International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2025, 15(5), 402-411.

Trading Gain, Environmental Pains of Bitcoin Activity: Emissions, Electricity, and Electronic Waste

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Received: 09 April 2025 **Accepted:** 24 July 2025 **DOI:** https://doi.org/10.32479/ijeep.20226

ABSTRACT

This study was conducted to examine the impact of rising bitcoin activity on carbon emissions, electricity consumption, and e-waste. The study utilizes data from 2020 to 2023 and applies Ordinary Least Squares (OLS) regression analysis, addressing potential issues such as heteroscedasticity, autocorrelation, and multicollinearity. The results of this study show that Bitcoin return and volume have a significant effect on increasing the amount of carbon emissions, while greater volatility may slightly reduce emissions. Global electricity consumption is significantly affected by Bitcoin volatility and hashrate. The amount of global e-waste is strongly influenced by transaction volume and mining activity. These findings remain robust under OLS, Robust Standard Errors, and Newey-West estimations, aligning with previous studies on the environmental impact of cryptocurrency. Suggesting rising Bitcoin activity indicates a measurable environmental impact, arguing needs for stronger regulatory oversight and development of more environmentally friendly technologies. This research distinguishes itself from previous studies by not solely focusing on cryptocurrency mining. Instead, it also analyzes how the increasing volume of cryptocurrency transactions directly contributes to rising carbon emissions, electricity consumption, and electronic waste.

Keywords: Bitcoin, Cryptocurrency, Carbon Emissions, Electricity Consumption, Electronic Waste, Environmental Impact, Energy Use
JEL Classifications: G0, G23, G3

1. INTRODUCTION

The amount of carbon dioxide (CO_2) emissions should be a major concern, considering the impact of carbon dioxide emissions which have a significant impact on global warming and climate change (Gürsoy et al., 2024). Public awareness of the issue of carbon dioxide emissions continues to increase, especially regarding the impacts caused by increased CO_2 emissions, the use of electricity resources and the increase in electronic waste which can worsen environmental health, but this has a much worse impact than the public expected. Crypto is one of the main contributors to global warming, due to its high carbon footprint despite its promising application in which the Bitcoin alone is estimated could increase global temperatures by 2 °C in the next three decades. There are millions of transactions done every single day on the crypto market, since the market opens 24 hours a day. However, cryptocurrency's electricity consumption is far greater than its technical performance. Though, Market Capitalization of cryptocurrency has grown exponentially in the last decade. Rising energy consumption of bitcoin, as a leading cryptocurrency coin, is not a trivial matter (Corbet et al., 2019; Huynh et al., 2022).

According to the estimation of electrical consumption from the University of Cambridge, Bitcoin's energy consumption is up to 0.38% of global electricity consumption surpassing electricity consumption of a few countries, like Belgium and Finland in November 2021. Bitcoin has used electricity more than Thailand with estimated around 190 TWh. a lot of these energy are generated by burning fossil fuels, creating emission around 90 million metric tons of CO_2 per year. A number that continues to rise around 22 million tons of CO_2 per year 2 years ago. This is reinforced by a compilation of various studies conducted between 2014 and 2018 on electricity consumption. Estimates of Bitcoin's power requirements during this period ranged from 2.5 GW to 14.8 GW, with annual energy consumption estimated between 22 TWh and 105 TWh in 2018. By March 2020, Bitcoin's power consumption was estimated at 4.3 GW, accounting for approximately 68% of the total energy consumption of 6.5 GW by the top 20 cryptocurrencies. Recent data from the University of Cambridge Bitcoin Energy Consumption Index (CBECI) indicate that Bitcoin's maximum and minimum energy consumption range between 26.09 TWh and 184.82 TWh, with an average estimate of 69.63 TWh. In 2021, the Digiconomist blog reported Bitcoin's energy consumption at 135.12 TWh and Ethereum's at 55.01 TWh. A study conducted by the University of Cambridge in 2020 revealed that, on average, 39% of the energy used in Proof-of-Work mining comes from renewable sources. However, a 2018 study suggested a higher figure of 78%. Despite this, the significant carbon footprint indicates that the majority of energy usage still relies on fossil fuels (source: https://ccaf.io/cbnsi/cbeci). Bitcoin's electricity usage is mainly contributed by mining hardware; the more powerful the Graphic processing unit (GPU) is, the more energy is used. Because the GPU hardware is used constantly for 24 hours, it will wear faster than normal GPU usage, directly increasing electronic waste. Moreover, the frequent GPU hardware changes highly contribute to electrical waste. Electronic waste (e-waste) refers to waste generated from the disposal of electrical or electronic devices. Although seldom a central topic of discussion, e-waste poses a serious environmental challenge. It contains toxic chemicals and heavy metals that can contaminate soil, air, and water, especially when recycling processes do not meet proper standards (de Vries and Stoll, 2021). This issue is exacerbated by the rapid development of technology and the increasing global usage of electronic devices. Each year, millions of tons of e-waste are produced, and the volume continues to grow rapidly. Among the contributors to e-waste are cryptocurrency mining devices.

Furthermore, de Vries et al. (2022) highlighted that cryptocurrency mining operations rely on specialized hardware designed exclusively for mining. These devices typically have a short lifespan, increasing the likelihood of becoming e-waste, which could harm the environment and human health. Annually, Bitcoin generates approximately 30.7 metric kilotons of e-waste. With the rising number of Bitcoin miners and fluctuating Bitcoin prices, this figure is expected to grow (de Vries and Stoll, 2021). Although regulations governing the import and export of e-waste have been enacted in various parts of the world (Jain et al., 2023), their implementation has not yet been effective. Tackling e-waste issues should be a top priority given its potential to harm both the environment and public health. Therefore, it is crucial to establish dedicated institutions to propose solutions that can mitigate the growing impact of e-waste (Jain et al., 2023).

