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Spillover Effects in Green and Traditional Assets During Global Crises: Evidence from TVP-VAR Analysis

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ABSTRACT

This paper employs the Time-Varying Parameter Vector Autoregression (TVP-VAR) model to analyze return and volatility spillovers, along with portfolio implications, across Green Bonds (GB), ESG stocks, the clean energy index (SP_CE), green cryptocurrencies (ADA, IOTA, XRP), Bitcoin (BTC), and gold. The study covers the COVID-19 pandemic and the Russia-Ukraine war. Results show a significant rise in total return and volatility connectedness during these crises, suggesting that global shocks heighten market interdependence. ESG stocks emerge as net transmitters of both return and volatility spillovers, while green cryptocurrencies (excluding ADA) are net receivers of volatility. Bitcoin exhibits asymmetric behavior—acting as a return transmitter but becoming a volatility receiver in crisis periods. Traditional assets such as gold, green bonds, and clean energy stocks remain net receivers in both return and volatility channels, underlining their defensive nature and potential role as hedging instruments during periods of turmoil.

Keywords: Green Assets, Traditional Assets, Clean Energy Index, Volatility Spillover, Return Spillover
JEL Classifications: G1, G11

1. INTRODUCTION

1.1. The Rise of Fintech and Digital Investment

In the mid-2010s, FinTech has started to grow, with startups attracting billions in venture capital (some of which have reached unicorn status), while established financial institutions either acquire new startups or develop their fintech solutions. It came first primarily in the payment space. In 2009, a fintech scheme already existed and is being implemented, allowing small businesses or vendors to process credit card payments using a mobile device. The term "financial technology" encompasses any innovation in business transactions, from creating digital currency to developing double-entry bookkeeping. Fintech is crucial in advancing financial innovation, which has been theoretically identified as risky but beneficial (Thakor, 2020). Recent research also highlights that it delivers significant value to investors (Qi et al., 2024). The Financial Stability Board (FSB) defines fintech as "technologically enabled financial innovation that could result in new business models, applications, processes, or products with an associated material effect on financial markets and institutions, and the provision of financial services."

Since the rise of the internet, financial technology has experienced rapid growth. Fintech is financial innovation driven by big data, artificial intelligence (AI), blockchain, and the Internet of Things (IoT). By leveraging innovations in digital platforms, mobile applications, and blockchain technology, fintech has streamlined financial services such as payments, lending, insurance, and investment management. These services have now become a crucial part of everyday life. They simplify transactions and investments, making financial services more accessible and user-friendly. Moreover, fintech uses data analytics and artificial intelligence to offer tailored solutions that cater to individual needs, further enhancing the customer experience. In the investment world, fintech makes it easier for individuals to invest more simply and affordably. In addition, fintech gives investors access to various types of investment instruments that were previously difficult to access, such as crowdfunding or blockchain-based investments. With more sophisticated and real-time data analysis, fintech supports more informed investment decisions, reduces risk and increases profit potential. Therefore, fintech not only simplifies transactions, but also opens up more opportunities for individuals to make better and more informed investment decisions. This shift has led to significant changes in investor behaviour, particularly within the digital financial industry, where traditional investment strategies are being reshaped by the influence of emerging technologies and the growing demand for digital assets.

The rapid development of financial technology (fintech) has resulted in significant changes, particularly regarding investment instrument options and investor behaviour. Fintech, which integrates modern technologies such as blockchain, artificial intelligence (AI), and decentralized finance (DeFi), has broadened access to financial services, introduced innovative investment options, and transformed traditional decision-making processes. One of the most prominent changes is the emergence of robo-advisors, AI-powered platforms offering personalized and automated investment management services. These platforms use massive amounts of data to provide customized investment strategies, making complex financial planning more accessible to a broader audience. Robo-advisors automation and personalization simplify the investment process, improve decision-making effectiveness, and reduce associated costs. This shift enables individual investors to be more actively involved in financial markets. Beyond robo-advisors, blockchain technology has a significant impact on transforming investment instruments. This technology decentralizes ledgers, ensuring transparency and immutable transaction records, which improves trust and safety in digital financial activities. Blockchain has set the foundation for the growth of cryptocurrencies, particularly Bitcoin and Ethereum, which have created new asset classes, options, and investment opportunities. Blockchain's decentralized structure has also resulted in the development of DeFi platforms, which enable peer-to-peer financial transactions without using traditional intermediaries. These innovations have broadened investing options while providing alternatives to conventional assets.

The growth of mobile investment applications emphasizes fintech's influence on investor behavior. These applications provide real-time market data, trading capabilities, and educational resources, enabling investors to manage their portfolios conveniently. However, the quality and features of these apps differ amongst providers. While specific platforms provide advanced functionality, others lack essential features, possibly affecting investment outcomes and user engagement. Concerns about app reliability and the possibility of excessive trading activity underline the importance of user-friendly interfaces that educate investors about biases and risks. Fintech innovations have impacted investor psychology, especially risk perception and behavioural biases. The accessibility and immediacy of information on fintech platforms might enhance cognitive biases including overconfidence and herding behaviour, potentially leading to impulsive investment decisions. However, fintech tools improve risk assessment and financial literacy, allowing for more informed decision-making. This twofold impact underlines the need to create responsible platforms to enhance service efficiency and encourage responsible investment practices. The fintech revolution significantly influenced investing instruments and investor behaviours. Fintech has expanded access to investing options while also empowering investors to take greater control of their financial futures. As the fintech landscape evolves, understanding its complex impact on investment practices is critical for financial ecosystem participants.

Cryptocurrency is one of the fintech instruments that is currently being widely discussed. Cryptocurrency uses blockchain technology to create digital currency and decentralized transactions in an online system. These digital innovations challenge and reshape conventional economic sectors, including asset management, trading platforms, financial derivatives, and market infrastructure. Cryptocurrencies gained significant attention due to their price volatility. Consequently, investor enthusiasm for digital currencies, including cryptocurrencies, is increasing. It allows individuals to access global financial markets without geographic restrictions and offers the potential for significant returns in line with their high price volatility.

Cryptocurrencies are widely known to have the potential to provide higher returns compared to other conventional assets. Especially Bitcoin (BTC), which is the first and most dominant currency in the crypto market with the largest market capitalization, is the main symbol of high-risk digital assets with high-yield potential, making global investors very interested in this digital asset (Baur et al., 2018). Bitcoin operates using blockchain technology with a Proof of Work (PoW) consensus system, where for each trading transaction, miners must complete a complex algorithm to verify transactions and add new blocks to the network (Qin et al., 2020). However, this process is very energy-intensive because it requires hardware with high computing power (Xiao et al., 2023). Bitcoin mining consumes large amounts of energy, even exceeding the annual energy consumption of several developing countries (Qin et al., 2023a). In addition, according to (Qin et al., 2023a), carbon emissions from Bitcoin mining activities can exceed the metal mining industry such as gold and copper. Thus, although cryptos like Bitcoin promise high returns, their environmental impact is an important concern, especially in the context of sustainable investment and ESG values.

1.2. ESG Considerations in Traditional and Digital Assets

In conditions of market uncertainty or ongoing economic crisis, gold has long been known as a traditional safe haven investment instrument. This traditional asset has historically proven its resilience in the face of market volatility and inflation, so investors do not hesitate to make this traditional asset their main choice in protecting the value of their wealth assets (Ondayo et al., 2023). However, on the other hand, apart from its usefulness as a store of value, this gold mining activity has a bad environmental impact. Where in the extraction process using toxic chemicals such as cyanide and mercury which produce high carbon emissions so that they can pollute water and soil resources (Wendl et al., 2023). Not only does it cause physical damage to the environment, but this gold mining also endangers the health of the community around the mining area. Therefore, although gold is an important asset instrument, it is still necessary to consider the environmental impact caused by this gold mining, especially in the era of sustainable investment where the principles of Environmental, Social, and Governance (ESG) are increasingly relevant.

In response to concerns about excessive energy consumption caused by blockchain mining activities, the response from the blockchain community was to develop an alternative mechanism, Proof of Stake (PoS), as a replacement for Proof of Work (PoW). Where this PoS system selects validators based on the amount of cryptocurrency they hold and are willing to stake as collateral, reducing the use of energy-intensive hardware, so that miners no longer have to solve complex mathematical problems using substantial computing power used by PoS, but instead consume much less electricity than PoW-based systems (Galinis et al., 2020; Barber et al., 2021). This lower energy usage is what makes PoS a greener and more environmentally friendly alternative system compared to PoW systems in its alignment with ESG principles and sustainable goals (Qin et al., 2023b). The shift from PoW to PoS implemented by Ethereum in 2022 is a significant step in encouraging greener crypto technology practices and in an effort to reduce the carbon footprint generated by blockchain without sacrificing decentralization and network security at the same time (Fabre et al., 2023).

As ESG (Environmental, Social, and Governance) investing continues to grow in popularity, investors are placing more emphasis on assets that align with sustainable and ethical principles. ESG investing focuses not only on financial gains but also on the environmental and social consequences of the investments. In today's global investment environment, there is a clear focus on environmental and social issues, as demonstrated by the rising incorporation of ESG (Environmental, Social, and Governance) factors into investment strategies across the globe. This shift in investor priorities pushes companies and other market participants to emphasize ESG factors more when making decisions (Paranita et al., 2025). Bloomberg projects that ESG asset management could exceed $53 trillion by 2025, representing a third of global asset management, with developed markets continuing to hold the majority share ([CSL STYLE ERROR: reference with no printed form.]). As a result, there are growing environmentally friendly assets such as ESG stocks and green cryptocurrency, and the ESG value of mining is increasing.

