check 2).
Note: The robustness check results are obtained using a TVP-VAR model with a lag length of order one (BIC) and a 10-step-ahead forecast horizon and a Minnesota prior.

4.3. *Robustness testing procedures*

Next, we perform additional robustness checks for both the connectedness and portfolio analyses. After obtaining time-varying variance/co-variance matrices (Antonakakis et al., 2020), such time-varying variance/co-variance matrices are then subsequently used for constructing four different multivariate portfolio models. Previously presented results are based on a TVP-VAR model with a lag length of order one (determined by BIC) and a 20-step-ahead forecast with a Bayes prior, which is consistent with the setup in Broadstock et al. (2022). Robustness checks are subsequently conducted through the alteration of the model specification of the TVP-VAR models, specifically by varying the lag order length, adjusting the forecast horizon, and changing the prior use.

We first present the results by changing the lag length of the order to two and varying priors. Dynamic connectedness results are presented as presented in Figs. 9 through 13, based on the alternative lag order and the prior selection.[10] We find that the portfolio weights' average, standard deviation, minimum and maximum are almost identical to those reported in Table 5. More importantly, the hedging effectiveness ratio and *p*-value also draw similar conclusions.[11] Overall, the connectedness and portfolio analysis results based on changing the lag length of order and a different Minnesota prior are consistent with those reported.

The results of the robustness checks on dynamic connectedness with varying forecast horizon and alternative Minnesota prior are presented as Figs. 14 through 16. By using an alternative forecast horizon and Minnesota prior, we conclude that connectedness results remain unchanged.[12] Further, Fig. 17 and Fig. 18 plot the cumulative returns of four different investment strategies and the dynamic portfolio weights, respectively. Overall, the results of the robustness checks on portfolio analysis with varying forecast horizons and alternative Minnesota prior also demonstrate comparable findings to those previously outlined.

5. Conclusion

Despite the emergence of ESG equity as a key investment vehicle to meet the growing demand for sustainable investing and non-pecuniary ESG preferences, research on ESG ETFs remains remarkably scarce. This study investigates the dynamic return connectedness of worldwide ESG leaders' ETFs and analyses the portfolio strategies and hedging

[10] For comparison, Table 6 presents the results of the dynamic multivariate portfolio weights with the hedging effectiveness ratios.

[11] Specifically. Fig. 11 plots the cumulative returns of four investment strategies during our selected sample period. The overall trend of cumulative portfolio returns aligns with that illustrated in Fig. 7. Fig. 12 presents dynamic portfolio weights, presenting the fluctuations in the composition of the individual portfolio. We observe similar findings compared to those reported in Fig. 8.

[12] This is compared to Table 7 illustrates the corresponding results of the dynamic multivariate portfolio weights with the hedging effectiveness ratio.

Table 6
Multivariate portfolio weights (Robustness check 1).

	Mean	Std.Dev.	Max	Min	HE	*p*-value
MVP						
Global	0.21	0.05	0.55	0.04	0.39	0.00
EAFE	0.26	0.08	0.54	0.00	0.34	0.00
USA	0.21	0.13	0.4	0.00	0.35	0.00
Canada	0.24	0.09	0.59	0.00	0.36	0.00
China	0.02	0.02	0.12	0.00	0.83	0.00
India	0.06	0.08	0.43	0.00	0.68	0.00
MCP						
Global	0.09	0.07	0.23	0.00	0.05	0.50
EAFE	0.03	0.03	0.09	0.00	−0.03	0.67
USA	0.19	0.07	0.29	0.02	−0.02	0.78
Canada	0.16	0.04	0.27	0.07	0.00	0.99
China	0.30	0.02	0.36	0.25	0.73	0.00
India	0.24	0.05	0.37	0.15	0.50	0.00
MCoP						
Global	0.09	0.07	0.33	0.00	0.04	0.53
EAFE	0.05	0.04	0.42	0.00	−0.04	0.63
USA	0.20	0.08	0.39	0.00	−0.03	0.73
Canada	0.15	0.05	0.5	0.00	0.00	0.97
China	0.27	0.04	0.42	0.00	0.73	0.00
India	0.24	0.06	0.5	0.00	0.5	0.00
RPP						
Global	0.18	0.01	0.2	0.16	0.36	0.00
EAFE	0.18	0.01	0.21	0.16	0.31	0.00
USA	0.19	0.02	0.23	0.15	0.32	0.00
Canada	0.19	0.02	0.23	0.14	0.33	0.00
China	0.12	0.03	0.17	0.07	0.82	0.00
India	0.15	0.02	0.2	0.13	0.67	0.00

Note: Robustness check results are obtained using a TVP-VAR model with a lag length of order two and a 20-step-ahead forecast. This table reports the average, standard deviation, minimum and a maximum of the portfolio weights. The hedging effectiveness (HE) ratio for each asset, along with its *p*-value, is also reported.

Table 7
Multivariate portfolio weights (Robustness check 2).

	Mean	Std.Dev.	Max	Min	HE	*p*-value
MVP						
Global	0.15	0.06	0.29	0.00	0.50	0.00
EAFE	0.28	0.08	0.57	0.04	0.46	0.00
USA	0.23	0.14	0.43	0.00	0.47	0.00
Canada	0.24	0.09	0.51	0.01	0.48	0.00
China	0.07	0.08	0.27	0.00	0.86	0.00
India	0.03	0.07	0.25	0.00	0.74	0.00
MCP						
Global	0.11	0.06	0.23	0.00	0.14	0.04
EAFE	0.05	0.03	0.11	0.00	0.07	0.34
USA	0.19	0.07	0.32	0.02	0.08	0.28
Canada	0.16	0.04	0.26	0.07	0.10	0.16
China	0.30	0.02	0.38	0.26	0.75	0.00
India	0.19	0.03	0.28	0.14	0.55	0.00
MCoP						
Global	0.11	0.05	0.26	0.00	0.14	0.03
EAFE	0.06	0.04	0.29	0.00	0.07	0.31
USA	0.19	0.07	0.34	0.03	0.08	0.25
Canada	0.16	0.04	0.26	0.00	0.10	0.15
China	0.29	0.03	0.37	0.03	0.76	0.00
India	0.19	0.03	0.32	0.05	0.55	0.00
RPP						
Global	0.18	0.01	0.20	0.16	0.39	0.00
EAFE	0.18	0.01	0.21	0.15	0.34	0.00
USA	0.19	0.02	0.24	0.15	0.35	0.00
Canada	0.19	0.02	0.24	0.15	0.36	0.00
China	0.12	0.03	0.19	0.07	0.83	0.00
India	0.14	0.02	0.19	0.12	0.68	0.00

Note: (Robustness check 2) This table reports the average, standard deviation, minimum and a maximum of the portfolio weights. The hedging effectiveness (HE) ratio for each asset, along with its *p*-value, is also reported.

efficiency of these ETFs. The main findings are as follows. First, we find a high degree of connectedness within the international ESG ETF system. The total connectedness index shows that return transmission within the system increased notably during the COVID-19 pandemic and the Russia-Ukraine conflict. Notably, the total connectedness index reached its highest level in early 2020, corresponding to the impact of COVID-19.

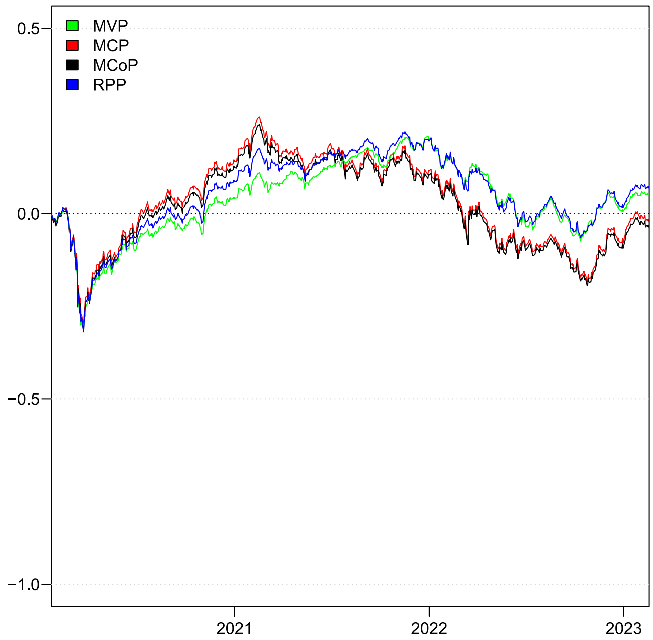

Fig. 17. Cumulative portfolio returns (Robustness check 2).
Note: (Robustness check 2) This figure displays the cumulative returns of four different portfolios for the period 2020 to 2023. Four portfolio strategies are considered, including minimum variance portfolios (MVP), minimum correlation portfolios (MCP), minimum connectedness portfolios (MCoP), and risk-parity portfolios (RPP).

Second, the net connectedness index results indicate that EAFE and Global ESG leaders' index ETFs are the main transmitters within the system, while China is the primary receiver. Pairwise connectedness confirms cross-regional spillovers, with EAFE consistently exhibiting stronger transmission effects. The results also reveal significant spillover effects involving the US and other markets post-2022, except for EAFE, underscoring the dominant roles of EAFE and US ESG ETFs in the global ESG return spillover system.

Third, the performance of portfolio returns is highly dependent on market conditions and extreme events. All four distinct portfolio strategies experienced significant declines at the onset of the COVID-19 outbreak. However, the sharp downturn in ESG ETF portfolios was relatively short-lived, with a sustained upward trend in subsequent performance. ESG ETF portfolios demonstrated resilience and potential for superior returns during the stabilisation phase following the pandemic. The return trends of the portfolio strategies during the Russia-Ukraine conflict show that MVP and RPP strategies are more effective in mitigating risk during periods of geopolitical turmoil, while MCP and MCoP strategies perform better during periods of relative stability.

Fourth, the dynamic portfolio weights illustrate how the composition of individual ESG portfolios changes in response to global events. The dynamic weights within the MVP approach differ noticeably from the other three approaches. The hedging effectiveness of the EAFE ETF is confirmed across all four alternative portfolio strategies. The HE ratio shows that incorporating the EAFE ETF into ESG investment portfolios significantly enhances hedging and reduces portfolio risk.

Overall, this research enhances the understanding of the resilience and potential benefits of ESG investments while considering the limitations and challenges they face in an unpredictable financial context. These findings provide insights into the dynamics of global ESG investments, highlighting the importance of market conditions and

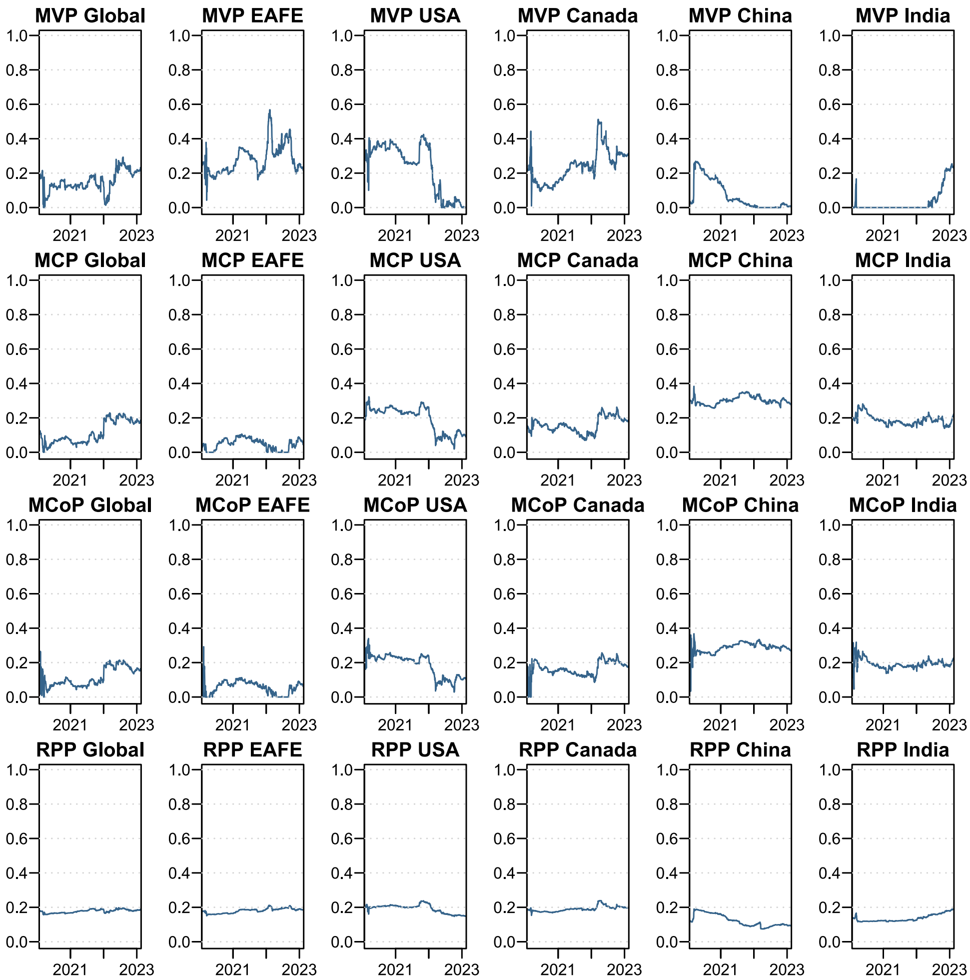

Fig. 18. Dynamic multivariate portfolio weights (Robustness check 2).
Note: (Robustness check 2) This figure displays the dynamic portfolio weights based on four different investment portfolio strategies, including minimum variance portfolios (MVP), minimum correlation portfolios (MCP), minimum connectedness portfolios (MCoP), and risk-parity portfolios (RPP).

portfolio strategies in achieving investment returns and effective risk management. This study contributes to the literature by offering a comprehensive analysis of the interconnectedness and stability of ESG investments, informing the evolution of sustainable investment strategies and approaches in the face of global crises and market volatility.

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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Chapter 7

Exploring the connectedness between major volatility indexes and worldwide sustainable investments

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Exploring the connectedness between major volatility indexes and worldwide sustainable investments

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ABSTRACT

This paper examines the dynamic connectedness between various measures of volatility indexes (e.g., Engle and Campos-Martins (2023)'s global common volatility index (COVOL), VIX, OVX, GVZ) and worldwide ESG leaders' equity markets, using an aggregated connectedness approach for the period January 2014 to April 2023. Several novel findings are presented. First, the COVID-19 pandemic has a significant impact on the dynamic total connectedness of the system compared to other major global events. Second, the COVOL is a receiver of aggregated global ESG while VIX is a major transmitter. Third, based on the stage of economic development for each ESG market, the aggregated developed-country ESG group plays a more dominant role in the transmission channel. Fourth, based on aggregated ESG markets by region, the VIX is the primary transmitter to four regional ESGs. Last, European ESG market has low connectedness with the major volatility indexes and other regional ESGs. These findings have important and practical implications for investors and portfolio managers in formulating effective risk management strategies for ESG-related investments.

1. Introduction

Environmental, Social, and Governance (ESG) investment, now forms the core of the global green transition and sustainable economy, attracting an increasing number of green and social-friendly investors. Recently, the scale of the global ESG market has demonstrated substantial growth from \$22.8 trillion in 2016 to \$30.6 trillion in 2018, escalated further to \$35.3 trillion in 2020, and reaching \$37.8 trillion by 2021. Projections anticipate that the global ESG market will reach \$53 trillion by 2025 (Chen & Lin, 2022; Naeem, Yousaf, Karim, Tiwari, & Farid, 2023). Undoubtedly, as the ESG market continues to expand, its influence and importance within the global financial market will also grow. Emerging investment markets often present unique patterns and volatility transmission with other financial assets. Consequently, exploring the dynamic relationship between ESG equity investments and the volatility of major global financial markets is crucial for investors to understand risk and return characteristics, optimize portfolio allocation and implement effective risk management strategies.