Numerous studies have been conducted globally on the relationship between cryptocurrency and the increase in carbon emissions, electricity consumption, and electronic waste. Most of these studies focus on the environmental footprint of popular cryptocurrencies such as Bitcoin. For instance, de Vries (2018) explores Bitcoin's rising energy consumption and presents various methods to estimate its current and future energy use, including projections of Bitcoin mining machine production. Similarly, Stoll et al. (2019) examine Bitcoin's carbon footprint, including methodologies for estimating its energy consumption and carbon emissions using empirical data from various sources. Another related study, conducted by de Vries and Stoll (2021), addresses the growing issue of electronic waste resulting from Bitcoin mining, proposing methods to estimate the volume of such waste and strategies to mitigate it. However, this research distinguishes itself from previous studies by not solely focusing on cryptocurrency mining. Instead, it also analyzes how the increasing volume of cryptocurrency transactions directly contributes to rising carbon emissions, electricity consumption, and electronic waste. This approach provides a more comprehensive understanding of the environmental impact of the growing adoption of cryptocurrencies, examining both the energy consumption from mining and the environmental footprint of heightened transaction activity.

The aim of this study is to investigate the correlation between the increasing volume of cryptocurrency transactions and the subsequent rise in carbon emissions, electricity consumption, and e-waste production. The data used in this study focuses on Bitcoin, which constitutes a significant portion of the cryptocurrency market capitalization. This study provides a deeper understanding of the environmental impact associated with Bitcoin's growing usage, particularly concerning its contribution to harmful emissions. The structure of this paper is as follows: section 2 discusses the literature review and hypothesis development, section 3 explains the research methodology, section 4 presents the research findings and discussion, and section 5 provides a general summary of the findings, identifies limitations encountered during the study, and offers recommendations for future research.

2. LITERATURE REVIEW

The increased use of electricity has led to a rise in carbon emissions and electronic waste, with the growing volume of cryptocurrency transactions drawing attention to its environmental impact. There are several studies investigating the impact of carbon emission, electrical consumption, and electronic waste on Bitcoin and the results are positive (Anon et al., 2020; Balcilar et al., 2017; Clough and Edwards, 2023; Conrad et al., 2018; de Vries, 2019; de Vries et al., 2022; de Vries and Stoll, 2021; Fagundes Isolani, 2023; Garay et al., 2017; Goodkind et al., 2020; Gürsoy et al., 2024; Huang et al., 2022; Jiang et al., 2021; Kohli et al., 2023; Krause and Tolaymat, 2018; Küfeoğlu and Özkuran, 2019; Li et al., 2019; Nofer et al., 2017; Sarker et al., 2023; Stoll et al., 2019; Zade et al., 2019). The studies found there are correlations between Bitcoin's return, volatility, transaction volume, hash rate, network difficulty, greenhouse gas emission, electricity consumption, electrical have an impact on rising carbon emissions, electrical consumption, and electronic waste. Because of Bitcoin's technology, requiring enormous computing power significantly drives the need for more power hence increasing the need of electricity, directly impacting carbon emissions, electricity consumption, and electronic waste.

A study by de Vries (2019), based on the Bitcoin Energy Consumption Index, revealed that as Bitcoin's transaction volume and computational power requirements increase, so does the amount of carbon emissions produce. Similarly, research by Küfeoğlu and Özkuran (2019), demonstrated a positive correlation between energy consumption and Bitcoin's price. A study on electronic waste by de Vries et al. (2022) found that the increasing complexity of mining and transaction volume accelerates the obsolescence of hardware, contributing to a surge in e-waste. These three factors are interconnected. The rise in transaction volume drives higher computational power demands, directly increasing electricity consumption. This, in turn, leads to higher carbon emissions, particularly in regions reliant on fossil fuels rather than renewable energy sources. Moreover, the growing demand exacerbates hardware obsolescence, resulting in increased electronic waste.

Various research on rising bitcoin return has been done, research done by Clough and Edwards (2023), states that Bitcoin has become one of the financial instruments used by investors and financial institutions to store value and obtain returns as its reward. The derivatives created and traded by investors influence Bitcoin's price. With the growing popularity of Bitcoin, more people are becoming interested in Bitcoin mining. The research by Gürsoy et al. (2024), found that higher carbon allowance prices reflect a market response to increasing carbon emissions, as higher price signifies greater scarcity of emission allowances and a higher cost for companies to pollute. The positive correlation found between bitcoin returns and carbon allowance prices suggests that, indirectly, higher carbon emissions are reflected in higher allowance prices and are associated with higher bitcoin returns. Since Bitcoin mining is very energy intensive. A large portion of Bitcoin's electricity generation comes from fossil fuels, resulting in higher carbon emissions and higher electricity consumption in the Bitcoin mining process. Therefore, the observed positive correlation between Bitcoin returns and high electricity consumption for mining.

Not only how the return affects bitcoin return on carbon emission, electricity consumption, and electrical waste is examined, but also volatility is one of the fields being studied by Conrad et al. (2018) broke down volatility into short-term and long-term components and studied the correlation between Bitcoin and other indices, such as the Baltic Dry Index. Balcilar et al. (2017) found that Bitcoin's price and volatility drivers can include sentiments or signals, such as opinions and trading volumes, which may lead to an increase in Bitcoin mining activities. Furthermore, research which focuses on Bitcoin's transaction volume is being done by Kohli et al. (2023) and research by Krause and Tolaymat (2018), explores the impacts of Bitcoin's rising transaction volume. When more bitcoin volumes are being traded, demands from blockchain platforms arise, leading to more power usage when mining and executing transactions of Bitcoin. So it can be concluded that an increase in the volume of bitcoin transactions has an effect on increasing the amount of energy consumption globally. Global energy consumption rose to approximately 170,000 TWh in 2022, a 5% increase from the previous year, with about 17% of this total attributed to electricity generation. Among the significant contributors to this growing energy demand are blockchain platforms, including cryptocurrencies (Balcilar et al., 2017).

