*International Journal of Accounting and Economics Studies*, 13 (1) (2026) 471-479

International Journal of Accounting and Economics Studies

*Website: www.sciencepubco.com/index.php/IJAES*
*https://doi.org/10.14419/q6a30k28*
***Research paper***

# Dynamic Interdependence between NFTs, DeFi Tokens and Sustainable Assets Across Geopolitical Crises

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*Received: December 27, 2025, Accepted: January 19, 2026, Published: January 26, 2026*

**Abstract**

This study examines the dynamic interdependence between Clean Energy indices, AI Robotics Index, and selected NFT and DeFi tokens across three major geopolitical crises: COVID-19 pandemic (January 2020–April 2021), Russia-Ukraine war (February 2022–December 2022), and Iran-Israel conflict (October 2023–June 2024). Employing continuous wavelet transform, wavelet coherence, and partial wavelet coherence techniques, we decompose relationships across short-term, medium-term, and long-term horizons using daily data from Bloomberg. Descriptive statistics reveal fundamental differences between sustainable investments and digital assets: Clean Energy (mean: 0.0008, variance: 0.0004) and AI Index (mean: 0.0003, variance: 0.0002) demonstrate positive returns with low volatility, while NFT and DeFi tokens exhibit negative average returns and substantially higher volatility, with AAVE showing extreme kurtosis (773.27) and variance (0.0167). Wavelet coherence analysis reveals crisis-dependent and scale-specific patterns. During COVID-19, only short-term and medium-term coherence emerged, indicating transitory speculative relationships. The Russia-Ukraine war marked a structural shift, with AAVE demonstrating long-term coherence with Clean Energy, suggesting deeper market integration driven by energy market disruptions. The Iran-Israel conflict exhibited the most complex patterns, with broader long-term coherence across ENJ Coin, Theta, Synthetix, Maker, and SUPERf, indicating structural convergence between energy transition narratives and selected DeFi/NFT projects. These findings demonstrate that NFT/DeFi-sustainable investment relationships are crisis-dependent, scale-specific, and selectively integrative, with significant implications for portfolio diversification strategies and systemic risk monitoring during geopolitical crises.

***Keywords***: *Wavelet Coherence; DeFi Tokens; NFTs; Clean Energy; Geopolitical Crises.*

## 1. Introduction

The global financial landscape has witnessed unprecedented transformation over the past decade, characterized by the rapid emergence of digital assets, decentralized finance (DeFi), non-fungible tokens (NFTs), and the accelerating transition toward sustainable energy investments. This convergence of technological innovation and environmental consciousness has fundamentally reshaped investment paradigms, creating complex interdependencies between traditional asset classes and emerging digital markets (Corbet et al., 2019; Mnif et al., 2020). Simultaneously, the increasing frequency and severity of geopolitical crises—ranging from the COVID-19 pandemic to regional conflicts—have exposed the vulnerability of global financial systems to exogenous shocks, triggering unprecedented volatility across asset markets and challenging conventional diversification strategies (Goodell, 2020; Sharif et al., 2020).

The cryptocurrency and blockchain ecosystem has evolved from a niche technological experiment into a multi-trillion-dollar market that increasingly intersects with traditional financial markets (Bouri et al., 2021a; Corbet et al., 2018). Within this ecosystem, DeFi protocols have emerged as alternative financial infrastructure, offering decentralized lending, borrowing, and trading mechanisms that bypass traditional intermediaries (Chen & Bellavitis, 2020; Zetzsche et al., 2020). Similarly, NFTs have introduced novel mechanisms for digital ownership and value representation, creating new asset classes that blur the boundaries between art, collectibles, and financial instruments (Dowling, 2022; Nadini et al., 2021). Despite their rapid growth and mainstream adoption, the fundamental characteristics of these digital assets—including extreme volatility, speculative nature, and uncertain regulatory frameworks—raise critical questions about their role in diversified investment portfolios and their relationship with traditional asset classes (Conlon et al., 2020; Kristoufek, 2020).

Concurrently, the global energy transition has accelerated investment flows toward clean energy and renewable technologies, driven by climate change concerns, environmental policies, and shifting investor preferences toward environmental, social, and governance (ESG) criteria (Reboredo et al., 2017; Pham, 2019). Clean energy investments have demonstrated distinct risk-return profiles compared to conventional energy sectors, exhibiting sensitivity to policy changes, technological innovations, and geopolitical developments (Ahmad et al., 2018; Bondia et al., 2016). The intersection of artificial intelligence (AI) and robotics with sustainable energy systems has further created new investment opportunities, as AI-driven technologies promise to enhance energy efficiency, optimize renewable energy deployment, and accelerate the transition toward carbon neutrality (Qarnain et al., 2020; Sovacool et al., 2020). Understanding how these sustainable investment sectors interact with emerging digital asset markets has become increasingly important for investors, policymakers, and financial institutions seeking to navigate the evolving landscape of global finance (Naeem et al., 2022; Ren & Lucey, 2022).

Recent geopolitical events have profoundly impacted both traditional and digital financial markets, creating natural experiments for examining crisis-dependent interdependencies across asset classes. The COVID-19 pandemic triggered unprecedented global economic disruption, forcing central banks to implement massive monetary stimulus programs and prompting investors to reassess portfolio allocations (Baker et al., 2020; Zhang et al., 2020). During this period, cryptocurrencies initially demonstrated correlation with equity markets during the March 2020 crash, challenging their purported status as safe-haven assets (Conlon & McGee, 2020; Goodell & Goutte, 2021). However, subsequent recovery phases revealed more complex dynamics, with certain digital assets exhibiting diversification benefits as traditional correlations weakened (Bouri et al., 2020; Ji et al., 2020).

