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# Bitcoin Mining's Energy Consumption and Global Carbon Dioxide Emissions: Wavelet Coherence Analysis

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# Bitcoin Mining Energy’s Consumption and Global Carbon Dioxide Emissions: Wavelet Coherence Analysis


## Abstract

Bitcoin mining has been attracting the attention of many authorities and decision-makers in terms of the environmental and climatic consequences associated with the excessive use of energy. The goal of this study, therefore, is to investigate the coherence association between bitcoin mining's energy consumption and the global carbon emissions index. An analysis of wavelet coherence was performed to investigate these relationships over the period of 2012-to-2021. The study's findings indicate that before 2013, there were in-phase associations between bitcoin mining's energy consumption and global carbon emissions index at various frequencies and within different time frames. Following 2013, the coherence association results indicate that there is no association between the Bitcoin’s mining energy consumption and global carbon emissions. More surprisingly, during the beginning of 2018, the association was anti-phase at a frequency of (16-32) weeks, when Bitcoin prices fell steeply, and Bitcoin mining businesses were not profitable. The anti-phase association could possibly be due to the fact that most governments around the world have raised their concerns about the environmental impact of cryptocurrency mining, which may have a significant effect on the closure of miners' firms in such countries. As a result, this study suggests that cryptocurrency miners should take the environmental impact side of mining’s carbon footprint seriously and apply alternative energy to power their operations such as wind and solar power. Furthermore, the study recommends that bitcoin miners switch their software code for validating and securing bitcoin transactions from "proof of work" to a "proof of stake" system that believes to reduce power consumption by 99 percent which consequently reduces carbon emissions.



**Key words**: Climate change, Bitcoin mining, Energy consumption, Carbon dioxide emissions

## Introduction

Global climate change is a long-term change in the temperature and weather patterns of our planet. It is true that some of these changes are natural, but human activities have been a primary cause of global climate change (Trenberth, (2018). Human activities have caused the atmosphere to be filled with carbon dioxide ($CO_2$) and other heat-trapping gases in such large quantities that the Earth's system and climate are accumulating heat (Hao, et al. 2008). The increasing temperature on Earth has resulted in melting ice caps, increasing sea levels, and increasing frequency of catastrophic weather events, such as high waves, wildfires, excessive rains, and floods (Kompas et al., 2018). Climate change impacts many aspects of our everyday lives, such as agriculture, energy use, public health, and many others (Tol, 2009). A changing climate affects almost all aspects of human life, and it is a long-term problem. For instance, as global warming progresses, property and infrastructure will be destroyed, productivity will be reduced, and mass migrations and security threats will be present (Keith Wade, 2016). Overall, climate change will most likely negatively affect economic growth in the long-run (Keith Wade, 2016).

In view of the increasing prominence of cryptocurrencies over the last few years, concerns have been raised about the sustainability of Bitcoin. The argument was based on the fact that the Bitcoin network relies on consuming a lot of electricity for the mining process, thereby posing an environmental threat (Köhler & Pizzol, 2019). The consensus mechanism in Bitcoin is a proof-of-work (PoW) approach, with peers competing for the permission to add the next block to the chain, a process known as "mining" conducted by the "miners" (Köhler & Pizzol, 2019). Each miner competes with other to solve a complex puzzle, which requires considerable processing power. Further, this also requires finding a random value known as a "nonce value". A mining algorithm converts the miner's guess of the nonce value into the block's length. This is what is known as a hash. If the hash value is below the required value, then the miner gets permission to add a new block (Gervais, et al 2016). As of 2018, the bitcoin network's hash rate ranged between roughly 15 million and 60 million Tera hashes (TH) per second, according to a respected website called Blockchain.com.

The amount of energy consumed by Bitcoin with application-specific integrated circuit (ASIC)-resistant algorithms is excessively large in comparison with their market capitalization (Gallersdörfer, et al., 2020). According to many scientists, Bitcoin networks emit about more than 100 million tons of carbon dioxide each year. Particularly, selecting, and operating mining devices presents significant challenges given the industry's secretive nature (Gallersdörfer, et al., 2020). A study by Kohler and Pizzol (2019) estimates Bitcoin mining's environmental impact and determines that it produced 17.29 Metric tons of carbon dioxide equivalent ($MtCO_2$) in 2018. In the study, it was found that by increasing a bitcoin miner's hash rate, the energy consumption and carbon footprint will decrease. However, Krause and Tolaymat (2018) still argue that rising network hash rates and energy consumption will lead to a rise in carbon emissions. Furthermore, the study of Mora et al (2018) estimated that the processing needed to run the Bitcoin network alone could lead to a 2°C increase in global temperatures by 2050 (Howson, 2019). Miners flocking to cheap renewable energy sources like hydropower and geothermal are partially responsible for the inflated estimates, which are likely to amount to 75 percent (Bendiksen & Gibbons, 2019). In light of this ambiguity, perhaps the time is not yet ripe for abandoning Bitcoin mining, or at least its underlying technology. As such, the present study examines whether there is a significant association between bitcoin mining energy consumption and carbon dioxide emissions globally index.