Within the context of economic globalization, the volatility connectedness between global financial markets is becoming more important and complex. As an emerging market, ESG investment can be heavily affected by volatility contagion across financial market categories such as equities, oil, and gold. This paper, therefore, serves as a catalyst for the exploration of the connectedness between various global factors (e.g., COVOL, VIX, OVX, and GVZ) and sustainable investments. For example, the VIX is generally regarded as a barometer of the financial market. A rise in the VIX typically indicates an increase in investor uncertainty, which in turn impacts the conditions of the ESG investment market (Lin & Su, 2021). In the same vein, the OVX, generally, refers to an index of growing panic in the crude oil market. According to Lin and Su (2020a), when panic sentiment in the oil market intensifies, investors are likely to move towards green investments and align with the low-carbon economy. GVZ is also linked with the ESG markets. Gold plays a pivotal role as a fundamental asset within diverse financial portfolios, encompassing hedging, risk management, portfolio optimization, and diversification. Typically, investor sentiment towards gold directly influences the proportion of investors' allocations to the emerging market. Given that ESG investments are often aligned with long-term sustainability goals and responsible practices, increased volatility in gold, as reflected in the GVZ, may signal an increased perception of risk in global financial markets. More importantly, the inclusion of VIX, OVX and GVZ in this paper to represent global factors is in line with previous research, see Ahmad, Hernandez, Saini, and Mishra (2021) and Urom and Ndubuisi (2023). Hence, the selection of volatility indexes is substantiated by the alignment with prior studies in the

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existing literature. In addition to the aforementioned volatility indexes, COVOL, a measure of common volatility shocks on the global financial market recently developed by Engle and Campos-Martins (2023), is also included in this research. The use of COVOL as a measure of financial risk has been the subject of a number of recent studies, see Xu, Hu, Corbet, and Goodell (2023), Zhang, Guo, Dou, and Xie (2023), Oxley, Hu, Corbet, and Goodell (2023) and Lang, Xu, Corbet, Hu, and Goodell (2024).

In this paper, we attempt to answer the following questions: i) Does the COVOL play the same role as other major implied volatility indexes on an aggregated ESG market measure? ii) Does separating worldwide ESG markets based on their sovereign economic development status, lead to differences in connectedness compared to developing markets? iii) When separating worldwide ESG markets by region, do the linkages differ across regions? iv) Which region is least affected by global factors and regional ESG markets?

In order to answer these questions, we examine the dynamic connectedness among selected ESG markets and key global factors using an aggregated connectedness approach. The rationale for aggregating international ESG markets across multiple dimensions is underpinned by several justifications, which are outlined below. The consolidation of different ESG equity markets into a global ESG market provides important insights for several reasons. First, a global ESG market approach allows for a comprehensive analysis of sustainable investments on a global scale. Second, global markets are increasingly interconnected and shocks in one market can have an impact on others. Third, the long-term impact of ESG investments can be explored through a global ESG market analysis. There are several reasons why this study separates developed and developing ESG equity markets when examining the dynamic linkages. First, developed ESG equity markets are more established and larger in terms of market capitalization and trading volume, while developing ESG equity markets are at an earlier stage of ESG integration. Second, developed ESG equity markets generally have higher levels of ESG awareness, adoption and necessary compliance, than developing ESG equity markets, as ESG awareness in developing markets may not be as high as in developed markets. Third, it is expected that developed ESG equity markets will typically require more comprehensive and rigorous ESG disclosure and reporting. It is also important to separate different regional ESG equity markets when examining the connectedness channel with major financial market volatility for other reasons. First, regional differences in ESG practices may affect the ability to adapt and integrate ESG practices into corporate and investment strategies. Second, investors in different regions may have different ESG investment and risk-taking preferences. Third, ESG equity markets in certain regions may experience different levels of currency risk and market volatility due to local financial markets and geopolitical factors. Therefore, segmenting ESG markets by region allows for a more accurate and comprehensive assessment of spillovers in this study.

This paper makes important and significant contributions to the existing literature on ESG research and differs from existing studies in a number of important ways. First, this paper examines the dynamic connectedness between the common volatility index (COVOL) of Engle and Campos-Martins (2023) and major ESG equity markets for the first time. The recently proposed global risk measure of the COVOL is used to represent a wide range of financial risks. The identification of the dynamic transmission between COVOL and ESG markets is therefore crucial to gaining a comprehensive understanding of ESG markets and the development of effective investment strategies. Second, our study differs from previous studies in terms of the data set used for the representation of global factors. We incorporate the potential influence of four major volatility indexes in our analysis of the interconnectedness transmission mechanism among the worldwide ESG markets. In particular, we consider the COVOL together with three major implied volatility indexes in stock, oil, and gold markets (e.g., VIX, OVX, GVZ) to analyse the inter-connectedness among global ESG markets. The inclusion of these four volatility indexes is particularly important for a comprehensive understanding of the variation in ESG market connectedness.

Third, this is the first paper to explore the dynamic connectedness between major ESG equity markets and global factors based on the aggregated connectedness approach. Our study therefore differs from existing studies in the econometric methods used. By aggregating major ESG markets across three different criteria using the aggregated connectedness approach of Gabauer and Gupta (2018), we explore the dynamic transmission of ESG markets across different dimensions and shed light on their relationship with major volatility indexes. In particular, we select eight major ESG markets including Europe, USA, Japan, Canada, Australia, Korea, China, and India. We also separate these eight worldwide ESG markets in three different ways; the aggregation of all ESG markets into one global market; the aggregation of different stages of economic development based ESG markets (developed-country and developing-country); and the aggregation of four regions (the Americas, Europe, Asia and the Pacific). The first approach allows for the aggregation of eight worldwide ESGs into a global ESG market and examines the dynamic connectedness between the global ESG market and four key indicators of financial market volatility. By aggregating all international ESGs into a global ESG market, our study offers a comprehensive examination of the impact of uncertainty in major financial markets on the overarching global ESG landscape. We also separate the eight ESG markets based on different states of sovereign economic development into two groups; developed-country ESG and developing-country ESG. In doing so, we attempt to identify whether develop-country ESG or developing-country ESG plays a more important, rather than simply a different role, in volatility transmission. Furthermore, the paper separates the eight mainstream ESG equity markets by region, for example, the Americas, Europe, Asia, and the Pacific and attempts to determine which region, if any, is associated with different volatility indexes during periods of high connectedness.

Last, this study makes a valuable contribution to the literature on sustainable investment during periods of extreme events and their aftermath, exemplified by events such as the emergence of COVID-19 and the subsequent post-pandemic era. Distinguishing the difference in dynamic connectedness transmission mechanism under the various markets' states across different dimensions of ESG markets has multiple implications. Our comprehensive consideration of various global factors and different dimensions of ESG markets allows us to provide a more thorough and nuanced analysis of the transmission mechanism within the global ESG markets. Such results can help both policymakers and investors to gain a more comprehensive understanding of investment in the ESG market during periods of high uncertainty, in potentially different financial markets.

The rest of this paper is structured as follows: Section 2 briefly discusses the previous literature. Section 3 introduces the econometric methodologies that are used in the paper and Section 4 provides a thorough explanation of the data used in the analysis. Section 5 presents the empirical findings, while Section 6 concludes.

2. Previous literature

Regarding the impact of ESG development at the firm level, Wang, Ma, Dong, and Zhang (2023b) find that ESG ratings have a significant positive effect on green innovation and enhance firms' green innovation capabilities. On the other hand, from a bond market perspective, Lian, Ye, Zhang, and Zhang (2023) point out that firms with strong ESG performance tend to have lower bond credit spreads. This phenomenon can be attributed to three main factors. First, strong ESG performance creates an "insurance effect" that attracts long-term green investors. Second, ESG ratings help improve corporate transparency, thereby reducing the information asymmetry between investors and firms. Finally, strong ESG performance mitigates debt agency problems. In addition, by analysing the impact of media coverage on companies' ESG performance, He, Guo, and Yue (2024) show that increased media attention improves firms' ESG performance by acting as an additional monitoring mechanism.

A growing body of literature has examined the risk spillover effects of cross-country linkages of sustainable finance. For example, Umar, Kenourgios, and Papathanasiou (2020) investigate the risk spillover effect among the ESG markets of 10 major countries by using the spillover index method. Their findings emphasize that there is notable volatility transmission among the worldwide ESG markets, particularly, the ESG of developed markets which are the shock transmitters to the emerging ESG markets. Similarly, Iqbal, Naeem, and Suleman (2022) reveal the asymmetric spillover effects among 14 country-level sustainability indexes. They find that the intensity of the spillover effects among countries' sustainable markets will be enhanced during financial crises. Chen and Lin (2022) identify the strong spillover effects across the eight mainstream ESG equity markets. Additionally, their research highlights the strongest cross-market link between the USA and Canada, suggesting that these two ESG markets serve as core shock transmitters within the global ESG equity market. To obtain an in-depth understanding of the connectedness transmission mechanisms of worldwide ESGs and its asymmetric effects, Gao, Li, Zhao, and Wang (2022) and Naeem et al. (2023) analyse the risk contagion of the inter-regional ESG markets. Gao et al. (2022) illustrate the specific risk contagion across different regions' ESG markets by using the yields ESG index of eight regions around the world. Naeem et al. (2023) explore the price asymmetric efficiency of four regional ESG markets including the Americas, Europe, Asia, and the Pacific, using the regional MSCI leader ESG indexes. Similarly, Xu, Corbet, Lang, and Hu (2024) and Wan, Yin, and Wu (2024) respectively investigate the return and volatility connectedness of different ESG equity markets and their results highlight the different transmission patterns of each ESG market globally. In particular, Wan et al. (2024) find that ESG stock indexes in Europe and North America show outward spillovers, while those in Asia-Pacific and India show predominantly inward spillover effects. Both studies confirm that there is a clear contagion risk effect across ESG market regions. The asymmetric effect across ESG regions becomes more pronounced during the COVID-19 pandemic.

Another key area of research in the sustainable investments literature is understanding the transmission channels between financial assets and market uncertainty, such as, climate uncertainty (Cepni, Demirer, Pham, & Rognone, 2023), climate risk (Lin & Wu, 2023), the uncertainty role of bank (Trinh, Cao, Li, & Elnahass, 2023), cryptocurrency (Huang, Duan, & Urquhart, 2023) and the uncertainty of ethically compliant equity (Bakar, Abdelsalam, Taamouti, & Elmasry, 2023). A number of studies have also looked at the impact of volatility indexes on financial markets. Basher and Sadorsky (2016) explore the role of the VIX on the emerging stock market. Lin and Su (2020b) explore the linkages between oil market uncertainty (OVX) and Islamic stock markets using a quantile-on-quantile approach and identify negative linkages between OVX and Islamic stocks. Kocaarslan and Soytas (2021) investigate the impact of uncertainty measures, such as VIX, OVX, and GVZ, on clean energy stocks. Lin and Su (2023) analyse the driving role of VIX, EPU and OVX on the green investment of both the US and China. Similarly, Pham and Do (2022) analyse the time-varying spillover effects between green bonds and various global measures of uncertainty, including the VIX, OVX, and GVZ. In addition, Ahmad, Sadorsky, and Sharma (2018) undertake research on the return correlations and volatility spillovers between gold, VIX, OVX, and clean energy equities while (Shahid, Azmi, Ali, Islam, & Rizvi, 2023) uncover the transmission mechanism between the Socially Responsible Investments (SRI) and the major volatility indexes, including the oil volatility index (OVX), the gold volatility index (GVZ), and the silver volatility index (VXSLV).

Given the rapid development of ESG equity markets and the impact of uncertainty indexes on financial assets, the examination of the relationship between ESG and various financial market uncertainties has gradually become a critical but still underexplored area of research. Specifically, Chen and Lin (2022) investigate the driving factors of spillover effects in ESG equity markets across different regions. They categorize the driving factors into five groups: stock market volatility (VIX), oil market volatility (OVX), currency market volatility (DXY), bond market volatility (10-year and 2-year U.S. Treasury Bonds, TBS), and the financial stress index (FSI). They find that the outbreak of the pandemic leads to increased financial market volatility and heightened globalization of ESG markets. Consequently, they conclude that the risks in global ESG markets become more pronounced during the pandemic. Subsequently, Naeem et al. (2023) examine the impact of various global factors on the market dynamic efficiency of ESG indexes across different regions. Based on regression analysis, they find that the volatility of different financial markets exhibits asymmetric effects on the efficiency of ESG markets in various regions. Bhattacherjee, Mishra, and Bouri (2024) analyse the impact of various uncertainty indexes on ESG equity investments across different regions from the perspective of ESG portfolio returns. Their results emphasize that uncertainty indexes, such as VIX, OVX, and GVZ, are the primary driving factors across return connectedness in ESG markets. Additionally, some recent studies focus on the impact of geopolitical risk (Fiorillo, Meles, Pellegrino, & Verdoliva, 2024) and climate risk (Cepni et al., 2023) on ESG markets. Although the literature on ESG issues continues to grow, a number of research questions, which this paper seeks to address, remain critical but underexplored in the literature and worthy of particular attention. First, examining the connectedness between ESG equity markets and major financial assets from a global perspective. Second, investigating whether ESG equity markets at different stages of economic development exhibit notable differences. Last, further research is needed to examine the volatility connectedness between ESG markets in different regions and various financial markets, in particular, to understand whether spillover effects are amplified during extreme events.

In terms of the methods used in the literature, the time-varying parameter vector autoregression (TVP-VAR) model is widely employed to investigate connectedness dynamics. For example, some papers focus on the connectedness of broad commodity markets (Balcilar, Gabauer, & Umar, 2021; Bouri, Lucey, Saeed, & Vo, 2021a; Corbet, Hou, Hu, Oxley, & Xu, 2021; Goodell, Yadav, Ruan, Abedin, & Malhotra, 2023; Hu, Lang, Corbet, Hou, & Oxley, 2023), cryptocurrencies (Akyildirim, Conlon, Corbet, & Goodell, 2023; Gunay, Goodell, Muhammed, & Kirimhan, 2023), clean and dirty energy (Umar, Farid, & Naeem, 2022; Wang, Guan, Ding, & Zhang, 2023a). In addition, a number of studies consider the connectedness between financial market uncertainty and financial markets. Lin and Su (2021) and Elsayed, Gozgor, and Lau (2022) study the risk contagion between VIX and financial markets; (Antonakakis, Cunado, Filis, Gabauer, & de Gracia, 2023) and Urom, Mzoughi, Ndubuisi, and Guesmi (2022) explore the linkages between OVX and a variety of financial assets; Ding, Huang, and Chen (2021) examine the risk spillovers between GVZ and financial markets. Other studies examine the relationship between global uncertainty and sustainable finance. Pham and Do (2022) utilize the TVP-VAR model examine the connectedness between the global uncertainty (VIX, OVX and GVZ) and green bonds where the findings of this study demonstrate significant time-varying spillover effects between global uncertainty and green bonds. Cepni et al. (2023) examine the effect of climate uncertainty on the spillover effects across the European conventional and ESG markets and they conclude that ESG assets can be used as a diversification tool against climate uncertainty.

A number of studies have adopted the TVP-VAR and various extensions to meet the different needs of connectedness analysis. For example, Adekoya et al. (2022) develop the asymmetric connectedness approach to explore the asymmetric propagation of return spillovers among financial markets. Baruník and Křehlík (2018) propose the frequency connectedness approach in order to examine the connectedness transmission with different frequency domains. Also, recently developed connectedness approaches, such as the wavelet connectedness approach (Antonakakis, Gabauer, Gupta, & Plakandaras, 2018b), DCC-GARCH connectedness approach (Gabauer, 2020), joint connectedness approach (Lastrapes & Wiesen, 2021) and quantile connectedness approach (Chatziantoniou, Gabauer, & Stenfors, 2021), received massive interest from research and applied to estimate the connectedness mechanism of financial markets. A number of studies also apply quantile connectedness approach of Ando, Greenwood-Nimmo, and Shin (2022) to different applications, see Bouri, Saeed, Vo, and Roubaud (2021b), and Yousaf, Pham, and Goodell (2023). Among the various approaches mentioned above, this paper follows (Stenfors, Chatziantoniou, & Gabauer, 2022) to adopt the aggregated connectedness approach of Gabauer and Gupta (2018) to explore the dynamic connectedness variation of ESG markets by aggregating the ESG into different dimensions.