The Russia-Ukraine conflict, which erupted in February 2022, created severe energy market disruptions, driving unprecedented volatility in oil, natural gas, and clean energy investments (Umar et al., 2022; Yousaf et al., 2022). This geopolitical shock coincided with significant turbulence in cryptocurrency markets, raising questions about potential spillover effects and contagion mechanisms between energy-sensitive assets and digital markets (Jiang et al., 2022; Kumari et al., 2023). Unlike the pandemic-induced crisis that affected all sectors simultaneously, the Russia-Ukraine conflict created sector-specific shocks with differential impacts on energy-dependent industries, potentially strengthening linkages between energy markets and energy-intensive blockchain networks (Sarkodie et al., 2022; Umar et al., 2023).

More recently, the Iran-Israel conflict has introduced additional geopolitical uncertainty, affecting regional energy markets and creating renewed risk aversion across global financial systems (Akan et al., 2024). Each of these crisis episodes presents distinct characteristics in terms of duration, sectoral impact, and transmission mechanisms, providing valuable opportunities to examine how the relationship between sustainable investments and digital assets evolves under different types of exogenous shocks (Mensi et al., 2023; Naeem et al., 2021).

The theoretical foundations for examining these relationships draw from portfolio theory, market integration literature, and safe-haven asset research. Modern portfolio theory suggests that assets with low or negative correlations provide diversification benefits, reducing overall portfolio risk without proportionally sacrificing returns (Markowitz, 1952). However, increasing evidence suggests that correlations between asset classes are time-varying and often increase during crisis periods, potentially undermining diversification strategies precisely when investors need them most (Christoffersen et al., 2012; Longin & Solnik, 2001). The safe-haven hypothesis posits that certain assets maintain or increase their value during market turmoil, providing downside protection when traditional assets decline (Baur & Lucey, 2010; Baur & McDermott, 2010). Bitcoin and other cryptocurrencies have been proposed as potential safe-haven assets, though empirical evidence remains mixed and highly context-dependent (Bouri et al., 2017; Urquhart & Zhang, 2019).

Recent methodological advances in time-frequency analysis have enabled researchers to decompose asset relationships across multiple time horizons, recognizing that short-term speculative dynamics may differ fundamentally from long-term structural relationships (Aguiar-Conraria & Soares, 2014; Rua & Nunes, 2009). Wavelet coherence analysis has emerged as a particularly powerful tool for examining time-varying co-movements between financial time series, allowing simultaneous examination of correlation patterns across different frequencies and time periods (Grinsted et al., 2004; Torrence & Compo, 1998). This approach has been successfully applied to study relationships between cryptocurrencies and various asset classes, including equities, commodities, and currencies (Jiang et al., 2021; Karim et al., 2022a).

Several recent studies have examined specific aspects of the relationships this paper investigates. Mensi et al. (2020) explored time-frequency co-movements between green bonds and traditional energy markets, documenting significant heterogeneity across different time scales. Naeem et al. (2021) analyzed asymmetric efficiency in cryptocurrency markets during COVID-19, finding that market efficiency varied considerably across different crisis phases. Karim et al. (2022b) examined the interrelatedness of NFTs, DeFi tokens, and cryptocurrencies, revealing complex network structures that evolved over time. Ren and Lucey (2022) investigated relationships between clean energy and cryptocurrencies, distinguishing between "clean" and "dirty" digital assets based on energy consumption profiles. Umar et al. (2022) documented increased connectedness between financial markets following the Russia-Ukraine conflict, highlighting the role of energy market shocks in transmitting volatility across asset classes.

Despite these valuable contributions, significant gaps remain in our understanding of how sustainable investment sectors interact with NFT and DeFi markets across different crisis contexts and time horizons. First, existing literature has largely focused on Bitcoin and major cryptocurrencies, with limited attention to the expanding DeFi ecosystem and NFT markets that represent distinct segments with potentially different risk characteristics and market dynamics (Ante, 2023; Chohan, 2021). Second, while several studies have examined cryptocurrency behavior during individual crisis periods, comprehensive comparative analysis across multiple geopolitical events with different characteristics remains limited (Mariana et al., 2021; Shahzad et al., 2021). Third, the specific relationship between AI-driven investment sectors and digital assets has received insufficient empirical attention, despite the growing recognition of technological synergies between blockchain and artificial intelligence (Salah et al., 2019; Dinh & Thai, 2018).

This study addresses these gaps by conducting a comprehensive wavelet coherence analysis examining the dynamic interdependence between Clean Energy indices, AI Robotics Index, and selected NFT and DeFi tokens across three major geopolitical events: the COVID-19 pandemic (January 2020–April 2021), the Russia-Ukraine war (February 2022–December 2022), and the Iran-Israel conflict (October 2023–June 2024). By employing wavelet coherence, wavelet correlation, and partial wavelet coherence techniques, this research decomposes the relationships across short-term, medium-term, and long-term horizons, revealing how crisis characteristics and duration influence the evolution of market interdependencies (Madaleno & Pinho, 2012; Vacha & Barunik, 2012).