The energy-intensive nature of cryptocurrencies, particularly Bitcoin, results in substantial carbon emissions. For instance, Bitcoin's carbon footprint was estimated at 63 $MtCO_2$ in 2018 and 55 $MtCO_2$ in 2019. A study in 2018 reported Bitcoin's emissions at 38.73 $MtCO_2$, equivalent to Denmark's annual emissions, over 700,000 Visa transactions, or nearly 49,000 hours of YouTube viewing (Kohli et al., 2023). These figures emphasize the environmental costs associated with cryptocurrency operations and their role in broader sustainability challenges. As Bitcoin's transaction volume increases, so does the demand for computational power, as transactions are verified through energy-intensive mining processes. This relationship amplifies energy consumption and subsequently raises carbon emissions. Research by Krause and Tolaymat (2018) highlights that the electricity demand for mining operations scales with transaction volume due to the competitive nature of proof-of-work systems. Mining's profitability drives the deployment of energy-intensive Application-Specific Integrated Circuits (ASICs), significantly increasing energy consumption and carbon emissions. Additionally, Bitcoin's e-waste problem correlates with transaction volume. The average lifespan of mining hardware is estimated at just 1.3 years, leading to approximately 30.7 metric kilotons of e-waste annually, comparable to the small IT equipment waste of the Netherlands (de Vries and Stoll, 2021). These discarded devices contribute to environmental degradation if not recycled appropriately. The high turnover rate of mining hardware is driven by the need of increasingly more powerful hardware to maintain competitive hashrates, since mining difficulty and network security scale with total computational power and hashrate used in proof of work (POW) process.

In addition, mining hashrate is the measurement of the computational power used in the proof-of-work process within a cryptocurrency network, either collectively or individually. Hashrate is utilized to determine the mining difficulty level of a blockchain network and its security scale. A hash is a randomly generated alphanumeric code. Hashing is the process of guessing the code or coming as close as possible, carried out by computers in the network. Hashrate measures how many guesses a miner can generate per second. Hash indicates the popularity level of a cryptocurrency. However, it also reveals the strength of a miner's competitors or peers. The higher the amount of dedicated computational power, the greater the miner's chance of earning rewards. Studies from Li et al. (2019) found that a higher hashrate leads to higher electricity consumption since hashrate is the processing power of the cryptocurrency network. Miners solving complex cryptographic problems to validate transactions and add new blocks to blockchain. The more powerful the hardware is, the higher hashrate, leading to more electricity being consumed in the process. While, the link between hashrate and carbon emissions is indirect but clear. Mining operations largely generated from fossil fuels in many regions. Leading to higher hashrate which as a result has a greater carbon footprint.

The speed of mining, influenced by hashrate, also correlates with network difficulty, a metric that indicates how hard it is to mine a new block in a specific cryptocurrency. More computational power is needed for the network, and the difficulty adjusts to ensure blocks are mined at a consistent rate. Although faster hashrate may initially lower difficulty due to quickly solve rate, the network will respond by increasing difficulty to maintain balance. High difficulty level means more power required to solve a valid hash, thereby enhancing network security. According to Garay et al. (2017), difficulty is regulated by a target value: the higher the target, the easier the block is to solve. Block chain itself is a sequence of data and packages each containing multiple transactions (Nofer et al., 2017). Research by Zade et al. (2019) emphasized that power demands are closely tied to rising network difficulty and improvements in mining hardware efficiency. While advanced GPU can solve blocks faster, they also draw large amounts of energy, leading to higher electricity usage and increasing electronic waste.

When mining Bitcoin, it requires a significant amount of energy. With the primary use of hardware such as GPUs that will consume vast amounts of electricity. High energy demand from GPUs leads to increased electricity consumption contributing to greenhouse gas emissions, especially in regions that rely on fossil fuel as an energy source. The rapid cycle of hardware usage and replacement driven by the need for efficiency and performance in mining leads to a rise in electronic waste, posing an additional environmental concern.

Greenhouse gas emissions, refer to gases into earth's atmosphere that trap heat and contribute to greenhouse gas effect, which leads to global warming and climate change. These gases allow sunlight to enter the atmosphere but prevent them from escaping into space. This warming effect is crucial for maintaining life on earth but has been intensified by human activities. Research done by Fagundes Isolani (2023), found that Bitcoin mining is energy intensive, requiring vast amounts of electricity to solve complex mathematical problems for transaction validation. Energy consumption rivals that of entire countries leading to high carbon emissions. A significant portion of energy used for Bitcoin mining comes from fossil fuels, further exacerbating greenhouse gas emissions. Which leads to more hardware usage thus far increasing electronic waste.

Bitcoin mining, driven by energy-intensive computational processes that often rely on fossil fuels, has significant environmental consequences, particularly in carbon emissions. Studies estimate annual energy consumption and carbon emissions from Bitcoin mining at approximately 4.58 TWh and 22.9 $MtCO_2eq$ (Stoll et al., 2019). Projections indicate a dramatic increase to 296.59 TWh and 130.50 $MtCO_2eq$ by 2024, comparable to the energy consumption of nations like Mexico or Italy (Jiang et al., 2021). Notably, Bitcoin ranks among the top 10-15 global energy consumers, with regions like coal-dependent China facing heightened environmental concerns. China's 2021 ban on cryptocurrency mining in several provinces further underscores these issues (de Vries et al., 2022). In the United States, cryptocurrency production contributes 0.2-0.3% of global greenhouse gas emissions, potentially jeopardizing national and international climate targets (Sarker et al., 2023). During Bitcoin's price surge from $1,000 to $20,000 in 2017, the industry's profitability prompted rapid expansion. For instance, Bitmain sold 1.87 million mining devices in the first half of 2018 alone, a substantial increase compared to prior years (de Vries and Stoll, 2021). This expansion has directly escalated energy consumption and electronic waste, emphasizing Bitcoin's resource intensity.

Recent analysis reveals even more troubling trends. In 2022, crypto mining and data centers collectively consumed 2% of global electricity, with forecasts projecting a rise to 3.5% by 2027, equating to Japan's current energy use. This surge could contribute approximately 0.7% of global carbon dioxide emissions by 2027 (source: https://www.imf.org/en/Blogs/Articles/2024/08/15/carbon-emissions-from-ai-and-crypto-are-surging-and-tax-policy-can-help). Each Bitcoin transaction requires as much electricity as the average person in Ghana or Pakistan uses in 3 years, exemplifying its disproportionate energy demands. Moreover, Bitcoin mining's climate and health impacts are significant. In 2018, its carbon footprint equaled those of countries like Jordan and Sri Lanka, with each $1 of Bitcoin mined causing $0.49 in damages in the United States and $0.37 in China (Goodkind et al., 2020). Extreme predictions warn that unchecked Bitcoin emissions could exacerbate global warming beyond 2°C, undermining global efforts to meet the Paris Agreement targets (de Vries and Stoll, 2021).