## Literature Review

In light of increased energy consumption and its effects on climate change and weather, the Bitcoin mining industry has caught the attention of relevant authorities, academics and mainstream media in regard to the environmental and climatic impact of excessive energy usage. As an example, article 2 of the Paris Agreement of Conference of the Parties calls on signatories to align their financial flows with carbon dioxide emissions levels and global warming in accordance with United Nations Framework Convention on Climate Change (UNFCCC (2015)). As a result of the 2015 Paris Agreement on Climate Change, major decision-makers, regulators, and practitioners focused on environmental sustainability, especially global warming. In previous research, different perspectives have been examined on the relationship between cryptocurrency and climate change. Several studies have been conducted on the electric consumption of Bitcoin mining, such as Roeck and Drennen (2022), Badea & Mungiu-Pupzan (2022), and Jiang, et al. (2021), while others have focused on the carbon dioxide emissions of cryptocurrency mining, such as Erdogan et al. (2022), Pham et al. (2022), and Panah et al. (2022). A few studies focused on specific regions rather than the global level such as Roeck and Drennen (2022); and Jiang et al. (2021).

Using the Life Cycle Assessment (LCA) method, Roeck and Drennen (2022) assess the environmental impact of Bitcoin mining in New York State. As environmental effects, the researchers looked at global warming, smog formation, acidification, and pollutant emissions. According to the study, Bitcoin mining not only undermines local climate measures, but also threatens national programs to combat climate change because Bitcoin mining is scalable, which is possible due to existing infrastructure and favorable financial conditions. In their work, Panah et al. (2022) emphasize the importance of integrating regulatory policies across markets to reduce GHG emissions globally. The study encourages greenhouse gas reduction by investing in green hydrogen production, and the study discusses the possibility of cryptocurrency mining becoming more profitable. In addition, a crypto tax was proposed to link the cost of hydrogen to the bitcoin market by allocating coins to mining assets and requiring bitcoin miners to provide dynamic support for electrolyzers based on emission factors and coin prices. Despite simulations to the contrary, the crypto tax leaves no traces once Bitcoin drops below USD 10,000. As of 2020 and 2021, cryptocurrency mining can be used to produce green hydrogen according to the study. Furthermore, the authors of Pham et al. (2022) use the quantile connectedness framework and daily closing prices for green, non-green, and carbon cryptocurrencies between 2017 and 2021 to analyse the two tails of carbon prices. The researchers found that green coins are only loosely related to Bitcoin and Ethereum, and their net connectedness is near zero, except for the outbreak of COVID-19. Further, macroeconomics, as well as financial considerations, contribute to the acceptance of green, as well as non-green crypto markets. Researchers found that diversifying among carbon, green, and non-green cryptocurrencies offer time-varying benefits, which can have substantial implications for policymakers and investors.