3. Methodology

The VAR-based approach proposed by Diebold and Yilmaz (2009, 2012, 2014) is a well-established framework for monitoring and evaluating spillovers in the literature. However, these approaches may suffer from some potential shortcomings in terms of outlier sensitivity, loss of observations, flattened parameters and arbitrary window size. These shortcomings have been addressed by Antonakakis, Chatziantoniou, and Gabauer (2020), who develop a dynamic connectedness approach based on time-varying parameter vector autoregressions, widely known as the TVP-VAR approach. The TVP-VAR approach has attracted considerable attention due to several advantages over the existing approaches. First, the TVP-VAR framework does not need to arbitrarily set the size of the rolling window or loss of observations, as no rolling window analysis is required. Second, this framework relies on a multivariate Kalman filter, which is less sensitive to outliers. Third, it offers considerable flexibility, allowing us to incorporate time-varying structures into the autoregressive parameters and the variance–covariance matrix of the errors. Many alternative extensions have been developed since this work see asymmetric connectedness approach (Adekoya et al., 2022; Baruník, Kočenda, & Vácha, 2017), frequency connectedness approach (Baruník & Křehlík, 2018; Chatziantoniou, Gabauer, & Gupta, 2023), Lasso connectedness approach (Demirer, Diebold, Liu, & Yilmaz, 2018; Gabauer, Gupta, Marfatia, & Miller, 2024), joint spillover approach (Lastrapes & Wiesen, 2021), DCC-GARCH connectedness approach (Gabauer, 2020), and quantile connectedness approach (Chatziantoniou, Abakah, Gabauer, & Tiwari, 2022; Chatziantoniou et al., 2021).

We examine the dynamic connectedness among selected ESG markets and key global factors using an aggregated connectedness approach. We follow (Stenfors et al., 2022) to utilize the aggregated connectedness approach of Gabauer and Gupta (2018) to aggregate the selected ESG markets in three ways to examine the linkages between the corresponding aggregated ESG markets on a wide range of volatility indexes. This approach allows us to examine the relationships between ESG markets across different dimensions and multiple global factors and has several advantages over the existing connectedness approaches. First, as (Stenfors et al., 2022) point out, a prominent concern regarding the monitoring and interpretation of spillovers is the increased complexity of interpretation resulting from the use of numerous series when using the popular TVP-VAR connectedness approach. This new framework allows to extract and disentangle spillover pattern easily, supporting and improving the interpretability of connectedness results. The aggregated connectedness approach is particularly suitable for analysing spillovers in our case, given the number of global factors and ESG markets considered in this paper, which increases the difficulty of interpreting the results. Second, the use of the aggregated connectedness approach also leads to a more in-depth analysis of the linkages between the variables of interest and can be used to gain a better understanding of the transmission dynamics. In this paper, we consider the aggregation of major ESG markets based on different dimensions, including the aggregation of all ESG markets into a global market, the aggregation of ESG markets based on different levels of economic development (developed- and developing-countries), and the aggregation of ESG markets by regions (the Americas, Europe, Asia and the Pacific). The aggregated connectedness approach differs from other existing connectedness approaches which can be used for analysing the connectedness for a number of series by aggregating these series into different group. This feature first allows us to examine spillovers between global factors and a global measure of ESG markets. This new technique, which decomposes shocks between developing and developed markets, also analyses the contribution of spillovers associated with global factors. In addition, we apply this technique to decompose shocks to analyse the contribution of regional spillovers associated with market uncertainties.

The TVP-VAR model is estimated with a lag length of one based upon the Bayesian Information Criterion (BIC) as follows:

$$\boldsymbol{z}_t = \boldsymbol{B}_t \boldsymbol{z}_{t-1} + \boldsymbol{u}_t \quad \boldsymbol{u}_t \sim N\left(\boldsymbol{0}, \boldsymbol{S}_t\right) \tag{1}$$

$$\operatorname{vec}\left(\boldsymbol{B}_t\right) = \operatorname{vec}\left(\boldsymbol{B}_{t-1}\right) + \boldsymbol{v}_t \quad \boldsymbol{v}_t \sim N\left(\boldsymbol{0}, \boldsymbol{R}_t\right) \tag{2}$$

where $\boldsymbol{z}_t$, $\boldsymbol{z}_{t-1}$ and $\boldsymbol{u}_t$ are $k \times 1$ dimensional vectors, representing all volatility series in t, $t-1$, and the error term. $\boldsymbol{B}_t$ and $\boldsymbol{S}_t$ are $k \times k$ dimensional time-varying parameter and variance–covariance matrices whereas $\operatorname{vec}\left(\boldsymbol{B}_t\right)$ and $\boldsymbol{v}_t$ are $k^2 \times k$ dimensional vectors and $\boldsymbol{R}_t$ is a $k^2 \times k^2$ dimensional parameter variance–covariance matrix.

The work of Koop, Pesaran, and Potter (1996) and Pesaran and Shin (1998) is used to calculate the H-step ahead (scaled) generalized forecast error variance decomposition (GFEVD). The GFEVD is based on the vector moving average (VMA) coefficients, and the TVP-VAR is then transformed into a TVP-VMA using the Wold representation theorem:

$$\boldsymbol{z}_t = \sum_{i=1}^{p} \boldsymbol{B}_{it} \boldsymbol{z}_{t-i} + \boldsymbol{u}_t = \sum_{j=0}^{\infty} \boldsymbol{A}_{jt} \boldsymbol{u}_{t-j}$$

The (scaled) GFEVD, $\tilde{\phi}^g_{ij,t}(H)$, normalizes the (unscaled) GFEVD, $\phi^g_{ij,t}(H)$, in order that each row sums to unity. Thus, $\tilde{\phi}^g_{ij,t}(H)$ represents the influence series j has on series i in terms of its forecast error variance share which can also be defined as the pairwise directional connectedness from j to i and computed by,

$$\phi^g_{ij,t}(H) = \frac{S^{-1}_{ii,t} \sum_{t=1}^{H-1} \left(\iota_i' A_t S_t \iota_j\right)^2}{\sum_{j=1}^{k} \sum_{t=1}^{H-1} \left(\iota_i \cdot A_t S_t A_t' \iota_i\right)} \tag{3}$$

$$\tilde{\phi}^g_{ij,t}(H) = \frac{\phi^g_{ij,t}(H)}{\sum_{j-1}^{k} \phi^g_{ij,t}(H)} \tag{4}$$

where $\sum_{j=1}^{k} \tilde{\phi}^g_{ij,t}(H) = 1$, $\sum_{i,j=1}^{k} \tilde{\phi}^g_{ij,t}(H) = k$ and ι_i corresponds to a zero vector with unity on the ith position.

Diebold and Yilmaz (2012) and Diebold and Yilmaz (2014) propose the following connectedness measures based on the GFEVD:

$$\begin{aligned} C_{i\to\bullet,t} &= \textstyle\sum_{j=1,i\neq j}^{k} \tilde{\phi}^g_{ji,t}(H) \\ C_{i\leftarrow\bullet,t} &= \textstyle\sum_{j=1,i\neq j}^{k} \tilde{\phi}^g_{ij,t}(H) \\ C_{it} &= C_{i\to\bullet,t} - C_{i\leftarrow\bullet,t} \\ C_t &= \tfrac{k}{k-1} \textstyle\sum_{i=1}^{k} C_{i\to\bullet,t} \equiv \tfrac{k}{k-1} \textstyle\sum_{i=1}^{k} C_{i\leftarrow\bullet,t}. \end{aligned} \tag{5}$$

$C_{i\to\bullet,t}$ is defined as the total directional connectedness to others while $C_{i\leftarrow\bullet,t}$ is defined as the total directional connectedness from others. C_{it} is the net total directional connectedness. If $C_{it} > 0$, series i is a net transmitter. If $C_{it} < 0$, series i is a net receiver. The total connectedness index, C_t, measures the average shock spillover from one series to all others. A relatively high TCI implies that a shock in one variable has, on average, a large impact on the whole network, and vice versa.

3.1. Aggregated connectedness approach

This section follows the decomposition approach of Gabauer and Gupta (2018) where we explore the spillovers between volatility indexes and aggregated ESG markets in three different ways. First, we aggregate the GFEVD for d groups, where d represents the number of aggregated ESG markets, the number of ESG groups by region, or the number of ESG groups by country classification.

$C^a_{mn,t} = \sum_{i\in k_m}\sum_{j\in k_n}\tilde{\phi}^g_{ij,t}(H)$, where $C^a_{mn,t}$ represents the aggregated impact group n has on group m, where k_m and k_n represent two disjoint index sets. $C^a_{mm,t} = \sum_{i\in k_m}\sum_{j\in k_m}\tilde{\phi}^g_{ij,t}(H)$ is a special case of the previous measure and represents the internal spillovers of the group. The following connectedness measures are calculated as follows:

$$
\begin{aligned}
C^a_{m\to\bullet,t} &= \sum_{n=1,m\neq n}^{d} C^a_{nm,t}\\
C^a_{m\leftarrow\bullet,t} &= \sum_{n=1,m\neq n}^{d} C^a_{mn,t}\\
C^a_{m,t} &= C^a_{m\to\bullet,t} - C^a_{m\leftarrow\bullet,t}\\
C^a_{t} &= \frac{d}{d-1}\sum_{m=1}^{d} C^a_{m\to\bullet,t} \equiv \frac{d}{d-1}\sum_{m=1}^{d} C^a_{m\leftarrow\bullet,t}
\end{aligned}
\tag{6}
$$

where $C^a_{m\to\bullet,t}$ reflects total group-specific connectedness to others, $C^a_{m\leftarrow\bullet,t}$ total group-specific connectedness from others, $C^a_{m,t}$ net total group-specific connectedness, and C^a_t total group-specific connectedness index. The aggregated connectedness measures can be interpreted as mentioned previously.

4. Data

In this paper, following Chen and Lin (2022), we select the eight mainstream ESG leaders' equity indexes, including the MSCI Europe ESG Leaders Index (EU), MSCI USA ESG Leaders Index (USA), MSCI Japan ESG Leaders Index (Japan), MSCI Canada ESG Leaders Index (Canada), MSCI Australia ESG Leaders Index (Australia), MSCI Korea ESG Leaders Index (Korea), MSCI China ESG Leaders Index (China), and MSCI India ESG Leaders Index (India), to capture the dynamics of the worldwide ESG equity investment markets.

There are two main reasons for using these indexes. First, MSCI is the world's leading provider of indexes and related services, offering the most widely used benchmarks for global investors since 1969, particularly for non-US equity markets. Of all the MSCI indexes, the standard country/region indexes are the most popular and are widely used by scholars to measure specific market performance. Furthermore, the methodology for constructing MSCI indexes has evolved over time, maintaining the validity and timeliness of their data (Chakrabarti, Huang, Jayaraman, & Lee, 2005).

Second, following Lucey and Ren (2023), we select indexes provided by the same company-MSCI to ensure consistency in benchmark construction and to avoid variability in company selection. For instance, the MSCI Europe ESG Leaders Index is designed to track the performance of companies selected from the MSCI Europe Index based on Environmental, Social, and Governance (ESG) criteria. This index excludes companies involved in specific business activities, ESG ratings, and ESG controversies, thereby providing an accurate and comprehensive measure of the performance of ESG companies in the European region. It is also worth noting that each of these selected indexes includes more than 40 listed companies with high ESG scores, which not only better reflects the global ESG equity market, but also mitigates the estimation bias caused by insufficient market diversification (Chen & Lin, 2022).[1]

We also choose several popular proxies for market uncertainty including the stock market volatility index (VIX), crude oil volatility index (OVX), and gold volatility index (GVZ). Those three volatility indexes are commonly used to capture the degree of uncertainty in the stock market, oil market, and gold market (e.g., Lin & Su, 2020b, 2023; Kocaarslan & Soytas, 2021). All ESG leaders' equity indexes and volatility indexes are sourced from the Thomson Datastream database. We also use the daily country-level ETF global common volatility index (COVOL), recently proposed by Engle and Campos-Martins (2023), which offers a fresh perspective on the measurement of global financial risk. This newly proposed volatility index differs from the three aforementioned implied volatility indexes, as the global COVOL is known as a broad measure of risk, incorporating broad factors such as geopolitical and climate risk, see Campos-Martins and Hendry (2024).[2]

To calculate the volatility of the ESG equity index, we first calculate the daily returns of the ESG equity index: $r_t = \log\left(\frac{P_t}{P_{t-1}}\right)$, where P_t is the closing price for day t. Following a series of papers including (Antonakakis, Cunado, Filis, Gabauer, & De Gracia, 2018a; Tan, Sirichand, Vivian, & Wang, 2020), and Pazouki and Zhu (2022), we use the absolute return volatility method of Forsberg and Ghysels (2007) to calculate the volatility of each ESG equity index. Forsberg and Ghysels (2007) demonstrate that the absolute returns exhibit superior performance in predicting volatility, such as immunity to jumps, fewer sampling errors, and excellent performance for population prediction.

This study utilizes a daily dataset spanning from January 2014 to April 2023, comprising 2,230 observations that capture the dynamic connectedness between uncertainty in various financial markets and major ESG markets under the backdrop of several critical economic events. The first of these is the 2014 oil crisis, followed by the signing of the Paris Agreement in November 2016. These events, influenced by both shifts in the energy market and growing environmental awareness among investors, led to a noticeable transformation in investment culture by 2017. As noted by Bhattacherjee et al. (2024), since 2017, institutional investors have increasingly adopted targeted strategies that integrate ESG stocks with other assets, and the market's response to ESG signals has become more pronounced. Subsequently, the 2018 US–China trade war provided further insight into the impact of trade policy conflicts between the world's two largest economies on various ESG markets. Finally, to analyse the uncertainties caused by black swan events such as the COVID-19 pandemic and the ongoing escalation of the Russia–Ukraine conflict, we particularly focus on the period from March 2020 to April 2023.

The time series plots of all volatility series are shown as Fig. 1. Table 1 presents some summary statistics for all the volatility series, and it can be seen that all variables have a positive mean volatility over the sample period. In addition, among all the volatility indexes, four global factors appear to have high volatility compared to the eight mainstream ESG indexes. The results of the skewness test of and kurtosis test show that the volatilities of all the indexes are significantly positively skewed and have a leptokurtic distribution. Furthermore, we find that all variables are non-normally distributed based on the Jarque–Bera (JB) statistical test of Jarque and Bera (1980) and stationary at the 1% level in accordance with the ERS unit-root test of Elliott, Rothenberg, and Stock (1996). The weighted Ljung–Box statistics test of Fisher and Gallagher (2012) shows that all series exhibit ARCH/GARCH errors and are significantly autocorrelated. The above results further support our choice of modelling the ESG market and four global factors with the TVP-VAR model.

[1] The construction of the MSCI ESG indexes is based on strict ESG standards that exclude companies with significant ESG controversies or involvement in controversial activities. This may result in selection bias, as only companies with better ESG performance are included. Additionally, this study focuses on observing the impact of risk on different dimensions of ESG, aiming to investigate the asymmetries in the ESG equity market across different regions due to factors such as investor ESG awareness, ESG disclosure, and ESG development. To avoid estimation bias caused by insufficient market diversification, the selected ESG indexes must include at least 40 constituents. As a result, regions with relatively underdeveloped ESG markets are not included.

[2] Further information about these global factors see Xu et al. (2023), Karim and Naeem (2022) and Naeem et al. (2023).

Table 1
Summary statistics.