Efforts to mitigate these impacts include advocating for renewable energy adoption in mining operations and introducing targeted policies like carbon taxes. A global carbon price, coordinated internationally, could significantly curb emissions, promote cleaner power sources, and encourage energy efficiency. Tax incentives for renewable energy usage and stricter regulations on high-emission mining operations are also proposed solutions to address these escalating environmental challenges.

These environmental impacts are not limited to carbon emissions alone. Another major consequence of energy intensive Bitcoin mining is the rapid turnover rate of mining hardware, which significantly contributes to the growing issue of Bitcoin electronic waste. Electronic waste is discarded electrical or electronic devices, which includes a wide range of items such as computers, smartphones, televisions, refrigerators, etc. Environmental concern stems from toxic chemicals and heavy metals like lead, mercury, and cadmium found in electronic components which seep into soil and water if disposed improperly. In the growing cryptocurrency market, more and more people have started to mine Bitcoin, which consumes vast amounts of electricity and requires more and more computing power. Research suggests that rapid advancements in mining hardware efficiency lead to shorter lifespans for mining on average 1.29 years. Resulting in significant amounts of e-waste being generated annually (Fagundes Isolani, 2023). Bitcoin mining requires enormous amounts of electricity which in 2017 alone released approximately 69 million metric tons of carbon dioxide emissions as a result of bitcoin mining (Anon et al., 2020). Proof of work (POW) algorithms contribute to increased energy consumption, and carbon emission. POW cryptocurrency mining consumed massive amounts of electricity that Bitcoin's global electricity consumption increased more than threefold between 2019 untill 2021 (Huang et al., 2022). There are a number of studies investigating the correlation between Bitcoin's electrical waste with the rise of carbon emission, electrical consumption and electronic waste on Bitcoin and the results are conclusive which indicates Bitcoin electrical waste has a positive correlation with rising carbon emissions, electrical consumption, and electronic waste. (Anon et al., 2020; Fagundes Isolani, 2023; Huang et al., 2022).

Based on the previous research discussed (Anon et al., 2020; Balcilar et al., 2017; Clough and Edwards, 2023; Conrad et al., 2018; de Vries, 2019; de Vries et al., 2022; de Vries and Stoll, 2021; Fagundes Isolani, 2023; Garay et al., 2017; Goodkind et al., 2020; Gürsoy et al., 2024; Huang et al., 2022; Jiang et al., 2021; Kohli et al., 2023; Krause and Tolaymat, 2018; Küfeoğlu and Özkuran, 2019; Li et al., 2019; Nofer et al., 2017; Sarker et al., 2023; Stoll et al., 2019; Zade et al., 2019), the hypothesis are as follow:

H_1: There is correlation between rising Bitcoin activity on rising carbon emissions

H_2: There is correlation between rising Bitcion activity on rising electricity consumption

H_3: There is correlation between rising Bitcoin activity on rising electronic waste.

3. RESEARCH METHODS

This study utilizes daily data from January 1, 2020 to December 31, 2023. The selection of this period is based on several significant considerations. First, this timeframe captures relevant market volatility trends, including significant price fluctuations during the COVID-19 pandemic, which had a profound impact on the global economy, including the cryptocurrency market itself (de Vries and Stoll, 2021). Second, this period marks the beginning of the maturation phase of the cryptocurrency market, as evidenced by the broader adoption of cryptocurrencies and the increasingly clear regulations surrounding them, which have directly influenced market dynamics. Moreover, technological advancements during this period—such as improvements in mining efficiency and energy usage for cryptocurrencies—make it a highly relevant timeframe for further analysis. Another key reason is the availability and reliability of data during this period. Data from earlier years lacks standardization and fails to reflect current market conditions. Meanwhile, data from January 2024 to December 2024 is excluded because, at the time this study was conducted, that year had not yet concluded. By focusing on this selected timeframe, the study ensures that the analysis is based on complete and reliable data, enabling the derivation of valid and relevant conclusions.

This study was conducted to examine the impact of rising bitcoin activity on carbon emissions, electricity consumption, and e-waste. The dependent variables are, carbon emission (CE), electricity consumption (EC), and electrical waste (EW). Meanwhile, the independent variable is bitcoin activity. Carbon emissions are proxied by worldwide carbon emissions and the data was collected from carbon monitor (source: https://carbonmonitor.org/). Electrical consumption is proxied by worldwide electricity consumption with data gathered from carbon monitor (source: https://power.carbonmonitor.org/). Electrical waste is proxied by worldwide electronic waste gathered from roundup statistics (source: https://theroundup.org/global-e-waste-statistics/). Bitcoin activity is proxied by Bitcoin return (R), Bitcoin volatility (Vly), Bitcoin volume (Vol), Mining hashrate (Hr), Network difficulty (NetDiff), Bitcoin greenhouse gas emission (BTC.GGE), Bitcoin electrical consumption (BTC.EC), Bitcoin E-Waste (BTC.EW).

In this study, Bitcoin price data is used as the basis for calculating the value of Bitcoin return and Bitcoin volatility. Data related to Bitcoin transaction volume is obtained from bitcoinity, previous study who obtained data from bitcoinity.com are the research done by Lo and Wang (2014). Data related to Bitcoin hashrate, and Bitcoin network difficulty is obtained from Bitcoin visuals, which is then processed into natural logarithm (ln) form, previous study that also obtained their data from Bitcoin visuals are the research done by Divakaruni and Zimmerman (2023). Data related to Bitcoin electricity consumption and Bitcoin greenhouse gas emissions are obtained from the Cambridge Bitcoin Electricity Consumption Index (CBECI), previous study that also obtained their data from Cambridge Bitcoin Electricity Consumption Index (CBECI) are the research done by Gallersdörfer et al. (2020). We also obtain data related to Bitcoin E-Waste from digiconomist.net, a platform widely recognized for launching and maintaining the Bitcoin Energy Consumption Index since late 2016. The platform was founded by Alex de Vries in 2014; de Vries is a researcher who conducts cryptocurrency-related research.