The findings of this study contribute to several strands of literature and have important practical implications. First, by documenting crisis-dependent and scale-specific coherence patterns, this research advances our understanding of how digital asset markets integrate with sustainable investment sectors under different stress conditions. Second, the identification of selective long-term coherence with specific DeFi protocols provides insights into which digital assets may be transitioning from purely speculative instruments toward vehicles that reflect fundamental economic trends. Third, the comparative analysis of Clean Energy and AI Robotics indices offers new evidence on how different sustainable investment sectors interact with the digital asset ecosystem. Finally, the multi-horizon perspective provides actionable insights for investors designing dynamic allocation strategies and for policymakers concerned with systemic risk transmission between energy markets and digital assets.

The remainder of this paper is organized as follows: Section 2 describes the methodology, data, and wavelet techniques employed. Section 3 presents the empirical results, including descriptive statistics and wavelet coherence analysis across the three crisis periods. Section 4 concludes with policy implications and recommendations for future research.

## 2. Review of Literature

The intersection of digital assets and sustainable investments has emerged as a critical research area, particularly following recent global crises that have reshaped financial market dynamics. This literature review synthesizes recent empirical findings on the relationships between cryptocurrencies, DeFi tokens, NFTs, and clean energy investments across different market conditions.

The COVID-19 pandemic catalyzed extensive research on cryptocurrency market behavior during extreme market stress. Conlon and McGee (2020) and Goodell and Goutte (2021) demonstrated that Bitcoin failed to serve as a safe haven during the initial pandemic shock, instead exhibiting significant positive correlation with equity markets. However, Bouri et al. (2021a) found heterogeneous patterns across different crisis phases, with certain cryptocurrencies providing hedging benefits during recovery periods. Naeem et al. (2021) extended this analysis by documenting asymmetric efficiency in cryptocurrency markets, revealing that market microstructure changed substantially across different pandemic stages. Zhang et al. (2020) and Sharif et al. (2020) highlighted the role of policy uncertainty and oil price volatility in transmitting shocks from traditional markets to digital assets, establishing multi-channel contagion mechanisms.

The Russia-Ukraine conflict introduced energy-specific dynamics into cryptocurrency research. Umar et al. (2022) documented unprecedented connectedness between financial markets following the conflict, with energy market shocks serving as primary transmission channels. Jiang et al. (2022) and Sarkodie et al. (2022) emphasized the energy-intensive nature of Bitcoin mining, creating direct linkages between geopolitical energy disruptions and cryptocurrency market performance. Yousaf et al. (2022) and Kumari et al. (2023) confirmed that the Russia-Ukraine crisis strengthened correlations between cryptocurrencies and commodity markets, particularly energy commodities, challenging previous assumptions about cryptocurrency independence from traditional asset classes.

The emergence of DeFi protocols and NFT markets has diversified the digital asset landscape beyond traditional cryptocurrencies. Karim et al. (2022a) examined the interrelatedness of NFTs, DeFi tokens, and cryptocurrencies, revealing complex network structures with time-varying dependencies. Dowling (2022) found that NFT pricing is significantly driven by cryptocurrency market movements, particularly Ethereum, suggesting strong technological and speculative linkages. Ante (2023) documented that NFT market volatility exceeds even cryptocurrency volatility, with extreme sensitivity to market sentiment and technological developments. Chen and Bellavitis (2020) and Zetzsche et al. (2020) highlighted the transformative potential of DeFi protocols in reshaping financial intermediation, while acknowledging regulatory uncertainties and systemic risks.

Recent research has begun exploring connections between clean energy investments and digital assets. Ren and Lucey (2022) distinguished between "clean" and "dirty" cryptocurrencies based on energy consumption profiles, finding that clean energy stocks exhibit different correlation patterns with energy-efficient versus energy-intensive digital assets. Naeem et al. (2022) compared green and conventional bonds during COVID-19, documenting superior efficiency in green bond markets that may influence their relationship with ESG-conscious cryptocurrency investments. Mensi et al. (2020, 2023) employed wavelet-based approaches to examine time-frequency co-movements between green bonds, energy markets, and alternative assets, revealing scale-dependent relationships that vary across investment horizons.

Methodological advances in time-frequency analysis have enhanced understanding of dynamic asset relationships. Jiang et al. (2021) applied quantile coherency perspectives to revisit cryptocurrency roles in stock markets, demonstrating that relationships differ substantially across return distributions. Vacha and Barunik (2012) and Madaleno and Pinho (2012) established wavelet coherence as a powerful tool for decomposing co-movements across time and frequency domains. Aguiar-Conraria and Soares (2014) advocated for continuous wavelet transforms in moving beyond traditional bivariate analysis, enabling multi-scale investigation of financial market integration.

Despite these contributions, critical gaps remain. First, comprehensive comparative analysis across multiple crisis periods with different characteristics is limited (Mariana et al., 2021; Shahzad et al., 2021). Second, the specific relationship between AI-driven investments and digital assets remains underexplored (Salah et al., 2019). Third, most studies focus on Bitcoin and major cryptocurrencies, with insufficient attention to the expanding DeFi ecosystem and NFT markets (Chohan, 2021). This study addresses these gaps by examining Clean Energy and AI Robotics indices alongside diverse NFT and DeFi tokens across three distinct geopolitical crises using multi-scale wavelet analysis.