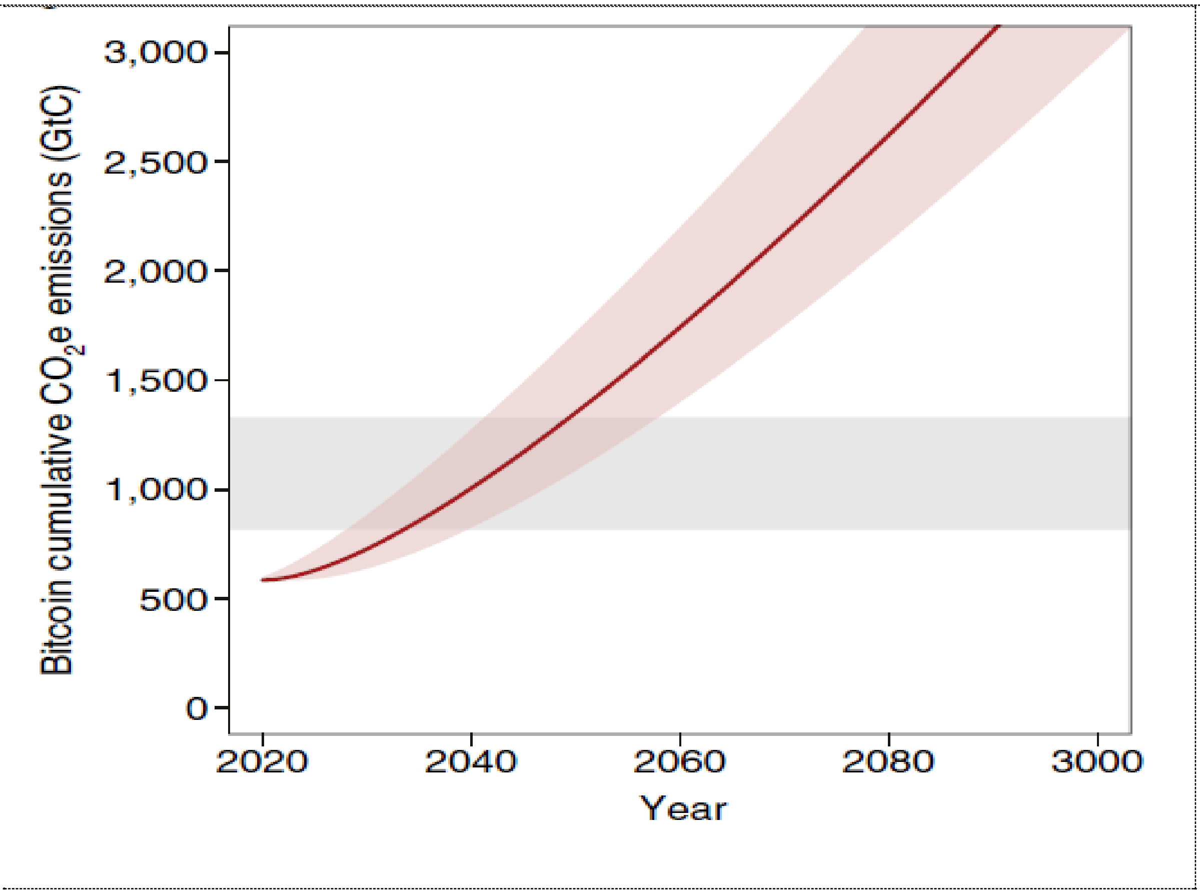
Using the Toda-Yamamoto and Toda-Yamamoto bootstrap-enhanced tests, the study of Erdogan et al. (2022) investigates whether there is an asymmetric association between cryptocurrency demand and environmental sustainability. Researchers found that the demand for cryptocurrency has detrimental effects on environmental deterioration, because the demand for Bitcoin (BTC), Ethereum (ETH) or Ripple (XRP) leads to environmental degradation. Bagea and Mungiu-Pupzan (2022) present a comprehensive review and evaluation of research on Bitcoin mining's economic and environmental effects, involving energy consumption and carbon dioxide emissions for the purpose of analyzing Bitcoin regulation and identifying potential methods to mitigate the negative effects on the environment and climate. The results of this investigation indicate that Bitcoin is still utilized in the economic context despite its high energy usage and negative environmental impact. Furthermore, in spite of the accusations made against Bitcoin, the increasing acceptance of Bitcoin in several countries suggests that the currency is gaining credibility.

De Vries's (2021) analysis finds that as bitcoin prices have risen, the negative externalities related to bitcoin mining have grown. Using a basic economic model, these findings demonstrate how bitcoin mining affects the environment at a given bitcoin price. As a result of bitcoin's record-breaking price at the start of 2021, the network could consume the same level of energy as all global data centres, resulting in a carbon footprint comparable to that of London. Besides its environmental consequences, the development of mining hardware with specialized features may increase the global electric chips shortage, affecting home workers, the recovery of COVID-19 issues, and electric vehicle production. The rising popularity of mining in some countries may endanger international security. Researchers concluded that policymakers must coordinate their efforts to minimize the environmental impact of cryptocurrency mining. Based on a parametric and semiparametric model of climate risk and predicted losses, Yang, and Xu (2021) developed a real-time synthetic price for the Bitcoin network's carbon footprint. Using the best estimates of VaR and shortfall (ES) for climate risk and ES, they find that the 95th and 99th percentiles are 8.04 and 10.37 billion EUR, respectively, and 11.33 and 14.15 billion EUR, respectively. Findings from this study may provide new insight into the relationship between Bitcoin and its environmental impacts, which could be useful for policymakers and investors alike.

