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Understanding the Association Between Bitcoin Mining and Environmental Sustainability in Light of the Sustainable Development Goals Through the DARDL and KRLS Methods

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ABSTRACT

Assuring environmental sustainability is essential for the continuity of the ecosystem. Every sector of the economy has some degree of impact on environmental sustainability. The United Nations (UN)' Sustainable Development Goals (SDGs) have placed these objectives within a broader global framework, offering a global plan aimed at ensuring environmental sustainability. This study assesses the role of cryptocurrency mining on environmental sustainability, incorporating monthly data for the period from 2015 to 2023. In this context, the impact of the electrical energy consumed in Bitcoin mining, which has the largest transaction volume among cryptocurrencies, and the climate policy uncertainty on Bitcoin greenhouse gas (GHG) emissions are examined by applying dynamic stimulated autoregressive distributed lag (DARDL) and kernel-based regularized least squares (KRLS) methods. The results of the empirical analysis indicate that the increase in Bitcoin electricity consumption and climate policy uncertainty have a significant negative impact on Bitcoin GHG emissions. Put another way, cryptocurrency mined using fossil fuels and climate policy uncertainty poses a considerable threat to environmental sustainability. These findings are crucial for policy makers and all stakeholders who want to achieve environmental sustainability goals to develop proactive proposals. It is also highlighted that Bitcoin mining should bring environmental regulations that can mitigate environmental degradation.

1 | Introduction

Over the past century, the dramatic increase in the use of high-carbon fossil fuels has significantly accelerated CO_2 emissions, contributing to the rise of greenhouse gas (GHG) emissions that trap heat in the atmosphere. Additionally, the increase in atmospheric GHG emissions has caused the Earth's temperature to exceed its natural levels. Particularly, the rise of global warming and climate change-related natural events, along with escalating issues such as water and food crises, has made this a critical concern for all of humanity. Therefore, in addition to the life sciences, social sciences also bear a great responsibility in ensuring ecological balance for a sustainable world. In light of these developments, countries that are parties to the United Nations (UN) Framework Convention on Climate Change (UNFCCC) aim to achieve net-zero emissions by 2050. The Sustainable Development Goals (SDGs) place these targets within a broader global framework, providing a comprehensive plan to ensure environmental sustainability (United Nations 2015). Additionally, the European Union has announced its goal of becoming the "first carbon-neutral continent" by 2050 through the European Green Deal.

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Achieving net-zero emissions requires significant transformations in energy, finance, transportation, industry, waste management, and other related sectors. In this context, understanding the relationship between cryptocurrency mining and environmental degradation has become an important issue. This study focuses on Bitcoin (BTC), which has the highest transaction volume among cryptocurrencies, and the type of energy used in its mining process. BTC has grown as a financial instrument, yet concerns have risen due to its consensus mechanism, which requires miners to consume large amounts of electricity. As this energy is largely derived from fossil fuels, it increases carbon emissions and causes significant environmental damage (Stoll et al. 2019; Mora et al. 2018).

To mitigate this impact, BTC miners have begun adopting renewable energy sources as a more environmentally friendly and cost-effective alternative. Energy sources such as solar, wind, and hydroelectric power help reduce both operational costs and environmental impact in mining activities. Notably, large-scale BTC mining operations have increasingly turned to solar energy (Pouresmaieli et al. 2023). Miners establish long-term partnerships with local and regional energy companies to develop solar energy projects and integrate renewable sources into data centers (Sovacool et al. 2022). This integration enhances sustainability while ensuring long-term cost savings (McNally and Kolivand 2024).

However, renewable energy sources have limitations in providing uninterrupted power, making energy storage solutions essential. Most mining data centers remain connected to the grid, and even with renewable energy adoption, meeting all energy demands from these sources can be challenging. Therefore, improving energy storage capacity is crucial for utilizing renewable energy more efficiently in mining operations (Kuznetsova and Anjos 2020).

Governments can support the mining sector by promoting renewable energy use through incentives and policies. For example, the United States (US) offers tax credit systems for zero-emission energy sources, providing incentives exceeding $30 per ton for eligible electricity sources (Lu et al. 2020). Other countries may introduce additional investment or production tax credits to encourage miners to adopt renewable energy. Such policies facilitate the expansion of green energy projects and support the transition of large-scale mining facilities to sustainable energy sources.

