

Assessing the linkage of energy cryptocurrency with clean and dirty energy markets

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ABSTRACT

The primary objective of this study is to explore the dynamic connectedness that exists among energy cryptocurrencies, clean energy metals, and conventional dirty energies. Moreover, we aim to investigate the time-varying effects of uncertainties on the connectedness that exists among these asset classes. We uncover heterogeneous reactions among energy cryptocurrencies and other assets. Common positive co-movement clustering is revealed mostly during the periods of the cryptocurrency crash and boom in 2018 and 2020, and the oil market crash, respectively. However, a constant weak and strong co-movement over shorter and longer horizons is observed throughout the sample period for all pairs analysed, with varying outcomes for longer horizons. Combining VIX and US EPU as measures of financial and economic uncertainty, we contend that uncertainty significantly affects energy cryptocurrencies, clean and dirty energies, and clean energy metals, with relatively weak impacts or influences observed for longer investment horizons. Our findings are highly beneficial to cryptocurrency investors, alternative asset investors, and policy makers, especially during periods of market turmoil.

1. Introduction

In international finance, intermarket connectedness and dependence are crucial factors that provide valuable insights for fund managers and policymakers. However, with the increasing reliance on fossil-fuel based economies, the emission of climate risks has become a significant concern in recent years. To promote sustainability, the adoption of clean energy has emerged as a promising approach to combat the climate risks associated with conventional energy systems (Chen et al., 2022a). The surge in demand for clean energy has led to a corresponding increase in demand for clean energy metals, which are required to produce solar panels, batteries, and other related technologies (Shao and Zhang, 2020). In addition, a series of unanticipated events, such as the EU debt crisis, Chinese market crash, China-US trade war, Covid-19 pandemic, and ongoing Russian-Ukraine war, have drawn significant attention to uncertainty measures, as they have a significant impact on financial markets (Bashar et al., 2013, Guo et al., 2018, Mei et al., 2018).

Therefore, this study focuses on three key objectives: first, to perform a dynamic connectedness assessment among energy cryptocurrencies and energy sources, which are classified as clean and conventional dirty energies. Second, to examine the connectedness among energy cryptocurrencies and alternative energy metals. Finally, to investigate the time-varying impact of uncertainties on the pairwise connectedness among cryptocurrencies, energy sources, and energy metals.

Cryptocurrencies have garnered significant attention since their inception, and bitcoin, being the first of its kind, has been considered as an asset class (Krückeberg and Scholz, 2019). Theoretically, conventional energy sources and cryptocurrencies are strongly interconnected through raw material channels. Without energy inputs, high-performing computers and programming knowledge would be rendered useless. In this regard, (Cagli and Mandaci, 2023, Nham, 2022) have observed a significant degree of connectedness between the cryptocurrency and oil markets, while (Okorie and Lin, 2020) have found evidence of volatility spillovers from the oil market to the cryptocurrency market. However,

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(Zeng et al., 2020) have demonstrated a weaker connection between the two markets. During normal market conditions, bitcoin's interdependence from the conventional energy market is highly pronounced, but this relationship evaporates during a crisis (Attarzadeh and Balcilar, 2022). Similarly, apart from the Covid-19 period, (Hung, 2022, Jareño et al., 2021) have observed the weakest form of connectedness between the cryptocurrency and oil markets, with both markets showing high dependence during times of market turmoil.

Despite the popularity of conventional cryptocurrencies, particularly bitcoin, as an investment (Urquhart, 2016), concerns have been raised about their energy inefficiency resulting from their algorithmic complexity (Maras, 2014). Environmental agencies have criticized their excessive energy consumption, with studies showing that bitcoin's yearly energy consumption exceeds that of the entire Argentine economy (Attarzadeh and Balcilar, 2022). In response, several alternative environmentally sustainable cryptocurrencies have emerged, and recent literature has argued that different cryptocurrencies have varying ecological footprints (Schinckus et al., 2022). As of March 22nd, 2023, there are nearly 23,000 cryptocurrencies, with a cumulative value equivalent to nearly half of the GDP of the UK and India. Given the growing emphasis on climate change and measures for climate control in global summits such as United Nations Climate Change Conference (COP26) and the Paris Agreement, it is crucial to investigate sustainable cryptocurrencies and their linkages with energy sources.

For many decades, the dominance of fossil fuel-based economies has contributed to environmental degradation through the increasing production of carbon dioxide. However, with growing concerns about environmental protection, clean energy has emerged as an appealing investment avenue for investors (Mirza et al., 2023; Naeem et al., 2023a; Naeem et al., 2023b; Naeem et al., 2023d; Naeem et al., 2023e; Naeem et al., 2023f; Naeem et al., 2023h). In addition to promoting sustainability, clean energy's sudden shock-absorbing capacity has led to an increased preference among investors. For example, (Dawar et al., 2021, Pham, 2019) have analysed the nexus between oil and clean energy stock returns during both bear and bull market conditions and have found that clean energy stocks are less dependent on oil prices, with their returns reacting negatively to falling oil prices. However, recent studies have shown that clean energy stocks are no longer shock-resistant, as they have significant transmissions from uncertainties such as stock market volatility, oil market volatility, and economic policy uncertainty (Sadorsky, 2022; Naeem et al., 2023h).

A wealth of literature exists on conventional metals, such as gold and silver, which are known for their hedging benefits (Gustafsson et al., 2022). Typically, gold and silver are found to complement each other, providing a strong hedge against uncertainties (Bampinas and Panagiotidis, 2015; Cheng et al., 2022; Chiang, 2022). Similarly, there are significant studies available in oil and metal literature (Reboredo and Ugolini, 2016). Precious metals have shown empirical resilience against oil price fluctuation risks and have been used as a hedge against inflation risks. Previous research has explored the co-movements between oil prices and precious metal markets (Ahmed et al., 2022), while others have examined the impact of oil price fluctuations on precious metal dynamics (Das et al., 2022).

With the escalating demand for clean energy, attention towards clean energy metals has also heightened, given that the growth of clean energy is inextricably linked with the availability of raw materials such as Aluminium, Copper, Lithium, Magnesium, Cobalt, Zinc, Nickel, etc. Notable surges in clean energy metals have been observed following jumps in the oil market, as evidenced by (Liu et al., 2021). Furthermore, (Shao and Zhang, 2020) examined the impact of oil prices on clean energy metals and established a substantial effect of oil market on energy metals, which amplifies significantly with growing uncertainty levels, as affirmed by (Shao et al., 2021). Recent literature has explored the connection between oil prices and energy metals, with scholars such as (Ren et al., 2022, Shao et al., 2021) identifying significant effects of uncertainties on clean energy metals. While non-ferrous metals as a

whole may offer hedging benefits (Chen et al., 2022b), other energy metals have limited ability to hedge against downside risks in clean energy stock markets, as noted by (Erdoğan et al., 2022). Consequently, inconsistent findings exist in this domain.

In the early days, cryptocurrency was often dubbed as digital gold, prompting an extensive number of studies to investigate its potential as a hedging instrument for commodities and its ability to offer portfolio benefits during market turmoil (Naeem et al., 2021; Naeem et al., 2023g; Rehman et al., 2023). Previous research examining the relationship between cryptocurrencies and energy metals suggests that clean energy acts as a safe haven for traditional cryptocurrencies (Ren and Lucey, 2022), while (Huyen et al., 2023) contend that cryptocurrencies have spillover effects on both clean and dirty energy sources. Conversely, (Tiwari et al., 2024) argue that bitcoin is more vulnerable to market shocks. Therefore, in light of the aforementioned literature, there remains an unexplored area in the domain of cryptocurrency and clean energy, specifically in estimating the time and frequency connectedness between sustainable cryptocurrencies and clean and dirty energy, as well as clean energy metals. Additionally, the impact of uncertainty factors on the pairwise connectedness of cryptocurrency and the energy sector is not yet fully understood.

To fill this literature gap, we investigate the dynamic connectedness among energy cryptocurrencies with clean and dirty energy markets. We further investigate the influence of uncertainties over crypto-energy sources pairs showing heteroscedasticity mostly global environment dependent. We show different cryptocurrencies react differently with different energy sources over various investment horizons. Given the high vulnerability of cryptocurrency markets to market shocks (Tiwari et al., 2024), the cross-market connections between energy cryptocurrencies and both clean and dirty energy markets will be best observed when robust techniques that can accommodate momentary and swift market changes are applied. Hence, to achieve this we utilise the bivariate wavelet coherence technique, which presents a robust means by which we can account for the lead-lag dynamics ingrained in the connectedness among these markets in a time-frequency spectrum. Although we take cognisance of other transform tools, like the Fourier transform, numerous distinct features of the bivariate wavelet coherence analysis naturally present it as an essential econometric approach in our study. E.g., among others, the bivariate wavelet coherence approach is robust in capturing the momentary frequency changes and non-flat attributes of the signal (original series). By doing so, it can more accurately reflect the nature of the signal's characteristics. Furthermore, the bi-wavelet coherence metric has a higher adaptability, signal decomposition efficiency, and computational speed relative to other transformation methods. These unique traits explain the wavelet technique's popularity in the landscape of financial economics research (Agyei et al., 2023; Umar et al., 2023). As such, the wavelet-based time-frequency analysis resorted to in our analysis helps us comprehend the fractality of the market, which renders investor behaviour time- and horizon-dependent (Kumar and Raj, 2022). Overall, using the wavelet approach, we are able to capture swift comovement dynamics portrayed in energy cryptocurrencies' connections with clean and dirty energy markets.

Energy cryptocurrencies represent a novel and evolving segment within the broader cryptocurrency and digital financial landscape. These digital assets are intricately tied to energy production and consumption, aiming to revolutionize the way energy is traded and utilized. Their inclusion in our study is significant as they offer a glimpse into the intersection of finance and energy, potentially reshaping investment strategies and contributing to the transition towards cleaner energy sources. Clean energy markets are proxied by the WilderHill Clean Energy Index and Solar Energy Index. These indices capture the performance of companies involved in renewable energy sources. Investigating the relationship between clean energy and energy cryptocurrency holds significance as it allows us to explore the alignment of sustainable investments with digital financial markets. As societies

strive for reduced carbon footprints and sustainable energy practices, understanding how clean energy aligns with or diverges from digital financial markets can inform investment decisions and contribute to the development of environmentally conscious portfolios. Clean energy metals, including aluminium, copper, and nickel, plays significant role in underpinning the infrastructure of renewable energy technologies. These metals are essential components in technologies like solar panels, batteries, and wind turbines. By exploring the connectedness of clean energy metals with energy cryptocurrency, we gain insights into their portfolio diversification opportunities. Additionally, the analysis documents the level of integration between clean energy metals and energy cryptocurrency within the broader energy market. Understanding their interconnectedness aids investors in constructing well-rounded sustainable energy-related portfolios. Furthermore, the co-movement informs risk management strategies for both investors and policymakers, offering guidance on how these assets behave during different market conditions and contributing to informed decision-making. And finally, dirty energy, represented by crude oil and natural gas, constitutes traditional fossil fuels that have been central to global energy consumption for decades. Their inclusion in our study provides a comparative perspective, allowing us to contrast their behaviour with cleaner energy sources. Investigating the relationship between dirty energy with energy cryptocurrency offers insights into the ongoing debates surrounding energy transitions, environmental concerns, and the potential for diversification strategies that account for both traditional and alternative energy sources.

We commence our investigation by examining the dynamic co-movements among energy cryptocurrencies, clean and dirty energy sources, and clean energy metals. Our findings indicate that energy cryptocurrencies display heterogeneity concerning clean and dirty energy and clean energy metals. We observe a positive co-movement clustering during 2018 and 2020, reflecting the cryptocurrency crash and boom, as well as the oil market crash in both periods. However, we note a consistent weak and strong co-movement over shorter and longer horizons, respectively, throughout the sample period for all pairs examined, but varying outcomes are obtained for longer horizons.

Secondly, we examine the effect of uncertainties on the interconnection between cryptocurrencies and both energy sources and clean energy metals. Our results reveal that uncertainties have a significant impact on energy cryptocurrencies, as well as on clean and dirty energies and clean energy metals, although longer investment horizons are relatively less affected. When it comes to energy sources, we find that while both the US Economic Policy Uncertainty (EPU) and the Chicago Board Options Exchange's CBOE stock market volatility Index (VIX) have an influence, the VIX index holds a stronger position. Although solar investment is considered a safer option for investors during periods of high VIX, we find that during normal conditions, the US EPU affects both clean energy sources. Finally, we find that different cryptocurrency pairs react differently to various uncertainties and are dependent on the global financial market.

Our research explores the underexplored field of alternative cryptocurrencies, specifically energy cryptocurrency, which has emerged as a valuable portfolio diversifier and advocate for climate finance (Yousaf et al., 2022b). A better understanding of their connection with other clean and dirty energy assets can offer extensive financial opportunities for investors and policy avenues for policy makers. To this end, our results contribute to the existing understanding of the interactions within the domain of sustainable energy through cryptocurrencies, clean and dirty energy markets, and clean energy metals in at least 5 ways. First, the study addresses a critical gap in the literature by explaining the dynamic relationships between energy cryptocurrencies, clean and dirty energy sources, and clean energy metals. This comprehensive approach unveils the complex interconnections that underlie these diverse asset classes, uncovering their collective behaviour. Second, the study uncovers the heterogeneity and clustering patterns of energy cryptocurrencies concerning clean and dirty energy markets. This shows how

different cryptocurrencies respond to various energy sources, enhancing our understanding of market synchronization. The identification of positive co-movement clustering during specific periods, such as cryptocurrency crashes and oil market fluctuations, offers valuable insights into the interconnectedness of these markets during events of market turmoil.

Third, the analysis on the influence of uncertainties, particularly the US Economic Policy Uncertainty (EPU) and the Implied Stock Market Volatility (VIX) indices, on energy cryptocurrencies, energy sources, and clean energy metals demonstrates the interplay between financial market uncertainties and asset behaviours. These results on the influence of external factors are important for stakeholders, enabling them to anticipate and navigate potential market fluctuations more effectively. Fourth, the study's recognition of energy cryptocurrencies as valuable portfolio diversifiers and advocates for climate finance introduces novel avenues for financial opportunities and sustainable investment strategies. This insight holds significant potential for guiding investors and policymakers in harnessing the benefits of energy cryptocurrencies to create robust and well-balanced portfolios.

Finally, by considering energy cryptocurrencies, the study contributes to the emerging field of alternative asset research. This expansion of the research frontier opens up new avenues for understanding how innovative digital assets intersect with conventional energy markets, and their beneficial aspects. Thus, paving the way for future research and innovation in this evolving landscape.