This study will employ OLS analysis. We acknowledge that using OLS we could face risks for heteroscedasticity, autocorrelation, and multicollinearity. OLS is a widely used method for estimating relationships between variables. Provide a clear and interpretable model for assessing how cryptocurrency correlates with carbon emissions, electricity usage, and e-waste. The primary assumption of OLS includes Linearity, where the relationship between dependent and independent variables is linear. Homoscedasticity, in which the variance of residuals is constant across all levels of independent variables. No autocorrelation with residuals is independent across observations. Normality in which the residuals are normally distributed. Ordinary Least Square (OLS) is employed, and there are three models as follow:

Model 1: Y1

$$CEt = \beta 0 + \beta 1 \cdot R_t + \beta 2 \cdot Vly_t + \beta 3 \cdot Vol_t + \beta 4 \cdot Hr_t + \beta 5 \cdot NetDiff_t + \beta 6 \cdot BTC.GGE_t + \beta 7 \cdot BTC.EC_t + \beta 8 \cdot BTC.EW_t + \epsilon_t$$

Model 2: Y2

$$ECt = \beta 0 + \beta 1 \cdot R_t + \beta 2 \cdot Vly_t + \beta 3 \cdot Vol_t + \beta 4 \cdot Hr_t + \beta 5 \cdot NetDiff_t + \beta 6 \cdot BTC.GGE_t + \beta 7 \cdot BTC.EC_t + \beta 8 \cdot BTC.EW_t + \epsilon_t$$

Model 3: Y3

$$EWt = \beta 0 + \beta 1 \cdot R_t + \beta 2 \cdot Vly_t + \beta 3 \cdot Vol_t + \beta 4 \cdot Hr_t + \beta 5 \cdot NetDiff_t + \beta 6 \cdot BTC.GGE_t + \beta 7 \cdot BTC.EC_t + \beta 8 \cdot BTC.EW_t + \epsilon_t$$

This study employs a stationarity test to ensure that the data we use in this study is stationary. This test is important to do, because if there is data that is not stationary, it can produce less accurate results in time series analysis. The reason we conduct the stationarity test is because the stationarity test is a statistical method that is suitable for time series data. In this study, we chose to use the Augmented Dickey-Fuller (ADF) Test to test the stationarity of the data. The Augmented Dickey-Fuller (ADF) Test is a developed version of the Dickey-Fuller test. The procedure performed in the Augmented Dickey-Fuller (ADF) Test is also similar to the Dickey-Fuller test, which tests the null hypothesis that the data has a unit root which indicates the data is not stationary (Mushtaq, 2011).

The stationary test is exercised using Augmented Dickey Fuller, the result are shown in Table 1, for the variable Carbon Emissions, Network Difficulty, Bitcoin Greenhouse Gas Emissions, Bitcoin Electricity Consumption, and Bitcoin E-Waste shows the result that the variable has a unit root, because hypothesis 0 which states that the variable does not have a unit root must be rejected, because the P-value of the variable is greater than the 10% significance level, we perform a differencing process on our variable so that the data can become stationary before being used in the regression model. For variable Electricity Consumption, the results show that the variable does not have a unit root, because hypothesis 0 which states that the variable does not have a unit root must be accepted, because the P-value of the variable is smaller than the 10% significance level. For the variable Bitcoin E-Waste, Return, Volatility, Volume, and Hashrate, the results show that the variable does not have a unit root, because hypothesis 0 which states that the variable does not have a unit root must be accepted, because the P-value of the variable is smaller than the 1% significance level.

Table 1: Stationary test

Variable	t-stat	P-value
Carbon Emissions (CE)	−1.784	0.3886
Electricity Consumption (EC)	−2.686	0.0766*
Electrical Waste (EW)	−3.910	0.0020***
Return (R)	−30.135	0.0000***
Volatility (Vly)	−28.193	0.0000***
Volume (Vol)	−15.713	0.0000***
Hashrate (Hr)	−4.670	0.0001***
Network Difficulty (NetDiff)	−0.099	0.9495
Bitcoin Greenhouse Gas Emissions (BTC.GGE)	−0.655	0.8580
Bitcoin Electricity Consumption (BTC.EC)	−0.521	0.8879
Bitcoin E-Waste (BTC.EW)	2.373	0.9990

*Sig at 10%, **Sig at 5%, ***Sig at 1%

Table 2: Autocorrelation test

Dependent variable	Prob >Chi-square
Carbon emissions (CE)	0.000
Electricity consumption (EC)	0.000
Electrical waste (EW)	0.000

Table 3: Heteroscedasticity test

Dependent variable	Prob >Chi-square
Carbon emissions (CE)	0.0753
Electricity consumption (EC)	0.0000
Electrical waste (EW)	0.0000

Table 4: Multicollinearity test

Variable	VIF	1/VIF
Bitcoin electricity consumption (BTC.EC)	5.99	0.166808
Bitcoin greenhouse gas emissions (BTC.GGE)	5.93	0.168622
Volume (Vol)	2.18	0.458696
Volatility (Vly)	2.13	0.468524
Hashrate (Hr)	1.06	0.943211
Bitcoin E-Waste (BTC.EW)	1.05	0.956209
Return (R)	1.02	0.981369
Network difficulty (NetDiff)	1.01	0.987320
Mean VIF	2.55	

An autocorrelation test is performed in regression analysis to ensure that the error terms are uncorrelated. Ignoring autocorrelation can lead to biased coefficient estimates and incorrect standard error calculations, thus compromising the reliability of the results. Detecting and addressing autocorrelation is essential for maintaining the robustness and validity of the regression model. In this study, we chose to use the Breusch-Godfrey test to test the autocorrelation of the data. The Breusch-Godfrey test is particularly suited for detecting autocorrelation in models with lagged dependent variables or multiple explanatory variables. This test allows for regressors that are not strictly exogenous, higher order of autoregressive schemes, simple or higher order of moving averages of white noise error term (ISLAM and TOOR, 2019). The other reason that we use the Breusch-Godfrey test uses a Lagrange Multiplier framework, which performs well in both small and large samples for detecting autocorrelation, its asymptotic equivalence to other advanced methods, like the Durbin - Watson h test for specific cases, demonstrates its versatility and appropriateness for modern econometric applications.