	COVOL	VIX	OVX	GVZ	Europe	USA	Japan	Canada	Australia	Korea	China	India
Mean	0.548	2.843	3.605	2.747	0.008	0.007	0.008	0.008	0.009	0.010	0.012	0.008
Maximum	2.848	4.415	5.784	3.891	0.136	0.129	0.070	0.139	0.115	0.145	0.156	0.147
Minimum	0.042	2.213	2.674	2.184	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Skewness	2.297***	0.715***	0.658***	0.249***	3.871***	4.133***	2.258***	5.362***	3.500***	3.180***	2.668***	4.349***
Ex.Kurtosis	11.864***	0.606***	2.770***	0.462***	34.595***	33.250***	8.479***	55.623***	24.423***	22.846***	15.117***	42.555***
JB	15714.199***	234.121***	913.091***	44.733***	122010.747***	113966.649***	8960.748***	311529.596***	62664.771***	54596.408***	24950.277***	183157.147***
ERS	−7.918***	−4.245***	−1.730*	−2.916***	−7.211***	−9.757***	−8.846***	−10.190***	−6.487***	−13.387***	−8.948***	−9.746***
$Q(20)$	13881.715***	18257.859***	20784.143***	19551.703***	968.663***	3013.210***	409.802***	2263.596***	1560.709***	901.369***	479.467***	871.100***
$Q^2(20)$	13321.955***	18081.981***	20317.738***	19225.521***	398.589***	2659.692***	433.451***	1876.226***	1967.672***	1640.786***	446.701***	1041.143***
Kendall	COVOL	VIX	OVX	GVZ	Europe	USA	Japan	Canada	Australia	Korea	China	India
COVOL	1.000	0.290	0.274	0.256	0.130	0.168	0.123	0.157	0.106	0.093	0.097	0.083
VIX	0.290	1.000	0.491	0.440	0.234	0.337	0.171	0.243	0.198	0.182	0.167	0.135
OVX	0.274	0.491	1.000	0.462	0.197	0.228	0.144	0.235	0.214	0.144	0.097	0.110
GVZ	0.256	0.440	0.462	1.000	0.172	0.191	0.142	0.201	0.180	0.123	0.069	0.084
Europe	0.130	0.234	0.197	0.172	1.000	0.233	0.124	0.275	0.190	0.125	0.095	0.128
USA	0.168	0.337	0.228	0.191	0.233	1.000	0.118	0.300	0.136	0.102	0.114	0.104
Japan	0.123	0.171	0.144	0.142	0.124	0.118	1.000	0.114	0.167	0.163	0.094	0.069
Canada	0.157	0.243	0.235	0.201	0.275	0.300	0.114	1.000	0.182	0.121	0.080	0.091
Australia	0.106	0.198	0.214	0.180	0.190	0.136	0.167	0.182	1.000	0.135	0.092	0.085
Korea	0.093	0.182	0.144	0.123	0.125	0.102	0.163	0.121	0.135	1.000	0.187	0.130
China	0.097	0.167	0.097	0.069	0.095	0.114	0.094	0.080	0.092	0.187	1.000	0.100
India	0.083	0.135	0.110	0.084	0.128	0.104	0.069	0.091	0.085	0.130	0.100	1.000

Note: This table reports the summary statistics for the COVOL, VIX, OVX, GVZ and the volatility series for eight mainstream ESG leader equity indexes. The above table also reports the estimation results of the D'Agostino (1970) Skewness test; the Anscombe and Glynn (1983) Kurtosis test; the normality test of Jarque and Bera (1980); and the Elliott et al. (1996) ERS unit root test, where *,**,*** indicate significance at 10%, 5%, and 1%, respectively. $Q(20)$ and $Q^2(20)$ represent weighted Portmanteau test statistics of Fisher and Gallagher (2012).

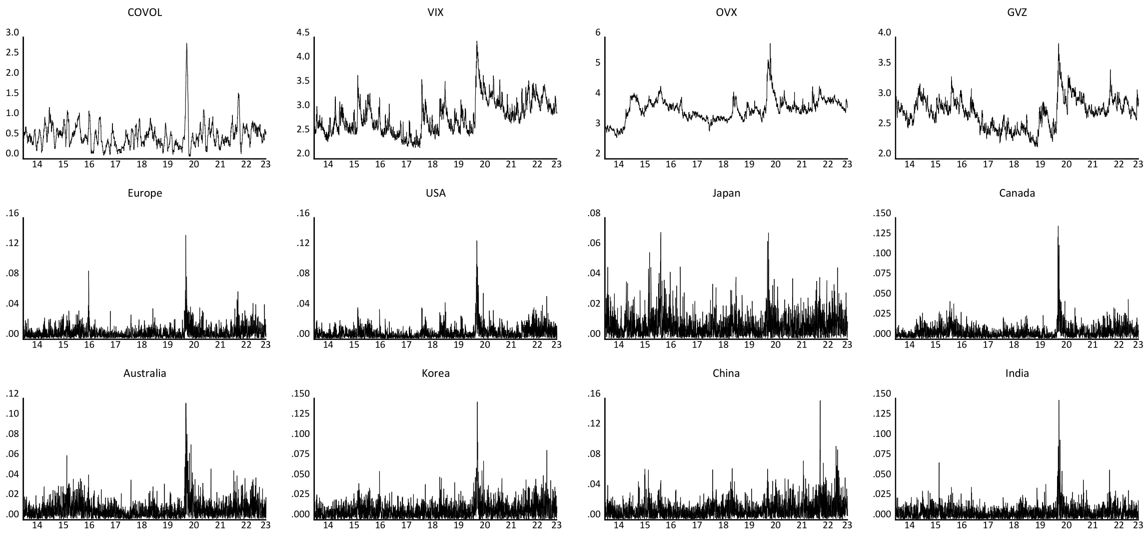

Fig. 1. Time series plot of all volatility series.
Note: The time series plot of the major volatility indexes (e.g., COVOL, GVZ, OVX, VIX) and the volatility of each ESG market is presented in this figure from the period January 2014 to April 2023. The COVOL, GVZ, OVX, and VIX indexes are presented in their original scale and the volatility series of each ESG asset market are calculated using the absolute return volatility method.

The Kendall correlation results indicate a positive correlation among all volatility indexes, with the highest correlations exhibited between the VIX and OVX. Concentrating on the correlation between ESG markets and global factors, it emerges that the most pronounced correlation is between the USA and the VIX, standing at 0.337. Conversely, the weakest correlation coefficient is found between China and the GVZ, which is 0.069. Turning to the correlations within the eight ESG regions, we find that the highest linkage exists between the USA and Canada. This correlation, at 0.300, underscores the substantial interconnection between these two North American ESG financial markets.

5. Results

The following section presents the dynamic aggregated connectedness results based on three different criteria. By aggregating the ESG markets in three different ways, we attempt to explore the relationship between aggregated ESG markets and the major volatility indexes. The adoption of the aggregated connectedness approach of Gabauer and Gupta (2018) allows the examination of dynamic connectedness between several important global factors (such as the COVOL, VIX, OVX and GVZ) and worldwide ESG markets across different dimensions. In particular, we segregate eight international ESG markets according to different criteria. The first dimension is to aggregate all ESG markets, as we are interested in the dynamic transmission between global factors and the overall worldwide ESG equity market. Subsequently, in order to investigate the connectedness transmission between ESG markets of different states of sovereign economic development and global factors, we divided the eight ESG markets into two groups, described as aggregated developed ESGs and aggregated developing ESGs. Finally, to further explore the dynamic connectedness between the differential efficiency of regional ESG markets and global factors, we divided the global ESG market into four regions, namely the Americas, Europe, Asia and the Pacific. The key findings of aggregate connectedness results are presented as follows.

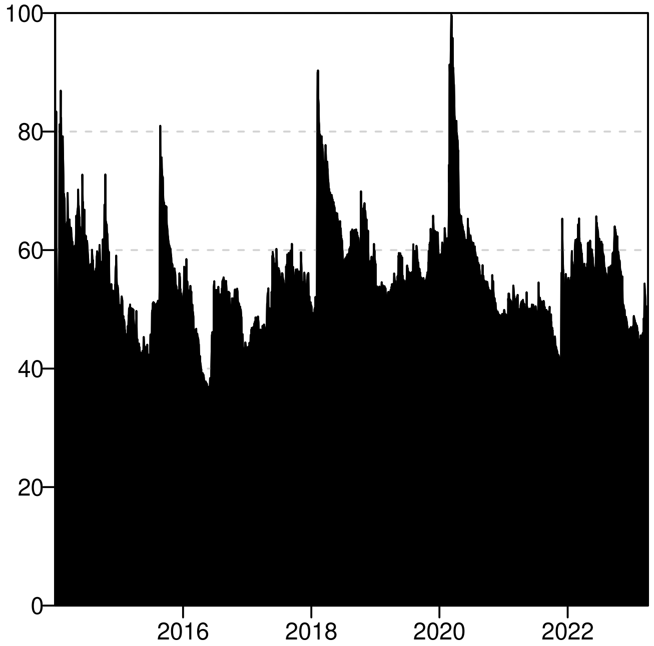

Fig. 2. Aggregated global ESG market dynamic total connectedness.
Note: Results are estimated by using TVP-VAR (0.99, 0.99) model with a lag length of order 1 and a 20-step-ahead forecast.

5.1. Aggregated global ESG equity markets

To represent the aggregation of worldwide ESG equity markets, we aggregate all ESG equity markets into one group, including Europe, the US, Japan, Canada, Australia, Korea, China, and India, and refer to this group as the aggregate global ESG market. In this section, we first examine the dynamic connectedness between four volatility indexes and the aggregated global ESG market based on a five-variable VAR model. Fig. 2 depicts the dynamic total connectedness index (TCI) across the variables. Evidently, the variation of TCI fluctuates between approximately 40% and 60% during most sample periods. Nevertheless, it can be seen that the trend of the TCI shows a significant increase during the three main periods; 2015 to early 2016; 2018 to 2019, and early 2020. These periods represent major events, namely the European debt crisis, the US–China trade war, and the COVID-19 outbreak. Of particular note is the peak of the TCI during the COVID-19 outbreak, underscoring the enormous shocks of the pandemic on the connectedness of major financial markets and worldwide ESG equity markets.

With the outbreak of COVID-19, governments around the world implemented unprecedented large-scale social distancing and restrictive measures, which greatly increased uncertainty in financial markets and exacerbated investor panic, leading to significant shifts in investment expectations. This heightened uncertainty led investors to withdraw from higher-risk assets in favour of safer havens (Lin & Su, 2023), further exacerbating financial contagion and spillovers across markets (Yarovaya, Brzeszczyński, Goodell, Lucey, & Lau, 2022). These findings align with the work of Chen and Lin (2022) and Gao et al. (2022), who suggest that large external shocks significantly increase the interconnectedness of the global ESG market. Regarding the most recent Russia–Ukraine conflict, although the TCI shows an upward trend, the magnitude of connectedness change is noticeably smaller compared to the aforementioned events.

Figs. 3 and 4 display the net directional connectedness and pairwise connectedness results between major global factors and aggregated global ESG market, respectively. As can be seen in Fig. 3, a distinct pattern can be observed from the net directional results. In terms of this specific network, the aggregated ESG market is consistently a shock receiver for most of the sample period. Aggregated global ESG is also a receiver in most periods. However, there is a notable shift in March 2020, which corresponds to the timeline of the occurrence of COVID-19. The net directional index of aggregated global ESG moves from negative to positive, illustrating the shift of aggregated global ESG markets to a shock transmitter.

With the outbreak of COVID-19 on a global scale, the net directional connectedness of global ESG markets has undergone a substantial shift. This shift reflects an evident increase in internal spillovers between key global ESG markets, ultimately leading to the transformation of the global ESG market from a net recipient of risk to a net transmitter of risk. Clearly, the global ESG market showed strong risk resilience during the pandemic; rather than being affected by spillovers from other major financial markets, it became a driving force behind the net directional connectedness index. The reasons for this phenomenon may be related to the following factors.

The non-pecuniary motivations of ESG investors play a crucial role. In times of crisis, ESG markets often outperform in terms of stock returns, growth rates and profitability because ESG investors place a higher premium on ESG markets or have non-pecuniary investment motivations. Thus, investor loyalty leads ESG markets to demonstrate better resilience and positive returns in extreme market conditions (Lins, Servaes, & Tamayo, 2017). For example, Albuquerque, Koskinen, Yang, and Zhang (2020) show that ESG investors (those who prefer ESG stocks) are less sensitive to the performance of ESG funds than traditional mutual funds. If the COVID-19 shock affected investors' attitudes to risk, causing many to sell their holdings, ESG investors would have shown greater resilience than other equity investors.

The heightened awareness of ESG investing among investors during the COVID-19 pandemic is another contributing factor. In consequence of the global economic uncertainties triggered by the pandemic, there has been a notable increase in the level of attention paid by investors to ESG performance and disclosures (Bae, El Ghoul, Gong, & Guedhami, 2021). Investors undertake a reassessment of their portfolios, with a particular preference for companies that have demonstrated excellence in social responsibility and environmental impact. The intensified focus on ESG performance resulted in increased capital flows into these companies, thereby reinforcing the dynamism of the ESG market and the extent of risk spillover effects. For instance, the findings from (Broadstock, Chan, Cheng, & Wang, 2021) confirm the growing importance of ESG performance during the COVID-19 pandemic. There is a growing perception that ESG investing is a means of improving portfolio performance, increasing returns, and reducing portfolio risk.

Turning to global factors, we notice that the VIX, GVZ and OVX are transmitters, while the COVOL has been a persistent receiver of shocks. Among them, VIX exhibits a notably higher degree of transmission within the system compared to OVX and GVZ, thereby establishing its role as the primary transmitter. On the other hand, the net directional connectedness index of COVOL remains negative for most of the sample period, indicating that it plays a crucial role as a key receiver within the system.

The specific pairwise transmission mechanism between the aggregated global ESG market and each volatility index is shown in Fig. 4. It appears that the COVOL is a shock recipient for aggregated global ESG, while VIX, OVX, and GVZ are the main transmitters to the aggregated global ESG. These results suggest that COVOL and the three implied volatility indexes do not play the same role in the pairwise volatility transmission channel in relation to aggregated global ESG. In brief, the aggregated global ESG can influence COVOL while also being affected by the spillover effects from the three major financial markets—stocks, oil, and gold. As a novel measure of global financial risk, COVOL is directly impacted when significant shocks or events occur in the global ESG market. Similarly, COVOL can be employed to observe the dynamics of the global ESG equity market, thereby assisting ESG investors in making rational and timely adjustments to