The rest of the paper is sorted as follows: section 2 shows data, section 3 describes methodological procedures, section 4 discusses the results and section 5 outlines the concluding remarks.

2. Data

This study comprises of daily data from a broad range of energy sectors. Data for energy cryptocurrency include Powerledger (POWR), Grid Plus (GRID) and SunContract (SNC) which were sourced from <https://coinmarketcap.com/>. while data for all other variables were from DataStream. Apart from the significance in low energy consumption, the selection of cryptocurrencies is based on their relatedness with energies. The given three cryptocurrencies promote sustainability in the energy sector through net zero carbon energy and their trading.

We consider two clean energy indices: WilderHill clean energy index (WilderHill) and Ardour solar energy index (Solar) while dirty energy was proxied through Brent crude oil (Brent) and AMEX natural gas index (Gas). Even though we are aware of several clean energy indices, in this study, we follow the suggestion of (Nobletz, 2022) who claimed among various clean indices, WilderHill indices properly fulfilling the clean and sustainability specifications. Similarly, we consider Ardour solar index which is an equal weighted index and also due to their grater composition of solar related companies within the index. The index only considers firms with about two-third of their business activities and(or) revenues through solar activities. Hence, the index is assumed to reflect the majority of solar market. The selection of dirty energies emanates from the fact that, nearly 60% of the global energy demand is fulfilled through crude oil and gas (IEA, 2023). The Russian invasion largely affecting both energies and consequentially the daily energy production in major economies (Wolff, 2022) thus, affecting the overall chain of production and leading towards growing uncertainty. Finally, among clean energy metals we considered Aluminium, Copper and Nickel as proxies. This selection was due to their importance in the clean energy industry. According to the International Energy Agency (IEA), the selected metals are the highest used raw materials for most of the clean energy technologies.¹ Therefore, understanding their dynamics with

¹ For further details, follow <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/mineral-requirements-for-clean-energy-transitions>

Table 1

Variables with abbreviations used in this study.

Variable	Abbreviation
Powerledger (Cryptocurrency)	POWR
Grid Plus (Cryptocurrency)	GRID
SunContract (Cryptocurrency)	SNC
Brent crude oil (Dirty energy)	Brent
AMEX natural gas index (Dirty energy)	Gas
WilderHill clean energy index (Clean energy)	WilderHill
Ardour solar energy index (Clean energy)	Solar
Aluminium (Clean energy metal)	Aluminium
Copper (Clean energy metal)	Copper
Nickel (Clean energy metal)	Nickel

Table 2

Descriptive statistics.

	SNC	GRID	POWR	Gas	Brent	WILDERHILL	Solar	Nickel	Aluminium	Copper
Mean	−0.165%	−0.110%	−0.130%	0.002%	0.018%	0.043%	0.068%	0.064%	0.011%	0.019%
Maximum	89.70%	99.41%	47.17%	17.74%	41.20%	13.40%	87.13%	36.66%	8.34%	5.69%
Minimum	−49.87%	−125.56%	−70.03%	−20.82%	−64.37%	−16.24%	−84.06%	−33.36%	−12.95%	−6.85%
St. Dev.	8.44%	15.69%	8.01%	2.20%	3.75%	2.64%	11.70%	2.45%	1.53%	1.34%
Skewness	1.1503	−0.0594	−0.5300	−0.3929	−3.1141	−0.3164	−0.3877	0.7700	−0.4455	−0.3216
Kurtosis	18.243	8.396	9.389	11.119	84.856	3.706	21.760	64.538	7.078	2.243
Jarque-Bera	18,637.938	3886.895	4921.107	6848.891	399,070.036	779.180	26,133.906	229,735.721	2805.532	300.023
Observations	1324									

other assets would benefit investors largely. The metals are listed under London Metal Exchange and data were sourced from <https://www.westmetall.com/>. Considering the availability of data, our sample ranges from January 02, 2018, until January 25, 2023 using daily observations (see Table 1).²

Table 2 illustrates the descriptive statistics for the sample under investigation. Energy cryptocurrencies, on average, produced negative returns while the other assets generated positive returns, with Solar index surpassing all (0.068%), and Gas exhibiting the least return among them (0.002%), in contrast to the highest returns in cryptocurrency by GRID+ (−0.110%). Energy cryptocurrencies showed higher risks than most other assets considered in this study, ranging roughly 4–5 times higher, with POWR showing the lowest risk indicator (8.01%). Copper had the least risk indicator (1.34%), while Solar had the highest (11.70%), despite having the highest return among all. All the return series were negatively skewed, except for SNC and Nickel. With respect to Jarque-Bera test results, we observe significantly high values indicating that the variables in question deviate largely from a normal distribution. As our sample period covers multiple global periods of uncertainty where markets especially the cryptocurrency market experience substantial turbulence, which could be a plausible cause behind such high outcomes. Additionally, with the onset of Russian invasion, demand for renewable energy surged and consequently resulting in a ripple effect on the energy metal's market (Umar et al., 2022a). This may have further laid an impact behind these high numbers.

3. Methodology

3.1. Continuous wavelet coherence (CWT)

To identify the dynamic connectedness among the variables observed, the given study employs wavelet coherence which was originally introduced by (Torrence and Compo, 1998). The wavelet coherence is extremely powerful in identifying the coherence with time and frequency among two variables and has been used in recent cryptocurrency literatures as well (Dowling, 2022; Goodell and Goutte, 2021a;

Goodell and Goutte, 2021b; Umar et al., 2022b). Unlike other mathematical models, wavelet eliminates the non-stationarity within a given time series and hence captures continuous co-movements between two series decomposing valuable signals for investment decisions.

Using natural log returns for all variables, we define the Cross Wavelet Coherence (CWT) among two time series $a(t)$ and $b(t)$ through:

$$W_{ab}(x, y) = W_a(x, y)W_b(x, y), \quad (1)$$

In the equation above, $W_a(x, y)$ and $W_b(x, y)$ refers to the two individual continuous transformations at time series $a(t)$ and $b(t)$ with x and y representing time and scale respectively.

In order to capture the co-movement among two time series, the

wavelet coherence is therefore defined through:

$$R^2(x, y) = \frac{|S(s^{-1} W_{ab}(x, y))|^2}{S(s^{-1} |W_a(x, y)|^2)S(s^{-1} |W_b(x, y)|^2)}, \quad (2)$$

In the equation above, we define S as the smoothing operator and that our $R^2(x, y)$ representing wavelet squared coherence whose value ranges between [0 and 1] where values closer to 1 indicates higher co-movement among two series, and vice-versa. Higher co-movements reflect warmer (red) colours while lower co-movements reflect cooler (blue) colours.

Since the wavelet model follows squared process for its outcomes, therefore, understanding of negative co-movements requires additional steps. So, to understand the causal relationship between two series, phase differences are incorporated which are defined through:

$$\Phi_{ab}(x, y) = \tan^{-1} \left(\frac{\text{Im}\{S(s^{-1} W_{ab}(x, y))\}}{\text{Re}\{S(s^{-1} W_{ab}(x, y))\}} \right), \quad (3)$$

Im and Re represents for imaginary and real components respectively on the smoothed cross wavelet transform.

Phase difference arrows are interpreted using their directions. Positive (negative) co-movements are identified against arrow pointing right (left). Additionally, $\searrow$ and $\swarrow$ will refer for first variable leading the second, while with $\nearrow$ and $\nwarrow$ second variable leading (Goodell and Goutte, 2021a).

3.2. Partial wavelet coherence (PWC)

Wavelet coherence only identifies the co-movement among two variables in time and frequency which may not be always sufficient for investment decisions as external factors may play a role behind any co-movement. Thus, understanding the impact of possible external variable is equally important for strategic positions. Therefore, to understand the impact of any third party within the original wavelet coherence, we extend the continuous wavelet coherence to partial wavelet coherence through which third party impacts are controlled. In this study we consider two possible external factors (the US EPU and VIX) that may influence the co-movement among our original variables.

According to investor's behaviour theory, uncertainty and investor's risk aversion are positively aligned. In other words, uncertainties

² For full list of energy cryptocurrency, please visit: <https://cryptoslate.com/cryptos/energy/>

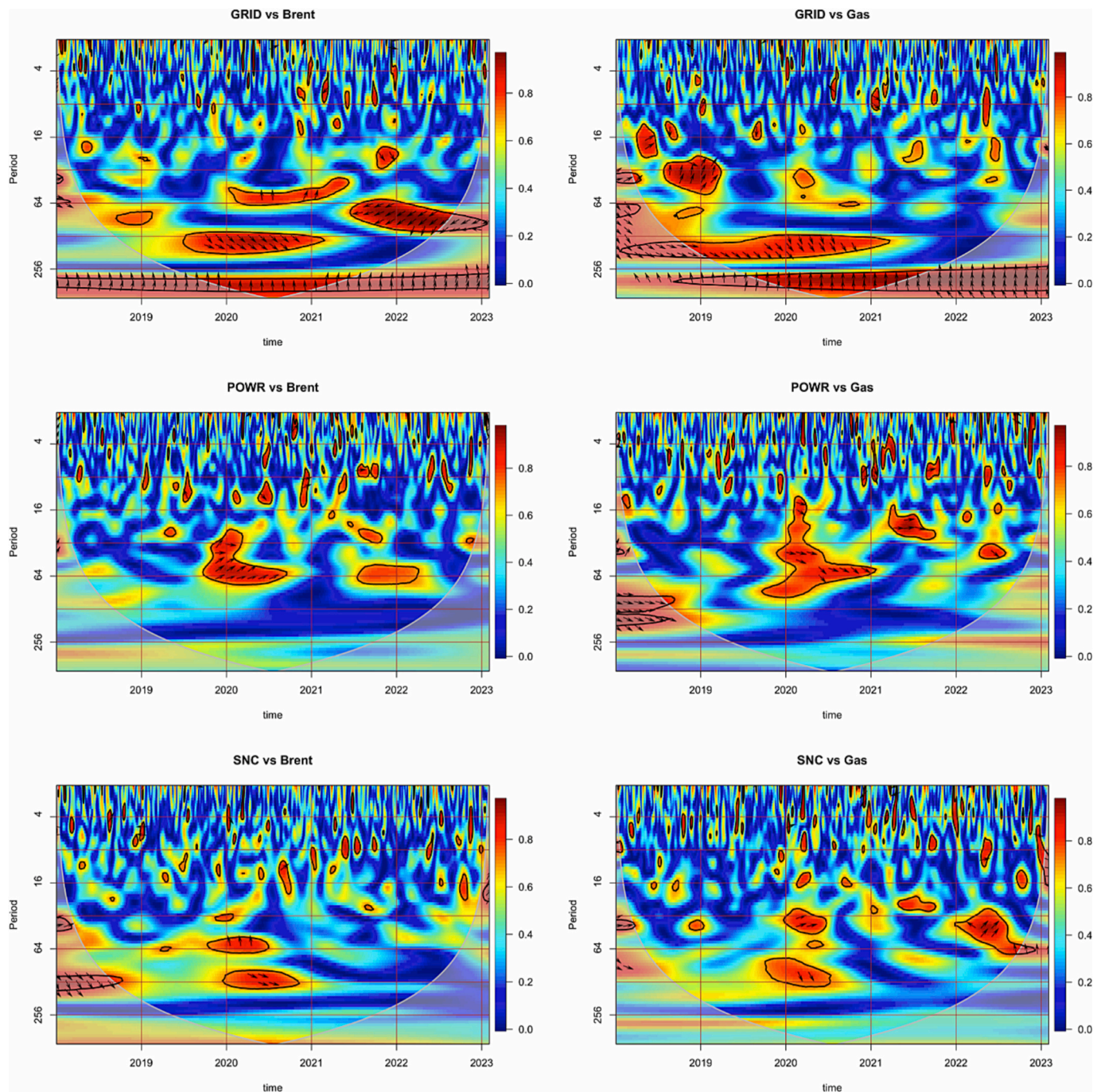


Fig. 1. Pairwise Wavelet Coherence between Energy cryptocurrency and Dirty energy sources.

significantly impact investors, making investors pessimistic of decisions and selecting assets due to concerns about future returns (Li et al., 2016). These uncertainties often arise from the broader economic and political environment, prompting policymakers to make adjustments to their policies. In recent decades, various events like the Global Financial Crisis (GFC), the Eurozone crisis, the China-US trade conflict, Brexit, the US presidential election, the COVID-19 pandemic, and the ongoing Russian conflict have all contributed to uncertainties surrounding policy and investment decisions. Given the current global financial market dynamics, the inclusion of the US Economic Policy Uncertainty (EPU) and the CBOE Volatility Index (VIX) as controlled variables emerges as a reasonable choice with distinct advantages. The selection of EPU and VIX proves especially beneficial due to their precise nature as indicators that gauge economic policy uncertainty and market volatility,

respectively. These variables cater specialized insights into the factors capable of wielding a profound influence on market dynamics and the behaviour of assets. EPU serves as a dependable indicator for measuring uncertainty stemming from governmental policies and economic conditions, while VIX quantifies investor's expectations regarding future market volatility. As such, these metrics encapsulate fundamental aspects that have the potential to significantly impact market sentiment, the decisions undertaken by investors, and the pricing of assets within the realm of financial markets.