Based on the autocorrelation test using the Breusch-Godfrey method, variable Carbon Emissions, Electricity Consumption, and Electrical Waste, shows the result that the variable has a autocorrelation problem, because the null hypothesis stating that there is no serial correlation is rejected, as the P-value is less than the 1% significance level. The autocorrelation test results is shown in Table 2.

The heteroscedasticity test is used to detect the presence of inequality of variance in the regression model. If the regression model shows homoscedasticity, it means that there is no inequality of variance between residuals from one observation to another, which indicates that the regression model is good and does not indicate heteroscedasticity (Puspa et al., 2021). The following are criteria that can be used to identify heteroscedasticity: (a) The existence of a widening and narrowing wave pattern, or dots that form a regular pattern, indicates heteroscedasticity; (b) No pattern is formed and the points are scattered above and around the number 0 on the Y-axis, indicating that the test performed shows homoscedasticity.

Based on the heteroscedasticity test using the Breusch-Pagan/Cook-Weisberg method shown in Table 3, variable Carbon Emissions, Electricity Consumption, and Electrical Waste, shows the result that the variable has a heteroscedasticity problem, because the null hypothesis stating that there is no heteroscedasticity is rejected, as the probability value (0.0000) is smaller than the general significance level (10%).

Multicollinearity, the term was introduced by Ragnar Frisch, meaning that there is a perfect linear relationship among some or all explanatory variables (Rockwell, 1975). The test evaluates the independent variables like transaction volume, mining activity, and energy use that might be correlated with each other, making it hard to disentangle their individual effects. Multicollinearity occurs when two or more independent variables are highly correlated, making it difficult to distinguish their individual effects on the dependent variable. Which can lead to unstable coefficient estimates and unreliable statistical inferences.

Based on the multicollinearity test results shown in the Table 4 below, all independent variables have VIF values below the 10 thresholds. Although the Bitcoin Electricity Consumption and Bitcoin Greenhouse Gas Emissions variables have multicollinearity values slightly above 5, they are still within acceptable tolerance limits. The remaining variables have VIF values lower than 5. This indicates that there is no serious multicollinearity problem in the regression model.

Based on the specification testing results, heteroscedasticity and autocorrelation are detected. To ensure the reliability of these regression models, we employ Newey-West robust regression analysis to control heteroskedasticity and autocorrelation in error terms, which violate the assumption of Ordinary least square (OLS) regression. Newey-West, better known as Heteroskedasticity and Autocorrelation Consistent (HAC) standard errors validates the significance of the relationship in robust versions of the model. Newey-West covariance matrix applied for the coefficient estimate using actual out of sample data to update daily variance errors. This updated variance is combined with estimated regression variance to generate a series of daily standard errors for forecast errors (Villanueva, 2024).

4. FINDINGS AND DISCUSSIONS

This study covers the period from January 1, 2020, to December 31, 2023, means the total number of observations in this study is 1461 data. In this case, the sample includes all available data for the period, which is 1461 samples, which are considered to reflect the population as a whole. The results of this study can reflect more accurate results regarding the relationship between increasing Bitcoin transaction volume and increasing the amount of carbon emissions, the amount of electricity consumption and the amount of electrical waste. This study consists of 1461 data for each variable, with a total observation of 17,532 data. The descriptive statistics of the variables in this study, including carbon emission (CE), electricity consumption (EC), and electrical waste (EW) Bitcoin return (R), Bitcoin volatility (Vly), Bitcoin volume (Vol), Mining hashrate (Hr), Network difficulty (NetDiff), Bitcoin greenhouse gas emission (BTC.GGE), Bitcoin electrical consumption (BTC.EC), Bitcoin E-Waste (BTC.EW), are summarized in Table 5.

Table 5: Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Date	1461	22645	421.899	21915	23375
R	1461	0.002	0.028	−0.199	0.13
Vly	1461	399.193	539.2	0.222	4754.795
Vol	1461	9.380e+08	8.640e+08	71757446	9.989e+09
Hr	1461	46.707	0.473	45.498	47.863
NetDiff	1461	30.917	0.456	30.192	31.908
BTC.GGE	1461	0.131	0.037	0.055	0.228
BTC.EC	1461	0.255	0.064	0.13	0.449
BTC.EW	1461	0.099	0.043	0.04	0.229
CE	1461	9.553	4.65	4.491	20.692
EC	1461	74.536	4.909	62.407	85.341
EW	1461	159.89	32.849	114.828	255.417

The result presented in the table below illustrates the relationship between dependent and independent variables. When examining correlation between independent variables, most of them show low correlation values. However, few exceptions where stronger correlation was observed, especially between variables Bitcoin volatility (Vly) and Bitcoin volume (Vol) (0.705) and between Bitcoin greenhouse gas emission (BTC.GGE) and Bitcoin electrical consumption (BTC.EC) (0.982), indicating a high correlation/association between variables. Contradictory to the correlation between dependent and independent variables tends to be low overall. Highest observed correlation in this category is between Bitcoin volume (Vol) and electrical waste (EW), with a value of 0.250. In this research we will employ correlation tests to determine the strength and direction of relationships between variables. One statistical method used for the test is the spearman correlation test, which is commonly applied in nonparametric statistics to evaluate the relationship involving ordinal scale data (Yasril and Fatma, 2021). The use of the spearman correlation test in this study is also justified by the fact that it does not require the assumption of normality test, making it more suitable for assessing the relationship between variables without relying on normality assumptions. Making it well suited for assessing variable relationships in datasets that do not meet normal distribution criteria. The correlation test result is shown in Table 6.