Not only that, but the increasing awareness of sustainability has also increased global interest in green bonds, clean energy and green stocks. Where green bonds are more specifically created to finance environmentally friendly projects such as energy efficiency, clean transportation, or renewable energy that are in line with ESG (Barber et al., 2021). A. While green stocks are more about stocks of companies that implement their business and operational models while considering the environment and implementing ESG principles (Galinis et al., 2020). In addition, clean energy stocks—representing companies engaged in renewable energy solutions like solar, wind, or hydro—have gained traction as critical instruments supporting the global transition toward a low-carbon economy. The increasing demand for investment instruments that prioritize sustainability is also what drives large financial institutions to create green stock and green bond indices, which screen assets based on environmental criteria. Examples include the S&P Green Bond Index and the MSCI Global Environmental Index, which help investors manage ESG exposure and measure ESG performance more effectively (Tang and Zhang, 2020). Market acceptance and investor approval can also be seen in the green bond index that provides real "greenium," where bonds get better prices with lower yields than conventional bonds. Meanwhile, on the equity side, green equity indices also continue to outperform traditional benchmarks supported by investors' shift to more sustainable corporate practices. As a result, green stock indices and green bonds play an important role in expanding ESG-aligned portfolios, which not only offer investors sustainability but also financial opportunities.

1.3. Research Gap and Objectives

Although there have been many studies discussing the connectedness of returns and volatility between assets, there are still few studies that discuss in depth the dynamic relationship between green bonds, ESG stocks, green cryptocurrencies, gold, and Bitcoin in a continuous analysis. Although previous studies are a clear example that there are studies discussing the relationship between ESG stocks and other assets, but the approach that is used is still static so that it does not consider temporal dynamics, especially related to global market shocks (Kamal and Bouri, 2025). In addition, although crypto assets have begun to be discussed in ESG, there is still limited discussion of the specific interactions between green cryptocurrencies and other sustainable financial assets, especially in the role of assets as net receivers or net transmitters of market volatility (Alharbi et al., 2025). There are also few previous studies that use the Time-Varying Parameter Vector Autoregression (TVP-VAR) dynamic model approach to capture changes in the connectivity between assets over time and under changing market conditions, so it is still limited in providing a more accurate understanding of non-stationary volatility spillover patterns. There are also few studies that analyse the use of green cryptocurrencies (such as XRP, IOTA, and ADA) with other traditional and sustainable instruments.

Therefore, this study aims to fill the gap in the literature by analysing the connectedness return and volatility of five major financial instruments, namely green bonds, ESG stocks, green cryptocurrencies (XRP, IOTA, ADA), gold, and Bitcoin, to understand how market shocks are transmitted between green and digital assets. The study also identifies the dominant role of each asset as a net receiver or net transmitter of shocks in an interconnected system. In addition, the study also evaluates the effectiveness of ESG stocks, gold, Bitcoin, and green cryptocurrencies as hedging and diversification tools against green bonds market movements. As well as assessing the potential for integrating digital and sustainable assets into a resilient investment portfolio that is in line with sustainability principles (ESG). Thus, the results of this study are expected to provide theoretical and practical contributions for ESG-oriented investors, asset managers, and policy makers in developing sustainable investment strategies in this digital era.

2. LITERATURE REVIEW

In recent years, attention to sustainability issues has driven significant transformations in global financial markets. Green financial instruments such as green bonds, clean energy index, and ESG (Environmental, Social, and Governance) stocks are increasingly in demand by investors who consider sustainability as a part of their investment strategies. On the other hand, digital assets such as Bitcoin and green cryptocurrencies are also attracting attention due to their high-yield potential and innovative role in sustainable financing. Amidst these dynamics, it is important to understand how the connectedness between these assets evolves, especially in the context of risk management and portfolio diversification.

Previous literature has explored the interconnectedness between various conventional and green assets but has been limited in combining all components green bonds, ESG stocks, Bitcoin, and green crypto in a single integrated analytical framework. Understanding the volatility spillovers, return spillovers and dynamic interconnections between these assets is crucial, given the increasing global uncertainty caused by climate change, geopolitical turmoil, and financial market fluctuations.

This study aims to summarize the literature on the connectedness of green assets, safe haven asset, green cryptos and Bitcoin, and evaluate portfolio implications for clean energy. By highlighting the empirical results and methodologies used in previous studies, this study also provides a basis for further analysis of the portfolio implications of such linkages, particularly in designing sustainable investment strategies that are resilient to market shocks.

In the last decade, growing concerns about climate change have driven significant growth in sustainable investments, including clean energy, ESG (Environmental, Social, and Governance) stocks, and green bonds. Empirical studies have shown that these assets not only offer financial returns but also serve as a means of diversification and hedging against environmental risks. One important approach to understanding the relationship between these assets is to analyze the dynamics of spillover, which is the transmission of volatility or returns from one market to another.

Several studies have shown that clean energy is closely related to traditional energy markets and other financial markets. For example, (He et al., 2021) found that oil prices affect clean energy sector returns, but the relationship is asymmetric and unstable over time. Furthermore, the study by (Attarzadeh and Balcilar 2022) found that clean energy markets and traditional stocks were the main contributors to surprises in Bitcoin and crude oil returns, while Bitcoin and oil were the sources of volatility for clean energy and stocks. During normal times, the correlation between the markets is relatively weak, but increases sharply during times of crisis such as the 2018 crypto market crash and the 2020 COVID-19 pandemic. These findings suggest that the correlation between clean energy markets and risk assets such as crypto is stronger during times of uncertainty, making it important to consider in sustainable portfolio diversification and risk management strategies. Moreover, a study by (Chatziantoniou et al., 2022a) uses a novel quantile frequency connectedness approach to analyze the dynamics of return transmission and market integration among four environmental financial indices. The results show that the S&P Global Clean Energy and S&P Green Bond Index act as net receivers in both the short and long term, meaning that they receive more impact from market shocks than they transmit. In contrast, the MSCI Global Environment and Dow Jones Sustainability Index World act as net transmitters. The total connectedness (TCI) is heterogeneous over time and is influenced by economic events, with asymmetries more pronounced in the short and long term than in the overall time domain.

The overall findings from these studies imply that the relationship between clean energy, ESG stocks, green bonds, and Bitcoin is dynamic, influenced by global economic factors, regulations, and investor sentiment. But, in the system of clean energy, green bonds, and ESG stocks, clean energy act as net receiver in full period.

A growing body of literature has examined the relationship between green bonds and the cryptocurrency market particularly Bitcoin due to its significant environmental impact stemming from high energy consumption. Bitcoin has gained widespread recognition as a digital asset underpinned by blockchain technology and is increasingly viewed as both a portfolio diversifier (Brière et al., 2015) and a hedging instrument (Bouri et al., 2017). Empirical evidence suggests that cryptocurrencies have demonstrated notable resilience in terms of market efficiency, even during periods of systemic stress such as the COVID-19 pandemic (Fernandes et al., 2022). For investors aiming to enhance risk-adjusted returns, cryptocurrencies like Bitcoin are often incorporated into diversified portfolios alongside sustainable instruments such as green bonds, which in some cases outperform traditional bonds (Zhao and Park, 2024). In this context, understanding the interconnectedness and volatility spillovers between green bonds, Bitcoin, and conventional assets including equities, gold, and cryptocurrencies becomes essential for assessing their effectiveness in mitigating portfolio risk. But incorporating the connectedness of green cryptocurrencies and green bonds remains unexplored.

Several studies have explored the dynamic relationship between green bonds, gold, and Bitcoin, although the majority of these investigations have been conducted within the time domain (Khalfaoui et al., 2022; Naeem and Karim, 2021; Rao et al., 2022). Naeem and Karim (2021), employing a time-varying copula model, analysed the tail dependence between Bitcoin and green bond markets. Their findings reveal a predominantly asymmetric and time-varying dependence structure, with green bonds demonstrating effectiveness as hedging instruments against Bitcoin risk. Complementarily, Le et al. (2021) assessed short-term volatility spillovers between green bonds and cryptocurrencies using both time and frequency domain connectedness approaches, concluding that green bonds offer long-term hedging capabilities. However, their study did not explicitly evaluate asset correlations, hedge ratios, or hedging effectiveness. In a different approach, (Goodell et al., 2022) utilized wavelet coherency and cross-wavelet transform techniques to analyse the interconnectedness between green assets, Bitcoin, and FinTech, providing insights into co-movements and covariance structures across multiple time scales.

Furthermore, (Khalfaoui et al., 2022) applied the quantile VAR connectedness model to investigate the transmission of shocks among green markets, Bitcoin, economic uncertainty, and the U.S. equity market, emphasizing the complexity of interdependencies across varying quantiles and economic conditions. In addition, other study assessed the connectedness of Bitcoin, conventional assets, and major global uncertainties measures using TVP-VAR approach, portrayed the TCI during market turmoil (COVID-19) becomes higher across those assets (Elsayed et al., 2022a).

Due to the growing global demand for green assets for the shift to low-carbon economies, a body of research under the energy transition to cleaner production looks at the relationship between green bonds and other financial markets, including the stock and crude oil markets (Jiang et al., 2022; Khalfaoui et al., 2022). Although most relevant research ignores the timeframe dependence at the tails and how the portfolio implications vary between the short- and long-term investment horizons, green bonds are generally shown to be a good hedge for stock market risk. Additionally, prior research has tended to ignore the global stock market and green cryptocurrencies in favour of concentrating only on traditional assets like U.S. equities, crude oil, and gold.