Concerning with cryptocurrency and financial markets, existing literatures claim a negative impact of the US EPU on the relationship among cryptocurrency and the US financial markets (Mokni et al., 2020) whereas the Chinese EPU and cryptocurrency markets are positively interconnected, indicating cryptocurrency's role to play a safe haven

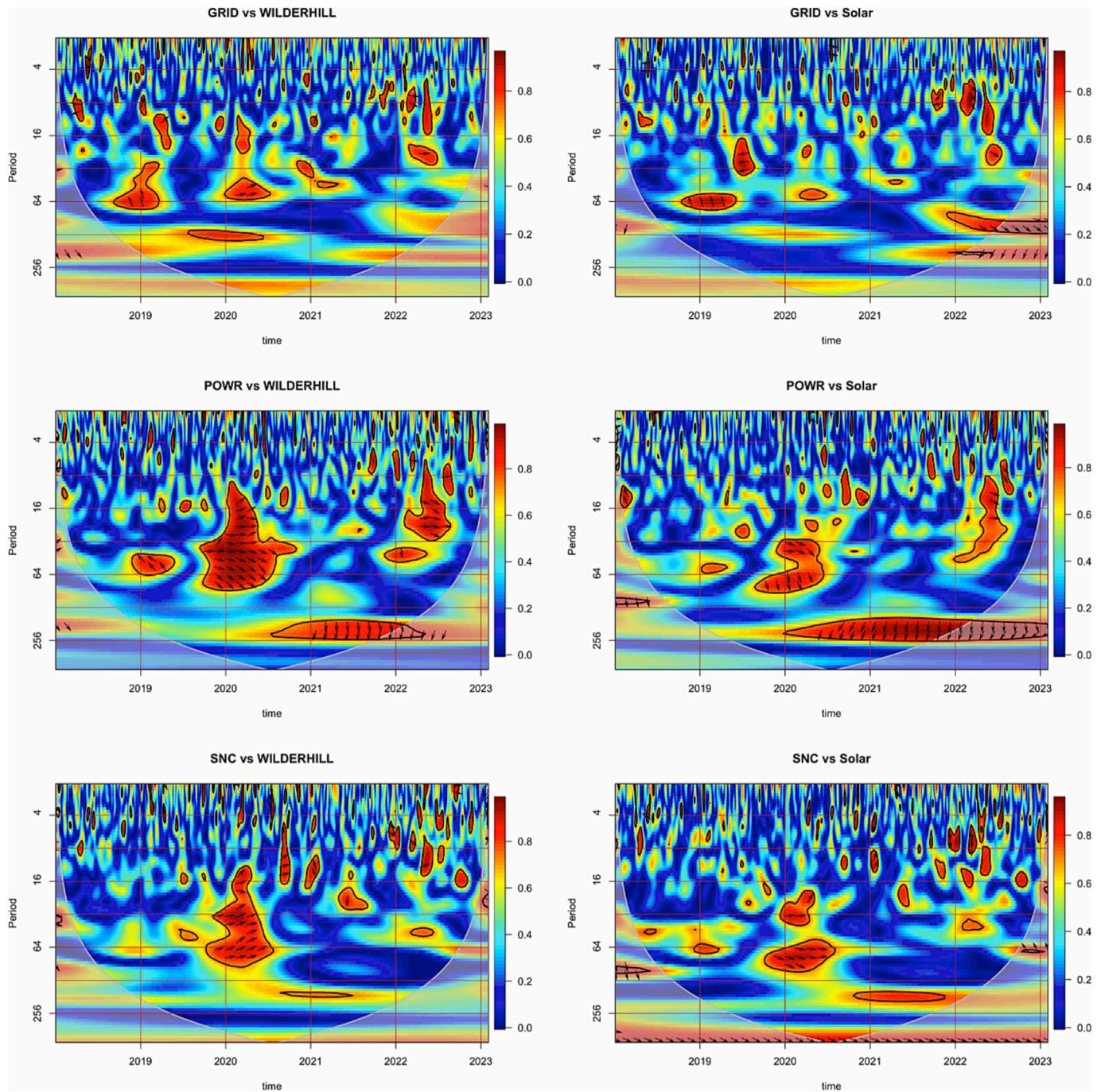


Fig. 2. Pairwise Wavelet Coherence between Energy cryptocurrency and clean energy sources.

attribute during heightened uncertainty (Mokni, 2021).

An inherent advantage of these external variables lies in their capacity for capturing the market's reactions to extreme events. Particularly noteworthy is the fact that surges in both EPU and VIX frequently align with major events, encompassing shifts in economic policies, geopolitical tensions, or substantial disruptions within the market. An exploration into the responses of cryptocurrencies and energy assets during these events can yield invaluable insights into the degree of their interdependence and whether they demonstrate parallel or contrasting reactions. Furthermore, it is worth recognizing that EPU and VIX can be construed as exogenous variables in your analytical framework, introducing external influences that possess the potential to exert a causal impact on the co-movements observed among the assets subject to investigation. This judiciously controlled approach aids in the

differentiation of the effects stemming from policy uncertainty and market volatility from the inherent dynamics of the assets themselves.

Conversely, considering a market index such as the S&P 500 as a controlled variable might not be as suitable because, even though the S&P 500 provides a broad overview of market conditions, it lacks the precision required to explore the specific nuances of economic policy uncertainty and market volatility. Additionally, incorporating the S&P 500 as a controlled variable could introduce endogeneity concerns, as existing studies claim the presence of influence from cryptocurrency to traditional financial markets (Corbet et al., 2020).

Upon eliminating third party $c(t)$, following (Aguar-Conraria and Soares, 2014) we estimate the partial wavelet coherence modified from the continuous wavelet coherence in (Eq. 2) of two time series $a(t)$ and $b(t)$ through:

$$R_{(abc)}^2(x, y) = \frac{|R_{ab}(x, y) - R_{ac}(x, y)R_{bc}(x, y)|^2}{|1 - (R_{ac}(x, y))^2||1 - R_{bc}(x, y)|^2} \quad (4)$$

In Eq. 4, we define, $R_{ac}(x, y)$ and $R_{bc}(x, y)$ as the wavelet coherence from time series $a(t)$ and $c(t)$ and, $b(t)$ and $c(t)$ respectively.

3.3. Vector wavelet coherence (VWC)

Here, the vector-wavelet methodology is employed as a robustness measure, gauging the overall coherence between the analysed systems across time and frequency domains. The methodological steps employed in this section follow the works of (Bossman and Agyei, 2022; Oygur and Unal, 2021). The vector wavelet coherence (VWC) methodology can be summarised as follows.

If b is the return series for a named cryptocurrency (SNC, GRID, or POWR) and the return series for the set of dirty energy (gas and Brent oil), clean energy (WilderHill and Solar), metals (nickel, aluminium and copper), or uncertainty measures (VIX and US EPU) are denoted as $a_1, a_2, a_3, \dots, a_n$, a squared n -dimensional VWC among them is formulated as $VR_{b(a_1, a_2, a_3, \dots, a_n)}^2$. This can be re-formulated as $VR_{a(q)}^2$ with dimensions³:

$$VR_{1(q)}^2 = 1 - \frac{C^d}{C_1^d}, \quad (5)$$

4. Results and discussions

4.1. Wavelet coherence

Assuming 2–16 days as ‘Short term’, 16–64 days as ‘Medium term’ and 64–256 days as ‘Long term’ investment horizons, following the definition provided in (Baruník and Křehlík, 2018), Fig. 1 plots the pairwise coherence between energy cryptocurrencies and conventional dirty energy indices. Mostly over investment horizons above 16 days, relatively higher levels of connectedness are observed for energy cryptocurrencies with Brent and Gas throughout the sample period. The higher co-movement between all the cryptocurrencies and Brent oil were observed prior to the Covid-19 pandemic, which was related to the crash in both crypto and oil markets in 2018. We observe large red islands (indicating high coherence) in all the pairs between late 2019 until late 2020 on medium and long horizons. These periods of high coherence between cryptocurrency and dirty energy indices correspond to the Covid-19 pandemic. The pandemic caused panic in the overall market which may have played a defining role behind this high coherence (Keane and Neal, 2021). As energy cryptocurrencies are PoS (Proof of Stake) based, thus independent from the influence of energy usage (Yousaf et al., 2022a). As a result, unlike conventional cryptocurrencies, (i.e., bitcoin that relies heavily on electricity, and electricity relies heavily on oil. Therefore, there is a direct linkage between oil and energy and thus conventional cryptocurrencies). In other words, there is less direct impact/influence from oil market to these PoS type cryptocurrencies. As a result, energy cryptocurrency and dirty energy markets are theoretically independent and should reflect inverse or weak coherence. But, during the early days of pandemic, energy cryptocurrency and oil and gas prices were symmetric in nature (i.e., both experienced downturns). Likewise, from mid-2020, both cryptocurrencies and oil and gas price start to go up. Therefore, this highlights the possibility of an external factor which might have also played a role behind this high level of coherence between the pairs (i.e., moving in the same direction as defined by the arrows pointing to right). Even though positive co-movement was noted, the causal influence revealed heterogeneous information (Bhuiyan et al., 2023). That is, during pre- and post-Covid (i.e., 2020 onwards), oil and gas led GRID+ for all horizons.

But, only during the pandemic, our observation shows GRID+ leading oil (for investment horizons 128 and above).⁴ Similarly, oil and gas in post-pandemic led SNC (between 4 and 16 days and 32–128 days). We also observed a bidirectional causality during the pandemic (i.e., SNC leading oil and gas only for beyond 128 days while lags when within 128 days are considered). For POWR pairs, our observation provided evidence for solo leadership by the oil index throughout the sample period. For gas, our finding show POWER leading the gas index for most of the periods assessed, with minor exceptions which we identify during late 2021 over 4–8 days horizon. This POWR-Brent connectedness may be of interest to cryptocurrency investors assuming oil as a signalling agent.

Notably, amidst the recent ‘energy game’ orchestrated by the Russian invasion (starting from February 2022 until present), while some moderate to high correlations are discernible for POWR and SNC pairs, an unequivocal negative correlation can be observed between GRID and Brent over investment horizons spanning 64–128 days, which effectively reduces to nearly zero for investment periods beyond 128 days. This negative co-movement strongly discourages investing or holding GRID+ along with Brent when the latter is surging. Furthermore, our phase difference arrow points towards Brent index leading GRID+ during the recent high co-movement phase, whereas GRID+ was leading Brent during the Covid pandemic.

Moving to the clean energy index (Fig. 2), the wavelet power spectrum exhibits the highest power for all pairs during the Covid-19 pandemic period, with few exceptions in GRID+ and Solar index that show moderate coherence (~ 0.6) [in defining the level of coherence, we followed the interpretation in (Bhuiyan et al., 2023, Husain et al., 2023, Vacha and Baruník, 2012) who identified $0 > \leq 0.4$ as weak, while $0.7 \geq$ has been identified as high (Aloui and Hkiri, 2014, Baruník and Vacha, 2015, Reboredo et al., 2017). Therefore, 0.5 and 0.6 are regarded as moderate in this study]. The coherence clustering is observed within 16–128 days during the pandemic with occasional instances between 8 and 16 days. In most cases, WilderHill leads cryptocurrencies, however, in contrast to (Yadav et al., 2023) which shows cryptocurrencies leading Solar index. Following the Russian invasion and the supply cut of oil and gas, coherence clustering restarts with mostly positive coherence being observed between GRID, POWR, and clean energy indices, where clean indices are leading (Anwer et al., 2023, Le, 2023). Notably, SNC demonstrates a unique outcome as the other two cryptocurrencies maintain moderate to high co-movements with both clean energy indices over long-range horizons (beyond 64 days), while SNC consistently maintains low coherence with both indices. This low coherence suggests the advantageous use of SNC for portfolio diversification alongside clean energies in times of rising uncertainty.

The interplay between energy cryptocurrencies and clean energy metals exhibits relatively similar individual characteristics. For example, the pairwise connectedness among POWR and SNC with other metals indicates relatively low coherence in both low and high investment horizons. However, for medium investment horizons, aside from GRID+, our coherence analysis reveals a higher degree of movement among the variables, indicating a position of financial benefit through the use (or non-use) of energy cryptocurrencies during periods of rising (or declining) clean energy metal markets. Regarding GRID+, we observe a transient negative co-movement with Aluminium during Covid-19, led by GRID+ (between 16 and 64 days horizon), but no further negative co-movements were detected thereafter. Moreover, we find that Aluminium and Nickel display a low frequency of connectedness with POWR and SNC over longer investment horizons (128 days and beyond), making them an ideal pair for investors seeking diversification in long-term investments.

³ Please, see Oygur and Unal (2020) and Bossman and Agyei (2022) for the full version of the VWC methodology.

⁴ please refer to the methodology section where we explained how are we going to interpret the lead and lag nature of assets using phase differential arrow.

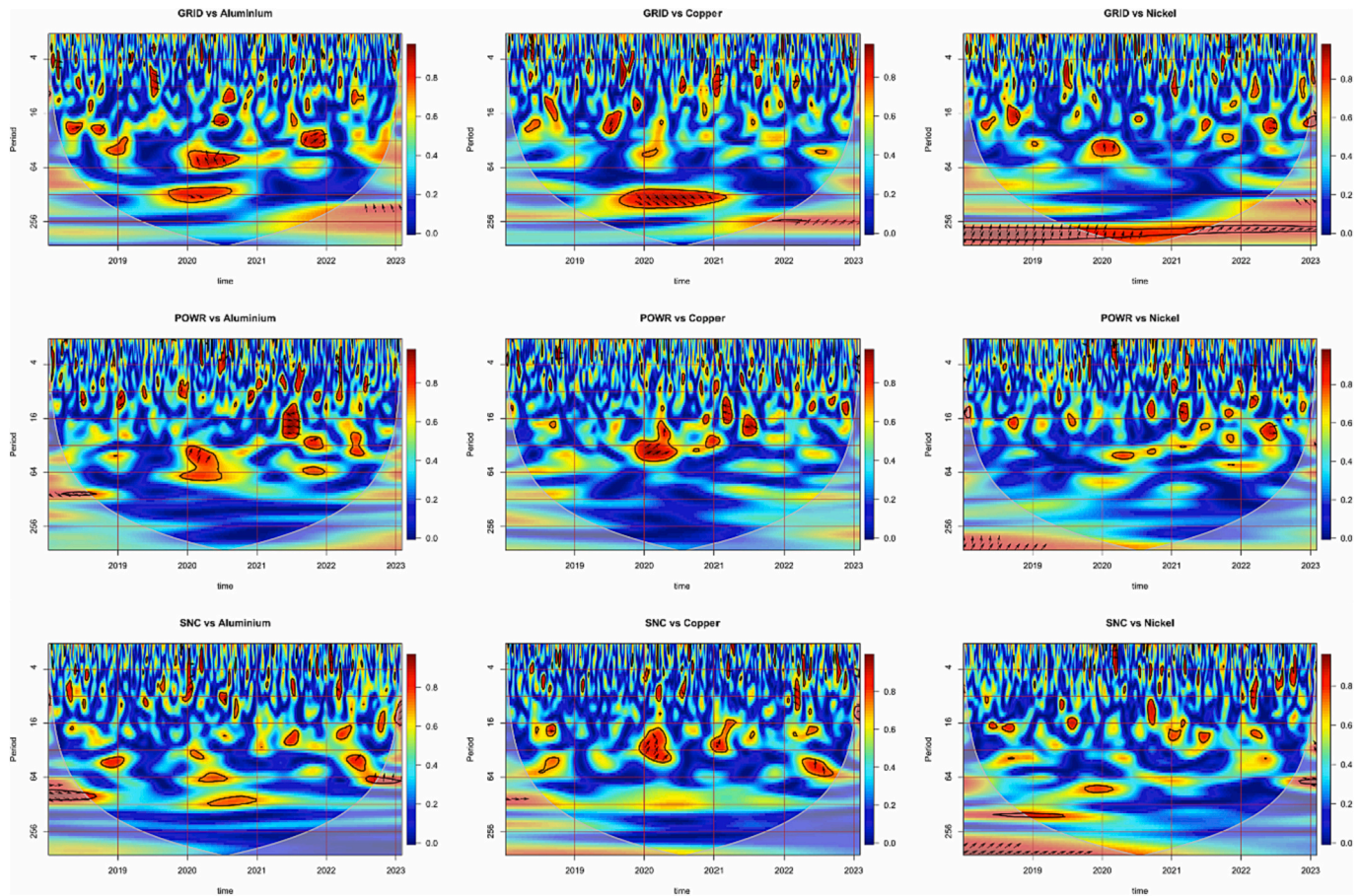


Fig. 3. Pairwise Wavelet Coherence between Energy cryptocurrency and clean energy metals.