## 3. Methodology

This section describes the methodology used to analyze the pattern of NFTs and DeFi with Carbon ETFs returns. The study uses a set of proxy tokens and funds to represent three emerging market segments NFTs, DeFi, and carbon/green energy investments over the period from January 1, 2020, to April 26, 2025. The NFT/digital asset basket (DAI, AAVE, Synthetix, Maker, Chainlink) demonstrate the development of the decentralized art, and collectibles, depending on their demand in the market, the use of technology, and the state of the economy. Tokens like, ENJ, Tezos, Decentraland, Chiliz, THETA, SUPERf, represent the broader DeFi/blockchain ecosystem basket, capturing the performance of decentralized financial platforms and blockchain technologies. The AI/clean energy segment is captured via funds/ETFs such as Global Clean Energy Indexed, and AI Robotics Indexed, tracking investments in renewable energy and technological markets, reflecting the impact of environmental policies, geopolitical factors, and the increasing focus on sustainability. Key events during the sample period include the COVID-19 pandemic (2020), the Russia-Ukraine conflict (2022) and Iran-Israel Conflict (2024). All data is sourced from Bloomberg.

The time series is decomposed into time-frequency space with Continuous Wavelet Transform (CWT) and the best time-frequency localization is provided by the Morlet wavelet with a parameter of $\omega_0 = 6$. The CWT of a time series (x(t)) is defined well as:

$$W_x(s,) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-u}{s}\right) dt \tag{1}$$

Where $W_x(u, s)$ is the wavelet transform coefficient, u is the time position (translation parameter) s is the scale parameter (inversely related to frequency), $\psi(t)$ is the mother wavelet function $\psi^*$ denotes the complex conjugate of the wavelet $\frac{1}{\sqrt{s}}$ is the normalization factor. Morlet Wavelet (used in this study) Parameter Where $\omega_0 = 6$ provides optimal balance between time and frequency localization (Torrence & Compo, 1998)

Further, Wavelet Coherence (WTC) quantifies the localized correlation between two time series, providing insights into their co-movement across different scales and time periods. The squared wavelet coherence is computed as:

$$R_{xy}^2(u, s) = \frac{\left|S\left(s^{-1}W_{xy}(u,s)\right)\right|^2}{S(s^{-1}|W_x(u,s)|^2)\cdot S\left(s^{-1}|W_y(u,s)|^2\right)} \tag{2}$$

Here, $W_x(u,s)$ and $W_y(u,s)$ are the wavelet transforms of the respective series, and $W_{xy}(u,s) = W_x(u,s)W_y^*(u,s)$ is the cross-wavelet transform. The coherence value ranges from 0 to 1, where values closer to 1 indicate strong correlation. Phase arrows in the coherence plots indicate lead-lag relationships.
In order to isolate the true bilateral relationship between two variables, Partial Wavelet Coherence (PWC) is introduced to reverse the effect of a third variable (z(t)). Squared partial wavelet coherence is represented as:

$$R^2_{xy|z}(u,s)=\frac{\left|R_{xy}(u,s)-R_{xz}(u,s)\cdot R_{yz}(u,s)\right|^2}{(1-|R_{xz}(u,s)|^2)\left(1-\left|R_{yz}(u,s)\right|^2\right)} \tag{3}$$

Where $R_{xy}(u,s)$, $R_{xz}(u,s)$, and $R_{yz}(u,s)$ represent the complex-valued wavelet coherence between each pair of variables.
Further, Wavelet Correlation (WCor) is calculated across diverse scales, explaining how correlations grow from short-term to long-term scales. The WCor at a explicit scale S is considered as:

$$\mathrm{WCor}_{XY}(s) = \frac{\sum_t W_X(s,t)W_Y(s,t)}{\sqrt{\sum_t W_X^2(s,t)+\sum_t W_Y^2(s,t)}} \tag{4}$$

In this formula, the numerator $\sum_t W_X(s,t)W_Y(s,t)$ represents the joint fluctuations of the series X and Y at scale S. while the denominator normalizes these fluctuations by the individual energies of each time series $\sum_t W_X(s,t)$ and $W_Y(s,t)$ at scale sss. This normalization ensures that the wavelet correlation remains within the range $[-1,1]$ making it interpretable as the strong point of the association amid the two-time series at diverse scales. A value near 1 means that there is a strong positive relationship whereas a value near -1 means that there is a strong negative relationship. A value close to 0 indicates low or no correlation.

# 4. Result Analysis and Interpretation

## 4.1. Data analysis

The descriptive results show clear differences between Clean Energy, the AI Index, and NFT–DeFi coins. Clean Energy (0.0008) and the AI Index (0.0003) record positive mean returns, whereas most digital assets such as AAVE (–0.0053), Decentraland (–0.0016), THETA (–0.0018), Chainlink (–0.0014), and Chiliz (–0.0014) exhibit negative average returns, indicating weaker performance of NFTs and DeFi coins during the sample period. Volatility is substantially higher for digital assets, with AAVE showing the highest variance (0.0167), compared to much lower variance in Clean Energy (0.0004) and the AI Index (0.0002), confirming the high-risk nature of crypto assets. Skewness results reveal strong asymmetry, particularly for AAVE (–22.4057), while DAI (1.1724) and Maker (1.0492) show positive skewness. Clean Energy and the AI Index display near-symmetric distributions. Excess kurtosis values are extremely high for digital assets, especially AAVE (773.2721) and DAI (62.2698), indicating heavy tails and frequent extreme price movements. Although lower, Clean Energy (5.8004) and the AI Index (5.3024) also show leptokurtic behavior. The Jarque–Bera statistics strongly reject normality for all series. ERS values close to unity indicate strong persistence, while significant $Q_{(20)}$ and $Q^2_{(20)}$ statistics confirm serial correlation and volatility clustering. Overall, the results demonstrate that NFT and DeFi coins are more volatile, asymmetric, and fat-tailed than Clean Energy and the AI Index, justifying the use of wavelet coherence to analyze their dynamic interdependence.