A copula model is examined to assess the connectedness, co-movement, and diversification benefit between green bonds and stock market, demonstrating that, despite their weak correlation with the stock market, green bonds offer investors significant diversification benefits (Reboredo, 2018). Evidence of green bonds' potential for diversification during the market turmoil (COVID-19) was presented, noting that green bonds are an effective hedge (Mensi et al., 2022). Moreover, a study exploring the connectedness between green bonds and stock market, found that green bonds act as net receiver of volatility and interdependency between them is more volatile in pandemic period (Elsayed et al., 2022c). It also suggests diversification benefit of green bonds, however, there is no hedge ratio or hedging effectiveness being examined. In the G7 market, it is analysed how shocks and volatility are transmitted over time and across frequencies between green bonds, crude oil, and G7 stock markets using the time–frequency spillover framework (Mensi et al., 2022). Their findings show that green bonds generally act as net recipients of spillovers across all time horizons. In contrast, oil and the U.S. stock market tend to receive spillovers mainly in the medium and long term. Additionally, the study highlights that green bonds offer better short-term diversification opportunities for G7 investors compared to crude oil.

In addition, a study in China concluded that green bonds is the net transmitter and environmental protection sector stocks as net receiver in terms of volatility (Wang et al., 2025). In the global sustainability, green bonds and clean energy appear as net receiver of shocks, while green equities as transmitter of shocks (Chatziantoniou et al., 2022b). But limited evidence explored about the portfolio implications between them. Lastly, a study in US technology stock market using TVP-VAR method findings shows that the S&P 500 ESG Index and Microsoft is the dominant net transmitter of volatility (Zeng et al., 2025). In contrast, the S&P Green Bond Index and Apple as net receiver of spillover. In all, previous research conducted the connectedness between green bonds and conventional stocks but, still limited evidence on return connectedness, especially in green bonds and green or ESG stocks and the hedging effectiveness between them.

Green cryptocurrencies have a unique position in the green finance ecosystem, as they combine the innovation of blockchain technology with sustainability principles. The literature on the connectedness of green crypto with other green assets is still relatively new, so there is limited research available to provide an overview of the connectedness between them. Several studies analyse the connectedness of green cryptocurrencies with several ESG stock indices globally, where the results show that green cryptocurrencies are recipients of return and volatility spillover, conversely, green stocks are net transmitters (Yousaf et al., 2024; Alharbi et al., 2025). The portfolio results also show that green cryptocurrencies are effective as a hedging tool.

In a portfolio context, it is important to understand the role of green cryptocurrencies as potential diversifiers or even risk amplifiers when combined with green assets such as green bonds and ESG stocks. Recent studies have used approaches such as Time-Varying Parameter VAR (TVP-VAR) and Quantile Connectedness to capture the dynamics of these relationships in a more in-depth and asymmetric way. In addition, there is no evidence about the connectedness of green cryptocurrencies and other green assets such as green bonds. Moreover, limited studies give the overview of their hedging effectiveness in market turbulence.

The literatures on the relationship between green assets such as green bonds and ESG stocks with digital assets has shown rapid development in recent years. Various methodological approaches have been used, including TVP-VAR, Quantile VAR, copula, and wavelet coherence models, to understand the dynamics of the relationship between these assets from the perspective of returns, volatility, and their transmission during stable and crisis periods.

In general, green bonds are often found to be net receivers of volatility and return spillovers, indicating their defensive role in portfolios. This instrument has also been shown to provide diversification benefits, especially against stocks and commodities such as crude oil. Green bonds offer better short-term diversification benefits compared to crude oil in the context of the G7 market. On the other hand, ESG stocks show a role as shock transmitters, reflecting their sensitivity to market pressures and economic factors, but remain attractive to investors due to their sustainability principles.

Bitcoin, as the most dominant crypto asset, has been extensively studied in the context of its connectedness with various conventional and green assets. Findings from the literature suggest that Bitcoin is highly volatile and acts as a shock emitter, especially in extreme market conditions. However, Bitcoin also has the potential to act as a diversifier or even a hedge in the short term, depending on market conditions and asset pairs used. Moreover, green cryptocurrencies are a new category in the literature, and empirical evidence is still limited. Early study suggest that these assets often act as net receivers in connectedness, while ESG stocks tend to be net transmitters (Alharbi et al., 2025). Nevertheless, green crypto shows potential as a hedging and diversification instrument, especially because of its technology and mission that support environmental sustainability.

Despite significant contributions in the literature, there are several research gaps that are still open and require further exploration. First, most studies only focus on a few assets separately and have not examined the comprehensive relationship between green bonds, ESG stocks, Bitcoin, and green cryptocurrencies in one integrated analytical framework. Second, there is still limited empirical evidence on the return and volatility spillover between green bonds and green crypto. Third, explicit evaluation of hedging effectiveness, hedge ratios, and portfolio performance across market conditions is still rare. Therefore, further research that integrates all asset categories in one dynamic and in-depth model is urgently needed to understand the role of each in a sustainable investment strategy that is resilient to global economic shocks. Therefore, it can be concluded to some hypothesis based on past studies that,

- H_1: Green bond, clean energy, and gold are the net receiver from the system of both return and volatility spillover.
- H_2: ESG stocks are net transmitter from the system of both return and volatility spillover.
- H_3: Bitcoin is net transmitter from the system of both return and volatility spillover.
- H_4: The TCI of all assets become higher during market turbulence such as COVID-19.
- H_5: Green cryptocurrencies provide a hedging function for clean energy index.

3. RESEARCH METHODS

This study is using daily price data of 2018-2024 which captures the period before COVID-19, COVID-19, and post COVID-19. The data of green bond is sourced from S&P Green Bond Index which represents a global green bond market (Table 1). Moreover, the index upholds strict eligibility standards, guaranteeing that only bonds with earnings solely devoted to environmentally friendly projects are featured. For the ESG and green stocks, this study choose STOXX Global Environment Index, STOXX Global Social Index, and STOXX Global Governance Index as the global ESG index and S&P Global Clean Energy Index as the global clean-energy related companies covering both emerging and developed countries. Green cryptocurrencies in this study are ADA, IOTA, XRP, which align in the study of (Alharbi et al., 2025). Lastly, Bitcoin (BTC) and safe haven asset (GOLD). Daily price is transformed into a daily log return with the formula of:

Table 1: Data Source

Notation	Data source
S&P_GB	www.spglobal.com
ENVIRONMENT	Refinitif
SOCIAL	Refinitif
GOVERNANCE	Refinitif
S&P_CE	www.spglobal.com
BTC	Investing.com
ADA	Investing.com
IOTA	Investing.com
XRP	Investing.com
GOLD	Bloomberg

$$r_t = \ln (P_t/P_{t-1}) * 100$$

Where r_t is the daily log return and P_t the price on the day. Additionally, the stocks and bonds market are only available on weekdays while cryptocurrencies are available every day. Therefore, we only capture weekdays on cryptocurrencies variable.

To address the research questions, this study employs the Time-Varying Parameter Vector Autoregressive (TVP-VAR) model, as formulated by (Koop and Korobilis, 2014). alongside the dynamic connectedness framework developed by Diebold and Yilmaz, (2012). The integration of the TVP-VAR model provides notable methodological enhancements over the traditional connectedness approach by Diebold and Yilmaz. One of the key advantages of the TVP-VAR framework is its ability to yield more accurate estimates of connectedness. This is particularly important given that the commonly used rolling-window method tends to introduce artificial persistence in the connectedness measures, thereby overstating the degree of interconnectedness and failing to capture its potential decline over time. Furthermore, the TVP-VAR model eliminates the need for an arbitrary selection of rolling window lengths, as it allows the model parameters to evolve over time, thereby more effectively reflecting the dynamic nature of financial relationships. An additional benefit is that the TVP-VAR approach retains all available observations, avoiding the data loss typically associated with rolling-window estimations. Furthermore, this method can be applied for low frequency data. Lastly, the model demonstrates a lower sensitivity to outliers, enhancing the robustness of the connectedness analysis (Antonakakis et al., 2018; Antonakakis et al., 2019; Korobilis and Yilmaz, 2018).

The basic specification of a first-order TVP-VAR (TVP-VAR(1)) model is as follows:

$$v_t = C_t v_{t-1} + \mu_t,\ where\ \mu_t \sim N(0, \tau_t) \quad (1)$$

$$vec(C_t) = vec(C_{t-1}) + \gamma_t,\ where\ \gamma_t \sim N(0, \varepsilon_t) \quad (2)$$

In the formulation above, v_t represents an n×1 dimensional vector of endogenous variables at time t, while v_{t-1} is its lagged value. The n×n dimensional matrix C_t contains the time-varying parameter coefficients. The vector μ_t, also n×1 dimensional, represents the innovation (error) vector, assumed to be normally distributed with a zero mean and a time-varying variance-covariance matrix Σ_t of dimension n×n. Equation (2) defines the evolution of the time-varying parameters C_t, where $vec(C_t)$ is the n2×1 dimensional column vector representation of the matrix C_t. These parameters are assumed to follow a random walk process, with γ_t as an n2×1 dimensional innovation vector that is normally distributed with a zero mean and an n2×n2 dimensional variance-covariance matrix Σ_t. Both matrices Σ_t and Σ_t are time-varying variance-covariance matrices.