While some points on renewable energy use and mining hardware improvements have been addressed, their integration into predictive models remains insufficient. Current models primarily rely on static assumptions to estimate the energy consumption and carbon footprint of mining activities, failing to incorporate adaptive hardware developments, such as immersion cooling systems and modular mining setups (Hossain and Steigner 2024). These technologies have the potential to enhance energy efficiency and reduce environmental impact, yet their role in shaping predictive models remains underexplored. Immersion cooling systems significantly improve thermal efficiency, reducing electricity demand while extending hardware lifespan—factors crucial for sustainable mining operations (Orun and Kurugollu 2023). Similarly, modular mining setups allow for greater flexibility by positioning mining farms closer to renewable energy sources, thereby minimizing reliance on fossil-fuel-based grids and optimizing operational efficiency (Masanet et al. 2024). However, without proper integration into computational models, these advancements cannot be accurately reflected in environmental impact assessments. To strengthen technological insights and improve predictive capability, future research must focus on refining existing models to incorporate AI-driven energy consumption analyses and dynamic carbon emission simulations (Andersson et al. 2020). Advanced modeling frameworks should account for the long-term impact of immersion cooling, the scalability of modular mining, and their potential for reducing carbon emissions in real-world applications. Additionally, adaptive machine learning techniques can be employed to create more responsive models that adjust predictions based on evolving hardware efficiency metrics. Without these advancements, sustainability assessments of BTC mining will remain incomplete, limiting the sector's ability to align with global climate goals. Therefore, the integration of next-generation mining hardware into predictive models is essential for achieving a more precise and forward-looking evaluation of BTC mining's environmental footprint.

Despite technological advancements in cryptocurrencies, their environmental impact remains a significant concern. Carbon emissions associated with BTC mining pose major challenges, particularly in countries dependent on coal-based electricity grids (De Vries 2018). The energy consumed for BTC mining is comparable to the annual electricity consumption of some countries (De Vries 2018), contributing to GHG emissions and further expanding BTC's carbon footprint (Mora et al. 2018). In particular, BTC mining operations in China have raised sustainability concerns due to their reliance on fossil fuels such as coal (Stoll et al. 2019).

Reducing energy consumption is becoming increasingly important to align the cryptocurrency sector with environmental sustainability goals. Regulatory frameworks and global initiatives play a crucial role in mitigating BTC mining's environmental impact. While former US President Donald Trump withdrew the US from the Paris Agreement, the country rejoined under President Joe Biden. The European Green Deal aims for carbon neutrality by 2050 and could introduce binding regulations for energy-intensive industries. Additionally, some US states have adopted policies promoting mining activities powered by renewable energy.

Decisions made at climate summits such as COP26 and COP27 have sought to strengthen international cooperation to reduce the environmental impact of energy-intensive activities like cryptocurrency mining. The Global Methane Pledge, signed at COP26, provides a cross-sectoral framework for reducing GHG emissions (UNFCCC 2021). While COP28 did not focus specifically on cryptocurrencies, it emphasized the importance of financial innovation and sustainable investments in climate action. For instance, at COP28, the United Arab Emirates (UAE) introduced Alterra, the world's largest private climate investment fund, committing $30 billion to fair climate finance (UNFCCC 2023). At COP29, a commitment was made to provide $300 billion annually in climate finance to support developing countries in mitigating climate change (UNFCCC 2024).

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China's restrictions on BTC mining serve as an example of efforts to regulate the sector's environmental impact. More effective global energy policies and regional regulations must be implemented to mitigate the consequences of cryptocurrency mining. The integration of renewable energy sources and the adoption of more efficient mining technologies remain key strategies in reducing these impacts. BTC's high energy consumption due to its Proof-of-Work (PoW) mechanism highlights the contradiction between environmentally friendly financial instruments and energy-intensive cryptocurrencies. While green financial products aim to reduce environmental risks, the rising popularity and electricity consumption of cryptocurrencies conflict with these sustainability goals. Addressing BTC's energy consumption is crucial for aligning the cryptocurrency sector with global climate targets.