4.2. Partial wavelet coherence

Regarding dirty energy sources, Figs. 4, 5, and 6 above demonstrate the partial wavelet coherence among GRID+, Power, and SNC, respectively, while isolating the effects of EPU and VIX. In comparison to the US EPU effect, the partial wavelet coherence reveals a relatively higher impact of VIX on the pairwise connectedness among GRID+, POWR, and SNC with Brent and Gas. After isolating both variables and comparing them with the original coherence in Fig. 1, a significant drop in connectedness among Brent and all the cryptocurrencies is evident, with an apparent VIX effect rather than the US EPU. Although there is a significant decline during Covid-19, the impact of the Russian war-induced energy price surge is continuous for oil pairs and relatively low for Gas pairs. Overall, Figs. 4–6 suggest the presence of a considerable impact from the US EPU and VIX over the pairwise connectedness where VIX holds the upper hand. We also find evidence of a greater impact of positive oil price shock over negative shock, especially for short and long-term investment horizons.

Figs. 7–9 above shows the partial wavelet coherence between energy cryptocurrencies and clean energy sources. With pairwise partial coherence among cryptocurrencies and clean energy sectors, we identify time dependent heterogeneous outcomes for different cryptocurrencies. For instance, generalising our outcomes, we find POWR (Fig. 8) is relatively isolated than the rest two (Fig. 7 and Fig. 9), signifying a low influence from both the US EPU and VIX for its pairwise partial connectedness with WilderHill index. For periods before 2020, significant influence from the US EPU and VIX is clear while during Covid and the recent energy crisis, compared to VIX effect, relative less influence from EPU is visible for horizons within 128 days. But, similar to others, when solar index is considered, compared with the US EPU, VIX impact

is well pronounced in the Fig. 8 under a given range. That is, the influence from VIX nearly zero or within a bearable range over shorter horizons (2–16 days) and 32–128 days, while no difference in effect (i.e., US EPU and VIX has no influence) is clear for beyond that range (128 days).

Upon observing the original coherence in Fig. 2 despite few islands of high coherency is present for GRID+ but are obviously limited compared to high co-movement clustering in POWR and SNC pairs. Based on the partial coherence in Fig. 7 and Fig. 9 while comparing with Fig. 2, an island with absolute coherence among GRID+, SNC and both the clean energy sources is observed when China-US trade war conflict arose leading to jump in the US EPU in mid-2018. Compared to the Solar index, pairs with WilderHill are found to be significant. Upon freezing the US EPU impacts, the islands are nearly vanished. While the influence of VIX is largely visible on both GRID+ and SNC for all the subsequent periods (i.e., 2019 and onwards), no significant impact of the US EPU has been spotted in any of the later periods on GRID+ pairs.

With SNC pair, even though we note a drop in coherence with both WilderHill and Solar indices, but the riddance as a result of VIX is eye-catching, for instance, almost zero coherence over 16–128 days in 2020 (Fig. 9) from a perfect correlation (Fig. 2). Even though the influence of VIX is more significant over WilderHill than Solar index but for both indices, the influence dims over horizons beyond 128 days.

Therefore, based on our results from isolating VIX and the US EPU impact over cryptocurrency and clean energy sector's connectedness, we summarise, the US EPU had greater impact over the pairs during pre-covid periods while VIX is on the lead from Covid times. Comparing both clean energy sources, we rehash the greater impact of uncertainty on WilderHill index than Solar index. Thus, given the recent conventional energy related uncertainty and that empirical strong nexus between oil

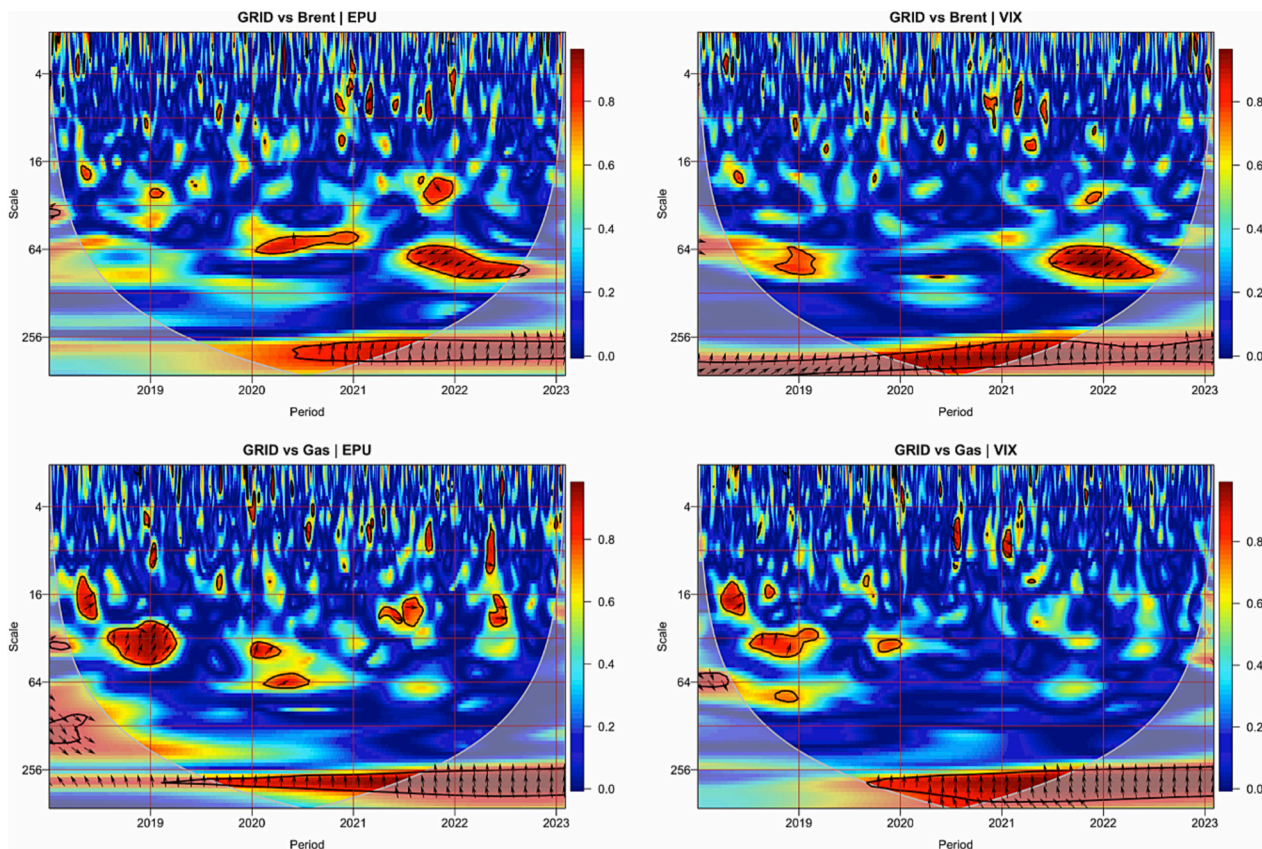


Fig. 4. Partial Wavelet Coherence between GRID+ and dirty energy.

and stock markets, we argue on notable comparative influence of VIX over the pairwise co-movement among energy cryptocurrencies and clean energy sources than the US EPU matching with (Roy et al., 2022; Sinha et al., 2022) finding greater influence of VIX than EPU over clean energy while contradicting (Fahmy, 2022) who noted weakest interrelation among VIX and solar energy index and, (Sadorsky, 2022) finding weak correlation among VIX and clean energy sources. Additionally, previous studies also show time-varying co-integration among uncertainties and Solar indices (Kocaarslan and Soytas, 2021; Szczygielski et al., 2022), and we note a near null impact of both factors on long run investments which contradicts with (Lo et al., 2022; Özdurak, 2021) who find presence of long run volatility spillover among uncertainty and clean energy.

Consistent with our previous findings on pairwise partial wavelet coherence among energy cryptocurrency and clean energy sources, the partial wavelet coherence for clean energy metals also presents Power as different than the rest two. Here, our results showing a relative higher influence from VIX to the pairwise coherence among Power and all the energy metals. Upon isolating EPU, the partial coherence in Fig. 11 barely differentiates from the original coherence in Fig. 3 which is evident through presence of red islands in both the figures with minimal variations in size. In contrast, the escape of red islands and the refinement of high connectedness areas to low connectedness through modification in wavelet coherency during 2020 evidences the significance of VIX in their connectedness. Having said that, it is also worthwhile to note the muted effect of both the US EPU and VIX during the recent year (from 2022).

As for GRID+ and SNC (Fig. 10 and Fig. 12) static behavioural pattern has been observed on the impact of the US EPU and VIX over them with minor varying outcomes, the partial coherence with GRID+ for instance (Fig. 10). Here, despite no visible differences (with both US EPU and VIX) are noted for pairs with GRID and Nickel, replacement of

red islands with green and light green islands during 2020 is clear GRID vs Aluminium and Copper respectively. But no variations are observed during the recent periods. For SNC (Fig. 12), no major variations are spotted when compared with the original (Fig. 3) indicating neutrality from both the US EPU and VIX over pairwise connectedness between SNC and clean energy metals.

In light of the above findings, we conclude that the impact of uncertainties on pairwise connectedness among energy cryptocurrencies and clean energy metals is inconsistent. Based on our analysis, we contend that uncertainty effects are perpetual for SunContract and energy metals, while the impact of the US EPU is relatively weaker compared to that of the VIX on pairwise connectedness among clean energy metals and Power, albeit conditional during global crises, negative oil price shocks or negative stock market shocks. With regards to GRID+ pairs, our analysis reveals a heteroscedastic response. For instance, although almost zero uncertainty effects were present during the start of the Russia war and energy price hikes, uncertainties had some influence over Aluminium and Copper during the initial covid period, but not over Nickel pairs. The muted behaviour of uncertainty factors in recent years can possibly be explained by the oil-cryptocurrency nexus and the oil-clean energy metals cointegration. While an empirically established inverse relationship exists between oil-metal connectedness, the growing attention towards clean energy has altered this relationship through the demand channel (i.e., increasing demand for clean energy metals). Therefore, an increase in oil price results in positive returns on clean energy metals as there is more reliance on clean energy.

Therefore, from an economic perspective on investment relating to energy cryptocurrency and other assets under observation, we argue that the observed patterns in coherence, particularly in light of economic uncertainty and market volatility, underscore a dynamic interplay that echoes the complexities of the global financial landscape.

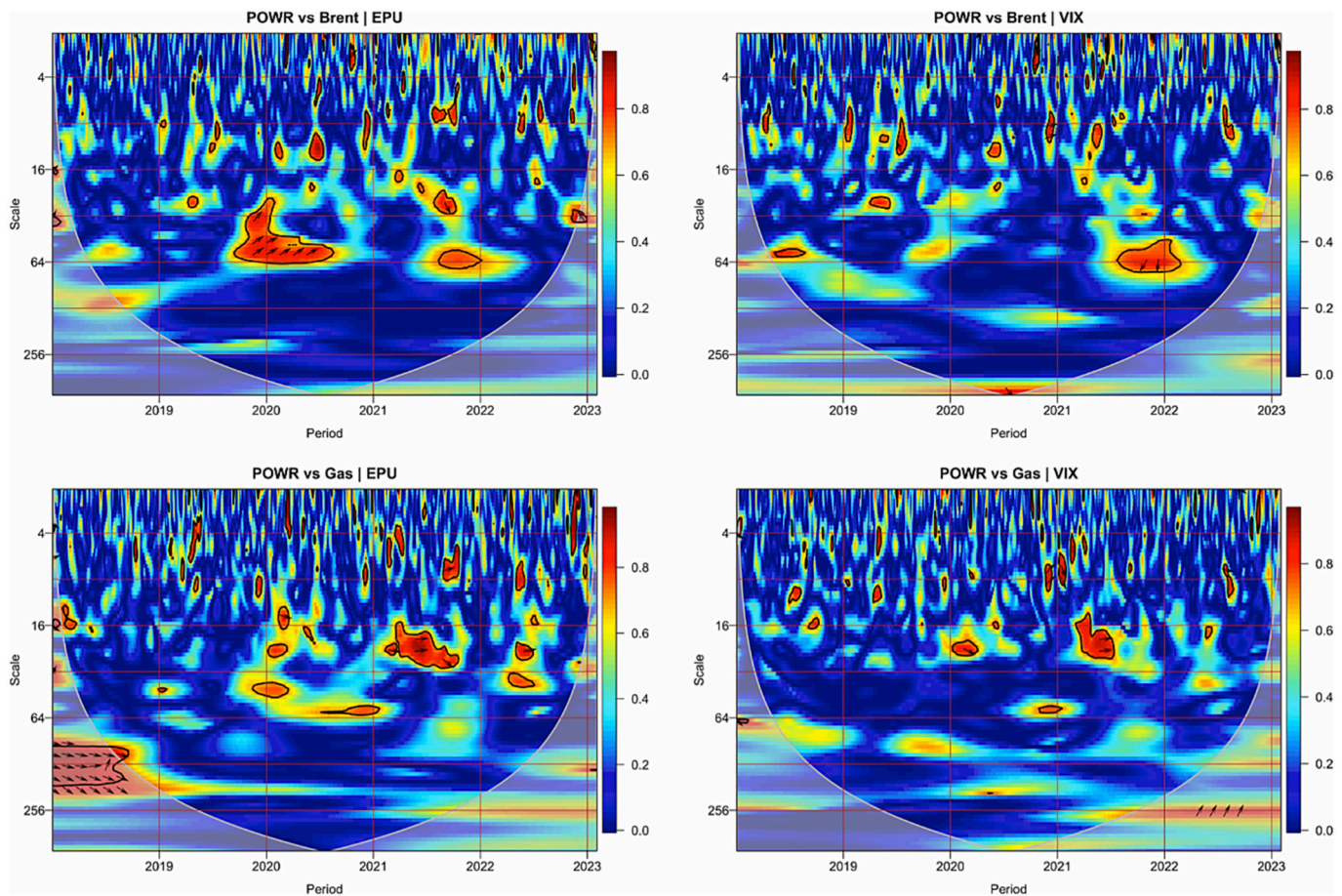


Fig. 5. Partial Wavelet Coherence between Power and dirty energy.