**Table 1:** Descriptive Statistics Analysis

| Variable | Mean | Variance | Skewness | Ex_Kurtosis | JB | ERS | Q_20 | Q2_20 |
|---|---|---|---|---|---|---|---|---|
| DAI | 0.0001 | 0 | 1.1724 | 62.2698 | 295594.955 | 1 | 494.6429 | 1424.6976 |
| AAVE | -0.0053 | 0.0167 | -22.4057 | 773.2721 | 45671786.7 | 0.9995 | 19.3238 | 0.0164 |
| Synthetix | -0.0003 | 0.0045 | 0.1429 | 5.0731 | 1965.3699 | 1 | 46.6588 | 123.562 |
| Maker | -0.0007 | 0.0034 | 1.0492 | 39.3818 | 118399.736 | 1 | 66.1996 | 74.6982 |
| Chainklink | -0.0014 | 0.0034 | 0.8724 | 11.7813 | 10797.8445 | 1 | 46.6821 | 109.6164 |
| ENJ Coin | -0.0004 | 0.0049 | 0.0497 | 8.9704 | 6126.3189 | 0.9997 | 51.9204 | 320.2095 |
| Decentraland | -0.0016 | 0.0047 | -1.3967 | 28.6266 | 62976.9302 | 1 | 23.2916 | 104.572 |
| Chiliz | -0.0014 | 0.0046 | -0.2311 | 20.9462 | 33415.5526 | 1 | 38.0403 | 223.1978 |
| THETA | -0.0018 | 0.004 | 0.808 | 9.9334 | 7710.2704 | 1 | 42.6346 | 75.5489 |
| SUPERf | -0.0002 | 0.004 | -0.8249 | 34.0129 | 88274.4844 | 1 | 112.9698 | 216.3747 |
| Clean Energy | 0.0008 | 0.0004 | 0.0588 | 5.8004 | 2562.2834 | 1 | 364.7893 | 1818.4415 |
| Ai Index | 0.0003 | 0.0002 | -0.128 | 5.3024 | 2145.2877 | 1 | 378.5583 | 1719.3267 |

## 4.2. Wavelet coherence results

### 4.2.1. Wavelet coherence analysis of clean energy with NFTs and DeFi coins

The dynamic interactions between Clean Energy indices and selected NFTs and DeFi tokens were analysed using wavelet coherence over three distinct geopolitical and global event periods: the COVID-19 pandemic (January 2020–April 2021), the Russia-Ukraine war (February 2022–December 2022), and the Iran-Israel conflict (October 2023–June 2024). The wavelet coherence method allows the investigation of co-movements between time series across both time and frequency domains, providing insights into short-term, medium-term, and long-term relationships between Clean Energy and digital assets.
During the COVID-19 Pandemic period (Jan 2020–Apr 2021, 1–480), short-term coherence was observed prominently between Clean Energy and Synthetix, Decentraland, SUPERf, and DAI. This indicates that the immediate, high-frequency interactions between Clean Energy markets and these tokens were significant, potentially reflecting rapid market responses to pandemic-driven shocks such as global lockdowns, stimulus measures, and fluctuating investor sentiment. Medium-term coherence was identified for Theta, Chilliz, and ENJ Coin. This suggests that these tokens exhibited stronger co-movement with Clean Energy indices over slightly longer horizons, likely reflecting investor perception of sustained opportunities or risk-adjusted responses to sectoral developments during the pandemic. Importantly, no long-term coherence was detected for any of the analyzed tokens during this period, indicating the absence of sustained interdependence between Clean Energy and NFTs or DeFi markets over extended periods during the early phase of the pandemic.

The outbreak of the Russia-Ukraine War (Feb 2022–Dec 2022, 764–1036), significantly altered global energy markets, creating volatility that extended to digital assets. In this period, short-term coherence between Clean Energy and Synthetix, Chainlink, Theta, SUPERf, and ENJ Coin was evident. This implies that immediate market responses to the geopolitical crisis were synchronized, potentially due to energy supply concerns, geopolitical risk hedging, and the reallocation of speculative capital toward digital assets. Medium-term coherence was observed for Chainlink, Chilliz, and SUPERf, suggesting a moderately sustained relationship with Clean Energy performance over intermediate horizons. Notably, AAVE demonstrated long-term coherence with Clean Energy during this period, indicating a more persistent linkage. This long-term coherence may reflect structural factors, such as the growing integration of DeFi protocols in energy-related financing and hedging mechanisms, or sustained investor confidence in AAVE as a stable DeFi instrument during times of global crisis.

During the Iran-Israel (Oct 2023–Jun 2024, 1371–1580), conflict, the wavelet coherence analysis revealed a more complex multi-scale interaction between Clean Energy and digital assets. Short-term coherence was present for Chilliz, Decentraland, ENJ Coin, Theta, Synthetix, and Chainlink, indicating that these tokens responded rapidly to geopolitical shocks affecting global energy markets. Medium-term coherence was observed for Maker, Decentraland, and AAVE, suggesting an intermediate, sustained co-movement between Clean Energy indices and these selected digital assets. Interestingly, a broader set of tokens, including ENJ Coin, Theta, Synthetix, Maker, and SUPERf, exhibited long-term coherence with Clean Energy. This long-term linkage may reflect structural alignment between the energy transition narratives and certain DeFi/NFT projects that have gained investor confidence over prolonged periods. For example, these tokens may have been perceived as hedges against traditional energy market risks or as alternative investment vehicles aligned with sustainability-oriented capital flows.