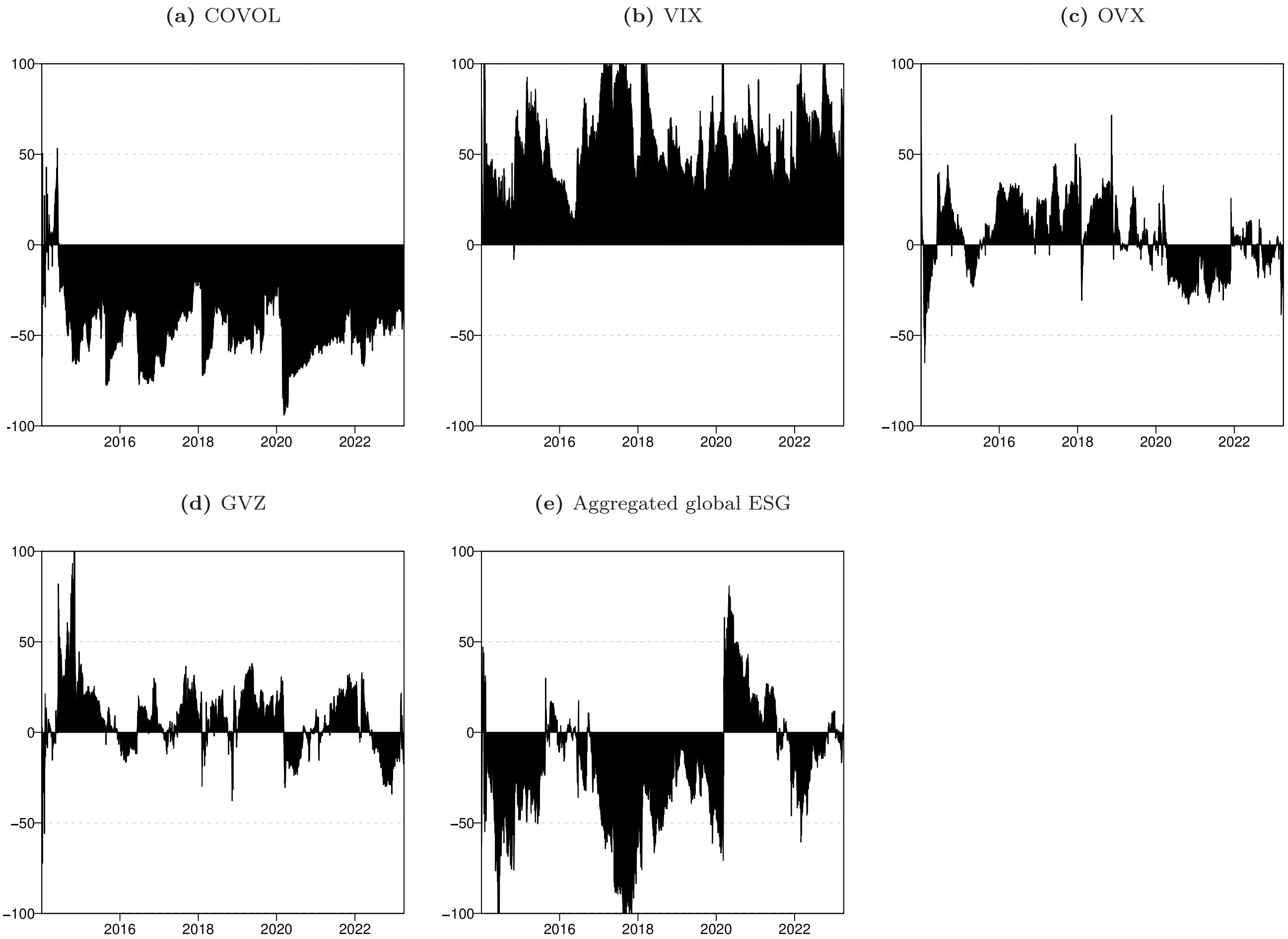

Fig. 3. Aggregated global ESG market net directional connectedness.
Note: Results are estimated by using TVP-VAR (0.99, 0.99) model with a lag length of order 1 and a 20-step-ahead forecast.

their portfolios. On the other hand, the global ESG market serves as a consistent recipient of the uncertainties inherent to the stock, oil, and gold markets. The connectedness pattern implies that when there are substantial fluctuations in the uncertainties of these three markets, the global ESG equity market tends to become more turbulent, with the transmission becoming more pronounced. The underlying logic of this spillover effect is frequently associated with the financial theories of flight to safety (Baur & Lucey, 2010) and portfolio reallocation (Bai, Wei, Zhang, Wang, & Lucey, 2023). This illustrates global ESG investing as a financial safe-haven asset, as perceived by investors.

On closer inspection, a clear pattern emerges, showing that aggregated global ESG transmits large amounts of shock to the COVOL during two specific periods: from 2015 to early 2016 and between 2020 and 2022. These periods coincide with two notable extreme events, namely the European debt crisis and the global outbreak of COVID-19. The intensity of volatility transmission for the COVOL-aggregated global ESG pair is intensified to its maximum surrounding the COVID-19 outbreak, and the magnitude of the transmissions slowly diminish as COVID-19 spread rapidly across international borders. Moreover, the intensity of the spillover effects from aggregated global ESG to COVOL could potentially be enhanced by certain other international financial events. For example, the US–China trade conflict in 2018 provoked a noticeable shock transmitted from the aggregated global ESG to the COVOL. As tensions in the US–China trade relationship escalated, they caused increased instability in the global financial system and the global aggregated ESG markets exhibited stronger outward spillovers to the COVOL. These results underscore the fact that extreme international financial events will lead to an increased level of risk contagion in the global ESG market, thereby transmitting noticeable shocks to the COVOL.

Moving to the pairing of the aggregated global ESG with VIX, OVX, and GVZ, we observe that the aggregated global ESG consistently acts as the recipient of shocks across all three pairs. The intensity of the spillover effect is found to be the largest for the VIX-ESG pair, followed by the OVX-ESG and GVZ-ESG pairs. In other words, within this specific system, VIX exerts the strongest spillover effect on the global ESG market, followed by OVX, with GVZ having the least impact. It can be observed that stock market uncertainty typically dominates the volatility in the global ESG equity market, followed by uncertainty in the oil market, and lastly, uncertainty in the gold market. This result suggests that stock market uncertainty can serve as a critical metric for monitoring the stability of the global ESG equity market, given its dominant role in the transmission mechanism. Specifically, we find that the VIX transmitted significant shocks to the aggregate global ESG market in early 2018 and March 2020. These findings correspond to the occurrence of major events during these periods, such as the US–China trade war and the COVID-19 outbreak. The occurrence of these events triggered panic among equity market investors, which subsequently led to volatility spillover effects in the global ESG market.

5.2. Aggregated developed-country ESG and developing-country ESG markets

In order to distinguish the transmission mechanisms between ESG markets with different levels of sovereign economic development status, and major volatility indexes, we divide the eight ESG markets

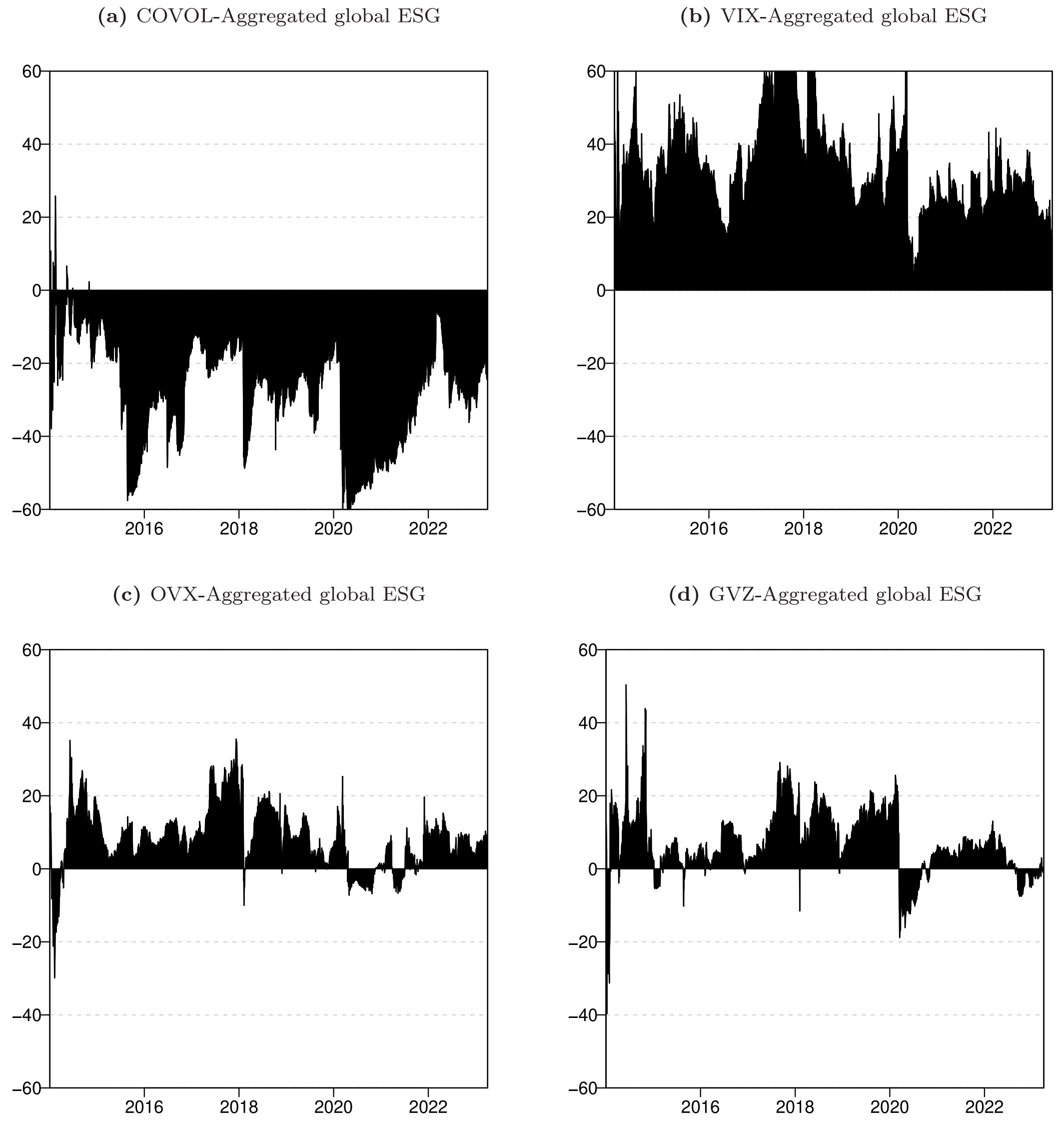

Fig. 4. Aggregated global ESG market pairwise connectedness.
Note: Results are estimated by using TVP-VAR (0.99, 0.99) model with a lag length of order 1 and a 20-step-ahead forecast.

into two different groups based on the level of economic development, and then aggregate these two corresponding ESG groups; namely aggregated developed-country ESG and aggregated developing-country ESG markets. The aggregated developed-country ESG group includes Europe, the US, Australia, Canada, Japan and Korea, while the aggregated developing-country ESG group includes China and India. This section, therefore, aims to provide a new investigation to explore these important inter-linkages between four major global factors and two aggregated developed/developing-country ESG based on a six-variable VAR model. The corresponding net directional connectedness and pairwise connectedness results are depicted in Figs. 5 and 6, respectively.[3]

Fig. 5 illustrates the results of net directional connectedness, where we can observe a stark contrast in the net connectedness index trend between aggregated developed-country ESG and aggregated developing-country ESG. Although both groups have predominantly negative net connectedness indexes for most of the sample period, the variation in the connectedness index for the aggregated developed-country ESG noticeably exceeds that for the aggregated developing ESG. In particular, it can be clearly seen that the net index of aggregated developed ESG shows an unusual variation in the three periods, including 2014–2015, 2018 and 2020, which correspond to the following timeline of events; the European debt crisis, the US–China trade war and COVID-19. These findings not only confirm that the intensity of connectedness of the ESG equity market increased during the financial crisis (e.g., Chen & Lin, 2022 and Naeem et al., 2023), but also reveals that the degree of connectedness variation in developed ESG markets is much greater than in developing ESG markets, when such financial events occur. An interesting observation is that when the World Health Organization (WHO) declared COVID-19 to be a pandemic in March 2020, aggregated developed-country ESG quickly shifted from being a shock receiver to a shock transmitter, while aggregated developing-country ESG maintained its position as a shock receiver.

Fig. 6 presents the pairwise connectedness results between aggregated developed-country ESG, aggregated developing-country ESG, and four major volatility indexes. Several interesting findings are identified as follows. First, in line with the results above, both the aggregated ESG markets of developed countries and those of developing countries act as transmitters to COVOL. Moreover, they also act as receivers to the other three implied volatility indexes. Second, the intensity of the spillover effect from the aggregated developed-country ESG to the COVOL is much

[3] We do not present the aggregated TCI results for this model to conserve the space but the results are available on request.

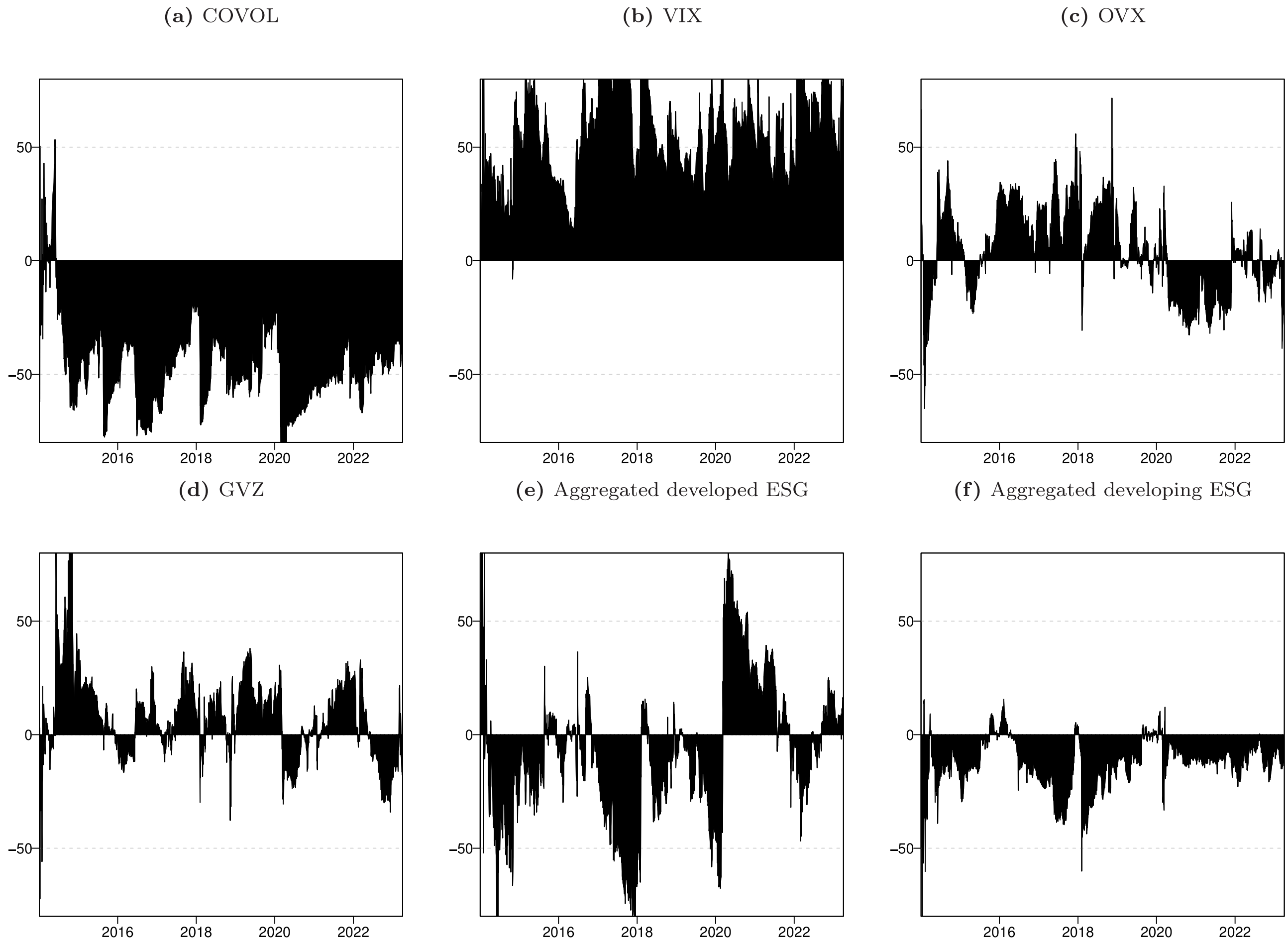

Fig. 5. Aggregated developed-country and developing-country ESG net directional connectedness.
Note: Results are estimated by using TVP-VAR (0.99, 0.99) model with a lag length of order 1 and a 20-step-ahead forecast.

larger than that from the aggregated developing-country ESG to the COVOL. Specifically, we observe that the pairwise connectedness index between COVOL and the developed countries remains below -20% for most of the sample period. This result suggests that, as a receiver, the degree of transmission from the ESG markets of developed countries to COVOL exceeds 20% most of the time. In contrast, the connectedness index between COVOL and developing countries fluctuates between 0% and −20%. In other words, although COVOL acts as a receiver in the pairings with both developed and developing countries' ESG markets, the degree of transmission from the ESG markets of developing countries is considerably lower than from developed countries. This finding highlights a crucial point that, from a global ESG market perspective, the impact of volatility in developed country ESG markets far exceeds that in developing countries. Notably, it can be observed that the transmission from the aggregated developed-country ESG to the COVOL is more pronounced, compared to the developing-country ESG, during the financial crisis, including the European debt crisis, the US–China trade war, and COVID-19. These findings further corroborate previous observations that the developed-country ESG market tends to exert a more dominant role relative to the developing-country ESG market. These findings further corroborate the earlier observation that the ESG markets of developed countries tend to play a more dominant role compared to those of developing countries. More importantly, in times of economic turmoil, the volatility of ESG equity markets in developed countries is relatively higher than in developing countries. Additionally, the magnitude of the information transmission from the three implied volatility indexes (e.g., VIX, OVX, GVZ) to the aggregated ESG markets of the developed countries is greater than that to the aggregated ESG markets of developing countries.