Notably, the VIX appears to exert a more pronounced influence compared to the EPU in shaping the interconnectedness among these assets. This phenomenon is notably conspicuous in interactions involving energy cryptocurrencies and dirty energy sources, where a surge in coherence during the Covid-19 pandemic mirrors broader market turmoil.

Furthermore, the distinctive nature of energy cryptocurrencies, rooted in Proof of Stake (PoS) systems, provides them with a degree of independence from traditional energy usage patterns, which are inherently tied to fossil fuels. This fundamental distinction reshapes anticipated co-movements. Nevertheless, a notable symmetry emerged during the early stages of the pandemic, suggesting the potential influence of an external factor. These findings aligning with the study by (Sharif et al., 2023), which highlights distinctive investment avenues for environmentally-conscious cryptocurrencies compared to their conventional counterparts, reinforcing the unique positioning of energy cryptocurrencies in the financial landscape.

Transitioning to the domain of clean energy, coherence analysis during the pandemic reveals a noteworthy strong co-movement, implying substantial correlation between energy cryptocurrencies and clean energy sources. This observation presents compelling opportunities for investors seeking to align with sustainable practices. Synchronically, the nuanced outcomes for different cryptocurrencies come to the fore. POWR, in particular, exhibits a relative insulation from the influence of both EPU and VIX. The temporal dynamics further illuminate how the influence of these factors evolves, underscoring the need for a context-specific approach (Yousaf et al., 2022a).

With respect to clean energy metals, a distinctive pattern surfaces for POWR. It demonstrates a heightened susceptibility to VIX, setting it apart from its counterparts. The interplay of EPU and VIX is further

dissected, revealing the dynamics of their impact on connectedness. These insights highlight the intricate relationship between economic uncertainties, market volatility, and the energy landscape. It is evident that this interplay is far from uniform, with certain cryptocurrencies and metals exhibiting distinctive responses. Similarly, previous studies for instance, (Fasanya et al., 2022; Ji et al., 2019a; Ji et al., 2019b; Le, 2023) also highlight the evolving and time-dependant dynamics between cryptocurrency and metals. This nuanced understanding is indispensable for investors, policymakers, and stakeholders navigating the intricate terrain of energy markets and cryptocurrencies, prompting a re-evaluation of traditional investment strategies and emphasizing the need for a nuanced comprehension of the underlying dynamics.

4.3. Vector wavelet coherence

Traditionally, vector wavelet analysis results are presented in scalograms along with heatmaps indicating the strength of coherence between the analysed series. The x-axis of each scalogram represents the time dimension, which can also be expressed in observational counts. In our case, the observational counts are located at the bottom of each scalogram, while the years are shown at the top. The y-axis displays periodicities or frequencies representative of the trading horizon or scale. Each scalogram is accompanied by a colour bar on the right, where warmer colours (green to blue) indicate low coherence, and hotter colours (yellow to red) indicate high coherence. Note that in the context of VWC analysis, a system of three variables is referred to as a multiple wavelet, four variables are referred to as a quadruple wavelet, and five or more variables are referred to as an n-dimensional wavelet. The results in this section are interpreted following these guidelines.

Fig. 13 displays the VWC-based multiple wavelet coherence between

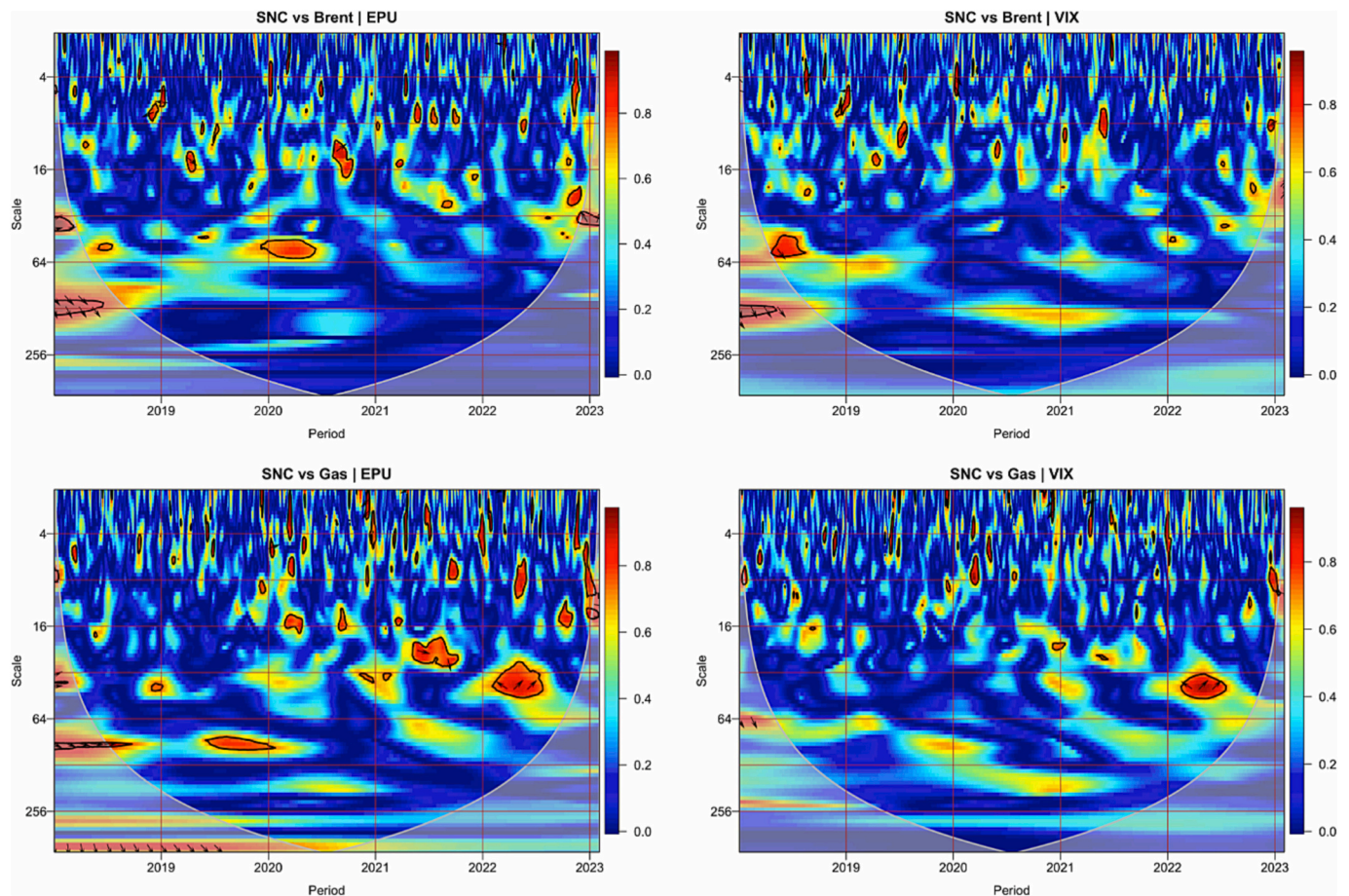


Fig. 6. Partial Wavelet Coherence between SunContract and dirty energy.

cryptocurrencies and clean energy. Panel A shows the results for SNC vs. clean energy assets while Panels B and C show those for GRID+ vs. clean energy assets and POWR vs. clean energy assets, respectively. The results show low overall coherence between cryptos and clean energy assets.

Across the high-frequency band, mainly from 2 to 8 days, which represents the weekly trading horizon, we find interspersed comovements amid the low interdependence between cryptocurrencies and clean energy assets. Meanwhile, across the low-frequency band (128-to-256 days and beyond), the scalograms are dominated by hotter colours, i.e., yellow to red, indicating high interdependence between the analysed cryptocurrencies and clean energy assets in the long term. Across the medium-term scale (16–64 daily cycles), the results show a mix of low and high interdependence across the period (January 2018 to January 2023). The spots of high interdependence, evidenced by the red-coloured areas of the scalograms, mainly corroborate the era of the coronavirus health crisis in 2020 and the Russia-Ukraine geopolitical conflict in 2022. This is comprehensible because risk propagation and the transmission of contagion – from developed markets to their developing counterparts – amplify in crisis periods (Umar et al., 2022c). With these observations, our results are consistent with the existing literature that report high cross-market connectedness in the era of the COVID-19 pandemic (Ma et al., 2022; Pham, 2021; Su et al., 2022) as well as the ongoing Russia-Ukraine conflict (Antonakakis et al., 2023; Jena et al., 2022; Yousaf et al., 2022b).

Aside from the high-frequency (short-term) commonalities across the three systems, the results reveal interesting system-specific conclusions in the long term, i.e., at low frequencies. First, the low (and, or absence of) interdependence between POWR and clean energy assets in the long run, i.e., beyond 256 days from late 2019 to 2023, demonstrate hedge

and safe haven advantages between these assets. This is shown by the deep blue-coloured scalogram across low frequencies (256–512 periodicities). Second, the mild interdependence between GRID+ and clean energy assets in the long-term signalling towards diversification advantages between GRID+ and clean energy assets. Third, the deep coloured regions of the scalogram for SNC vs. clean energy assets show strong interdependence and, hence, the absence of diversification, hedge, or safe haven opportunities in the long term. The conclusions on the hedge, safe haven and diversification attributes between the analysed systems are consistent with the base definitions provided by (Baur and Lucey, 2010) for hedges, safe havens, and diversifiers.

Fig. 14 portrays the VWC-based multiple wavelet coherence between cryptocurrencies and dirty energy. Panel A shows the results for SNC vs. dirty energy assets while Panels B and C show those for GRID+ vs. dirty energy assets and POWR vs. dirty energy assets, respectively. Here, also, like the clean energy scalograms, the results show low coherence between cryptos and dirty energy assets in the short term while the medium and long term reveals a mix of low, medium, and high coherence. Across the long-term frequency band, the following system-specific observations are worth noting. First, in terms of SNC vs. dirty energy assets, a medium-to-high degree of interdependence is observable across the 200-to-512 daily cycles over the analysed period. This indicates some potential for diversification. Second, regarding the GRID+ vs. dirty energy assets, there is a dominance of strong power coherence between the variables and, hence, suggests an absence of diversification, hedge, or safe haven advantages. Third, for POWR vs. dirty energy stocks, the long-term (200–512 daily periodicities) is mainly characterised by low or mild interdependence, suggesting some potential for diversification.

Fig. 15 shows the VWC-based multiple wavelet coherence between cryptocurrencies and metals. Panel A shows the results for SNC vs.

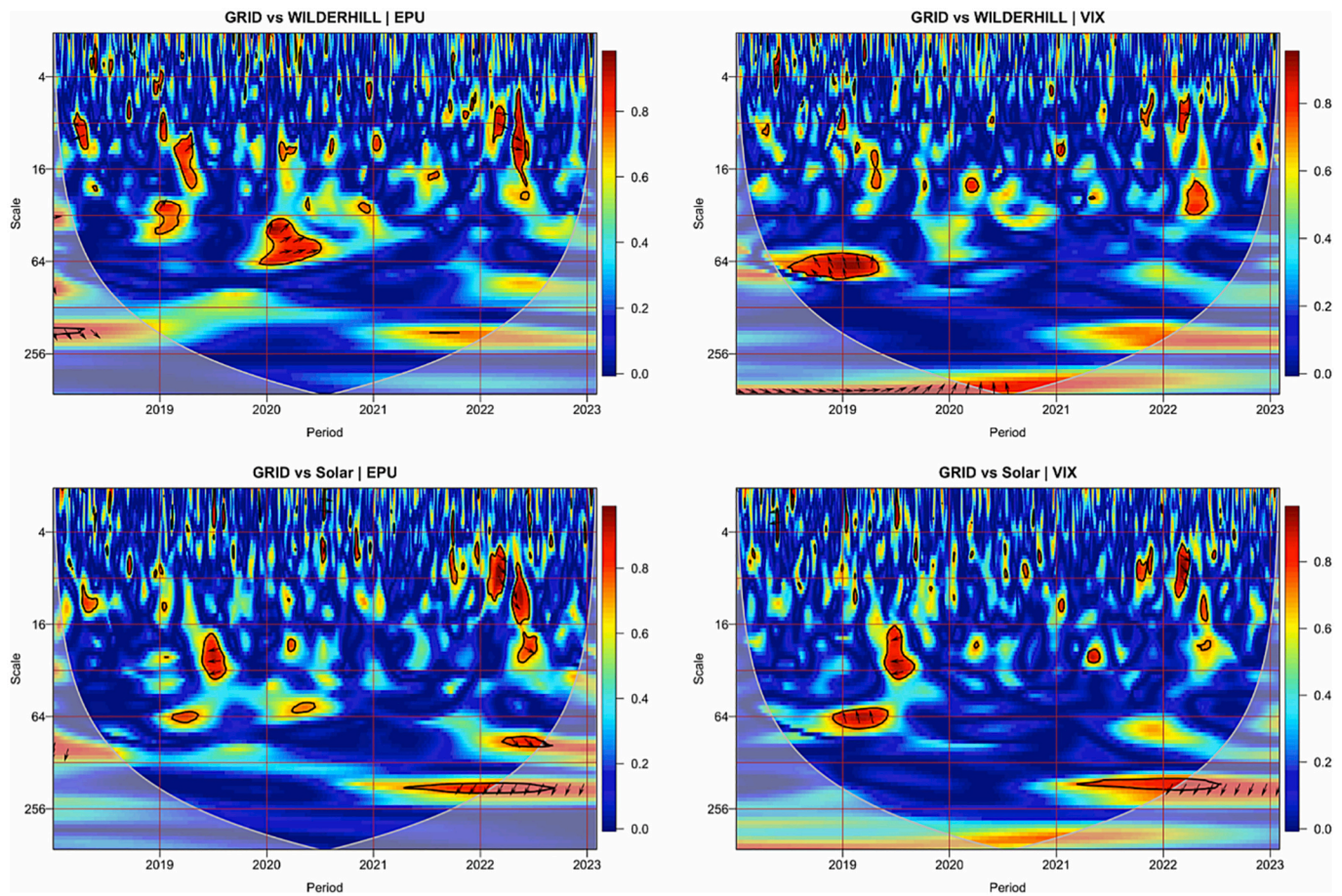


Fig. 7. Partial Wavelet Coherence between GRID+ and clean energy.

metals while Panels B and C show those for GRID+ vs. metals and POWR vs. metals, respectively. Unlike the previously analysed systems, we find high co-movements between cryptocurrencies and metals across the high-frequency band (2-to-8 daily cycles). Hence, unlike energy assets that could render some diversification attributes in the short term, the combination of cryptocurrencies and metals hardly yields diversification benefits across the high-frequency band, spanning up to the weekly trading horizon. Both the medium-term and long-term scales also reveal high interdependencies with interspersed could-coloured regions – an indication that the overall interdependence between cryptos and metals leaves behind little room for hedging against market shocks.