Across all three periods, a clear temporal differentiation in coherence patterns emerges. Short-term coherence consistently indicates that NFTs and DeFi tokens react promptly to exogenous shocks in Clean Energy markets, likely reflecting investor sentiment and high-frequency trading dynamics. Medium-term coherence reflects more sustained alignment, possibly driven by adaptive investment strategies and sectoral interdependence. Long-term coherence appears selectively in the Russia-Ukraine and Iran-Israel periods, suggesting that structural factors, market integration, and evolving narratives around energy transition and digital finance drive extended interdependence. Overall, these results highlight the evolving and multi-scale relationship between Clean Energy markets and NFTs/DeFi coins. While short-term interactions dominate during sudden shocks, long-term linkages emerge during sustained geopolitical crises, indicating a potential structural convergence between sustainable energy investments and the growing digital asset ecosystem. This underscores the importance of considering multiple time horizons when analyzing the co-movement of emerging financial technologies with sectoral markets like Clean Energy.

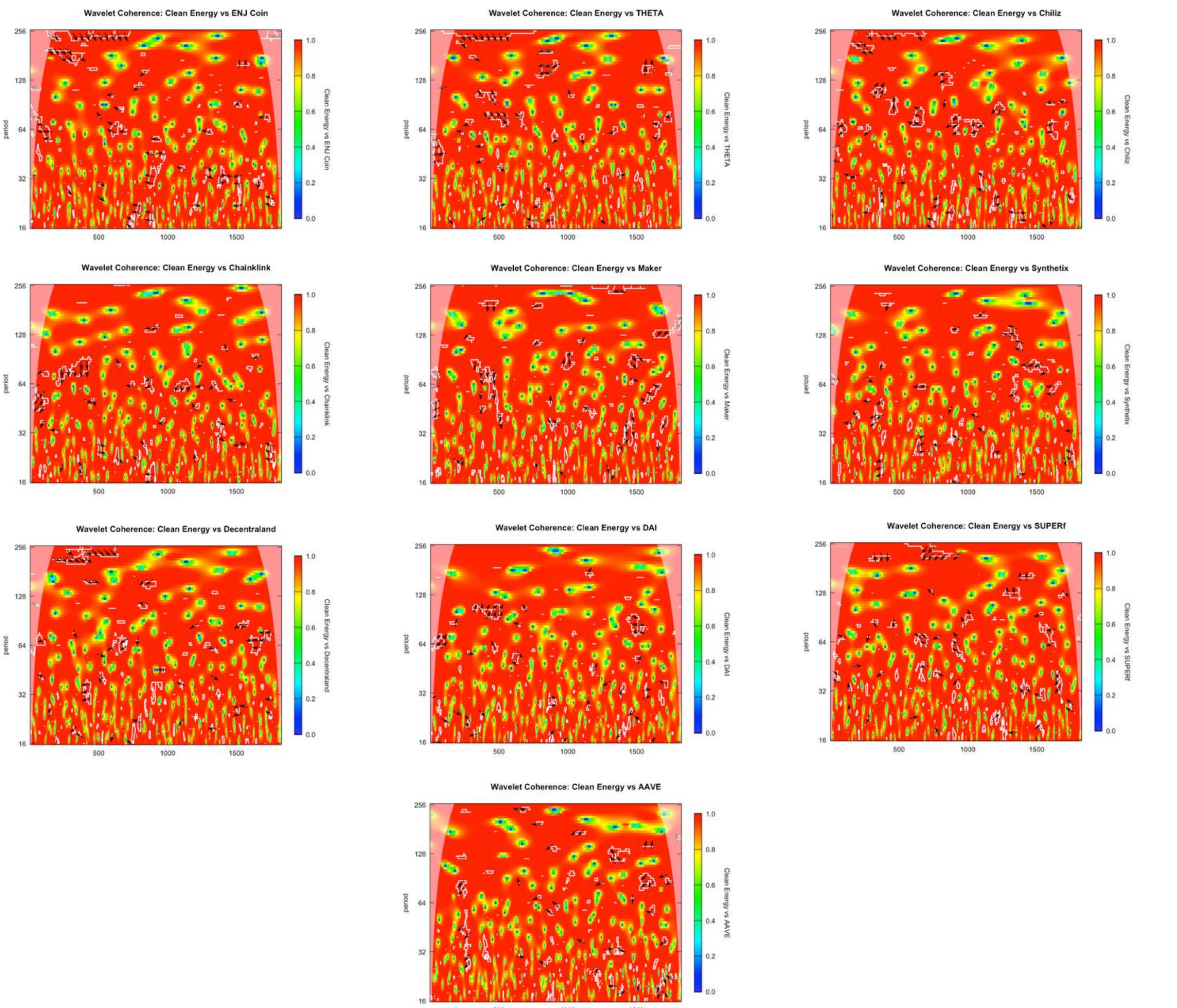


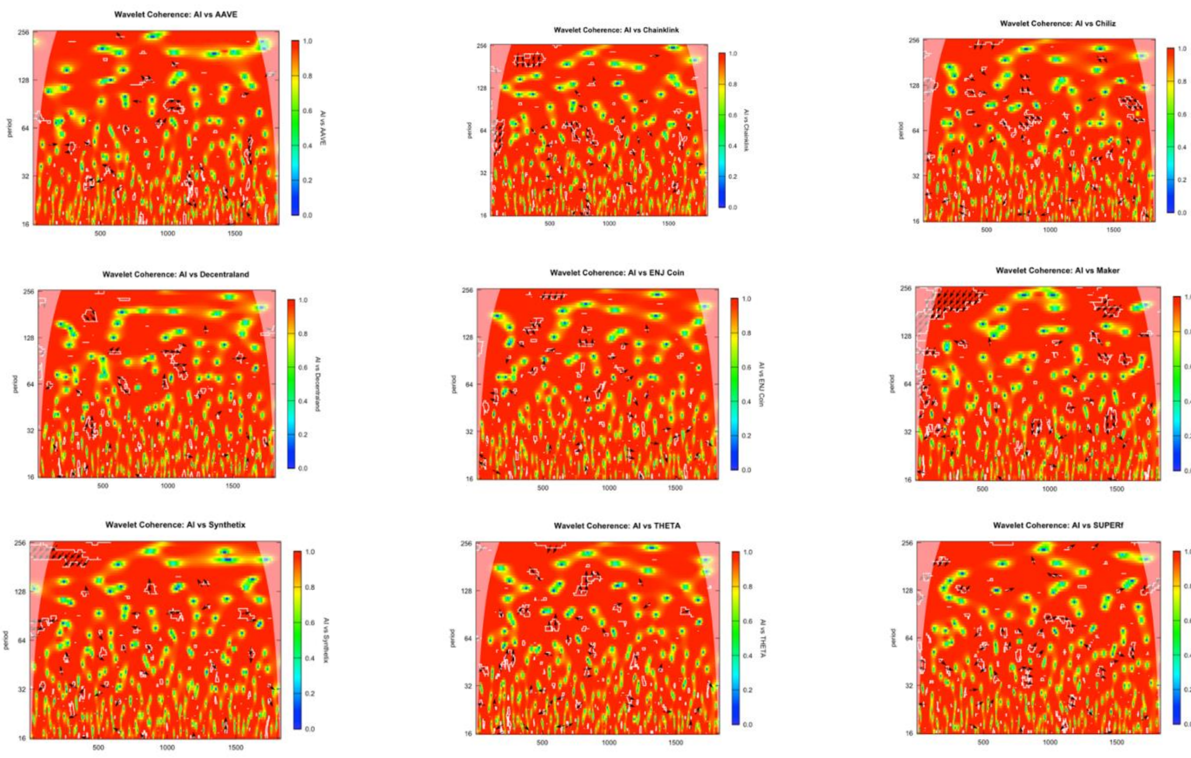

**Fig. 1:** Wavelet Coherence Analysis of Clean Energy with NFTs and DeFi Coins.

### 4.2.2. Wavelet coherence analysis of AI robotics index and selected NFT and DeFi coins

To examine the dynamic interdependence between AI Robotics Index and selected NFT and DeFi coins, wavelet coherence analysis was employed across three major global event periods: COVID-19, the Russia-Ukraine war, and the Iran-Israel conflict. This method captures time–frequency co-movements, allowing the identification of short-term, medium-term, and long-term coherence patterns. During the COVID-19 crisis (Jan 2020 – Apr 2021; Observations 1–480), short-term coherence between Clean Energy and SUPERf, Theta, Chilliz, Decentraland, ENJ Coin, Synthetix, and AAVE was dominant. This indicates that these digital assets reacted quickly and synchronously with Clean Energy market fluctuations. The high-frequency coherence reflects heightened uncertainty, speculative trading behavior, and rapid information transmission during the pandemic. Investors