The regression results, including OLS, Robust Standard Error, and Newey-West standard error, are shown in Table 7. In Model 1 Carbon Emission (CE), Bitcoin Return (X1) and Bitcoin Volume (X3) are positively significant at the 1% level. This suggests that increases in Bitcoin returns, and transaction volumes contribute to higher carbon emissions. Bitcoin Volatility (X2) is negatively significant at the 10% level, implying that greater volatility may slightly reduce emissions. Bitcoin E-Waste (X8) is marginally significant at the 10% level. The findings of this study are in line with past work by de Vries (2018) and Stoll et al. (2019), which highlighted the role of increased transaction activity and hardware obsolescence in environmental impacts. When applying Robust Standard Errors, Bitcoin Return (X1), Bitcoin Volume (X3), and Bitcoin Volatility (X2) retain their significance levels, although Bitcoin E-Waste (X8) shows weakened stability. Under the Newey-West estimation, Bitcoin Return (X1) and Bitcoin Volume (X3) remain positively significant at the 1% level, while Bitcoin Volatility (X2) continues to show marginal negative significance. However, Bitcoin E-Waste (X8) becomes insignificant, emphasizing the impact of correcting for autocorrelation and heteroscedasticity. As expected, no R-squared value is available under Newey-West, while the OLS regression shows an R-squared of 0.049.

Table 6: Correlation test

	R	Vly	Vol	Hr	NetDiff	BTC.GGE	BTC.EC	BTC.EW	CE	EC	EW
R	1.000	0.048	0.036	−0.045	−0.016	0.033	0.036	0.030	0.037	−0.029	−0.019
Vly	0.048	1.000	0.705	−0.031	0.008	−0.043	−0.050	−0.030	−0.019	−0.007	0.027
Vol	0.036	0.705	1.000	−0.060	0.013	−0.026	−0.029	−0.037	−0.060	0.004	0.074
Hr	−0.045	−0.031	−0.060	1.000	0.019	0.036	0.038	0.120	0.032	0.010	0.250
NetDiff	−0.016	0.008	0.013	0.019	1.000	0.012	0.006	−0.030	−0.001	0.013	−0.022
BTC.GGE	0.033	−0.043	−0.026	0.036	0.012	1.000	0.982	0.159	0.019	−0.079	−0.009
BTC.EC	0.036	−0.050	−0.029	0.038	0.006	0.982	1.000	0.164	0.020	−0.036	−0.007
BTC.EW	0.030	−0.030	−0.037	0.120	−0.030	0.159	0.164	1.000	0.029	−0.009	0.003
CE	0.037	−0.019	−0.060	0.032	−0.001	0.019	0.020	0.029	1.000	0.017	0.113
EC	−0.029	−0.007	0.004	0.010	0.013	−0.079	−0.036	−0.009	0.017	1.000	0.086
EW	−0.019	0.027	0.074	0.250	−0.022	−0.009	−0.007	0.003	0.113	0.086	1.000

Table 7: Regression result

Variable	Statistic Description	Model 1			Model 2			Model 3		
		OLS	Robust Standard Error	Newey West Standard Error	OLS	Robust Standard Error	Newey West Standard Error	OLS	Robust Standard Error	Newey West Standard Error
Constant	Coefficient	4.102	4.102	4.102	−178.724***	−178.724***	−178.72	84.618***	−734.694***	−734.69***
	T-value	0.34	0.36	0.26	−15.87	−14.46	−10.35	−8.68	−8.32	−5.97
	P-value	0.734	0.719	0.796	0.000	0.000	0.000	0.000	0.000	0.000
Bitcoin Return (R)	Coefficient	14.013***	14.013***	14.013***	−1.782−0.45	−1.782	−1.782	12.052	12.052	12.052
	T-value	3.26	3.22	2.95	0.656	−0.44	−0.40	0.40	0.43	0.38
	P-value	0.001	0.001	0.003		0.658	0.690	0.689	0.668	0.702
Bitcoin Volatility (Vly)	Coefficient	−0.0005*	−0.0005*	−0.0005*	0.00075**	0.0007***	0.0007***	−0.0035	−0.003	−0.003
	T-value	−1.81	−1.71	−1.66	2.54	3.17	3.15	−1.57	−1.57	−1.63
	P-value	0.071	0.088	0.096	0.011	0.002	0.002	0.117	0117	0.103
Bitcoin Volume (Vol)	Coefficient	1.38***	1.38***	1.38***	−1.62	−1.62−	−1.62	3.82***	3.82***	3.92***
	T-value	6.83	5.87	4.94	−0.86	1.10	−0.95	2.7	2.95	2.71
	P-value	0.000	0.000	0.000	0.390	0.272	0.344	0.007	0.003	0.007
Bitcoin Hashrate (Hr)	Coefficient	0.09	0.092	0.092	5.419***	5.419***	5.419***	19.108***	19.108***	19.10***
	T-value	0.36	0.38	0.27	22.52	20.56	14.72	10.56	10.10	7.24
	P-value	0.720	0.704	0.784	0.000	0.000	0.000	0.000	0.000	0.000
Bitcoin Network Difficulty (NetDiff)	Coefficient	8.583	8.583	8.583	−8.631	−8.631	−8.631	−36.888	−36.888	−36.88
	T-value	1.36	1.51	1.52	−1.47	−1.25	−1.25	−0.84	−0.89	−0.89
	P-value	0.174	0.131	0.129	0.142	0.210	0.210	0.403	0.374	0.372
Bitcoin Greenhouse Gas Emission (BTC. GGE)	Coefficient	99.664	99.664	99.664	57.107	57.107	57.107	616.755	616.755	616.755
	T-value	0.94	1.27	1.26	0.58	0.69	0.68	0.83	0.77	0.76
	P-value	0.349	0.203	0.206	0.564	0.490	0.496	0.407	0.440	0.449
Bitcoin Electrical Consumption (BTC.EC)	Coefficient	−1.076	−1.067	−1.076	−98.683*	−98.683**	−98.683**	−614.63	−614.632	−614.632
	T-value	−0.02	−0.02	−0.02	−1.75	−2.02	−1.97	2−1.45	−1.35	−1.30
	P-value	0.986	0.982	0.982	0.081	0.044	0.049	0.148	0.733	0.193
Bitcoin E-Waste (BTC.EW)	Coefficient	152.16*	152.1602*	152.16	−19.06	−19.060	−19.06	−209.024	−734.694	−209.024
	T-value	1.71	1.80	1.53	−0.23	−0.26	−0.22	−0.33	−8.32	−0.29
	P-value	0.088	0.071	0.125	0.818	0.794	0.823	0.738	0.733	0.772
	R Squared	0.049	0.054		0.2646	0.2646		0.0738	0.0738	
	F-test	0.000	-	0.0047	0.000	-	0.0000	0.000	0.000	0.0000