Fig. 16 presents the VWC-based multiple wavelet coherence between cryptocurrencies and uncertainty measures. Panel A shows the results for SNC vs. uncertainty measures while Panels B and C show those for GRID+ vs. uncertainty measures and POWR vs. uncertainty measures, respectively. The results show that the interdependence between cryptos and uncertainties of the US economy is generally low across the time-frequency spectrum. The results demonstrate the time-frequency-dependent hedge ability of cryptos against investor sentiment, gauged by the VIX and economic policy uncertainty of the US. A notable observation is that, among the analysed systems, the POWR vs. uncertainty system demonstrate low coherence in the very long term between 256 and 512 daily scales. However, for all three analysed systems, high interdependencies are found across the apogee of the COVID-19 pandemic and the inception of the Russia-Ukraine geopolitical risk conflict. This means that the dynamics of returns in cryptocurrency markets may be affected by policy shocks emanating from major world economies generally and the US particularly.

4.4. Summary of results

Overall, for dirty energy analysis, large pockets of red islands are clear among all the pairs observed with some being considerably notable than others. For instance, among dirty energy indices, only GRID+ showed consistent red islands over longer versions of investment horizons where negative co-movements are evident for the later part of the sample period when GRID+ was leading while for all prior periods, Brent index led. The negative co-movements between GRID+ and the dirty energy sources indicating a potential hedging effect against unfavourable movements in the energy markets. Interestingly, for GRID+, the red islands persist over longer investment durations, implying that as the investment horizon extends, the cryptocurrency's performance becomes increasingly independent of dirty energy price movements. This could be attributed to GRID+'s unique market positioning or strategic shifts in its underlying business model. Prior to this phase, the Brent crude oil index led the relationship, suggesting a prevailing reliance on traditional energy markets.

For others such as POWR and SNC, lower coherence is observed from 2021 at investment frequency starting 128 days and above. This reduced coherence could be indicative of these cryptocurrencies gradually decoupling from the influence of dirty energy markets. It may signal a strategic manoeuvre towards cleaner and more sustainable energy sources, aligning with growing environmental concerns and shifting investor preferences. However, with respect to pairwise connectedness with Gas, despite holding high connectedness during covid, 128 days and above horizons maintained lower connectedness even during covid periods which suddenly strengthened following the invasion. This observation reflects the cryptocurrency market's responsiveness to external shocks and the potential for unexpected shifts in

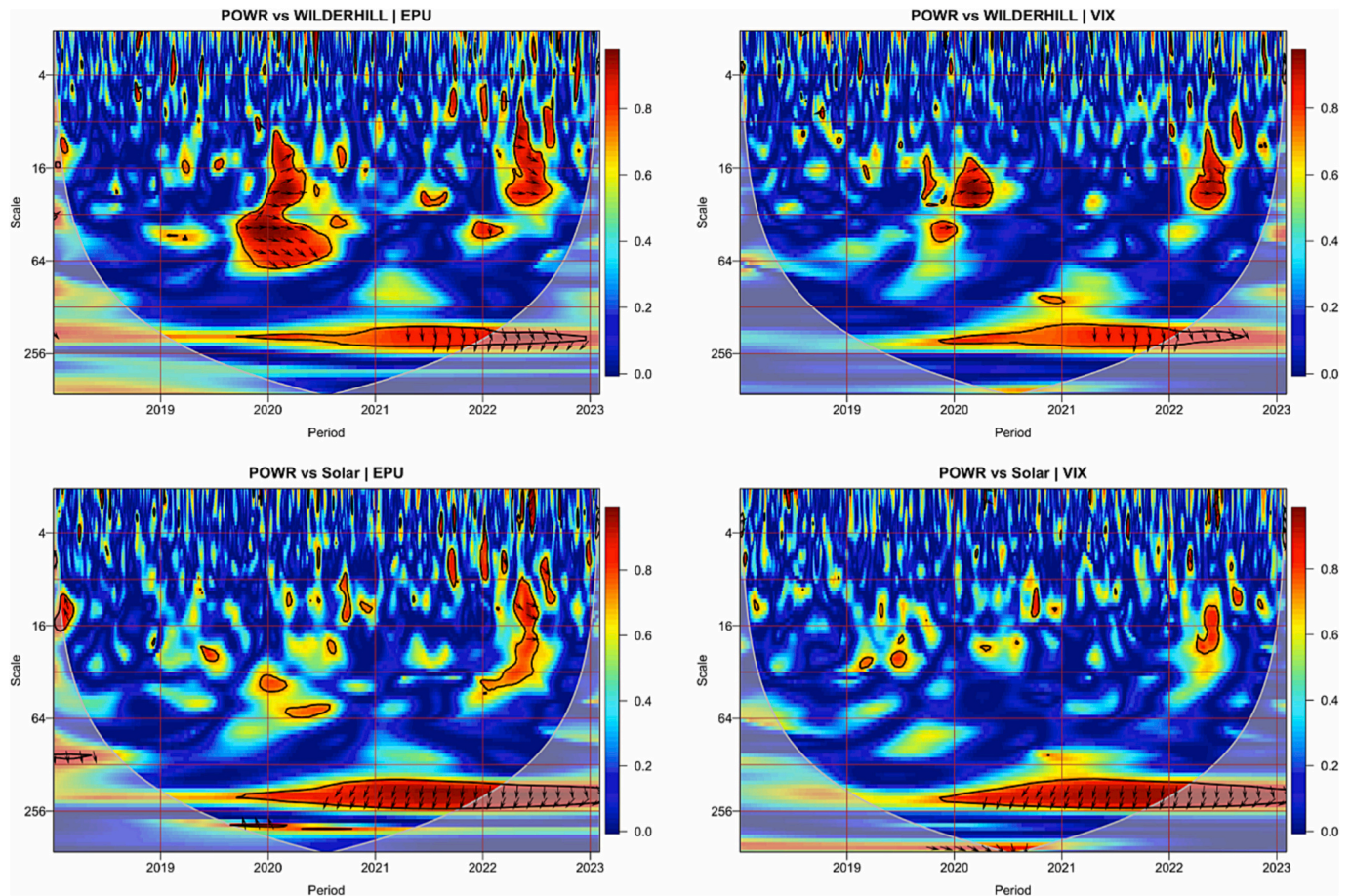


Fig. 8. Partial Wavelet Coherence between Power and clean energy.

interconnectedness during times of crisis (Pham et al., 2022).

Regarding investment plans, all the cryptocurrencies reflect lower connectedness in lower horizons irrespective of market conditions and for higher ends, only POWR showed some diversification benefits over 128 days and above eliminating the 2018 cryptocurrency market crash effect. This implies that, irrespective of prevailing market conditions, these cryptocurrencies tend to be more independent in the short term.

With respect to clean energy indices, apart from covid-19, little regions of absolute co-movements are located for all except with POWR. Despite most indices show high co-movement clustering during pandemic, GRID+ show relatively low clustering during Covid pandemic which was substantial during the recent invasion period when others were relatively low. Similarly, SNC was constant in maintaining lower co-movements with both the clean indices examined making them ideal choice as diversifier. However, in terms of causality, we note nonstationary outcomes.

Except for Covid-19, the results imply that the energy cryptocurrencies, SNC, GRID+, and POWR, exhibit a varied degree of correlation with clean energy indices. The heightened co-movement clustering during pandemic period could be attributed to the broader market turbulence and heightened investor sensitivity to global events during such periods (Madaleno et al., 2022). Surprisingly, GRID+ exhibit relatively lower clustering with clean energy indices amid the pandemic. This distinctive behaviour could be indicative of GRID+'s unique market positioning and resilience, and thus, it might be less susceptible to the immediate impacts of global crises. The non-stationarity in causal relationship implies that traditional linear cause-and-effect relationships might not adequately capture the complexity of these interactions. Instead, the interplay between energy cryptocurrencies and clean energy indices is likely influenced by a multitude of

factors, including market sentiment, technological advancements, policy changes, and investor behaviour (Yousaf et al., 2022a).

For clean energy metals, our wavelet coherence analysis showing presence of low co-movements in shorter and longer investment horizons with occasional abnormality, GRID+ and Copper for instance. The high co-movements during Covid period is fairly justified where pockets of red islands are present due to global emergency where market participants across the board were facing unprecedented challenges. This suggests a heightened interconnectedness during times of acute uncertainty, highlighting the ripple effects of global crises (Ghosh et al., 2023). However, with the current global tension in position, Copper and Nickel exhibit absolute negative co-movements with SNC during early 2022 when Copper and Nickel had downwards trend. Even though the negative correlation was short lived, yet indicating for SNC's sudden shock resistance, should they be placed in metal portfolio, which is consistent among clean energy indices as well. From an economic standpoint, the consistency of this shock resistance across both clean energy metals and energy cryptocurrency indicates a broader trend. The energy cryptocurrencies, particularly SNC, appear to exhibit a degree of resilience that aligns with the goals of clean energy and sustainability. This may position them as attractive options for investors seeking not only financial gains but also alignment with environmentally conscious investment strategies.

Upon isolating the US EPU and overall market volatility indicator (VIX), our partial wavelet coherence displays varying findings. First, with pairwise coherence with dirty energy sources, we find both the US EPU and VIX influencing the pairwise co-movement between energy cryptocurrencies and dirty energy where VIX is considerably stronger. This points to a dynamic interplay between broader market volatility and the behaviour of energy cryptocurrencies in relation to dirty energy.

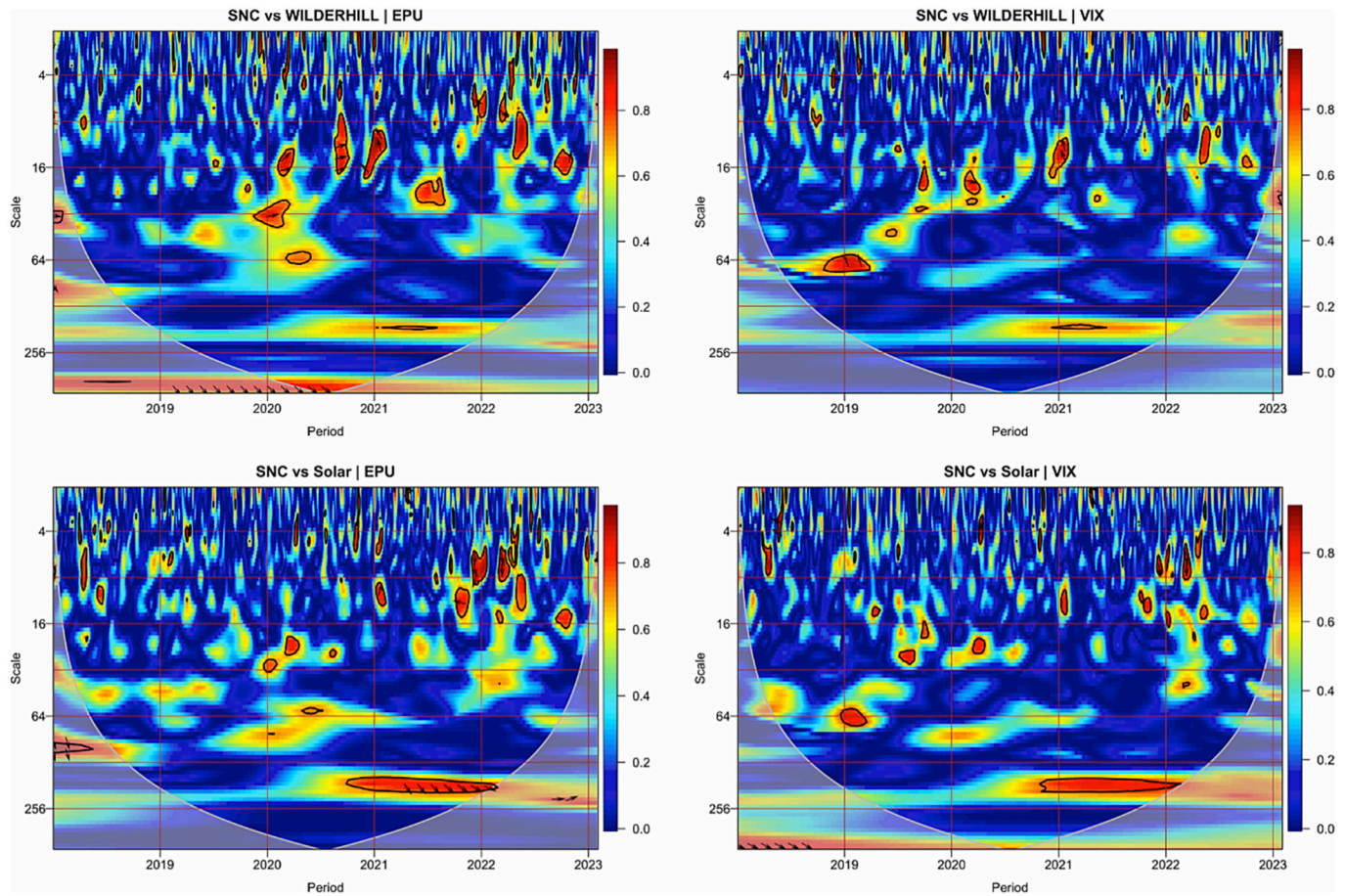


Fig. 9. Partial Wavelet Coherence between SunContract and clean energy.

In addition to that, positive oil price shock is found to have affected the pairs in greater magnitude over short and long investment horizons. In other words, when oil prices experience upward jolts, these shocks reverberate across the energy cryptocurrency and dirty energy markets, engendering a heightened co-movement (Naeem et al., 2023a, 2023b, 2023c, 2023d, 2023e, 2023f, 2023g, 2023h).

The pronounced influence from the VIX, compared to the US EPU highlights the influence of market sentiment and risk perception. This indicates that during periods of heightened uncertainty, investor's apprehension and speculative fervour can lead to rapid shifts in asset relationships. Similarly, with the presence of influence from oil price, an economic narrative unfolds that emphasizes the interconnectedness of energy markets. Such shocks can ripple through both traditional dirty energy and emerging energy cryptocurrency sectors, indicating a shared sensitivity to critical developments in global oil markets.