Jiang, et al. (2020) study illustrates how the Bitcoin blockchain process produces carbon emissions in China using a simulation-based model. As a result, China's annual energy consumption of bitcoin blockchain is estimated to reach 296.59 TWh in 2024, causing 130.50 million metric tons of carbon emissions, similar to the combined greenhouse gas emissions of the Czech Republic and Qatar. Study findings recommended that Bitcoin blockchain processing's carbon footprint could be reduced more effectively by modifying the energy consumption structure. The research conducted by Köhler & Pizzol (2019) focuses on the effects of Bitcoin mining, one of the most popular blockchain-based cryptocurrencies. The study looked at how much energy mining is supposed to consume and the carbon footprint that Bitcoin mining has. In the study, the well-established Life Cycle Assessment methodology was used to examine the drivers of Bitcoin mining network's past and future environmental impacts. The researchers found that the Bitcoin network consumed 31.29 TWh in 2018 and generated a carbon footprint of 17.29 $MtCO_2$. It released that the geographical distribution of miners and mining equipment efficiency are the primary factors influencing this effect.

In a paper published by Mora et al. (2018), the huge carbon footprint of Bitcoin, which constituted only approximately 0.033 percent of the approximately 314.2 billion cashless transactions made worldwide in 2017, raised environmental concerns. The researchers calculate that if Bitcoin adoption follows that of other popular technologies, it will result in a demand for electricity that will cause global warming to exceed 2 degrees Celsius in a few decades (see Figure 1). The findings indicates that in light of bitcoin's decentralized structure and its desire for maximum economic gains, it is highly likely that bitcoin's validation computation will move to regions with low electricity prices, so carbonizing electricity can be a useful means of reducing bitcoin's carbon footprint - but only if it is done correctly. In their study, the authors suggest that electricity produced from renewable resources is cheaper and more environmentally friendly than electricity produced from fossil fuels.

Figure (1): Estimated of Bitcoin Cumulative $CO_2$ Emissions




*Source: Mora et al. (2018), P2: "As a function of cumulative anthropogenic carbon emissions, in **Figure (1)** The dashed line indicates the COP-21 goal of 2°C global warming, while the gray shaded area reflects $CO_2$-equivalent emissions. The top and lower quantiles' boundaries are coloured red, and the red line represents the median tendency among technologies. Trends for each technology are represented by grey lines*".

In light of the dominance of descriptive and analytical studies about relationships between Bitcoin mining's energy consumptions and climate change, the novelty of this study is that it employs the most advanced econometric model based on wavelet coherence analysis to examine these relationships. Moreover, a review of recent literature on the environmental impact of cryptocurrency mining showed that most studies were conducted on a country or region level, while the present study is focusing more on the global level by examining the association between bitcoin mining energy consumptions that measured by The Cambridge Bitcoin Electricity Consumption Index (CBECI) and Global carbon emissions index.

## Methodology

### *Data and Data Sources*

Weekly frequency data of number of Bitcoin mining, Bitcoin network electricity consumptions and global carbon dioxide emissions index ($CO_2$) are applied in this study to examine their coherence associations over the period 1 January 2012 to 31 December 2021. The data of number of Bitcoin mining coins is obtained from the website of "https://www.blockchain.com/charts#mining" and the data on the weekly amount of electricity consumed by the Bitcoin network are collected from the website "https://ccaf.io/cbeci/index" using the Cambridge Bitcoin Electricity Consumption Index (CBECI), while data on Carbon dioxide global emissions have been obtained from data-stream data-base.

### *Variable Measurements*

Carbon dioxide is a chemical compound that is a colourless gas occurring as an acidic substance with a density of 53 percent greater than dry air (Rahman et al., 2017). A carbon dioxide molecule is composed of two oxygen atoms covalently bonded together. Carbon dioxide is naturally occurring in the atmosphere on Earth. While the process of mining bitcoin involves solving puzzles and creating new bitcoin (O'Dwyer & Malone, 2014). Mining machines contain specialized chips that compete against each other to solve mathematical problems. Bitcoin is awarded to the first bitcoin miner who solves the puzzle in these systems. Additionally, the mining process assures the trustworthiness of the cryptocurrency network (Küfeoğlu & Özkuran, 2019). Cryptocurrencies are mined by bitcoin miners using powerful computers that consume a lot of electricity. This may negatively affect our environment and cause climate change.

The Cambridge Bitcoin Electricity Consumption Index (CBECI) was developed to estimate the amount of daily electricity used by the Bitcoin network. Marc Bevand developed the underlying techno-economic model in 2017 using a bottom-up approach based on the profitability thresholds of various types of mining equipment as the starting point. Due to the inability to determine the exact consumption of electricity in Bitcoin networks, CBECI estimates the amount of electricity used based on hypothetical lower and upper bounds. Furthermore, a best-guess estimate has been generated within these bounds to provide a more realistic estimate of Bitcoin's real electricity consumption.