The consensus mechanism used by a cryptocurrency is a key factor in determining its environmental impact. For example, BTC's PoW system is criticized for its high energy consumption. However, alternative consensus mechanisms also need to be examined. Ethereum's transition to the Proof-of-Stake (PoS) system reduced its energy consumption by 99%. Similarly, less energy-intensive projects like Cardano and Solana demonstrate the potential for achieving sustainability goals (Khosravi and Säämäki 2023). Addressing this issue requires the development of more energy-efficient hardware, wider adoption of renewable energy, and a shift toward alternative low-energy consensus mechanisms (Siddik et al. 2023). The concentration of mining in countries with abundant low-cost energy, such as Kazakhstan, Russia, and Iran, has contributed to the persistence of high carbon emissions. In Kazakhstan, for example, the rapid expansion of mining activities has strained the national power grid, leading to electricity shortages and prompting the government to impose stricter regulations on mining operations (IEA, 2023). This development underscores the necessity of evaluating mining's environmental impact not only based on total energy consumption but also in relation to the energy mix and regional regulatory frameworks. Conversely, mining operations in countries with a higher share of renewable energy, such as Canada and Scandinavian nations, have demonstrated significantly lower carbon footprints due to the availability of hydroelectric and wind power infrastructure (Sedlmeir et al. 2022). However, mining in these regions faces limitations due to higher operational costs and regulatory uncertainties, which have restricted large-scale adoption (Gallersdörfer et al. 2020).

Given the critical role of regional energy policies in shaping the environmental impact of BTC mining, further research should focus on how shifting energy sources affect overall sustainability. The implementation of regulatory measures, such as carbon taxes, renewable energy incentives, and transparent energy reporting mechanisms, could play a pivotal role in mitigating mining's environmental footprint (Masanet et al. 2024). Additionally, the development of international carbon tracking protocols and the enforcement of environmental reporting standards for mining operations would enhance transparency and accountability, ensuring that BTC mining aligns more closely with global sustainability goals.

A comprehensive analysis of the crypto ecosystem is essential. Ethereum, initially using PoW, transitioned to PoS in 2022 with "The Merge," significantly reducing energy consumption and eliminating mining competition (Khosravi and Säämäki 2023). Additionally, Solana's low energy consumption, at only 0.166 Wh per transaction, provides a model for improving cryptocurrency sustainability.

BTC mining has rapidly expanded in developing countries due to low energy costs and regulatory uncertainties, but this growth has led to high carbon emissions and increased strain on energy grids. Following China's 2021 ban, mining operations shifted to countries like Kazakhstan, Iran, Venezuela, and Malaysia, where energy is cheaper. In Kazakhstan, coal-based electricity usage has significantly increased carbon emissions, while Iran struggles with frequent power outages due to unregulated mining activities. In Venezuela, subsidized electricity has encouraged mining, but poor infrastructure and strict government controls have limited sustainable development. Malaysia, on the other hand, faces major energy losses due to illegal mining, prompting the government to introduce stricter regulations (Alzoubi 2023). While BTC mining offers economic opportunities in these regions, stronger regulations and increased adoption of renewable energy sources are essential for long-term sustainability (Masanet et al. 2024).

Another major concern regarding cryptocurrencies is electronic waste (e-waste) generated from mining hardware. As the crypto market grows, mining hardware is continuously upgraded, creating a challenge for disposal. E-waste contains toxic chemicals, including heavy metals such as lead, which can harm the environment and biodiversity if not properly managed (Lu 2023).

Water consumption is another environmental factor associated with cryptocurrency production. The water footprint of cryptocurrencies is nearly twice that of traditional currencies, as crypto mining is concentrated in regions with high water intensity in electricity production. Fossil fuel and nuclear power plants require significant amounts of water for cooling processes, further increasing crypto mining's environmental impact.

In an effort to mitigate environmental drawbacks, BTC miners have begun adopting renewable energy sources to provide environmentally friendly and cost-effective energy. Energy sources such as solar, wind, and hydroelectric power help reduce both the energy costs of mining operations and their environmental impact. In particular, solar energy has been observed to grow rapidly in the large-scale mining sector (Pouresmaieli et al. 2023). Miners establish long-term partnerships with local and regional energy companies to implement solar energy projects and integrate renewable energy sources into data centers (Sovacool et al. 2022). This integration not only enhances environmental sustainability but also provides long-term cost savings (McNally and Kolivand 2024).

However, the ability of renewable energy sources to provide uninterrupted 24/7 power is limited, making energy storage solutions crucial. Most mining data centers are grid-connected, and even if they choose to use renewable energy, they may not be able to meet all their energy needs from these sources alone. In this regard, improving energy storage capacity is a critical requirement for the more efficient use of renewable energy in mining operations (Kuznetsova and Anjos 2020).

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Governments are also expected to support the mining sector through policies such as tax credits and green energy projects to encourage the use of renewable energy. For example, in the US, tax credit systems for zero-emission energy sources provide incentives of more than $30 per ton for eligible electricity sources (Lu et al. 2020). In other countries, additional investment or production tax credits may be offered to miners under renewable energy investment plans. Such policies promote the broader implementation of green energy projects and enable large-scale energy production initiatives to support mining farms.