Subsequently, to test the pairwise directional connectedness from variable j to variable i, the Generalized Forecast Error Variance

Decomposition (GFEVD) proposed by Koop et al., 1996 is computed. The GFEVD method quantifies the contribution or impact of a shock in variable j on the forecast error variance of variable i. The proportion of the H-step forecast error variance of variable i attributable to shocks in variable j $\left(\tilde{\theta}_{ij,t}(H)\right)$ is represented as:

$$\tilde{\theta}_{ij,t}(H) = \frac{\sum_{t=1}^{H-1} \omega_{ij,t}^2}{\sum_{j=1}^{n} \sum_{t=1}^{H-1} \omega_{ij,t}^2} \tag{3}$$

Where $\sum_{j=1}^{n} \tilde{\theta}_{ij,t}(H) = 1$ and $\sum_{i,j=1}^{n} \tilde{\theta}_{ij,t}(H) = n$. In Equation (3), $\omega_{ij,}$) represents elements derived from the impulse response functions, reflecting the impact of shocks from variable j on variable i at time horizon t within the forecast period H. The numerator in this equation accumulates the squared impact of shocks from variable j on variable i over the forecast horizon H−1. The denominator sums these squared impacts from all variables j (including j=i) on variable i. The forecast horizon H is set to 10 periods.

Based on the GFEVD, the Total Connectedness Index (TCI) is then calculated to measure the overall level of interconnectedness within the system. The TCI is formulated as:

$$T_t(H) = \frac{\sum_{i,j=1,i+j}^{n} \tilde{\theta}_{ij,t}(H)}{\sum_{i,j=1}^{n} \tilde{\theta}_{ij,t}(H)} = \frac{\sum_{i,j=1,i,j}^{n} \tilde{\theta}_{ij,t}(H)}{n} \tag{4}$$

Equation (4) represents the total connectedness index, which is essentially the average of the cross-variable forecast error variance contributions (i.e., from variable j to variable i where i=j) within the system. This index provides an aggregate measure of the extent to which shocks propagate among all analyzed variables. For a more in-depth understanding of the nature of connectedness, this total spillover can be further decomposed into directional connectedness "TO" (to other variables), "FROM" (from other variables), and "NET" (net connectedness) for each variable in the system. An aggregate representation for the directional connectedness "TO" can be formulated as:

$$T_{i\to j,t}(H) = \frac{\sum_{i,j=1,i+j}^{n} \tilde{\theta}_{ji,t}(H)}{\sum_{i,j=1}^{n} \tilde{\theta}_{ji,t}(H)} \tag{5}$$

$$T_{i\leftarrow j,t}(H) = \frac{\sum_{i,j=1,i+j}^{n} \tilde{\theta}_{ijpt}(H)}{\sum_{i,j=1}^{n} \tilde{\theta}_{ij,t}(H)} \tag{6}$$

Equations (5) and (6) quantify the spillover effects, specifically detailing the extent to which variable (i) transmits shocks "TO" the system and receives shocks "FROM" the system. Building upon this, the net directional connectedness for variable (i) at time t is determined as the difference between the "TO" and "FROM" spillovers:

$$T_{i,t} = T_{i\to j,t}(H) - T_{i\leftarrow j,t}(H) \tag{7}$$

Equation (7) thus provides a measure of net directional connectedness. A positive value for $T_{i,t}$ indicates that variable (i) is a net transmitter of shocks to the system, while a negative value signifies that it is a net recipient of shocks from the system.

Lastly, for the portfolio analysis component of this study, time-varying variance and covariance matrices are utilized, a methodology consistent with the approaches of (Kroner and Ng (1998). The optimal portfolio weight for each pair of stock and cryptocurrency is computed based on the framework established by:

$$W_{xy,t} = \frac{h_{y,t} - h_{xy,t}}{h_{x,t} - 2h_{xy,t} + h_{y,t}} \tag{8}$$

The calculated weight, $W_{xy,t}$ is then constrained as follows to ensure practical applicability:

$$W_{xy,t} = \begin{cases} 0, \textit{If } W_{xy,t} \langle 0 \\ W_{xy,t'}, \textit{If } 0 \le W_{xy,t} \le 1 \\ 1, \textit{If } W_{xy,t} > 1 \end{cases} \tag{9}$$

In this context, $W_{xy,t'}$ (adjusted from $W_{xy,t}$ in the source) represents the proportion of a one-dollar portfolio allocated to the stock asset (x) at time t. The terms h_{xt} and h_{yt} denote the conditional variances of the green stock and the green cryptocurrency, respectively, at time t. The conditional covariance between these two assets at time t is represented by $h_{xy,t}$.

The optimal hedge ratio is defined following the work of (Kroner and Sultan 1993):

$$\beta_{xy,t} = \frac{h_{xy,t}}{h_{y,t}} \tag{10}$$

Here, $\beta_{xy,t}$ is the hedging ratio, indicating the extent to which a long position in the green stock can be offset by a short position in the green cryptocurrency.

Finally, the effectiveness of this hedging strategy is assessed using the Hedge Effectiveness (HE) measure, as proposed by (Ku et al., 2007).

$$HE = \frac{variance_U - variance_H}{variance_U} \tag{11}$$

In this equation, $variance_U$ and $variance_H$ represent the variances of the unhedged and hedged portfolios, respectively. It is important to note that an increase in the HE value signifies an improved effectiveness in risk management, with an HE value of 1 indicating a perfect hedge.

4. FINDING AND DISCUSSION

Figure 1 shows the daily return dynamics of green assets (Environment, Social, Governance), green bonds (S&P_GB),

green equity (S&P_CE), as well as conventional assets such as gold, Bitcoin, and green cryptocurrencies (ADA, IOTA, XRP). It shows that crypto assets exhibit much higher return volatility compared to other assets, especially during crisis periods such as COVID-19 and the beginning of the Russia-Ukraine conflict. Meanwhile, returns on green assets and green bonds tend to be more stable, reflecting their defensive characteristics.

Table 2 shows descriptive statistics to understand the main characteristics of the return data for each asset used, starting from Green Bonds (S&P_GB), Clean Energy Stocks (S&P CE), Bitcoin (BTC), Green Cryptocurrencies (ADA, IOTA, XRP), Gold (GOLD), and ESG Stocks (ESG_E, ESG_S, ESG_G). The statistics analyzed include:

The mean (average return) during the observation period shows that the sustainable assets studied have an average daily return that varies quite a bit approaching zero. This reflects the difference in return and risk from each financial instrument. The slightly negative mean return of S&P_GB (−0.0042) shows that green bonds are experiencing market pressure which makes the green bonds market conditions less than optimal during the observation period. The opposite condition occurs in ESG_E (0.0204), ESG_G (0.0177), and ESG_S (0.0177) which have a positive but small average return, indicating a fairly stable but not spectacular performance. For S&P_CE (0.0113) and Gold (0.0355) also have positive returns, indicating that there is growth and increasing global interest in renewable energy and traditional assets although not as high as the average Bitcoin return. Where BTC has the highest average positive return (0.0727) which shows the potential for extraordinary crypto asset returns compared to other instruments. However, for 3 green cryptocurrencies (ADA: −0.0923, IOTA: −0.1540, XRP: −0.0526) have a negative average return indicating poor performance on these digital assets during the study period.

This variance (risk) can indicate asset volatility, measuring how spread the asset return is from its mean. High variance (>15) is found in the assets IOTA (37.5824), XRP (34.7655), ADA (34.7554), then BTC (15.5806). This shows that green cryptocurrencies and BTC are very volatile and have very high volatility, which is in line with the nature of crypto assets which are high risk high return. In the middle class variance, there are S&P_CE (2.7484), ESG_S (1.2674), ESG_G (1.2625), and ESG_E (1.1823) which indicate moderate asset risk. Then in the low class variance, there are S&P_GB (0.1574) and Gold (0.7888) which indicate asset stability with its role as a safe haven.

The skewness of all assets has a negative value, indicating that the return distribution is skewed to the left, there is a risk of an extreme decline to occur compared to a positive return spike. The