Third, it is noteworthy that the magnitude of the spillover effects between aggregated developed-country ESG and the four major volatility indexes is much larger than that of the aggregated developing-country ESG. A plausible explanation for this finding could be the later start and lower degree of internationalization of ESG markets in developing countries, while developed countries have an earlier start and higher degree of internationalization, resulting in a high degree of connectedness transmission with other global financial markets (Bai & Lin, 2024; Su & Lin, 2022). Finally, the pairwise connectedness results between the aggregated ESG markets of developed and developing countries show that the aggregated developed-country ESG is a transmitter, suggesting that the ESG markets in developed countries such as Europe, the US, and Canada, which are the core of the international ESG system, dominate ESG markets in developing countries. This result is in agreement with Umar et al. (2020) and Akhtaruzzaman and Shamsuddin (2016), who find that countries with more mature ESG markets are leading those countries whose development of ESG markets is relatively new.

5.3. Aggregated ESG markets by region

In addition to the above results, it is also important to explore the difference in connectedness between regional ESG markets. Following the work of Naeem et al. (2023), we divide the major ESG markets into four different regions; the Americas, Europe, Asia and the Pacific, and then aggregate the corresponding ESG markets by region. For instance, the Americas include the ESG equity market of the USA and Canada, and Europe represents the performance of the Europe ESG equity market, Asia encompasses the ESG equity markets of Japan, China, Korea

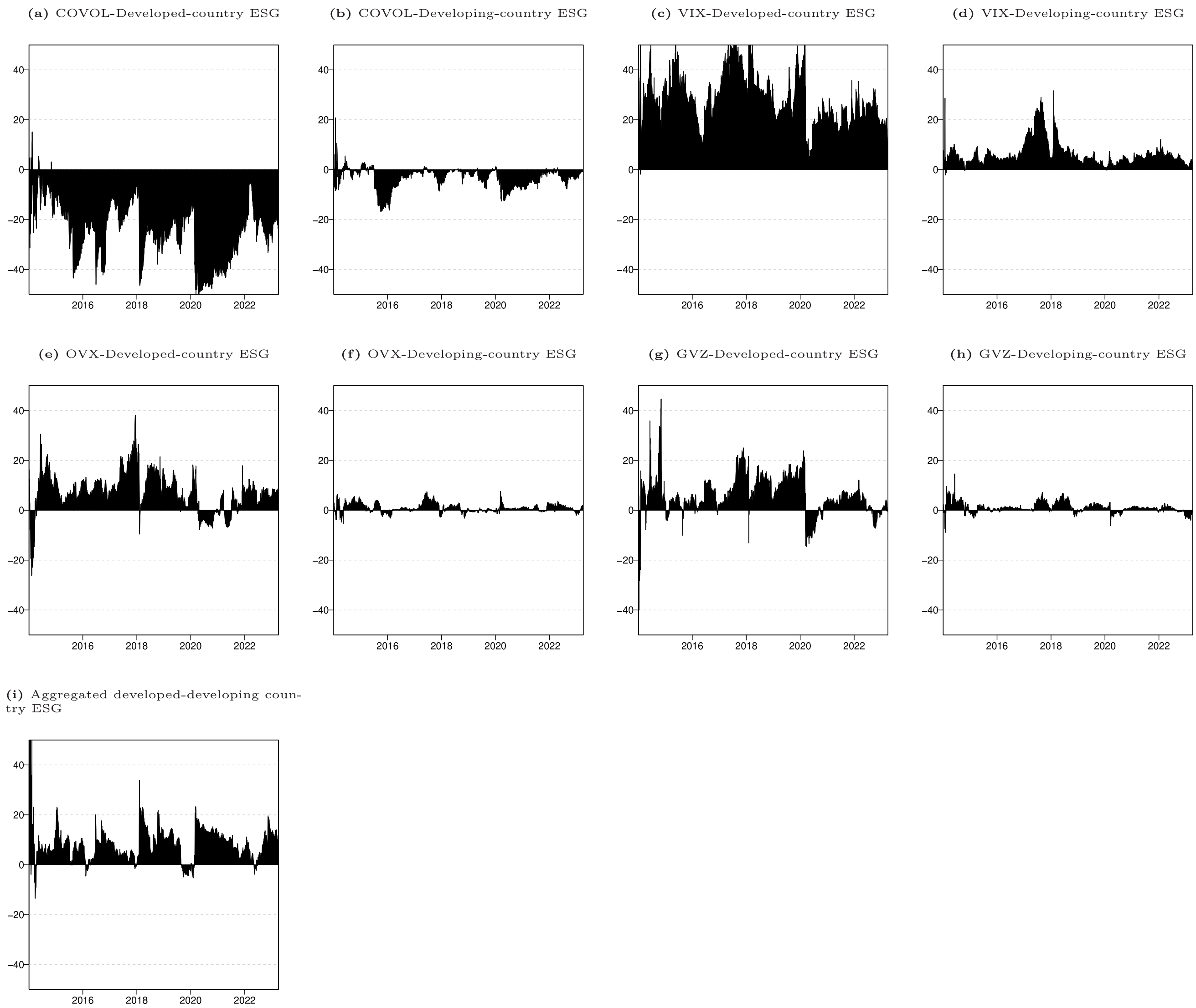

Fig. 6. Aggregated developed-country and developing-country ESG pairwise connectedness.
Note: Results are estimated by using TVP-VAR (0.99, 0.99) model with a lag length of order 1 and a 20-step-ahead forecast.

and India, and the Pacific ESG contains Australia. This allows us to investigate the dynamic connectedness between four important global factors and four regional ESG markets (e.g., the Americas, Europe, Asia and the Pacific) based on an eight-variable VAR model.[4]

The net directional and pairwise connectedness results between different regional ESG markets and major risk indexes are presented as Fig. 7 and Fig. 8, respectively. We start with Fig. 7, which illustrates the net dynamic connectedness results. COVOL is a receiver, while the other three volatility indexes (e.g., VIX, OVX, and GVZ) appear to be transmitters. Focusing on the aggregated region's ESG markets, we notice that the Americas stand out as the most prominent transmitter among the four aggregated regional ESG markets, followed by Europe. Moreover, compared to Europe, the Americas transmitted substantial shocks to the system in the periods March 2018 and March 2020, corresponding to the timeline of the US–China trade war and the outbreak of COVID-19. In contrast, both the Asian and Pacific ESG markets are shock recipients. Furthermore, the shocks received by Asia are much stronger than those received by the Pacific region.

[4] Similarly, we do not present the aggregated TCI results to conserve the space but the results are available on request.

As shown in Fig. 8, the results illustrate the pairwise connectedness between the major volatility indexes and each regional ESG. It can be seen that COVOL stands out as a consistent recipient of shocks, where the shocks received from the Americas are generally larger in size than the other three regional ESGs, which highlights the dominant role of the Americas ESG among the global ESG markets. This result is somewhat similar to the findings of Gao et al. (2022), who concluded that the ESG market in North America is the core of the risk spillover system among global ESGs. Furthermore, it can also be observed that both the Americas and Asia transmit considerable shocks to the COVOL during the Chinese stock market crash in August 2015, the US–China trade war in March 2018, and the COVID-19 outbreak in March 2020. In terms of Europe, it has been a persistent transmitter, but the intensity of the transmission to the COVOL has not shown an obvious escalation during the aforementioned financial crisis, compared to the Americas and Asia. The Pacific region has the lowest connectedness with COVOL. This could be due to the fact that the Pacific is at an early stage in the development of the ESG market, so the influence of the ESG market on global financial market uncertainty is much lower than in relatively mature regions such as the Americas and Europe.

Focusing on the three implied volatility indexes, the VIX, GVZ, and OVX are transmitters in general for each regional ESG. We observe that the VIX is the strongest transmitter to the four regional ESGs compared

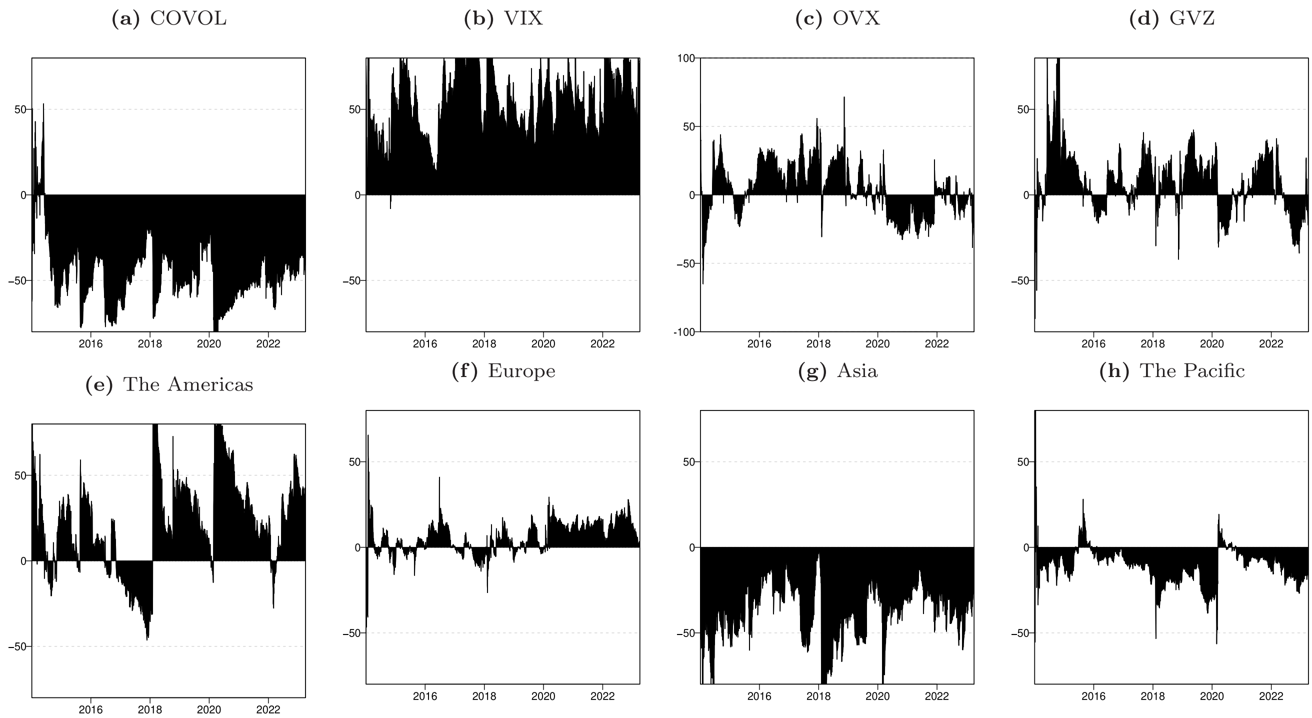

Fig. 7. Aggregated regional ESG net directional connectedness.
Note: Results are estimated by using TVP-VAR (0.99, 0.99) model with a lag length of order 1 and a 20-step-ahead forecast.

to the OVX and GVZ. In addition, the spillover effects from the VIX to the Americas and Asia are relatively strong compared to Europe and the Pacific. Such results further support the dominant role of VIX in the connectedness variation of ESG markets. Compared to the VIX, the spillover effect between the OVX/GVZ and regional ESG markets is much lower. In particular, the pair of GVZ-Europe exhibits the lowest level of connectedness transmission, followed by OVX-Europe, as identified in this study.

Turning to the interconnectedness transmission among the four aggregated regional ESG markets, we note that there is a higher level of interconnectedness between aggregated ESG in the Americas and the other three regions. A positive pairwise index between the Americas and the other three regions indicates that the Americas are a major transmitter of the worldwide ESG market. In particular, the largest spillover effect is observed between the Americas and Asia, reaching its peak in the year 2018. Furthermore, the intensity of connectedness is the lowest between the Americas and Europe. Conversely, it is evident that Asia and the Pacific regions are recipients of shocks, with Asia experiencing significantly greater shocks compared to the Pacific region. The rationale behind these results may be that the ESG market is still an emerging industry in both Asia and the Pacific. The development of the ESG market in emerging markets appears to be primarily driven by mature markets such as the Americas and Europe, which therefore have a strong influence on the ESG industry in both Asian and Pacific markets (Iqbal et al., 2022).

Overall, through a comprehensive investigation of the transmission mechanisms between various financial market uncertainties and four regional ESGs, it becomes evident that the ESG equity market in Europe holds a prominent and distinct position on the global stage. On closer inspection, Europe emerges as a prominent and mature ESG market, with many features that make it stand out. For example, Europe's relatively stable connectedness with the COVOL, limited exposure to spillovers from various financial market fluctuations and relatively low exposure to external shocks from the Americas, which make the region a unique and resilient player in the global ESG market. Such results further support the findings of Naeem et al. (2023), who state that due to the large market capitalization and maturity of the European ESG market, investing in European ESGs is more likely to act as a potential diversifier, hedger and risk mitigant for ESG markets in other regions. For the Americas, we note that despite its dominant position among the four regions, it is also the largest recipient of global financial market uncertainty factors, particularly the VIX. Therefore, our results suggest that investors should pay attention to the impact of global uncertainty on the ESG market, particularly in terms of risk contagion of the stock market triggered by extreme financial events. As a major recipient, Asia notably experiences a higher degree of volatility transmission in comparison to the other three regions. The main reason could be attributed to its relatively late development of the ESG markets, while at the same time, holding a crucial position in the global financial market (Chen & Lin, 2022). Therefore, it is not only influenced by global uncertainty but also received spillovers from developed ESG regions, such as the Americas, and Europe. In terms of the Pacific, we observe that its connectedness with major volatility indexes is relatively low, while its association with the regional ESG markets exhibits a higher degree of connectedness. Such results suggest that when investing in Pacific ESG markets, the focus should be more on the risk contagion between different regional ESG markets as compared to global uncertainty indexes.

5.4. Robustness checks

5.4.1. Alternative model specification

As a robustness check, we try an alternative model specification for estimating the TVP-VAR model using a lag length of order 1 (as also determined by the BIC) and a 10-step-ahead forecast rather than a 20-step-ahead forecast. The results of the robustness checks are carried out using three different aggregated connectedness models based on three dimensions, and the results are consistent with the results obtained in Sections 5.1–5.3.[5]

[5] The results of the robustness checks are not presented here for reasons of space. They are available on request.