appeared to rebalance portfolios frequently in response to lockdown policies, stimulus measures, and shifting expectations about sustainable energy investments. DAI exhibited medium-term coherence with Clean Energy, suggesting a relatively stable but moderate co-movement over intermediate horizons. As a stablecoin, DAI's coherence may reflect its role as a liquidity and hedging instrument rather than a speculative asset. Importantly, no long-term coherence was observed for any NFT or DeFi coin during this period, implying that the pandemic shock did not create persistent structural linkages between Clean Energy and digital assets. Instead, the relationship was largely transitory and driven by short-term market sentiment. Overall, the COVID-19 period highlights that Clean Energy and NFT/DeFi markets were primarily connected through short-lived reactions rather than enduring financial integration.

The Russia-Ukraine war (Feb 2022 – Dec 2022; Observations 764–1036), significantly disrupted global energy markets, which is clearly reflected in stronger and more persistent coherence patterns. Short-term coherence was observed between Clean Energy and DAI, SUPERf, Theta, Chilliz, Decentraland, and Chainlink, indicating immediate market reactions to geopolitical risk, energy supply concerns, and volatility spillovers. Medium-term coherence expanded substantially, involving SUPERf, Theta, Chilliz, Decentraland, ENJ Coin, Synthetix, Chainlink, and Maker. This suggests that during this period, the relationship between Clean Energy and digital assets became more sustained, possibly due to investors viewing DeFi and NFT assets as alternative investment channels amid traditional energy market instability. Notably, AAVE and Theta demonstrated long-term coherence with Clean Energy. This long-term interdependence indicates a structural linkage rather than a purely speculative one. AAVE's role as a major DeFi lending platform and Theta's blockchain infrastructure relevance may have strengthened investor confidence in their long-run association with sustainable and technology-driven investment narratives. Compared to the COVID-19 period, the Russia-Ukraine conflict marks a transition from short-term speculative connections to deeper, more persistent integration between Clean Energy and selected DeFi assets.