Figure 1: Returns graph

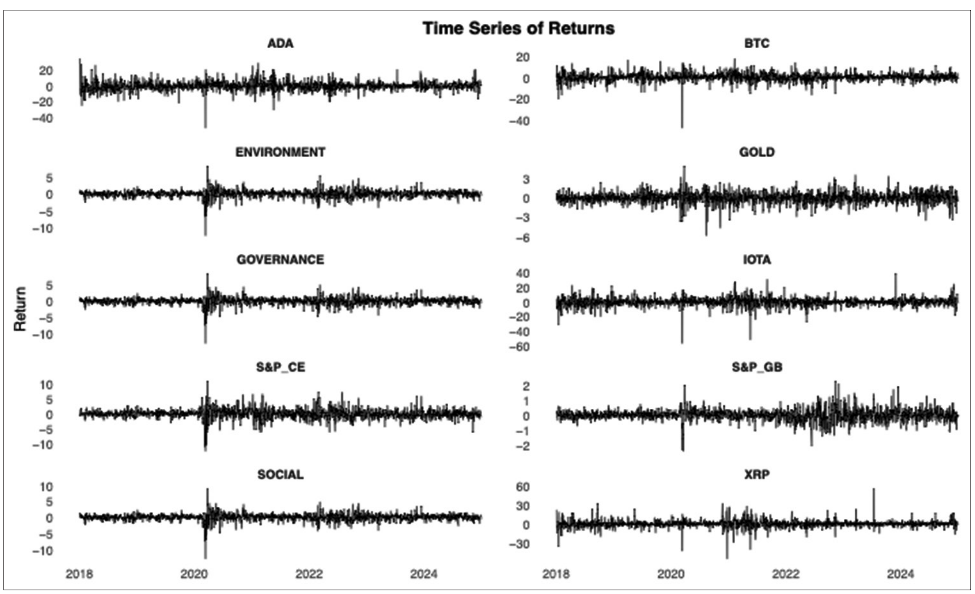


Table 2: Descriptive statistics

Variable	S&P_GB	S&P_CE	BTC	ADA	IOTA	XRP	Gold	Environment	Governance	Social
Mean	−0.0042	0.0113	0.0727	−0.0923	−0.154	−0.0526	0.0355	0.0204	0.0177	0.0177
Variance	0.1574	2.7484	15.5806	34.7554	37.5624	34.7655	0.7888	1.1833	1.2625	1.2674
Skewness	−0.056	−0.3442***	−1.0954***	−0.1266**	−0.6026***	−0.0512	−0.3487***	−0.9256***	−1.0496***	−1.0011***
Ex.Kurtosis	4.4792***	7.1998***	14.2329***	6.7477***	9.7435***	14.2535***	3.3725***	13.9425***	15.0697***	15.1463***
JB	1501.50***	3912.38***	15509.92***	3410.22***	7209.10***	15195.58***	887.05***	14795.26***	17314.56***	17457.82***
ERS	−16.90***	−17.52***	−9.01***	−1.36	−10.86***	−2.1	−14.29***	−16.29***	−15.98***	−14.77***
Q20	74.70***	94.31***	26.01	38.92***	16.5	30.44*	29.12*	85.80***	79.77***	89.63***
Q2(20)	662.77***	1314.38***	31.28*	105.60***	76.01***	92.60***	216.65***	771.04***	775.88***	799.15***

*P<0.1; **P<0.5; ***P<0.01

most extreme value among all research assets is owned by BTC (−1.0954), ESG_G (−1.0496), then ESG_S (−1.0011). However, they are still in the medium skewness category because they are still at −1 to −2. Then low skewness is owned by ESG_E (−0.9256), IOTA (−0.6026), S&P_GB (−0.0560), XRP (−0.0512), GOLD (0.3487), S&P_CE (−0.3443), and the lowest skewness is ADA (-0.1266) closest to 0, indicating a relatively symmetrical return distribution. Then for BTC, ADA, IOTA, GOLD, ESG_E, ESG_G, ESG_S skewness is negative but significant, indicating a negative tail risk tendency which is a negative extreme return tendency. Only the S&P_GB and XRP distributions are close to symmetrical because they are not statistically significant.

Excess Kurtosis owned by all assets has a value of >3, significant and positive, indicating that the distribution of leptokurtic returns has fat tails, so that the possibility of extreme returns, both positive and negative, occurs more often than the return of a normal distribution. In addition, excess kurtosis can also show the possibility of outliers in the assets studied. Especially in crypto assets (BTC: 14.2329, XRP: 14.2535) and ESG stocks (ESG_E: 13.9425, ESG_S: 15.0697, ESG_G: 15.1463) with very high kurtosis values (extreme leptokurtic). However, for crypto assets (ADA: 6.7477, IOTA: 9.7435) including high kurtosis values (leptokurtic). Meanwhile, S&P_GB and GOLD are still classified as moderate and are still leptokurtic but more moderate.

The Jarque-Bera (JB) statistic owned by all assets has a very high value and is significant at the 1% level ($p < 0.01$), indicating that none of the asset returns studied are normally distributed, which is also seen in the significant skewness and leptokurtic kurtosis in the analysis above.

Engle's LM Statistic on most significant assets except ADA and XRP which are not significant at the 1% level shows that there is an ARCH effect, so there is conditional heteroscedasticity in the return data studied. This causes the volatility of asset returns to tend to be inconsistent, changing over time. Only ADA and XRP have relatively more stable volatility than other assets.

Q (20), Ljung-Box at the 20th lag shows that most assets have significant values except BTC and IOTA, indicating that there is autocorrelation in most return data. This means that most current returns are still influenced by past return patterns, there is a time dependency in returns. Then the relatively random returns are only found in BTC and IOTA. Q^2 (20) also shows that almost all assets including BTC, although they have a weakly significant value, indicate the presence of an ARCH effect or conditional heteroscedasticity which is increasingly evidence that volatility is not constant and there is heteroscedasticity in the return data.

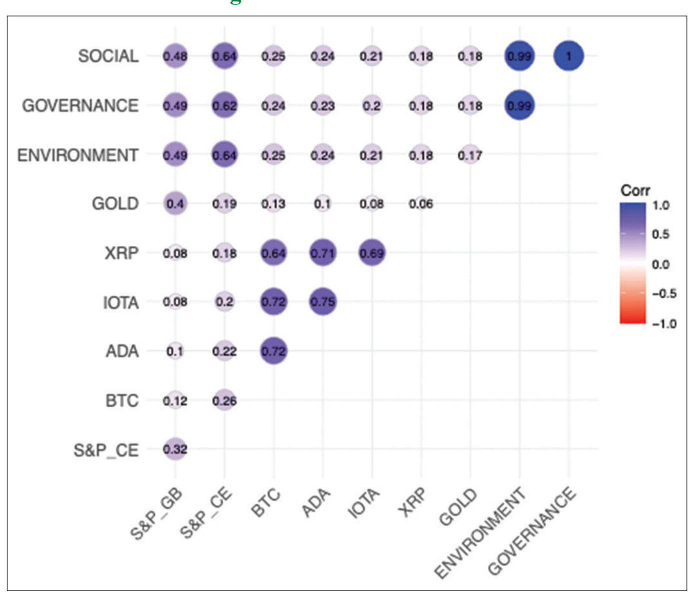
The correlation plot in Figure 2 shows clear trends in the connections among ESG stocks, clean energy stocks, gold, Bitcoin, and green cryptocurrencies (XRP, ADA, IOTA). Stocks focused on ESG (as indicated by the S\&P Global ESG Index) demonstrate moderate positive correlations with eco-friendly cryptocurrencies, notably 0.64 with XRP, 0.72 with IOTA, and 0.72 with ADA. This suggests that ESG stocks and eco-friendly cryptocurrencies often react similarly, implying they could be affected by common elements such as investor attitudes toward sustainability, advancements in technology, or regulatory changes connected to environmental objectives.

In comparison, the clean energy stock index (S\&P Clean Energy) shows lower yet still positive correlations with green cryptocurrencies. For instance, it demonstrates a correlation of 0.32 with ADA, signifying a degree of co-movement, though not as robust as the connection with wider ESG stocks. This implies that although clean energy stocks and green cryptocurrencies might attract comparable investor groups prioritizing sustainability, they are influenced by different market forces.

Bitcoin, on the other hand, shows low or negative correlations with ESG stocks (−0.26), clean energy stocks (−0.32), and environmentally friendly cryptocurrencies (e.g., −0.26 with ADA). This illustrates Bitcoin's detachment from the ESG investment sector, probably because of its significant energy use and its general connection to speculative or alternative investments instead of sustainable finance. Gold, in contrast, exhibits little correlation with other asset classes. This strengthens its conventional position as a safe-haven asset, mostly uninfluenced by ESG trends or fluctuations in digital and clean energy-related assets. In summary, the data indicate that green cryptocurrencies correlate more closely with ESG-related stocks than Bitcoin or gold, implying their increasing potential function within sustainable investment portfolios.

Table 3 presents the static return spillover estimates among a set of sustainable and traditional financial assets, including the S&P Green Bond Index, ESG stock index, S&P Clean Energy Index, green cryptocurrencies (ADA, IOTA, XRP), Bitcoin, and Gold. The results reveal a high degree of integration across the system, as reflected by a total spillover index of 62.10%. Notably, the ESG stock index exhibits its highest return spillover effect toward the clean energy equities, with a magnitude of 14.85, suggesting a strong transmission channel within the sustainable equity domain. Among the green cryptocurrencies, Cardano (ADA) exerts the most significant return spillover on Bitcoin, amounting to 18.32, highlighting a notable

Figure 2: Correlation matrix



linkage between the emerging green crypto space and mainstream digital assets. Furthermore, gold demonstrates a considerable return transmission toward the S&P Green Bond Index, with a spillover value of 11.59, underscoring the role of traditional safe-haven assets in influencing sustainable fixed-income instruments.

The result of connectedness "TO" the system reveals that the environment stocks (87.08%) transmits the highest return spillover to the system and followed by social stocks (86.91%). On the digital assets side, green cryptocurrency (ADA) transmits the highest with value of 69.86%, followed by Bitcoin (65.28%) and other green cryptocurrencies (IOTA, XRP). Meanwhile, the transmission of gold to the system is the lowest (20.91%).

The "FROM" column reflects the return spillovers received by each asset from the overall system. The findings show that the Social and Environment components each receive the highest level of return shocks with a value of 74.30 and 74.26, closely followed by Governance at 74.16. This indicates that these three ESG dimensions are the most susceptible to influence from movements within the broader financial network.