In particular, the lower bound estimate corresponds to the absolute minimum electricity load of the Bitcoin network. A lower bound estimate is determined by assuming that all miners run the most efficient hardware available. It can be described mathematically as follows:

***Constructing the lower bound estimate***

$$E_{lower}(P_{el}) = \min\left(Eq_{prof}(P_{el})\right) * H * PUE * 60 * 60 * 24 * 365.25,$$

$$with$$

$$E_{lower} - lower\ bound\ power\ consumption\ _{[W]}$$

$$min\left(Eq_{prof}(P_{el})\right) - energy\ efficiency\ of\ the\ most\ efficient\ hardware\ [j/h]$$

$$H - hashrate\ [h/s]$$

$$PUE - power\ usage\ effectiveness$$

***Constructing the upper bound estimate***

Bitcoin's upper bound estimate corresponds to its maximum electrical consumption. In estimating the upper bound, it is assumed that all miners always use the least efficient hardware available at any given time. This is as long as it is still profitable from an electricity cost perspective. Using the following formula, we can calculate the upper bound:

$$E_{upper}(P_{el}) = \max\left(Eq_{prof}(P_{el})\right) * H * PUE * 60 * 60 * 24 * 365.25,$$

$$with$$

$$E_{upper} - upper\ bound\ power\ consumption\ _{[W]}$$

$$max\left(Eq_{prof}(P_{el})\right) - energy\ efficiency\ of\ the\ least\ efficient\ but\ still\ profitables\ hardware\ [J/h]$$

$$H - hashrate\ [h/s]$$

$$PUE - power\ usage\ effectiveness$$

***Constructing the best-guess estimate***

In light of the fact that both lower and upper bound estimates are based on unrealistic assumptions. The index is intended to provide an educated guess that is intended to quantify the actual energy consumption of Bitcoin. This is based on the assumption that all miner types other than Antminer S7 or S9 machines employ a basket of hardware types that are all profitable in electricity terms. This can mathematically presented as follow:

$$E_{estimated}(P_{el}) = \frac{\sum_{i=1}^{N} \partial_i}{N} * H * PUE * 60 * 60 * 24 * 365.25,$$

$$with$$

$$E_{estimated} - best\ guess\ power\ consumption\ _{[W]}$$

$$\frac{\sum_{i=1}^{N} \partial_i}{N} - energy\ efficiency\ of\ the\ least\ efficient\ but\ still\ profitables\ hardware\ [J/h]$$

$$H - hashrate\ [h/s]$$

$$PUE - power\ usage\ effectiveness$$

**Method of Analysis**

***The Wavelet Coherence Analysis***

Based on Morlet (1982), this study examines the relationship between Bitcoin mining's electricity and $CO_2$ index over both time and frequency using the wavelet coherence framework as illustrated in the following:

$$\Psi_{a,b}(t) = \frac{1}{\sqrt{b}} \varphi \left(\frac{t-a}{b}\right), \Psi(.) \subset L^2(\mathbb{R})$$

where*:*

There are two wavelets in the frequency domain: “a” indicates where the wavelet is in the time domain, and “b” specifies where it is located in the time domain.

The wavelet variance is thus normalized by factor $\frac{1}{\sqrt{b}}$ , according to Yang et al. (2017).

Yang, et al (2017) as well as Rua and Nunes (2009) state that continuous wavelet transformations (CWT) are employed using the following form:

$$W_x(a,b) = \int_{-\infty}^{\infty} x(t) \frac{1}{\sqrt{b}} \Psi \left(\frac{t-a}{b}\right) dt$$

The CWT is estimated by $w_{x(a,b)}$ based on the prediction of the mother wavelet $\Psi$ using the sample time series $x(t) \in l^2$ (R). A CWT decomposes and reconstructs a function $x(t) \in l^2$ (R) as illustrated in the following equation:

$$x(t) = \frac{1}{C_\psi}\int_0^\infty \left[\int_{-\infty}^{\infty} W_x(a,b)\psi_{a,b}(t)da\right]\frac{db}{b^2}, b > 0$$

Variances can be expressed as follows when conducting a power spectrum analysis:

$$\|x\|^2 = \frac{1}{C_\psi}\int_0^\infty [|W_x(a,b)|^2 \, da]\frac{db}{b^2}, b > 0$$

In this situation, the square power of $|W_x(a,b)|$ indicates the wavelet power spectrum, which explains local variance *x* (t) scale by scale (Yang, et al, 2017).