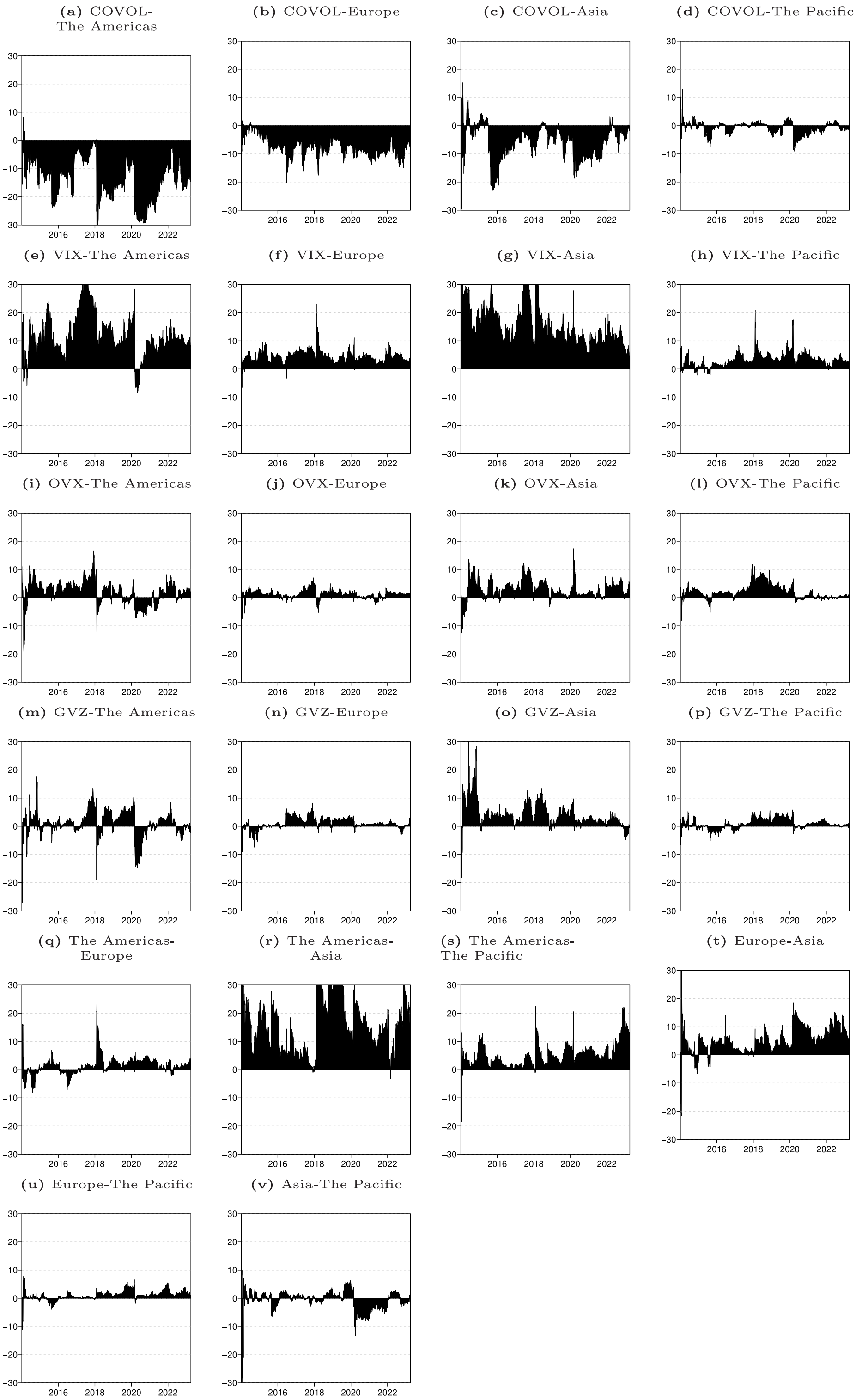

Fig. 8. Aggregated regional ESG pairwise connectedness.
Note: Results are estimated by using TVP-VAR (0.99, 0.99) model with a lag length of order 1 and a 20-step-ahead forecast.

5.4.2. Alternative COVOL index

In addition, we also use the daily asset-based USCOVOL index of Engle and Campos-Martins (2023), which is a measure of common volatility in US asset prices. We then use the USCOVOL index to replace the global COVOL in the aggregated connectedness analyses, and the corresponding results are also found to be identical to those obtained in Sections 5.1–5.3 above.[6]

[6] For reasons of space, the results of the robustness checks are not presented here, but are available on request.

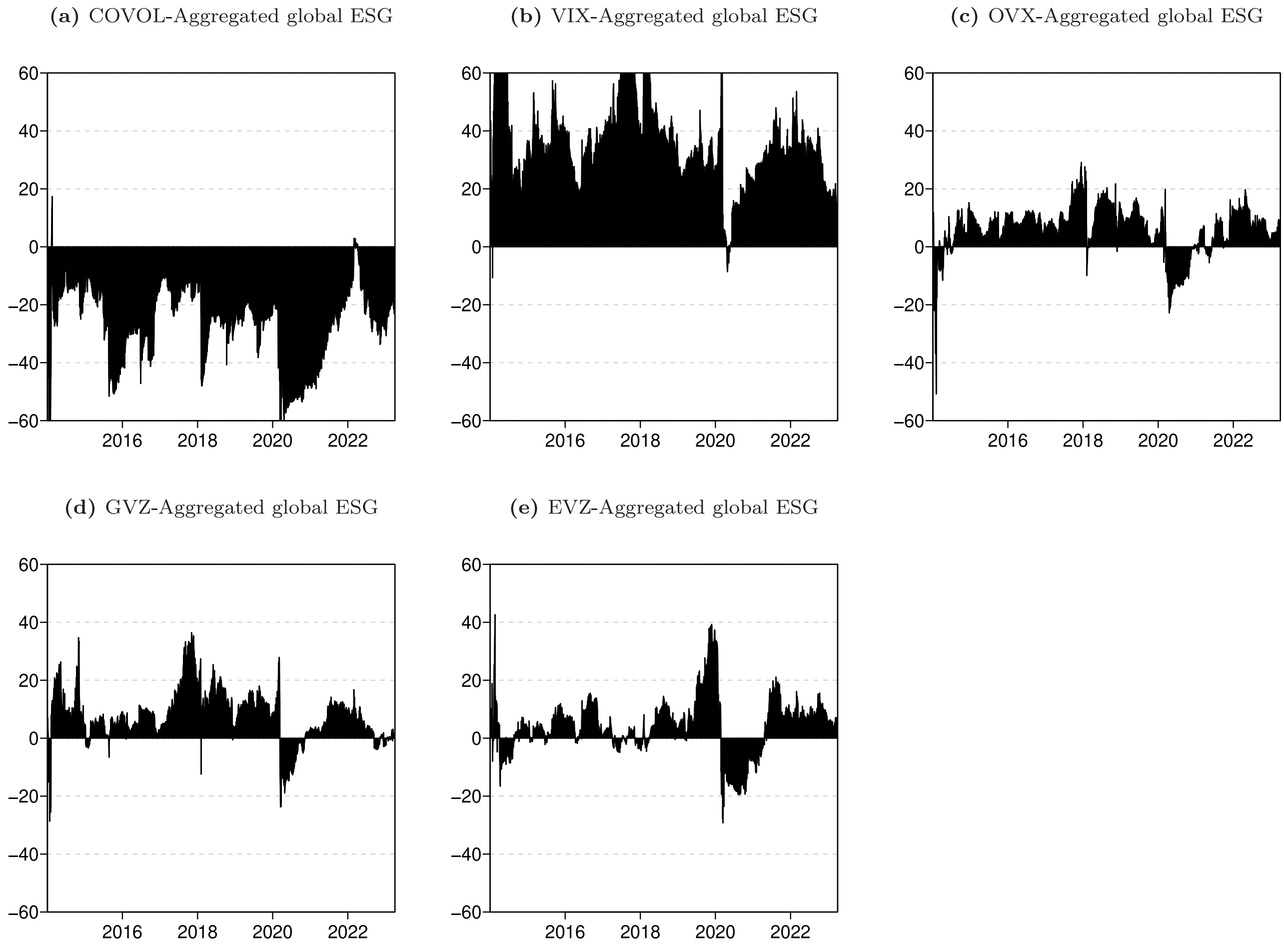

Fig. 9. Aggregated global ESG market pairwise connectedness with EVZ (Robustness check).
Note: Robustness check results are estimated by using TVP-VAR (0.99, 0.99) model with a lag length of order 1 and a 20-step-ahead forecast.

5.4.3. Additional volatility index

We also carry out robustness checks by including additional the CBOE exchange rate volatility index-EVZ for the analysis. In this case, we select four implied volatility indexes (VIX, OVX, GVZ, and EVZ) with COVOL as global factors. This section then investigates the dynamic connectedness between these five global factors and international ESG equity markets using the aggregated connectedness approach based on the same criteria in Sections 5.1–5.3. We present the pairwise results between global factors and aggregated ESG markets in Figs. 9–11.[7] For example, Fig. 9 presents the pairwise results between the aggregated global ESG market and five global factors. Comparing Fig. 9 with Fig. 4, our key findings still hold. In particular, EVZ has a similar dynamic transmission pattern with those of GVZ and OVX. Fig. 10 presents the pairwise results between aggregated developed-country ESG, aggregated developing-country ESG, and five major volatility indexes. Similarly, our findings are also identical to those presented in Fig. 6. Fig. 11 presents pairwise connectedness between five volatility indexes and regional ESGs. Our main findings remain unchanged when comparing Fig. 11 with Fig. 8.

6. Conclusion

This study follows Stenfors et al. (2022) to employ the aggregated connectedness approach of Gabauer and Gupta (2018) to investigate the dynamic connectedness between major financial market uncertainties (e.g., the COVOL, VIX, OVX, GVZ) and eight major ESG markets based on a range of criteria. Our study not only shows the interaction of financial market volatility indexes with aggregated ESG markets across different dimensions, but also the interconnectedness of ESG markets. To do this, we apply the aggregated connectedness method of Gabauer and Gupta (2018), which allows us to disentangle and extract complex spillover patterns, thereby improving the interpretability of the connectedness dynamics of ESG markets. Thus, the main findings of this paper can be divided into three parts based on different dimensions of the ESG market, such as the aggregation of all ESG markets into one global market, the aggregation of different stages of economic development-based ESG markets (developed-country and developing-country), and the aggregation of four regions (the Americas, Europe, Asia and the Pacific).

This paper presents a number of important findings as follows. First, the COVID-19 pandemic has a much larger impact on the dynamic total connectedness of the system compared to other major global events. We find that the TCI shows a significant increase during the European debt crisis, the US–China trade war and the COVID-19 outbreak. The magnitude of the change in connectedness due to the Russia–Ukraine conflict is much smaller compared to the aforementioned global major events. Second, the COVOL is a primary recipient of volatility transmission to the ESG equity markets, while the VIX, OVX, and GVZ are major transmitters. The COVOL does not play the same role as the other three implied volatility indexes. More specifically, we observed that COVOL receives strong volatility spillovers from the aggregated global ESG market during the European debt crisis and COVID-19. Meanwhile,

[7] To save space, we only present the pairwise results based on three different dimensions, but the other results are available on request.

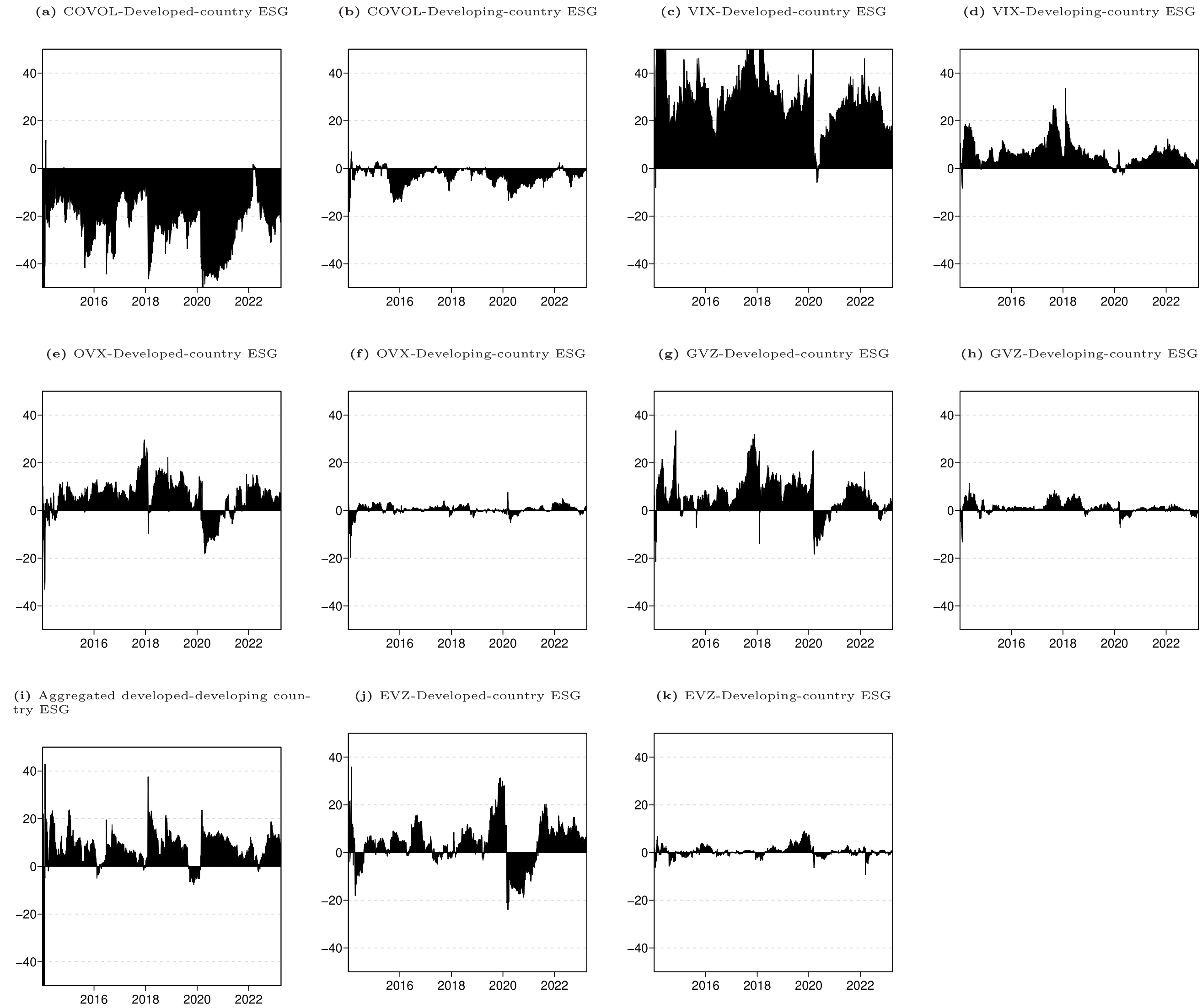

Fig. 10. Aggregated developed-country and developing-country ESG pairwise connectedness with EVZ (Robustness check).
Note: Robustness check results are estimated by using TVP-VAR (0.99, 0.99) model with a lag length of order 1 and a 20-step-ahead forecast.

the VIX, OVX and GVZ transmit significant shocks to the ESG market, with the VIX being the main driver of the global ESG transmission channel.

Third, based on the stage of economic development for each ESG market, we find that both developed and developing country aggregate ESG markets act as transmitters to COVOL, while they act as receivers to the other three implied volatility indexes. Therefore, the connectedness of developed markets differs from that of developing markets. Moreover, the magnitude of the spillover effect between aggregated developed-country ESG and four major volatility indexes is much stronger than that of aggregated developing-country ESG. In addition, aggregated developed-country ESG dominate ESG markets in developing countries.

Fourth, when separating worldwide ESG markets by region, the level of connectedness varies from region to region. Our examination of aggregated ESG markets by region uncovers several notable and significant findings. Among these, the unique role of the European ESG equity market in the global framework is particularly prominent. Europe has the lowest level of connectedness with both the major financial market uncertainties and the other three regional ESGs, indicating that Europe is the least influenced by global factors and regional ESGs. Moreover, our empirical analysis shows that the American equity market plays a critical role as the main recipient of volatility spillovers from global uncertainty, while also acting as the main transmitter of other regional ESGs. Asia has become a major recipient of global financial market uncertainty and regional ESG spillovers. Last, the Pacific region has lower connectedness with major volatility indexes, but higher volatility transmission with ESG markets in other regions.