The "NET" return spillover values are shown in the two last row of the table; positive numbers indicate that an asset acts as a net transmitter of return shocks, while negative values mean that the asset acts as a net recipient. Different transmission patterns are revealed by the observed return spillovers across the different assets, underscoring the unique responsibilities that each asset plays in the larger return spillover network. The ESG stocks (Environment, Social, Governance) act as return transmitter to the system, aligned with (Alharbi et al., 2025). The highest transmitter is from Environment (12.82), followed by Social (12.62) and Governance (11.01). Meanwhile, the green cryptocurrencies reveal that mostly act as return transmitters, where in previous studies they acted as net receivers (Pham et al., 2022; Alharbi et al., 2025). The results in the Table 2 show that only XRP acts as a net receiver. This is due to the research variables of this study which combine several other assets besides stocks. Moreover, Bitcoin is indicated as net transmitter with value of 1.44. This finding are in consonance with (Elsayed et al., 2022b; Liu et al., 2024). In addition, S&P Green Bond, S&P Clean Energy, and gold are found to be strong net receiver of return spillover in the system.

Table 4 presents the static volatility spillover among a set of sustainable and traditional financial assets, including the S&P Green Bond Index, ESG stock index, S&P Clean Energy Index, green cryptocurrencies (ADA, IOTA, XRP), Bitcoin, and Gold. The TCI value of 59.58% indicates a strong level of volatility integration among the assets analyzed, including ESG (Environmental, Social, Governance) indices, green assets, green crypto, Bitcoin, and gold. Thus, volatility movements in one asset have a significant impact on the volatility of other assets, which is important to consider in risk management strategies and portfolio formation. The ESG stocks transmits highest volatility spillover to the S&P Clean Energy index with social stocks of 13.48, followed by environment (13.30) and governance (13.22). Green cryptocurrencies transmits high volatility to Bitcoin with Cardano (ADA) is the highest (16.81).

Table 3: Return spillover

Variable	S&P_GB	S&P_CE	BTC	ADA	IOTA	XRP	Gold	Environment	Governance	Social	From
S&P_GB	47.08	5.82	1.7	1.43	1.07	1.12	11.59	10.05	10.19	9.95	52.92
S&P_CE	4.25	41.48	2.93	2.26	2.09	1.72	1.9	14.85	13.84	14.67	58.52
BTC	1.01	2.4	36.16	19.22	18.32	15.4	1.08	2.25	2.01	2.19	63.84
ADA	0.75	1.82	18.47	34.69	19.23	18.2	0.64	2.16	1.95	2.11	65.31
IOTA	0.64	1.81	18.43	19.92	36.45	16.9	0.59	1.84	1.65	1.79	63.55
XRP	0.59	1.51	16.12	19.9	17.8	38.7	0.5	1.7	1.54	1.66	61.33
GOLD	13.86	3.12	2.01	1.33	1.15	0.99	67.2	3.33	3.47	3.53	32.8
ENVIRONMENT	5.33	10.06	1.93	1.98	1.53	1.4	1.48	25.74	25.17	25.39	74.26
GOVERNANCE	5.53	9.58	1.8	1.85	1.43	1.3	1.56	25.47	25.84	25.63	74.16
SOCIAL	5.27	9.99	1.89	1.96	1.5	1.37	1.57	25.41	25.34	25.7	74.3
TO	37.22	46.11	65.28	69.86	64.14	58.3	20.91	87.08	85.16	86.91	620.98
Inc. Own	84.3	87.59	101.4	104.6	100.6	97	88.12	112.82	111.01	112.6	cTCI/TCI
NET	−15.7	−12.41	1.44	4.55	0.59	−3.03	−11.88	12.82	11.01	12.62	69.00/62.10

Table 4: Volatility spillover

Variable	S&P_GB	S&P_CE	BTC	ADA	IOTA	XRP	Gold	Environment	Governance	Social	From
S&P_GB	45.83	9.62	2.37	1.33	1.3	1.08	4.42	11.71	11.46	10.88	54.17
S&P_CE	6.34	41.81	3.61	2.39	1.91	1.07	2.85	13.3	13.22	13.48	58.19
BTC	1.69	3.11	40.1	16.81	13.05	7.09	1.66	5.59	5.39	5.49	59.87
ADA	0.83	1.75	16	40.26	17.16	13.6	0.64	3.29	3.22	3.27	59.74
IOTA	0.74	1.6	13.4	18.23	44.56	11.7	0.71	3.05	2.99	3.03	55.44
XRP	0.64	1.05	8.5	17.55	13.66	53.1	0.35	1.72	1.72	1.68	46.87
GOLD	5.53	4.55	2.28	1.35	1.16	0.84	65.75	6.12	6.2	6.2	34.25
ENVIRONMENT	5.94	9.09	4.17	2.57	2.34	1.32	2.81	24.28	23.65	23.83	75.72
GOVERNANCE	5.85	9.13	4.1	2.54	2.32	1.34	2.83	23.71	24.25	23.94	75.75
SOCIAL	5.59	9.28	4.15	2.59	2.33	1.32	2.84	23.84	23.89	24.16	75.84
TO	33.15	49.19	58.5	65.37	55.22	39.4	19.12	92.33	91.75	91.8	595.84
Inc. Own	78.99	91.01	98.7	105.6	99.78	92.5	84.87	116.61	116	116	cTCI/TCI
NET	−21.01	−8.99	−1.34	5.63	−0.22	−7.48	−15.1	16.61	16	15.96	66.20/59.58

The result of connectedness "TO" the system reveals that the environment stocks (92.33%) transmits the highest volatility spillover to the system and followed by social stocks (91.8%). On the digital assets side, green cryptocurrency (ADA) transmits the highest with value of 65.37%, followed by Bitcoin (58.53%) and other green cryptocurrencies (IOTA, XRP). Meanwhile, the volatility transmission of gold to the system is the lowest (19.12%).

The "FROM" column reflects the volatility spillovers received by each asset from the overall system. The findings show that the Social and Governance components each receive the highest level of return shocks with a value of 75.84 and 75.75, closely followed by Environment at 75.72. These findings indicate that all three ESG pillars are highly vulnerable to volatility shocks originating from systemic dynamics in the financial markets as a whole.

The "NET" section brings all conclusion that ESG stocks are the net transmitter in both, return and volatility connectedness. The green cryptocurrencies show only XRP and IOTA act as net receiver, while ADA stays as net transmitter in volatility spillover. This findings in green cryptocurrencies are not aligned with previous literatures that stated all green cryptocurrencies as net receiver in return and volatility spillover. This due to the research variables of this study which combine several other assets besides stocks. Moreover, Bitcoin becomes a net receiver in the system. Lastly, green bonds, clean energy and gold are net receiver in volatility spillover.

Figure 3 shows the net pair-wise return spread between various assets, including ESG stocks, green cryptocurrencies, and conventional assets such as gold and green bonds. In this graph, the yellow colour depicts assets that function as net receivers, that is, they receive more return impacts from other assets than they give. Conversely, the blue colour depicts assets that act as net transmitters, that is, they transmit (flow) more return volatility to other assets.

From this visualization, the assets in yellow such as S&P_CE (Clean Energy Index), S&P_GB (Green Bond Index), GOLD, and XRP function as net receivers. This shows that the returns of these four assets are highly influenced by the movement of returns from other assets in the system. These assets tend to absorb market impacts rather than transmit them. The role as a receiver may indicate a more passive character in conveying market information or be caused by its sensitivity to changes from other, more dominant assets.

In contrast, blue assets such as SOCIAL, ENVIRONMENT, ADA, IOTA, and BTC act as net transmitters. They act as the primary source of return shocks to other assets. These assets have the ability to influence the entire system, demonstrating a proactive nature in sending returns between markets. In particular, ESG assets and green crypto in this category reflect a significant role in broader market dynamics.

The pattern shows strong connectivity between assets, especially between crypto and ESG assets. This finding is relevant in the context of portfolio diversification, as it indicates that shocks from transmitter assets can have a significant impact on receiver assets, so investors should pay attention to their respective functions in risk management.

From Figure 4, it can be seen that assets such as IOTA, XRP, GOLD, S&P_GB (Green Bonds), S&P_CE (Clean Energy), and BTC are dominated by yellow. This shows that these assets are more susceptible to volatility transmitted from other markets, and are less likely to be the main source of instability in the system. The role as a net receiver shows that these assets can be used as indicators of market pressure recipients, although they are still affected by external dynamics.