Wavelet coherence of two time series (X and Y) is described by Torrence and Webster (1999) as follows:

$$\mathrm{R}_\mathrm{n}^2(b) = \frac{\mathrm{I}B\left(b^{-1}W_n^{xy}(b)\right)\mathrm{I}^2}{B\left(b^{-1}\mathrm{I}W_n^{x}(b)\right)\mathrm{I}^2 . B\left(b^{-1}\mathrm{I}W_n^{y}(b)\right)\mathrm{I}^2}$$

Whereas $\mathrm{R}_\mathrm{n}^2(b)$ the squared wavelet coherency coefficient. $0 \leq \mathrm{R}_\mathrm{n}^2(b) \leq 1$. If these values tend to zero, then we have a weak correlation. Otherwise, we have a strong correlation (Torrence & Webster, 1999). $B$ indicates for a smoothing parameter, and b refers to a wavelet scale. Time series Y is represented by $Wn^x$ (*b*) as a continuous transform. The cross-wavelet transforms of X and Y Time Series are shown in $Wn^{xy}$ (*b*).

***The Phase Patterns***

We used wavelet phase differences to examine the dependency and causality between Bitcoin Mining's units in the circulation and global $CO_2$ index systems following Bloomfield (2004). Using the following equation, we can calculate the phase difference between the two-time series x(t) and y(t):

$$\emptyset_{xy} = tan^{-1}\left(\frac{\Im\{B\left(b^{-1}W_{xy}(a,b)\right)\}}{\Re\{B\left(b^{-1}W_{xy}(a,b)\right)\}}\right), \quad with\, \psi_{xy} \in [-\pi, \pi] \qquad (9)$$

Wavelet coherence maps have arrows indicating phase patterns. It is possible to use phase patterns to identify causal relationships. An arrow pointing to the right indicates that X (t) and

Y (t) are in phase. Conversely, if the arrow points left, X (t) and Y (t) are antiphase. Using the arrow, we can also see the relationship between the two variables. If the arrow is pointing left-up or right-down, it signifies that X (t) follows Y (t). In cases where the arrow points left-down or right-up, Y (t) should follow X (t) (Yang et al., 2017; Pal & Mitra, 2017).

**Findings and Discussions**

Figures (2, 3, 4 and 5) display the outcomes of wavelet coherence associations between the number of Bitcoin mining, minimum electricity consumption (lower bound) estimate, maximum electricity consumption (upper bound) estimate, and the best-guess electricity consumption estimate and global $CO_2$ index. In all figures, the vertical axis shows the frequency, while the horizontal axis shows the time (the lower the frequency, the bigger the scale). In time-frequency space, wavelet coherence identifies regions where two time series are co-varying. In addition, colder colors (blue) in all figures indicate a lower degree of dependence between the series, whereas warmer colors (red) represent significant interdependence between the series. The cold areas outside of the significant areas represent time and frequency without dependence. Right-directed arrows (→) indicate a positive association between Bitcoin's electricity consumption and global $CO_2$ emissions. However, the leftward directed arrows (⟵) suggest a negative association between them. A leading and lagging effect, respectively, can be inferred from the upward (↑) and downward (↓) directed arrows in the series.

In particular, figure (2) presents findings of a wavelet coherence plot of the number of Bitcoin mining (BTCM) and the global $CO_2$ index. From 2012 to 2020, almost no significant relationship is shown between the two indicators, which suggests that an increase in Bitcoin mining isn't associated with an increase in carbon dioxide emissions. As an exception, in 2013, where, during a short run of 4 weeks different frequencies, the red colour may indicate a significant relationship, however there is no arrow to indicate the direction of the relationship. Further, the leftward directed arrows (⟵) at various frequencies of 4 to 32 weeks and time frames of end 2021 suggest an anti-phase negative relationship between these pairs. In addition, figure (3) reports the findings of a wavelet coherence plot of maximum electrical consumption (MAXTWH) by Bitcoin miners and the global $CO_2$ index. The findings indicates that over the period of the end of 2012 and beginning of 2013 the right-directed arrows (→) indicate a positive association between Bitcoin mining's carbon footprint and global $CO_2$ emissions. More so, the arrow (↑) is pointing right-up is signified that Bitcoin mining produce more $CO_2$ emissions at various frequencies of (4-32) weeks and (65) week in 2012, however, after 2013 there is an absent of coherence association between these pairs.