Unlike dirty energies, in terms of clean energies, we find in recent times VIX became more dominant in influencing cryptocurrency and clean energy pairwise connectedness, and compared to the Solar index, WilderHill is largely affected. This makes Solar investment a safer avenue for investors during heightened VIX. This aligns with the broader narrative of clean energy's reputation as a steadfast and sustainable choice, even in the face of market turmoil (Yousaf et al., 2022d). However, during normal market conditions, we emphasize on close monitoring over the US EPU as it was found to influence both clean energy sources before 2020. This implies that economic policy decisions display a substantial impact on the interconnectedness between energy cryptocurrencies and clean energy markets.

The dominance of the VIX as a driver of connectedness highlights the essential role of market sentiment and risk perception in shaping investment decisions. Clean energy's (especially solar) resilience in the

face of VIX-driven turbulence indicates its role as a dependable instrument of stability during uncertain times (Gustafsson et al., 2022). Conversely, the influence of the US EPU indicates the role of economic policies, hinting a delicate balance between governmental decisions and how they affect the direction of investments in clean energy. As societies shift towards cleaner energy sources (i.e., when greater portion of society adopted clean energy), the policy designed can greatly affect how confident investors feel and how the market behaves (Álvarez-Ayuso et al., 2018).

Finally, interestingly with respect to clean energy metals, we find different cryptocurrency pairs react differently with different uncertainties and are global financial market dependent. For instance, POWR and clean energy metals pairs react more with VIX, while staying stationary against EPU. This suggests that market sentiment and the perception of risk plays significant role in influencing the relationship between POWR and clean energy metals. In contrast, their response to US EPU, implies that while economic policy decisions may have less impact but, market volatility lays a more pronounced influence.

Moreover, while GRID did not react to any uncertainties from 2022, but during Covid, pairs with Aluminium and Copper were affected through uncertainties and Nickel pairs were unaffected throughout the sample period. More surprisingly, all the SNC pairs with energy metals remained most insignificantly affected and showed consistency over the periods. These results highlight the potential for sudden events like the pandemic to temporarily alter the interaction between GRID+ and certain clean energy metals. While the results on SNC suggests that SNC's relationship with clean energy metals remains robust and resilient over different periods and varying uncertainties.

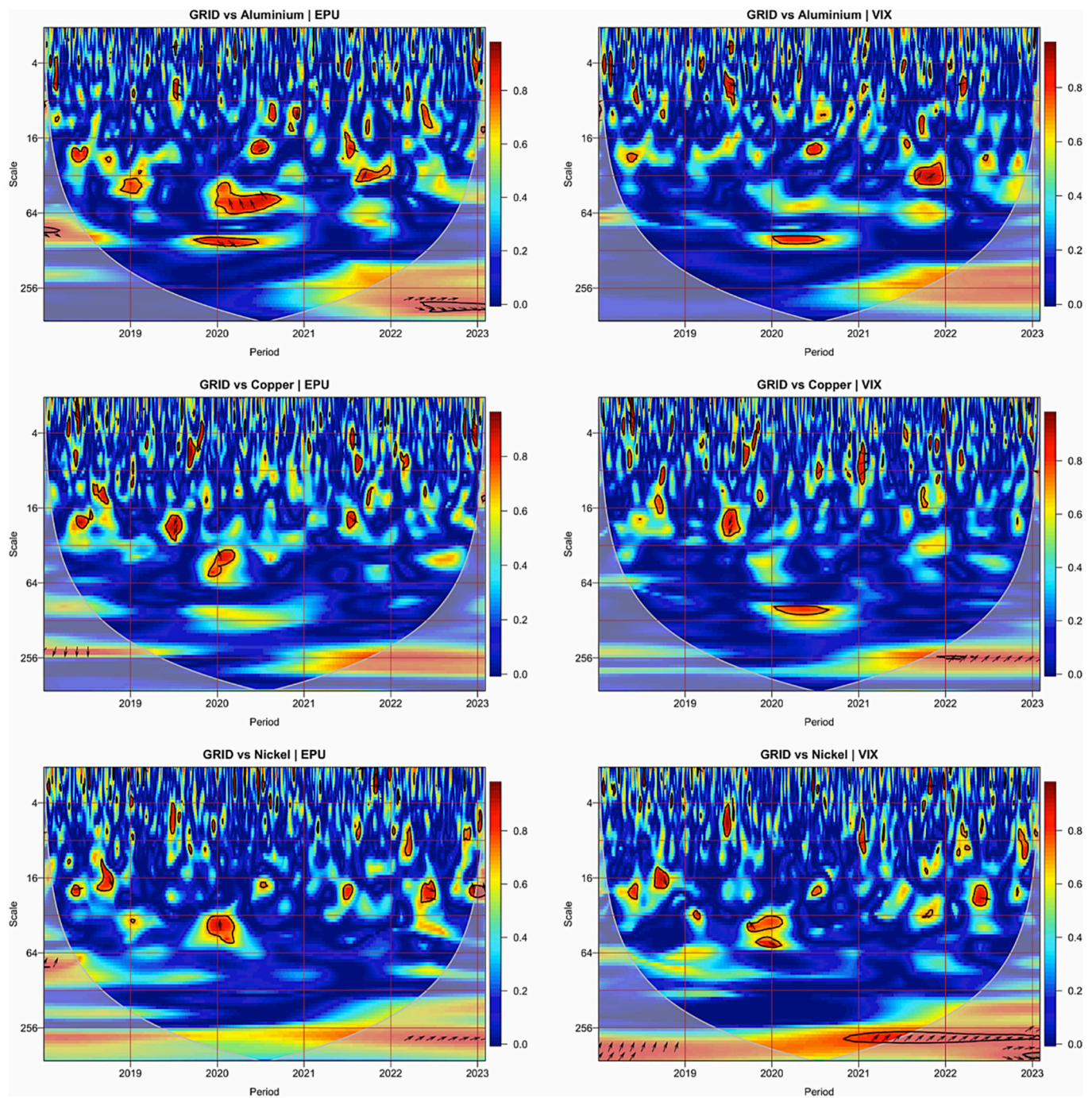


Fig. 10. Partial Wavelet Coherence between GRID+ and clean energy metals.

5. Conclusion

The mounting interest relating to tools for achieving net-zero emission has been a growing concern for global policymakers and environmentally concerned investors. Several tools in supporting the global energy transition have been developed and researched on. Cryptocurrency has been at the centre of discussion for many years, and recently, a new stream of cryptocurrency has been developed for environmentally conscious investors. Given the growing concern relating to sustainable future, the emergence of renewable energy related investments, and the current global uncertainties, we extend the current understanding on clean energy investment and linked them with uncertainty. As such, the current research presents a study on the pairwise

linkage among a new member of cryptocurrency family and energy sectors under time and frequency domain. Particularly, we examine on dirty and clean energy alongside clean energy metals. This study employed multiple wavelet methods: wavelet coherence, partial wavelet coherence, vector wavelet coherence, where first one is widely used method in understanding the time-varying connectedness among time series analysis and the latter is a recent inclusion to identify third party influence.

As societies worldwide strive for reduced carbon footprints and more sustainable energy practices, the role of energy cryptocurrency becomes increasingly pivotal. These digital assets have the potential to reshape not only investment strategies but also the entire energy landscape. Understanding the intricate connections between energy

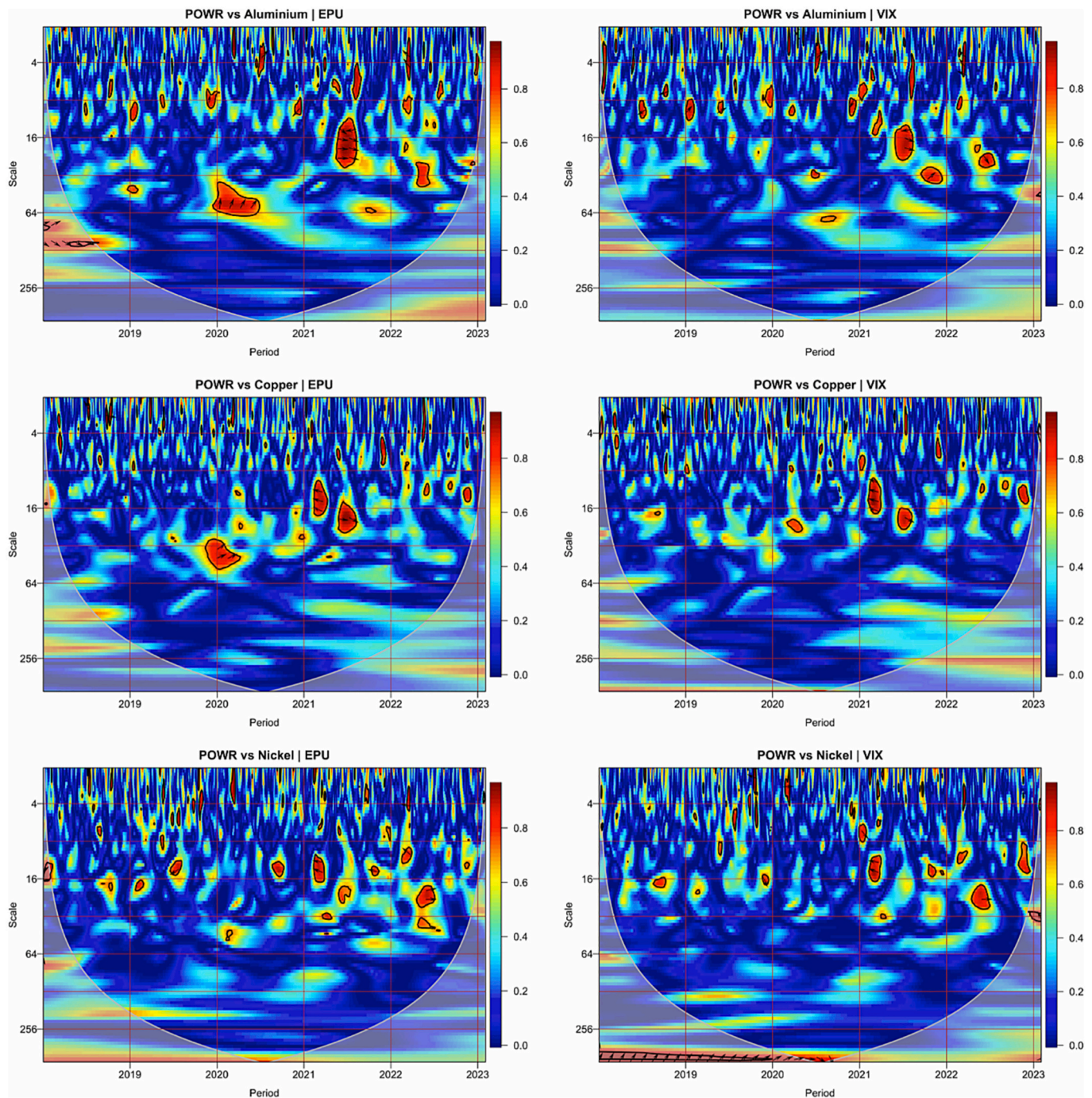


Fig. 11. Partial Wavelet Coherence between Power and clean energy metals.

cryptocurrencies and both clean and dirty energy sources is important primarily in the context of energy transitions and environmental concerns. We shed light on the synchronicities and disparities between emerging digital assets and traditional energy markets. This understanding is particularly important for policymakers seeking to create well-rounded and sustainable energy portfolios, bridging the gap between the conventional and the emerging technologies of cleaner and more efficient energy systems.

Additionally, the importance of investigating the impact of uncertainty on the linkage between energy cryptocurrency and clean energy cannot be overstated. The global investment landscape has become increasingly uncertain due to a multitude of factors, including geopolitical tensions, economic fluctuations, and ongoing environmental

concerns. As such, understanding how these uncertainties influence the relationship between energy cryptocurrencies and clean energy is crucial.

Throughout our analysis, our results indicate the potential role of this new cryptocurrency type to lay a beneficial position in the investment portfolio. Furthermore, we find uncertainties (economic policy and market volatility) leaving significant influential marks on the connectedness among pairs. Even though our results show the influential capacity of both the uncertainty measures, we confirm VIX as more influential than the US EPU. Despite both uncertainties tend to leave an impact over co-movements among cryptocurrencies and other variables assessed, but during heightened uncertainties, we confirm, pairing all cryptocurrencies with solar investments showing safer avenues

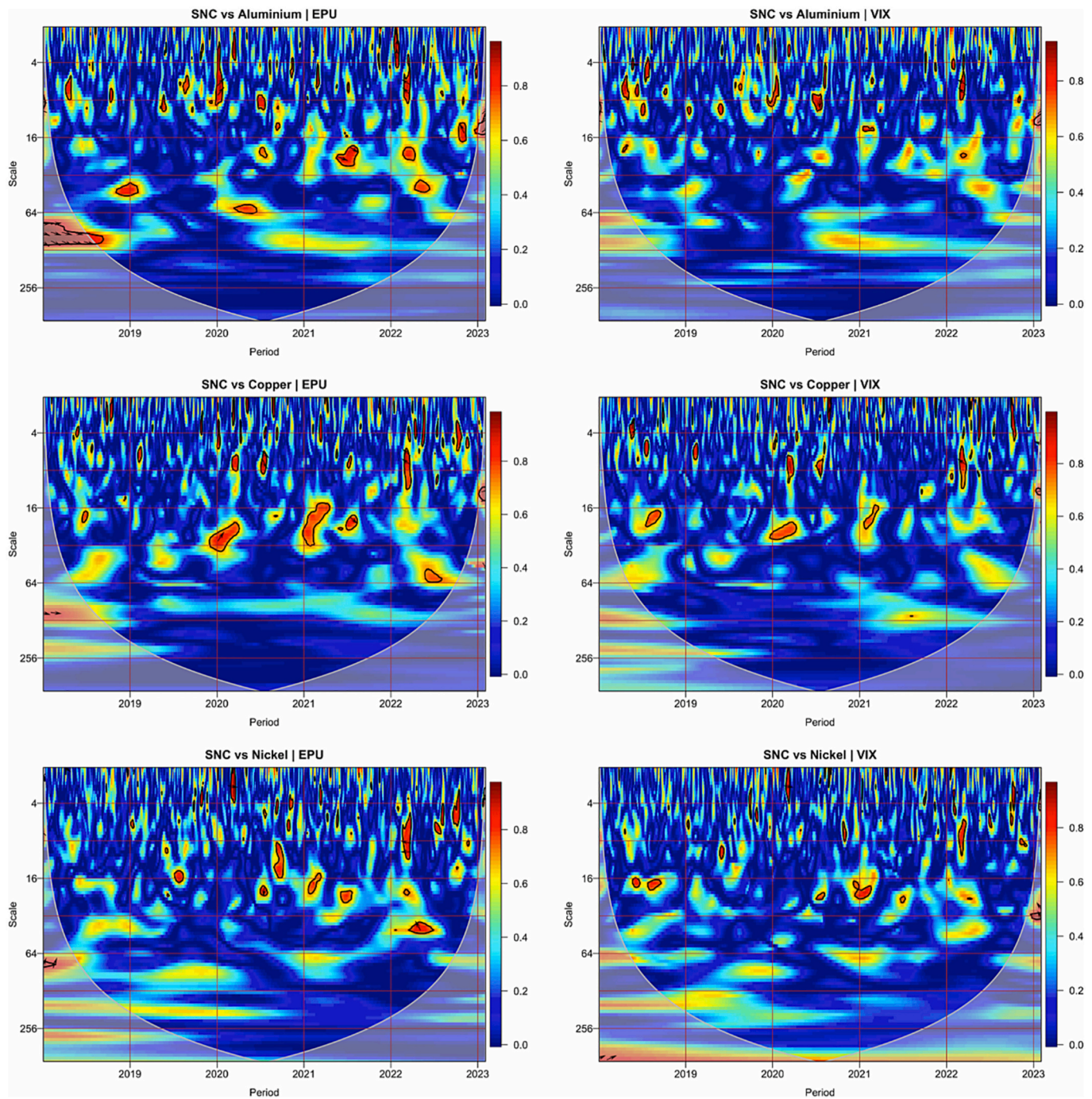


Fig. 12. Partial Wavelet Coherence between SunContract and clean energy metals.