Figure 3: Net pair-wise return spillover

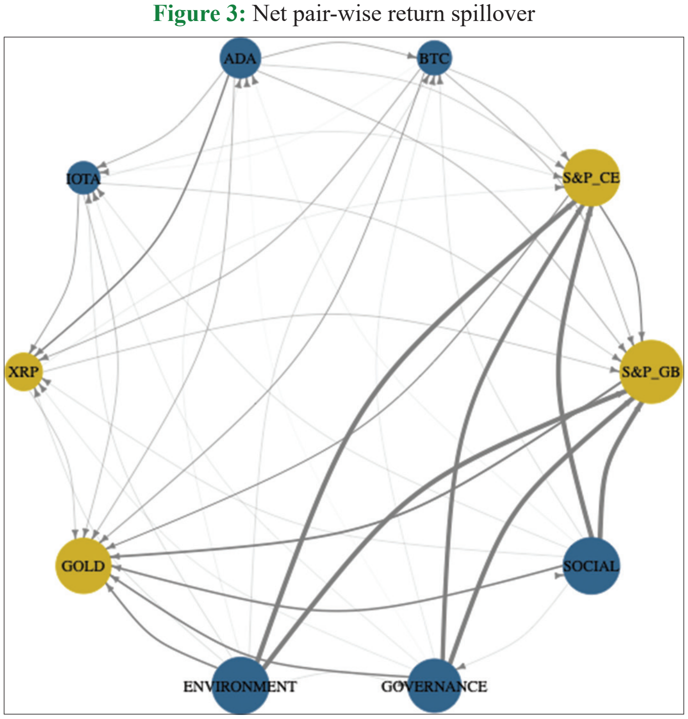
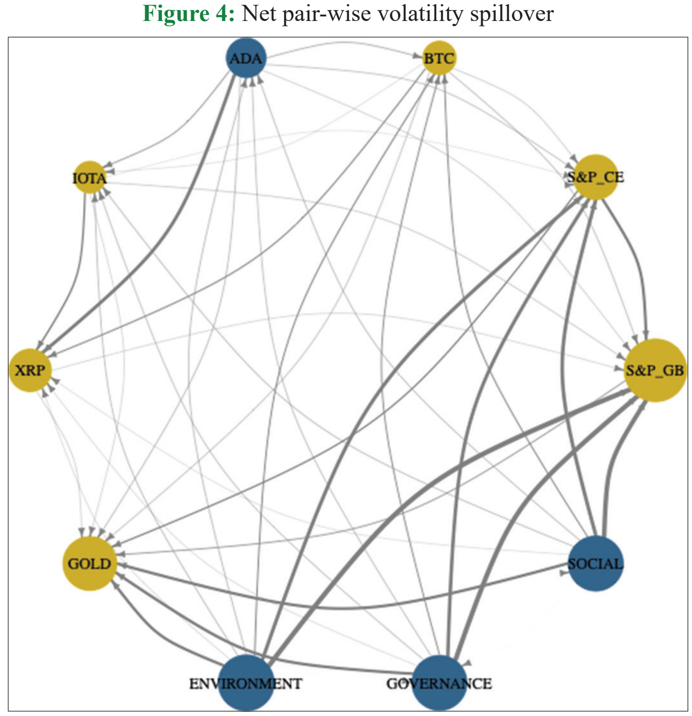


Figure 4: Net pair-wise volatility spillover



On the other hand, assets in blue such as ADA, SOCIAL, ENVIRONMENT and GOVERNANCE function as net transmitters. They show a greater ability to spread volatility to other assets, thus acting as a center for transmitting uncertainty in the system. This reflects that ESG assets (especially the social and governance dimensions) and some cryptos, have systemic power in creating volatility instability in the sustainable financial market.

This connectivity structure shows the complexity of strong cross-asset relationships. Investors and risk managers need to consider the role of transmitters and receivers, as transmitter assets tend to be the main drivers of market shocks, while receivers can be indicators of vulnerability to changes in the external environment.

Figure 5 shows the Net Return Spillover graph for various assets divided into three periods: pre-COVID and early (20182019), COVID period (2020-2021; marked in blue), and post-COVID including the Russian-Ukrainian invasion (2022-2023; marked in orange). Positive net spillover values indicate a role as a net transmitter, while negative values indicate a role as a net receiver. In general, green cryptocurrencies (ADA, IOTA, XRP) and Bitcoin act more often as net transmitters, especially at the end of the period. This shows that digital assets tend to transmit return shocks to other assets, especially in increasingly interconnected markets. In contrast, green finance such as S&P Green Bonds (S&P_GB) and Clean Energy (S&P_CE) tend to be net receivers, as seen from the consistently negative net spillover values throughout the period.

During the COVID-19 crisis, the ESG index remained a net transmitter, but the spillover value tended to decline. Furthermore, green cryptocurrencies, ADA and XRP, turned to be net return receivers, reflected by negative values during that period. On the other hand, IOTA is still a net transmitter with a declining value. Gold and green finance (S&P Green Bonds and S&P Clean Energy) remain net return receivers.

Entering 2022, when geopolitical tensions increased due to the Russia-Ukraine war, the shift in net spillover was again seen. Green cryptocurrencies such as ADA and XRP increased their role as transmitters, while IOTA turned into a net receiver. S&P Green Bonds remained the main receiver, strengthening its image as a defensive asset during geopolitical uncertainty. The ESG category again recorded high fluctuations with ENVIRONMENT tending to be a transmitter post-war, indicating the sector's sensitivity to energy issues and global environmental policies due to conflict. After the peak of the war, there was a consistent trend that digital assets (ADA, XRP, BTC) became stronger as return shock transmitters. This is in contrast to traditional assets such as GOLD whose role was more neutral or even slightly as a receiver. Green finance still tends to be a receiver and ESG stocks remain a net transmitter.

Figure 6 illustrates the evolving roles of various asset classes as net transmitters or receivers of volatility across three distinct periods: the full sample (2018-2024), the COVID-19 pandemic (2020-2021), and the Russia-Ukraine conflict (2022). Over the entire observation period, green cryptocurrencies such as IOTA and XRP