*Sig at 10%, **Sig at 5%, ***Sig at 1%

In Model 2 (Electricity Consumption - EC), Bitcoin Volatility (X2) and Bitcoin Hashrate (X4) are positively significant at the 1% level, while Bitcoin Electrical Consumption (X7) is negatively significant at the 10% level. The findings of this model are consistent with those reported by Li et al. (2019) and Zade et al. (2019), who demonstrated how increasing computational demands raise electricity consumption. When adjusting for Robust Standard Errors, Bitcoin Volatility (X2) remains strongly significant, and Bitcoin Electrical Consumption (X7) becomes significant at the 5% level. In the Newey-West estimation, the significance of Bitcoin Volatility (X2), Bitcoin Hashrate (X4), and Bitcoin Electrical Consumption (X7) remains consistent, further supporting the robustness of these results. The OLS R-squared for Model 2 is 0.2646, the highest among the three models, indicating a relatively strong model fit.

In Model 3 (Electronic Waste - EW), Bitcoin Volume (X3) and Bitcoin Hashrate (X4) are significant positive predictors at the

1% level across OLS, Robust Standard Errors, and Newey-West estimations. This supports findings by de Vries and Stoll (2021) and Fagundes Isolani (2023), which identified mining activity and transaction volume as major contributors to rising electronic waste. Other independent variables in this model show no statistical significance across methods. The OLS R-squared for Model 3 is 0.0738, indicating a modest but stable explanatory power.

This study provides empirical evidence that Bitcoin return and transaction volume significantly contribute to carbon emissions, while volatility slightly mitigates them, and e-waste plays a marginal but notable role. The strong positive relationship between Bitcoin market activity (returns and volume) and carbon emissions highlights an urgent need for regulatory frameworks that address the environmental consequences of cryptocurrency operations. Governments and international bodies could consider (1) Carbon taxation or energy tariffs specifically targeting mining operations, especially in regions heavily reliant on fossil fuels; (2) Mandatory disclosure of energy sources and emissions by mining firms and large-scale crypto operations to improve transparency and accountability; (3) Environmental licensing and zoning policies that restrict mining to areas with access to low-carbon or renewable energy sources. Such policies can disincentivize environmentally harmful mining practices and encourage the adoption of cleaner alternatives. The findings also point to the need for technological shifts within the cryptocurrency industry. Bitcoin's current Proof-of-Work (PoW) mechanism is inherently energy-intensive. To mitigate its environmental footprint, the industry should prioritize (1) Investment in energy-efficient mining hardware, which can reduce the emissions associated with both operations and e-waste; (2) Research and development into hybrid blockchain models that balance decentralization, security, and sustainability. Technological innovation is a key lever for long-term environmental sustainability in the digital currency ecosystem. Further, at the firm and industry level, more sustainable operational practices can help address the negative environmental externalities identified in this study (1) Integrating renewable energy sources into mining operations—such as solar, wind, or hydro—can significantly cut carbon emissions; (2) Implementing circular economy principles to address e-waste, including hardware recycling programs, second-hand mining equipment markets, and product life extension strategies; and (3) Voluntary ESG disclosures by cryptocurrency firms can attract environmentally conscious investors and consumers, reinforcing market-driven sustainability incentives.

In conclusion, the study's results make it clear that without coordinated policy, technological, and business model changes, the financial expansion of Bitcoin is likely to come at a growing environmental cost. However, by leveraging smart regulation, adopting cleaner technologies, and embedding sustainability into operational practices, it is possible to balance cryptocurrency growth with environmental responsibility. The results also underscore the urgent need for a multidimensional response to the environmental challenges posed by cryptocurrency mining. Regulatory action, technological innovation, and responsible business practices must work in tandem to reduce the environmental burden of the industry. Without such interventions, the profitability and popularity of Bitcoin may continue to drive unsustainable energy consumption and hardware waste. However, the findings also offer a path forward: by shifting toward energy-efficient technologies, increasing the use of renewables, and integrating environmental considerations into crypto policy frameworks, it is possible to support the development of a more sustainable and resilient digital financial system.

5. CONCLUSION

As environmental concerns intensify globally, the rapid rise of cryptocurrency—particularly Bitcoin—has introduced new sustainability challenges. While prior studies focused on economic growth and traditional energy use, this research examined the environmental consequences of Bitcoin activity in emerging markets, particularly its effect on carbon emissions, electricity consumption, and electronic waste. The results show that Bitcoin return, and transaction volume are positively associated with increased carbon emissions, highlighting the energy-intensive nature of mining during high market activity. Volatility and hashrate significantly raise electricity usage, while volume and hashrate also contribute to higher electronic waste due to frequent hardware replacement. These findings are robust across OLS, Robust SE, and Newey-West estimations, reinforcing the conclusion that Bitcoin activity imposes substantial environmental costs. Although some variables show sensitivity under different methods (e.g., Bitcoin e-waste becomes insignificant under Newey-West), the overall patterns remain consistent.

This study offers three key implications. First, emerging market policymakers should consider environmental regulations targeting crypto mining, including carbon pricing, energy efficiency standards, and e-waste management. Second, financial stakeholders must evaluate cryptocurrency exposure through an ESG lens, as unchecked digital asset growth may conflict with sustainability mandates. Third, coordinated energy and financial policy is essential, as the relationship between Bitcoin activity and environmental impact is shown to be long-term and, in some cases, bidirectional. While this study provides strong macro-level evidence, it does not account for factors like regional electricity sources, regulatory differences, or urbanization. Future research should examine these moderating variables and compare the ecological impact of alternative cryptocurrencies such as Ethereum or Solana that use more energy-efficient mechanisms. In sum, Bitcoin activity has a measurable and growing environmental impact. Without strategic financial and policy interventions, its unchecked growth may undermine sustainability efforts in the very markets where it is expanding most rapidly.

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