During the Iran-Israel (Oct 2023 – Jun 2024; Observations 1371–1580), conflict, the coherence structure shifted again. Short-term coherence was observed between Clean Energy and AAVE, Theta, Chilliz, Decentraland, and ENJ Coin, indicating renewed immediate sensitivity of these digital assets to geopolitical energy-related shocks. Medium-term coherence was limited to Maker and Synthetix, suggesting that only a few DeFi platforms maintained sustained intermediate-horizon alignment with Clean Energy movements. This may reflect selective investor trust in governance-driven and protocol-based DeFi projects during periods of geopolitical uncertainty. Interestingly, only SUPERf exhibited long-term coherence with Clean Energy during this period. This indicates that SUPERf developed a unique persistent relationship with Clean Energy markets, possibly due to its evolving utility, investor perception, or alignment with long-term technological and sustainability narratives. Compared with the Russia-Ukraine period, the Iran-Israel conflict shows a contraction in long-term coherence, implying that long-run integration between Clean Energy and most NFTs/DeFi coins weakened, while short-term speculative reactions remained dominant.



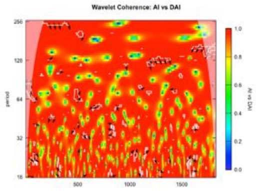



**Fig. 2:** Wavelet Coherence Plots of AI Robotics Index and Selected NFT and DeFi Coins

## 5. Conclusion

This study examined the dynamic interdependence between Clean Energy indices, AI Robotics Index, and selected NFT and DeFi tokens during three major geopolitical events: COVID-19 (January 2020–April 2021), Russia-Ukraine war (February 2022–December 2022), and Iran-Israel conflict (October 2023–June 2024) using wavelet coherence analysis. The descriptive statistics revealed fundamental differences between sustainable investments and digital assets. Clean Energy (0.0008) and AI Index (0.0003) demonstrated positive mean returns with low variance (0.0004 and 0.0002 respectively), while NFT and DeFi tokens showed negative average returns and substantially higher volatility, with AAVE exhibiting the highest variance (0.0167). Extreme kurtosis values, particularly for AAVE (773.2721) and DAI (62.2698), confirmed heavy-tailed distributions and frequent extreme price movements, consistent with Corbet et al. (2018) and Conlon et al. (2020) regarding cryptocurrency market volatility during crisis periods.

The wavelet coherence analysis revealed distinct temporal patterns across the three crisis periods. During COVID-19, short-term coherence dominated between Clean Energy and Synthetix, Decentraland, SUPERf, and DAI, while medium-term coherence appeared for Theta, Chilliz, and ENJ Coin. Notably, no long-term coherence emerged, indicating purely transitory relationships driven by speculative trading rather than structural integration, aligning with Goodell and Goutte (2021) and Conlon and McGee (2020). The Russia-Ukraine war marked a critical shift toward deeper market integration. Short-term coherence emerged with Synthetix, Chainlink, Theta, SUPERf, and ENJ Coin, while medium-term coherence expanded to include Chainlink, Chilliz, and SUPERf. Significantly, AAVE demonstrated long-term coherence with Clean Energy, suggesting structural linkages potentially reflecting DeFi's growing role in energy-related financing, consistent with Umar et al. (2022) and Ren and Lucey (2022). During the Iran-Israel conflict, coherence patterns became more complex and selective. Short-term coherence was observed with Chilliz, Decentraland, ENJ Coin, Theta, Synthetix, and Chainlink, while medium-term coherence contracted to Maker, Decentraland, and AAVE. Long-term coherence expanded significantly to include ENJ Coin, Theta, Synthetix, Maker, and SUPERf, indicating structural convergence between energy transition narratives and selected DeFi/NFT projects, supporting findings by Mensi et al. (2023) and Karim et al. (2022). The AI Robotics Index exhibited similar but distinct patterns. During COVID-19, short-term coherence dominated with SUPERf, Theta, Chilliz, Decentraland, ENJ Coin, Synthetix, and AAVE, while DAI showed medium-term coherence. The Russia-Ukraine war strengthened integration substantially, with medium-term coherence expanding to SUPERf, Theta, Chilliz, Decentraland, ENJ Coin, Synthetix, Chainlink, and Maker, while AAVE and Theta achieved long-term coherence. During the Iran-Israel conflict, long-term coherence contracted to only SUPERf, suggesting selective structural alignment.

These findings demonstrate that NFT/DeFi-sustainable investment relationships are crisis-dependent, scale-specific, and selectively integrative. While short-term speculative connections persist across all periods, medium-term and long-term structural linkages emerge during sustained geopolitical crises, indicating gradual integration of digital assets with sustainable investment narratives, consistent with Naeem et al. (2021) and Shahzad et al. (2021).

## 6. Recommendations

### 6.1. For investors

Adopt dynamic, time-horizon-specific allocation strategies recognizing that short-term coherence indicates speculative co-movement, while selective long-term coherence with AAVE, Theta, and SUPERf offers potential diversification benefits during sustained crises. Implement rigorous risk management given extreme volatility and fat-tailed distributions (Bouri et al., 2021; Kristoufek, 2020).

For Policymakers: Develop monitoring frameworks for systemic risk transmission between energy markets and digital assets, particularly during geopolitical crises. Establish clear ESG taxonomies for digital assets to reduce greenwashing and support market maturation. Coordinate energy security policies with financial stability considerations to mitigate spillover effects.

### 6.2. For future research

Investigate directional causality using wavelet-based Granger methods, examine asset-specific characteristics driving selective coherence patterns, analyze differential relationships between AI and Clean Energy indices with digital assets, and explore macroeconomic factors determining whether speculative connections evolve into structural linkages (Mensi et al., 2023; Naeem et al., 2022).

## Acknowledgments

We are grateful to the anonymous reviewers for their valuable suggestions and comments on our manuscript.

## Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

## Declaration of Conflicting Interests

The authors declared no potential conflicts

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