The empirical findings of this study have notable implications for investors, policymakers and regulators. Firstly, at the global ESG market level, a notable spillover effect was observed between the ESG market and several key volatility indexes, most notably the COVOL index and the VIX index. Therefore, investors may consider using COVOL and VIX as important risk metrics to monitor the dynamics of the global ESG market. Policymakers should focus on maintaining the stability of the overall financial environment, especially during periods of heightened global market volatility, by formulating effective policies to mitigate the adverse impacts of these fluctuations on the ESG market. Secondly, our study reveals that, from the perspective of different stages of economic development in ESG markets, there are distinct patterns of spillover effects on developed and developing countries. In developed countries, the flow of transmission channel in ESG markets is primarily driven by VIX. Therefore, policymakers should enhance stock market regulation and implement robust financial policies to reduce the impact of VIX-induced market volatility on ESG investments. For investors, they should adopt a strategy of monitoring VIX market fluctuations

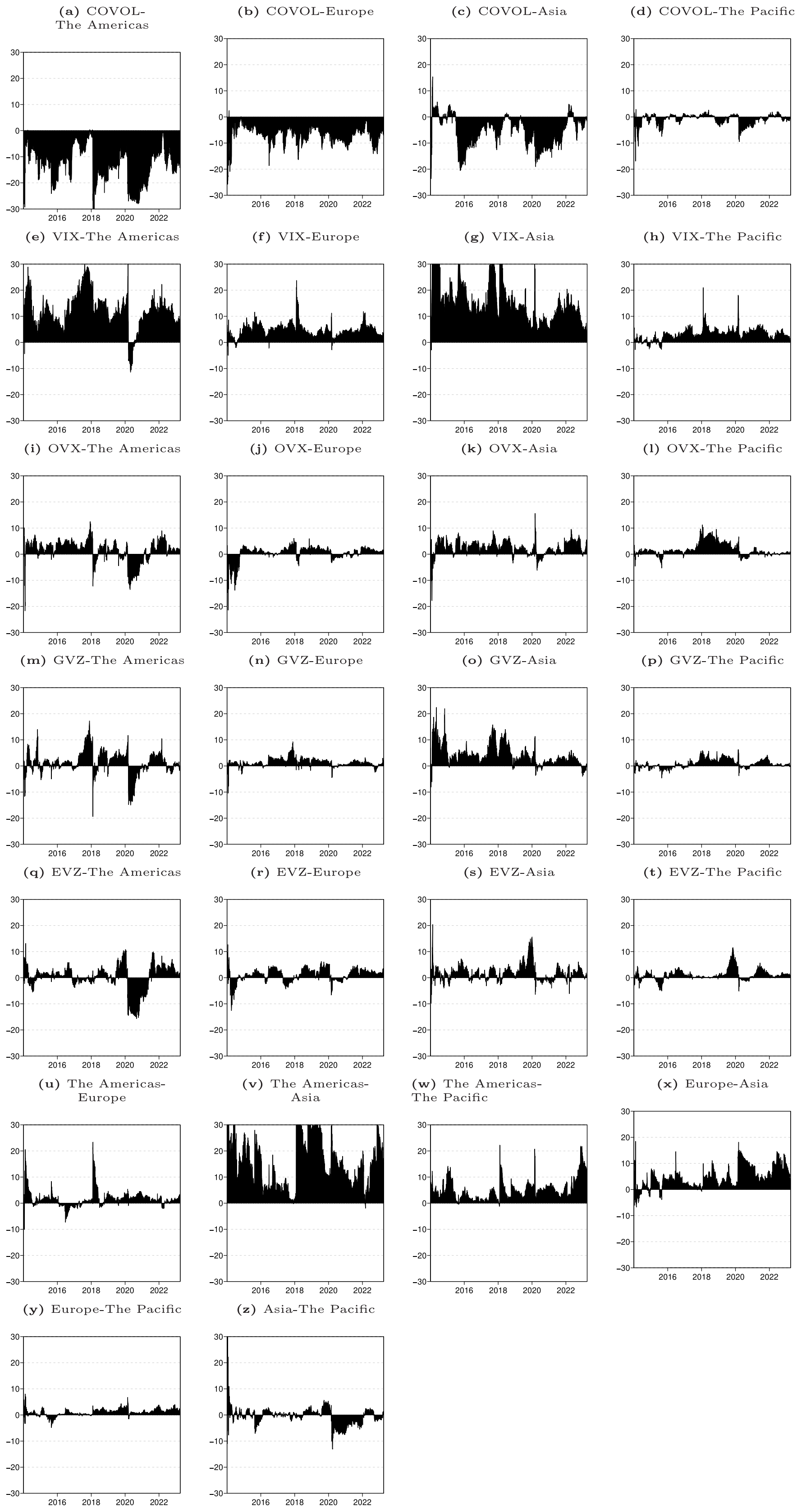

Fig. 11. Aggregated regional ESG pairwise connectedness with EVZ (Robustness check).
Note: Robustness check results are estimated by using TVP-VAR (0.99, 0.99) model with a lag length of order 1 and a 20-step-ahead forecast.

when managing ESG portfolios as a means of reducing the volatility of ESG investments. In the context of ESG markets in developing countries, the potential for vulnerability arises not only from financial market volatility but also from the ESG markets of developed countries. Thus, policymakers should actively promote the development of their domestic ESG markets, such as through tax incentives and the establishment of green financial infrastructure, to enhance their competitiveness in the international market and mitigate the influence of external factors. For those investing in emerging markets, while there is an inherent degree of uncertainty associated with ESG investments, there are nevertheless distinctive investment opportunities, particularly when the policy environment is conducive to such investments. Finally, regarding the ESG markets in different regions, our findings highlight the differences between these regions. To illustrate, the European ESG market exhibits a relatively lower level of interconnectedness with major uncertainty indexes and other regional ESG markets, suggesting that it may serve as a potential tool for hedging against various financial risks. Consequently, during periods of heightened global uncertainty, investors should consider increasing their allocation to the European ESG market in their portfolios. In contrast, the ESG markets in the Americas and Asia are more affected by external uncertainties. Policymakers in these regions should prioritize timely monitoring of different financial market uncertainties to effectively respond to the impact of global uncertainty on the ESG market and to assist investors in reducing losses during periods of market volatility. Furthermore, it would be beneficial for regulators to consider strengthening regional policy coordination in these markets, as this could contribute to enhancing overall market stability and resilience. Future work could explore the dynamic connectedness between ESG markets and key financial market uncertainties using the frequency-dependent connectedness approach to determine whether the connectedness is established at low or high frequencies. The distinction between low-frequency and high-frequency connectedness could be useful for understanding the mechanism of volatility propagation.

Declaration of competing interest

The authors declare that this paper has not been published or is under consideration elsewhere and that it is a genuine collaboration with no conflicts of interest.

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Data availability

No.

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Chapter 8

Conclusion

8.1 Overview

Green finance refers to financial activities that support sustainable development through financial instruments and policies, aiming to harmonize economic growth with environmental protection while facilitating the transition to a green and low-carbon economy. It encompasses various domains, including green bonds, green equities, and ESG investments, with the objective of directing capital towards low-carbon, eco-friendly, and sustainable projects and industries. In the green economic transition, green finance plays a pivotal role by optimizing resource allocation, encouraging enterprises to increase environmental investments, accelerating technological innovation, and promoting industrial structural upgrades. As global climate change and environmental issues intensify, green finance has become an increasingly critical tool for countries to achieve economic transformation, carbon neutrality goals, and to address environmental challenges, thereby fostering the growth of green industries and raising societal awareness of environmental sustainability.

This thesis investigates the dynamic characteristics and risk connectedness of green financial markets from multiple perspectives, revealing the mechanisms through which financial and climate risks impact green finance and proposing recommendations for optimizing green investments and policy-making. Notably, the study emphasizes that financial risk is the primary driver of connectedness in green financial markets, while climate risks exert a more significant influence on volatility connectedness, with physical climate risk showing strong short-term effects on volatility connectedness. Furthermore, the thesis finds that green bonds in the U.S. and China demonstrate potential as hedging and risk diversification tools during financial crises and market turmoil, highlighting significant differences in green investors' behavior across regions. Regarding ESG investment strategies, the thesis reveals the dominant role of Europe in the global ESG system through an analysis of regional ESG markets and proposes effective portfolio management strategies. Lastly, it examines the connectedness between global volatility indices and ESG markets, showing that risk transmission in ESG markets is significantly influenced by regional economic development and geopolitical events. The empirical results for these scenarios are presented in detail in Chapters 3 through 7.

8.1.1 Key results

Chapter 3 employs dynamic connectedness analysis to highlight that financial risk is the primary driver of return and volatility connectedness in the green financial markets, while climate risk, particularly physical climate risk, has a substantial short-term impact on volatility connectedness. By adopting a combination of the maximal overlap discrete wavelet transform (MODWT) and continuous wavelet transform (CWT), this study provides novel insights into the heterogeneous effects of financial and climate risks on the connectedness of green financial markets and their characteristics across different time frequencies. Our findings also indicate that the impact of financial risks on the returns and volatility of the green finance markets is substantially greater than that of climate risks. Based on the empirical findings, policymakers should enhance climate risk management, particularly in mitigating the short-term impacts of physical climate risks, while improving the transparency of green finance to strengthen market resilience. For investors, it is important to be flexible in adjusting asset allocation strategies based on the time-frequency characteristics of different risks, prioritizing green assets with greater resilience to climate risks to build more stable investment portfolios. These findings not only deepen the understanding of the dynamic characteristics of green financial markets but also provide practical guidance for policymakers and investors.

Chapter 4 analyzes the dynamic connectedness between US green bonds and traditional financial markets (e.g., stocks and gold) as well as emerging markets (e.g., Bitcoin) during periods of crisis, such as the COVID-19 pandemic and the Russia-Ukraine conflict. This study shows that US green bonds exhibit significant differences in connectedness across crises, demonstrating strong short-term hedging capabilities and notable long-term risk diversification potential. By applying a frequency-dependent connectedness approach, this thesis provides insights into the dynamic characteristics of green bonds across short- and long-term frequencies, thereby broadening the understanding of green bond markets. Furthermore, the analysis highlights the resilience of green bonds under market stress, particularly in advanced economies. Based on these findings, it is recommended that policymakers promote the robust development of green bond markets, especially during periods of market volatility. For investors, green bonds serve as effective hedging tools during crises and can be utilized to construct diversified portfolios over the long term, leveraging their low connectedness characteristics to mitigate the risks of traditional assets. This chapter underscores the unique role of green bonds in navigating market crises and offers valuable guidance for policymakers and investors in complex market environments.

Chapter 5 analyzes the return connectedness between China's green bonds and several important investment markets for Chinese investors (index exchange-traded funds, oil, gold and currencies). This study finds that China's green bonds exhibit low connectedness with these assets, indicating their potential as hedging tools and instruments for risk diversification. During major market disruptions, such as COVID-19 and geopolitical events, Chinese green bonds demonstrate significant market resilience. This study also uses several well-established and more recently proposed portfolio construction methods and the portfolio analysis also shows that green bonds can act as an efficient hedging tool. Based on these findings, it is recommended that policymakers improve the regulatory framework for green bonds, enhance market transparency, and promote their adoption through incentives such as tax benefits. For investors, green bonds can serve as effective tools for risk mitigation during periods of market volatility and as valuable components in long-term investment portfolios to achieve diversification through their low connectedness characteristics. This chapter provides practical guidance for both policymakers and investors, as well as an important understanding of the unique role of green bonds in China's financial system.

Chapter 6 examines return connectedness and portfolio performance using the TVP-VAR and several popular portfolio approaches for six worldwide ESG ETFs between 2020 and 2023. European ESG ETFs demonstrate superior return stability and risk diversification capabilities compared to other regions, such as the United States and Asia, and exhibit strong resilience during global crises, including COVID-19 and geopolitical conflicts. The analysis shows substantial regional differences in ESG investment performance, influenced by geographic and economic conditions. By incorporating several portfolio strategies, such as the minimum variance and minimum connectedness portfolio approaches, this chapter also provides insights into effective asset allocation in ESG markets. The findings of the study suggest that policymakers should promote the harmonization of global environmental, social and corporate governance disclosure standards to reduce uncertainty in cross-regional investments and support the development of emerging markets. For investors, European ESG assets are recommended as a priority during crises due to their high stability, while globally diversified ESG investments can mitigate regional risks and enhance overall portfolio stability.

Chapter 7 examines the dynamic connectedness between major volatility indices (e.g., COVOL, VIX, OVX, and GVZ) and global ESG markets. The analysis indicates that the risk transmission in ESG markets is significantly influenced by regional economic development and geopolitical events, including the pandemic of 2020 and the ongoing conflict between Russia and Ukraine. Mature markets, such as the United States and Europe, are identified as primary risk transmitters while emerging markets tend to act as risk receivers. This study also highlights distinct characteristics across different time frequencies: volatility indices have a pronounced short-term impact on ESG markets during global crises, while long-term connectedness remains relatively stable but with notable regional disparities. The findings suggest that policymakers should foster regional collaboration to enhance the resilience of ESG markets in emerging economies and implement comprehensive risk mitigation policies to address geopolitical and economic uncertainties. For investors, it is necessary to adopt strategies that account for the short-term influence of volatility indices. In addition, the long-term diversification into stable

ESG markets can optimize portfolio risk-return characteristics. This chapter offers valuable insights into the connectedness of global ESG markets and offers practical recommendations for both policymakers and investors.

8.2 Future work

Future research can expand upon this thesis in three key areas. First, green financial market, as a critical tool for promoting global sustainable development, exhibit significant differences across regions and types of markets. Developed markets, such as Europe and the United States, tend to prioritize the standardization and transparency of green bonds, providing relatively stable investment returns for investors. In contrast, emerging markets, such as China and India, focus more on financing needs and driving economic transitions. Against this backdrop, examining the diversity of green markets is crucial for understanding their functional roles on a global scale and their ability to address regional climate and economic challenges. Moreover, exploring the dynamic interconnectedness between different markets could provide valuable insights into the integration of global green financial markets. Therefore, future research could explore underdeveloped areas within green financial markets, such as green derivatives markets and green trade funds (ETFs). Expanding research into green financial markets can not only reveal the dynamic characteristics of global green finance but also provide data-driven insights for policymakers to design targeted regional policies. Furthermore, these studies can help investors identify opportunities and risks across various green markets, ultimately optimizing their investment decisions.

Second, in recent years, the rapid advancement of artificial intelligence (AI) technology has created new opportunities and challenges in the field of green finance. The robust data processing and analytical capabilities of AI have the potential to address critical issues such as climate change, ESG reporting, and carbon liability assessments. The integration of AI technologies can help financial institutions to effectively identify and manage environmental risks, optimize green investment portfolios, and enhance operational efficiency. Future research could consider investigating the various applications of AI in the area of green finance, focusing on the development and implementation of techniques, including natural language processing (NLP), optimization algorithms, machine learning, and deep learning techniques.

Third, the concept of corporate green finance is a vital driver for the development of green financial markets. As key participants, corporations play a dual role in green finance, acting both as capital demanders and implementers of green finance standards. Examining how corporations integrate green finance into their strategies not only facilitates the implementation of green projects but also enhances market mechanisms. By aligning corporate sustainability goals with financial objectives, green finance can achieve a win-win scenario of environmental and economic benefits. Future research could focus on analyzing how corporations of different sizes and industries engage with green finance while promoting corporate innovation in green finance. Additionally, future studies could also look at how companies' decisions to invest in green projects can affect their financial performance and social impact. This provides new perspectives on how green financial markets can make companies more successful.

Chapter 9

Appendix: Co-Authorship form

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Chapter 3: Dynamic co-movement between financial risk, climate risk and green finance: Evidence from wavelet approaches

Nature of contribution by PhD candidate	Writing original draft. Methodology. Formal analysis. Investigation.
Extent of contribution by PhD candidate (%)	70%

CO-AUTHORS

Name	Nature of Contribution
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Yang(Greg) Hou	Review & editing, Data curation, Conceptualization
John W. Goodell	Review & editing, Investigation, Conceptualization

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- that the candidate wrote all or the majority of the text.

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Shaen Corbet	Review & editing, investigation
Yang (Greg) Hou	Review & editing, supervision, methodology
Les Oxley	Critical feedback, methodological discussion, supervision, investigation.

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Chunlin Lang	Methodological discussion, formal analysis, investigation

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Extent of contribution by PhD candidate (%)	70%

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Shaen Corbet	Review & editing, visualization, investigation
Chunlin Lang	Methodological discussion, formal analysis, investigation

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