Similarly, Figure (4) and (5) present findings of a wavelet coherence plot of minimum electrical consumption (MINTWH), a best-guess (GUESS) estimate of energy consumption by Bitcoin miners, and the global $CO_2$ index. In both figures, the rightward directed arrow (→) at various frequencies and time frames (2012 and 2013) suggests an in-phase (positive) relationship between Bitcoin mining's electricity consumption and global $CO_2$ emissions. Nevertheless, after 2013 to 2021, there is no meaningful coherence association between these pairs, except for the variance frequency of (16-13) weeks and the time frame from the middle of 2018 to the beginning of 2020. Further, the left-directed arrows (←) indicate anti-phase (negative) association between Bitcoin mining's electricity consumption and global $CO_2$ emissions. Furthermore, the left-up directed arrows (↑) indicate global $CO_2$-legged Bitcoin mining's electricity consumption over the period 2018 to 2021, on a frequency band of (16-32) weeks. The reason for this is that at the beginning of 2018, governments started becoming more aware of the environmental impact of Bitcoin mining and of its energy consumption, which prompted many governments to ban crypto mining. As an example, the Chinese government banned crypto mining in September 2019 in an effort to create its own digital currency backed by fiat. Because of this move, many miners have moved to countries with cheaper power over the world.

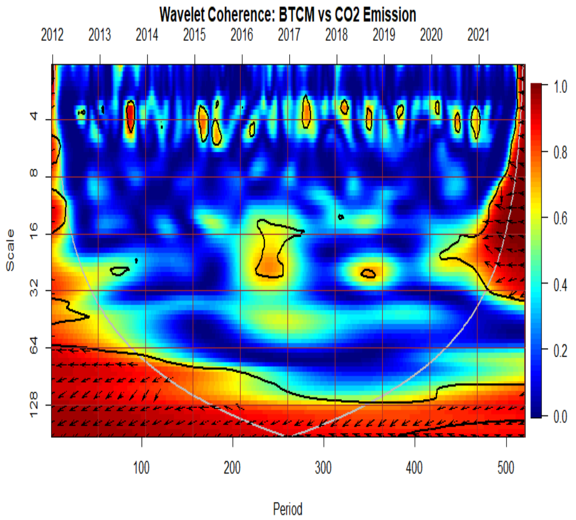



Figure (2): wavelet coherence between (BTCM & $CO_2$)

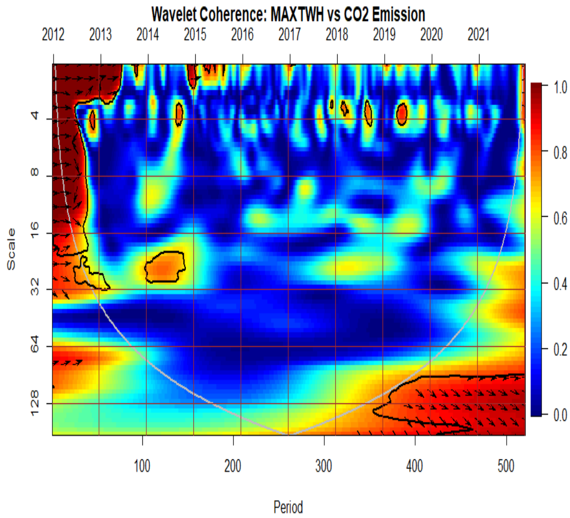



Figure (3): wavelet coherence between (MAXTWH & $CO_2$)

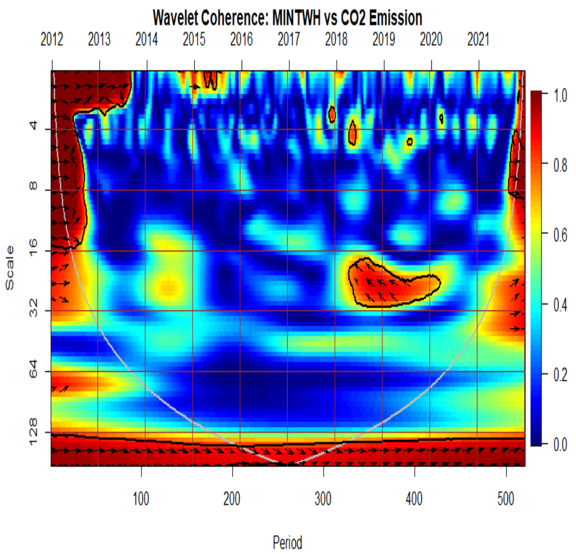



Figure (4): wavelet coherence between (MINTWH & $CO_2$)

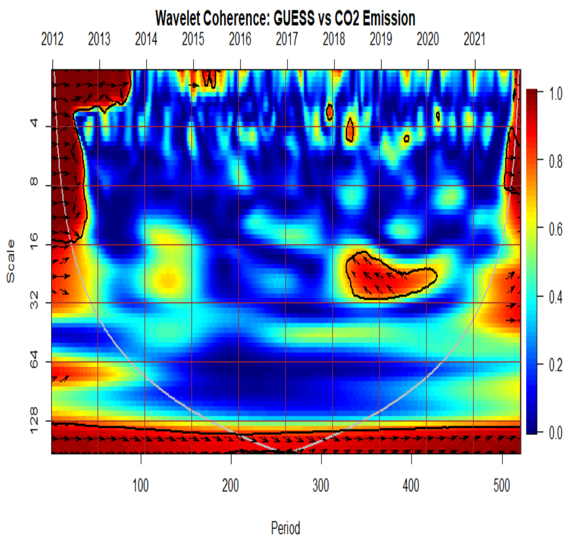



Figure (5): wavelet coherence between (GUESS & $CO_2$)