compared to pairing with WilderHill. This finding is beneficial for cryptocurrency investors as it provides guidance on constructing more resilient and potentially less volatile portfolios. Solar investments, being part of the clean energy sector, tend to exhibit a level of stability during times of uncertainty, as they align with sustainability goals and are less affected by traditional market shocks. Therefore, cryptocurrency investors looking for a safe avenue against market movement might consider incorporating solar investments into their portfolios to mitigate risk.

Among clean energy metals, only SNC confirms beneficial features. But for pairing cryptocurrencies with dirty energies, apart from uncertainties considered in this study, we argue on close monitoring over oil price shocks for decision making. Additionally, our results highlight

that different cryptocurrency pairs exhibit diverse responses to distinct uncertainties which indicates the complex nature of their connections within the global financial landscape (Hoang and Baur, 2023). This insight therefore brings the need for tailored risk management strategies when incorporating energy cryptocurrencies into investment portfolios. Thus, we conclude arguing the beneficial aspects of utilizing energy cryptocurrencies alongside dirty energy, clean energy and clean energy metals (Yousaf et al., 2022c). Given the analysis above and due to their relative lower connectedness, energy cryptocurrencies may be worth considering for energy sector investors.

Given the aggressive movements in conventional cryptocurrency price, investors seeking cheaper diversification opportunities can consider energy cryptocurrencies as a worthwhile alternative option.

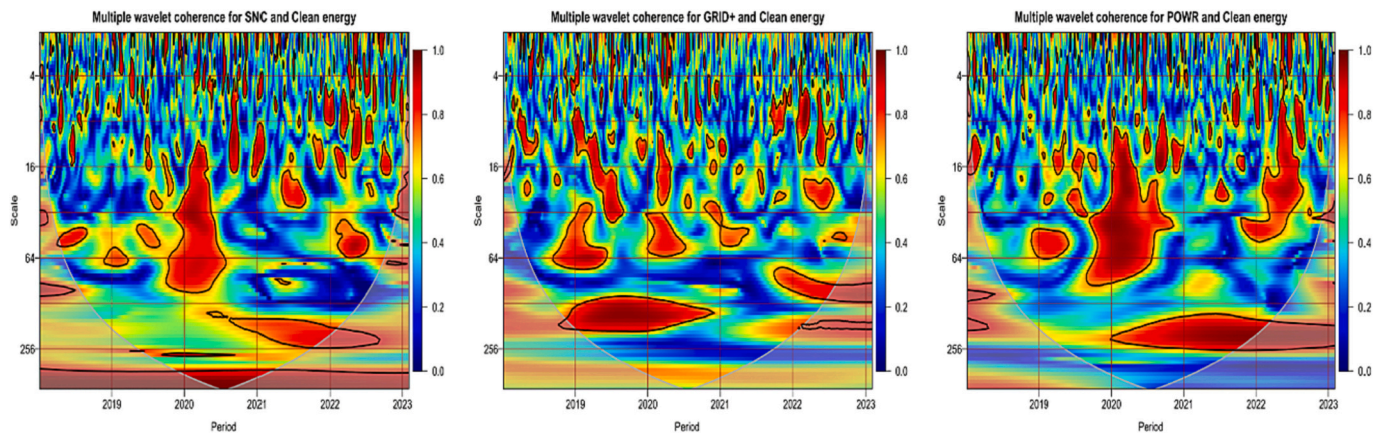


Fig. 13. Multiple wavelet coherence between cryptocurrency and clean energies.

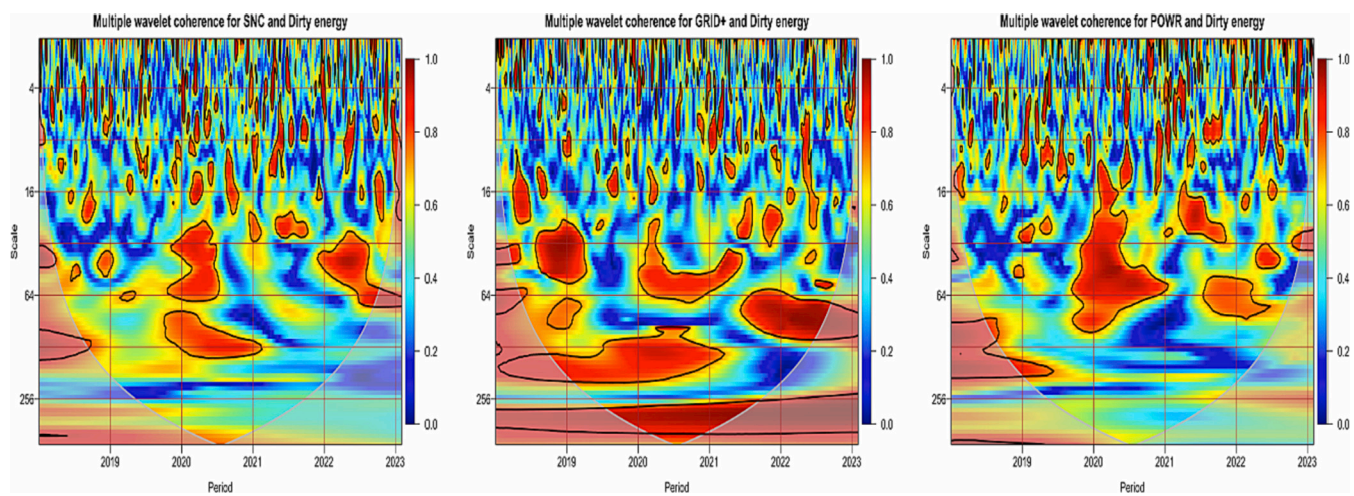


Fig. 14. Multiple wavelet coherence between cryptocurrency and dirty energies.

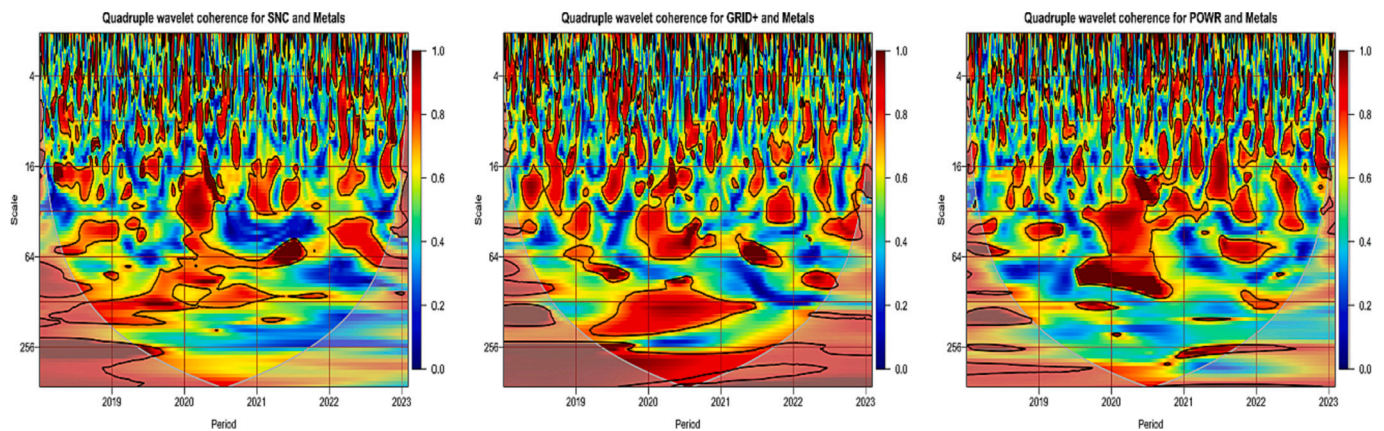


Fig. 15. Multiple wavelet coherence between cryptocurrency and clean energy metals.

Additionally, the identification of significant influential marks from economic policy and market volatility on the connectedness among pairs indicates the relevance of considering these factors in investment decisions. Specifically, the dominance of market volatility (VIX) over economic policy uncertainty (EPU) implies that investors need to closely monitor and adapt to market sentiments and trends (Smales, 2022). As a result, for all energy and metal investors, even though we stress over close monitoring on VIX for investment decision making, substantial

attention on oil price shocks are also required from oil and gas investors for profitable investment decisions aligning with the findings by (Gustafsson et al., 2022; Zhang et al., 2023). This proactive stance is vital for making informed decisions in a volatile energy market. Among all cryptocurrencies, fund managers may need to allocate relatively higher proportions into SNC while considering the trend in EPU and VIX, constant rebalancing between POWR and GRID are advised. Moreover, the confirmation that pairing all cryptocurrencies with solar

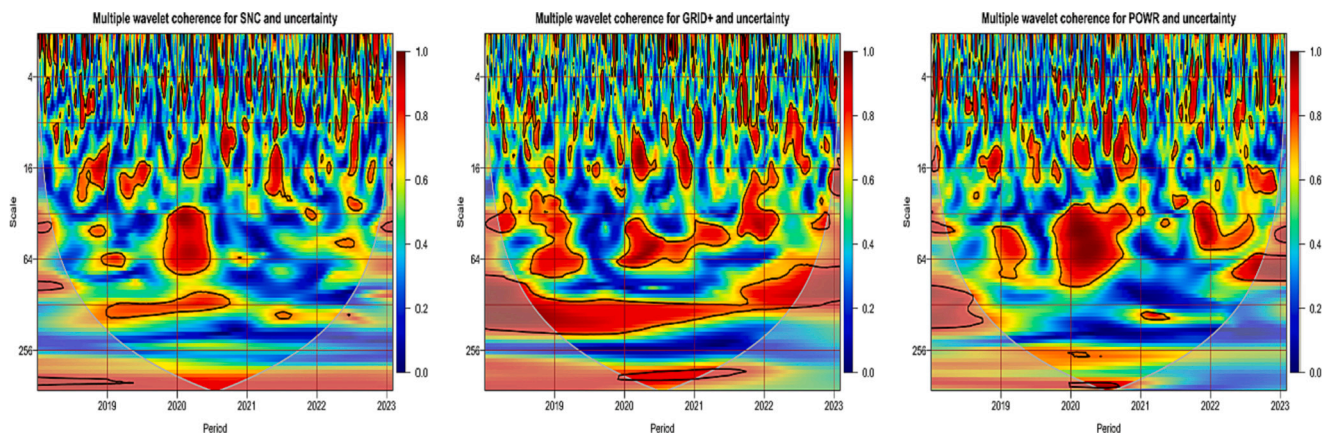


Fig. 16. Multiple wavelet coherence between cryptocurrency and uncertainties.

investments provides safer avenues compared to WilderHill is pivotal for risk-conscious investors. This insight offers a clearer investment path, potentially reducing exposure to market fluctuations.

Similarly, the results of this study hold significant implications for policymakers navigating the evolving landscape of energy investments. The recognition of uncertainties, both in economic policy and market volatility, as influential factors in the connectedness among energy assets reiterates the need for policies that promote stability and transparency in these domains. Moreover, the emphasis on VIX as the more dominant influence highlights the importance of monitoring and mitigating excessive market fluctuations. Policymakers should consider measures that foster market resilience and reduce excessive volatility, potentially providing a more conducive environment for investors. As our results confirm energy cryptocurrencies reacting differently against different uncertainties, thus, policy makers may consider acknowledging the type of cryptocurrencies as independent asset class. Additionally, the recommendation to pair cryptocurrencies with solar investments for safer avenues aligns with broader clean energy objectives. Policymakers can encourage investments in solar energy projects by offering incentives, grants, or favourable regulatory frameworks. Furthermore, the acknowledgment of SNC's beneficial features against clean energy metals points to the need for targeted support and incentives for technologies and materials that promote sustainability. The call for careful observation in monitoring oil price shocks is a signal for policymakers to implement mechanisms that buffer against sudden spikes in oil prices. This could include strategic reserves or market stabilizing measures. Therefore, given the beneficial aspects discussed above, acknowledging the growing trend and demand for alternative investment as well as alternative cryptocurrencies, as the type of cryptocurrency still in their growth stage, we draw regulator's attention to closely monitor and drawing necessary policies on the analysed cryptocurrencies in order to prevent speculation like their mainstream counterparts.

This study results are not only valuable for cryptocurrency regulators and investors but also equally important for energy and energy metal investors. This study excludes the mainstream cryptocurrencies as they were widely studied (Attarzadeh and Balcilar, 2022; Kamal and Hassan, 2022; Ren and Lucey, 2022), and all found inverse relationship with clean energy indices which does not fit for our study.

CRedit authorship contribution statement

Muhammad Abubakr Naeem: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Visualization, Writing – review & editing. **Afzol Husain:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources,

Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ahmed Bossman:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sitara Karim:** Writing – review & editing.

Declaration of Competing Interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.eneco.2023.107279>.

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