Figure 5: Net return spillover plot

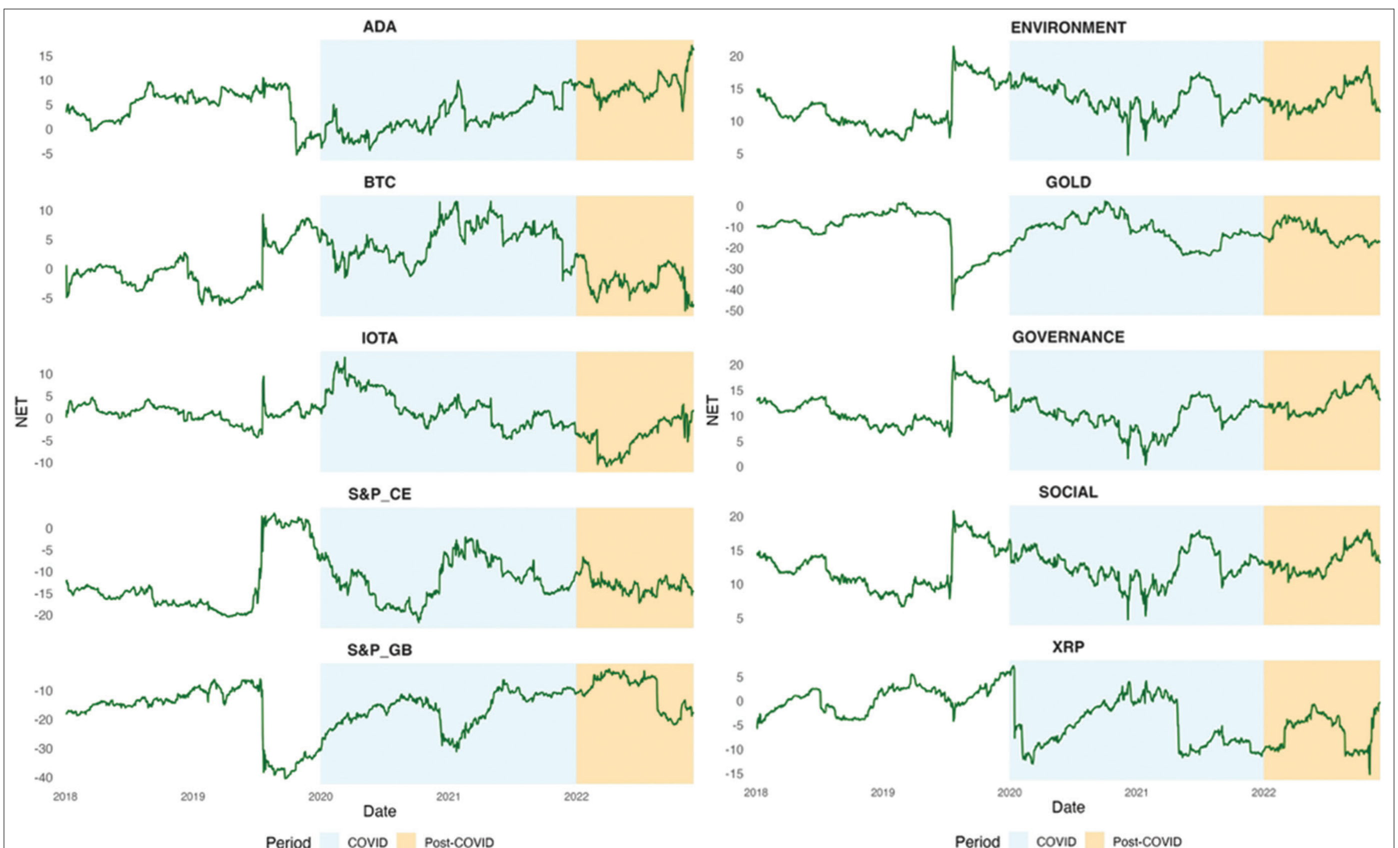


Figure 6: Net volatility spillover plot

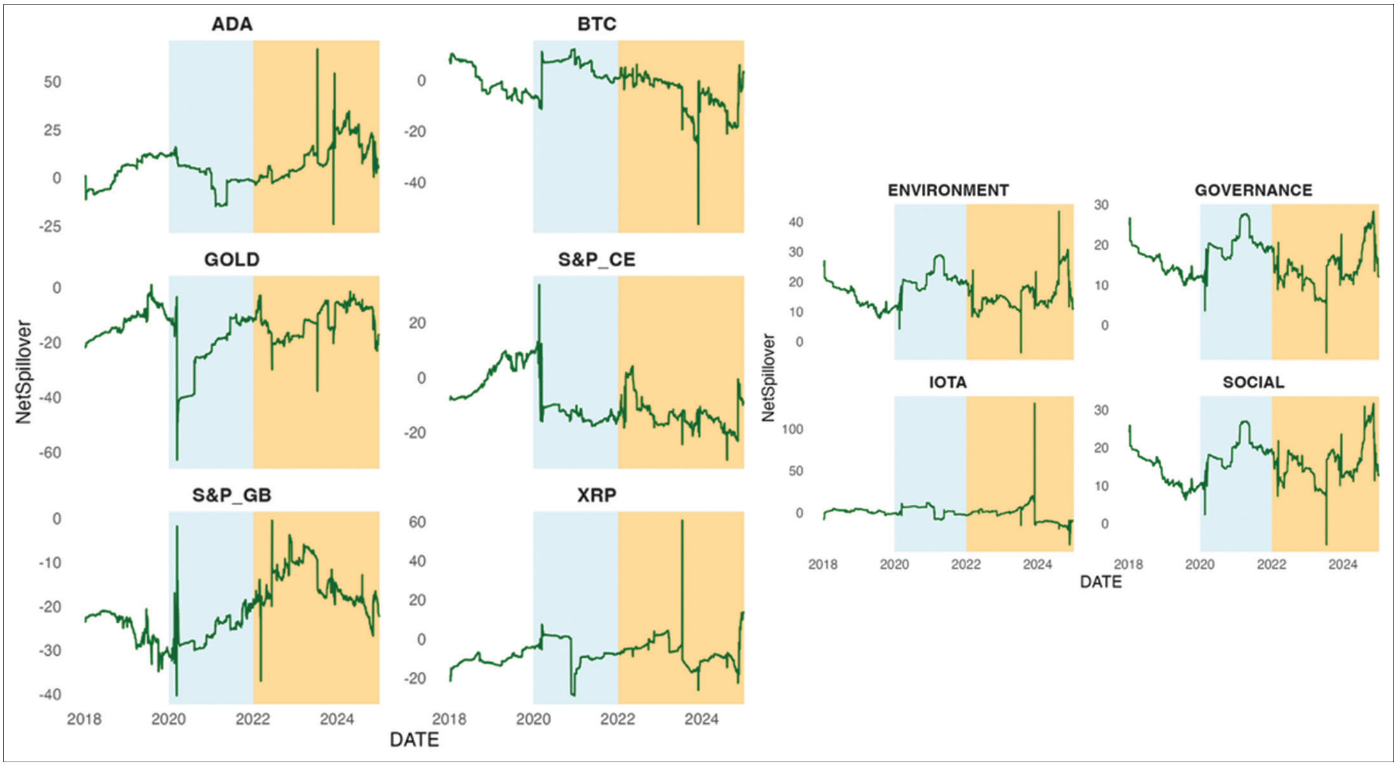
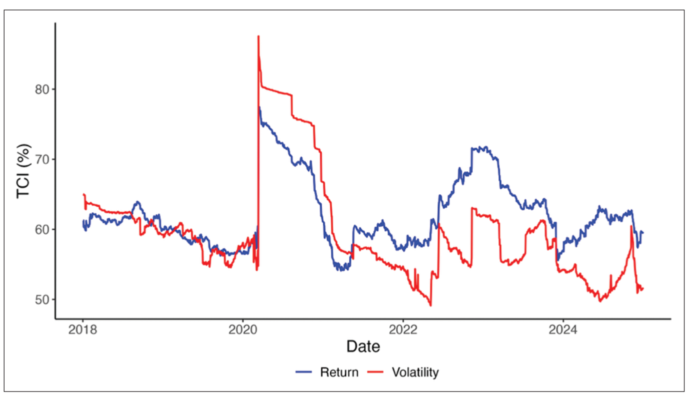


Figure 7: TCI plot



predominantly functioned as net receivers of volatility, reflecting their heightened vulnerability to systemic market disturbances. Meanwhile, ADA keeps its role as net volatility transmitter. Conversely, Bitcoin (BTC) consistently exhibited characteristics of a net volatility receiver. S&P Green Bonds primarily operated as volatility absorbers, underscoring their perceived “safe haven” status under stable market conditions. ESG stocks remains to be the volatility transmitter to the system.

The volatility transmission structure underwent considerable transformation during the COVID-19 pandemic. Bitcoin turns into net volatility transmitter. It’s influence as a volatility source intensified, reaffirming its dominant role during episodes of elevated market uncertainty. Notably, S&P Green Bonds consistently play its role as net receiver and S&P_CE shifted to be a net transmitter for a while. Gold becomes strongly absorbed the volatility during the COVID-19 period. Lastly, ESG stocks (ENVIRONMENT, SOCIAL, GOVERNANCE) become stronger as net volatility transmitter.

The onset of the Russia-Ukraine war further reconfigured volatility spillover dynamics, driven by escalating geopolitical tensions. Green cryptocurrencies—particularly XRP—transitioned into net transmitters, likely due to their sensitivity to energy-related developments. The S&P Clean Energy Index also emerged as a source of volatility, capturing market concerns surrounding energy supply disruptions. Gold remains the same, as net receiver. Interestingly, the ESG Governance pillar maintained a net transmitter profile.

As can be seen in Figure 7: Total Connected Index Plot, the TCI Return and TCI Volatility values in 2018-2019 were quite stable in the range of 55-65% with TCI Volatility slightly higher than TCI Return. However, when entering early 2020, the COVID-19 crisis caused TCI Volatility to jump significantly to its peak of above 85%, indicating that the uncertainty that occurred globally due to COVID-19 made asset instruments interdependent and connected. On the other hand, TCI Return also jumped to almost 80% but was still not as intense as TCI Volatility.

Post-pandemic, in the 2021-2022 period, TCI Volatility and TCI Return fell significantly. However, TCI Volatility fell lower than TCI Return to nearly 50%, indicating that the market was starting to stabilize again after the pandemic, weakening the connectedness of volatility between assets. TCI Return post COVID-19 decreased but remained connected, quite stable at 55-60%, fluctuating at a small level. This shows that the market is calmer, the dependence of returns between assets is starting to normalize but has not been completely separated. This phenomenon shows that after a major crisis, the market tends to maintain connectivity on the return side, while volatility connectivity weakens again as systemic uncertainty decreases.

Entering the 2022-2024 period, TCI Return increased to a moderate level, with the highest spike around mid-2023. This shows investor sentiment that is interconnected even though volatility is more controlled. The increase in TCI return at the end of this period could also be caused by global inflation, geopolitics or ESG issues. Meanwhile, for TCI Volatility, the movement is lower, still fluctuating but not as high as 2020.

5. CONCLUSION

This research investigates the dynamic return and volatility connectedness among sustainable and digital financial instruments—namely green bonds, ESG stocks, clean energy stocks, green cryptocurrencies (ADA, IOTA, XRP), Bitcoin, and gold—within the period of January 2018 to December 2024. Utilizing the Time-Varying Parameter Vector Autoregressive (TVP-VAR) framework, the study captures inter-asset relationships under both normal market conditions and periods of heightened uncertainty, particularly during the COVID-19 pandemic and the Russia-Ukraine conflict. The empirical findings shed light on the evolving nature of cross-asset spillovers and their implications for risk management, portfolio diversification, and sustainable investment strategies.

The analysis reveals that ESG-related equities, across the environmental, social, and governance dimensions, consistently act as net transmitters of return and volatility shocks throughout the sample period. This indicates their influential role within the system and heightened responsiveness to macroeconomic and financial disturbances. In contrast, traditional safe-haven assets such as gold, along with green bonds and clean energy stocks, are identified as net receivers of shocks, reflecting their defensive characteristics and utility in stabilizing portfolios during market stress.

Green cryptocurrencies exhibit heterogeneous behavior. While XRP and IOTA tend to function as net receivers of volatility, ADA stands out as a volatility transmitter, diverging from prior findings that portrayed green cryptocurrencies as passive recipients of shocks. Bitcoin, on the other hand, displays asymmetric characteristics—acting as a net return transmitter during tranquil periods but shifting to a volatility receiver in times of crisis—underscoring its dual role as both a speculative asset and a potential hedging instrument.

The Total Connectedness Index (TCI) further supports the assertion that systemic events intensify market interdependence. During the early phase of the COVID-19 pandemic, TCI values for both return and volatility surged, with volatility reaching levels above 85%, signaling elevated systemic risk. Although interdependence declined as the market gradually stabilized, post-crisis TCI levels remained above pre-crisis norms, indicating persistent structural connectivity across asset classes.

In terms of portfolio construction, green cryptocurrencies demonstrate superior performance as hedging instruments for clean energy assets, offering high hedge effectiveness and consistent optimal weighting across various market regimes. Meanwhile, ESG stocks provide moderate hedging benefits, functioning more effectively as diversifiers. Conversely, gold and green bonds are found to be relatively inefficient hedging tools in the context of clean energy exposure due to their low risk reduction capability and high hedging costs.

In summary, this study contributes to the growing body of literature on sustainable finance by integrating green cryptocurrencies into the analysis of ESG asset interlinkages through a dynamic modeling approach. The results offer practical implications for ESG-conscious investors and policymakers seeking to build resilient, diversified portfolios. For future research, it is recommended to extend the scope by incorporating additional ESG-oriented digital assets, examining regional or sectoral variations, and employing high-frequency data to capture finer transmission dynamics under extreme market conditions.

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