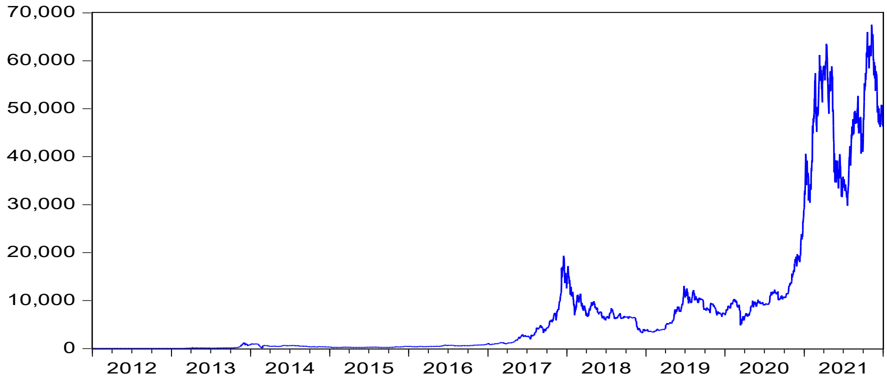



Figure (6): Bitcoin daily price level over the period (2012 to 2021).

Moreso, the cost of electricity used by bitcoin miners is also considered a key determinant of the size of bitcoin mining, as well as its environmental footprint. As shown in figure (6), especially at the beginning of 2018, when the price level of bitcoin started to drop, bitcoin mining became unprofitable for miners, resulting in reduced mining activity. Thus, as the cost of mining increases, the number of bitcoins mined will decrease. This is in line with Krause and Tolaymat (2018), who argue that even with continued network hash rate growth for cryptocurrency mining and increased energy consumption, the carbon cost is still a significant concern. Overall, the results suggest that the amount of energy consumed per bitcoin mined is expected to decrease as the number of hash rates on the network increases.

Furthermore, Kruse (2022) demonstrates that in their campaign, called “Change the Code Not the Climate”, which is coordinated by Greenpeace USA, Environmental Working Group, and other groups that oppose mining bitcoins, they are advocating that bitcoin mining be changed to address its large carbon footprint. The Bitcoin miners use "proof of work" software code to validate and secure bitcoin transactions, which requires massive computing power to run it. Miner's proof of work verifies that they have solved the complex cryptographic puzzles required to create bitcoins. On the contrary, "Proof of stake" software code has been proposed as an alternative system that will reduce its energy consumption by 99 percent. Miners pledge their coins to verify transactions in a proof of stake model, which imposes penalties for inaccurate information. According to the campaign, without a change to the code, bitcoin's code will still encourage maximum energy use. Therefore, some bitcoin miners have recently switched over to using the new software code called "Proof of stake", while others have switched to wind and solar energy to power their operations.

**Conclusion**

The aim of this study was to investigate the coherence relationship between bitcoin mining's energy consumption (BTCM, MAXTWH, MINTWH, GUESS) and global carbon emissions index. The study applied a wavelet coherence analysis approach to investigate these relationships. The findings of the study indicate that before 2013, there was an in-phase association between Bitcoin mining's energy consumption and global carbon emissions index at various frequencies and time frames. While after 2013 the coherence analysis results indicate the absence of associations between Bitcoin mining's energy consumptions and the global carbon emissions index. Interestingly, the association was anti-phase during the period of beginning of 2018, when the price of Bitcoin dropped sharply, and bitcoin mining businesses were not profitable. The antiphase association may be due to government warnings about the environmental impacts of cryptocurrencies' mining, which may have played a significant role in the closure of several mining businesses in the Asian region, like China. The results of this study suggest that cryptocurrency miners must take the environmental impact side of mining seriously and consider using alternative energy such as wind or solar to power their operations. Additionally, the study suggests that bitcoin miners should switch from "proof of work" as a means of verifying transactions to "proof of stake," which is expected to reduce bitcoin mining's energy consumption by 99 percent.

For further research It is possible to extend the model of this study to include other cryptocurrencies' mining energy consumptions to examine the associated environmental impact side effects and their influence on global carbon dioxide emissions.

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