In conclusion, BTC mining poses a significant environmental challenge due to its high electricity consumption and dependence on fossil fuels. As global climate policies and sustainability initiatives accelerate, evaluating the environmental impacts of cryptocurrencies and exploring cleaner energy solutions will become increasingly important. The contribution of this study to the literature lies in its detailed examination of energy (electricity) consumption and environmental impacts in cryptocurrency mining, one of the fundamental functions of blockchain technology. Specifically, it will focus on the impact of BTC mining on carbon emissions during the process of adding new blocks to the blockchain. Additionally, it will address energy consumption and the GHG emissions caused by the computational power required to validate a block.

According to the obtained data, energy consumption and carbon emissions associated with BTC mining have increased annually since 2013. For instance, while annual electricity consumption was 0.06 terawatt-hours (TWh) in 2013, it reached 138.96 TWh by 2023, with carbon emissions rising significantly over the same period (Cambridge Centre for Alternative Finance 2023b). This increase demonstrates that the environmental impact of mining activities is inconsistent with global climate goals, as they largely rely on coal and other fossil fuel-based energy sources.

This study will also explore how these environmental impacts can be mitigated through energy-saving measures and the use of more efficient devices, providing recommendations for making current mining activities more sustainable. Another objective of this research is to examine the relationship between BTC mining and environmental degradation, aiming to reduce these negative impacts through clean energy solutions and more efficient mining technologies. It also seeks to propose steps for reducing GHG emissions from BTC production in line with the decisions made at the UN Climate Change Conference in Glasgow (COP26) and the Climate Change Conference in Sharm El-Sheikh (COP27). The emphasis on emission reduction at COP26 and the introduction of the “loss and damage” mechanism at COP27 have once again highlighted the critical importance of reducing fossil fuel-based energy consumption.

In this context, the high energy consumption associated with BTC mining is in clear contradiction with sustainability goals. Our aim is to support the transition of energy sources used in BTC mining from fossil fuels to renewable energy and to promote the adoption of alternative, less energy-intensive consensus mechanisms such as PoS. By doing so, the cryptocurrency sector can be aligned with global climate targets. Additionally, this study aims to determine the impact of climate policies on BTC's GHG emissions. Therefore, the hypotheses of this study are as follows:

H1. *The type of energy used in BTC mining triggers environmental degradation.*

H2. *Increasing uncertainty in climate policies contributes to rising BTC GHG emissions.*

H3. *The use of renewable energy sources in BTC mining can be an effective strategy for mitigating carbon emissions.*

H4. *As BTC's market value increases, the demand for mining rises, leading to higher energy consumption and exacerbating its environmental impact.*

1.1 | Research Gap

Previous studies have examined the environmental impacts of BTC mining from various perspectives. For instance, *The Carbon Footprint of Bitcoin* by Stoll et al. (2019) analyzes BTC's global carbon emissions, while *Bitcoin Emissions Alone Could Push Global Warming Above 2°C* by Mora et al. (2018) highlights the risks of BTC mining on climate change. Additionally, *Bitcoin's Growing Energy Problem* by De Vries (2018) quantitatively assesses the increasing electricity consumption of BTC mining.

However, more recent studies have focused increasingly on the growing environmental concerns associated with BTC mining. For example, *The Environmental Stake of Bitcoin Mining: Present and Future Challenges* by Arfelli et al. (2024) estimates that in 2022 alone, BTC mining was responsible for approximately 51.7 million tons (Mt) of CO_2 emissions due to electricity consumption. Similarly, *Balancing Innovation and Sustainability: Addressing the Environmental Impact of Bitcoin Mining* by Hossain and Steigner (2024) emphasizes the ongoing conflict between financial innovation and sustainability, arguing that without regulatory interventions or a transition to renewable energy, BTC's environmental impact will continue to increase.

Although previous studies have examined BTC mining's electricity consumption and emissions, they often lack a comprehensive analysis integrating global sustainability frameworks. Research indicates that BTC's annual electricity consumption has reached levels comparable to those of some small countries (Cambridge Centre for Alternative Finance 2023a; De Vries 2018). According to the Cambridge University Bitcoin Electricity Consumption Index, BTC mining consumes over 100 TWh of energy annually, exceeding the yearly energy consumption of countries like Argentina and the Netherlands (Cambridge Centre for Alternative Finance 2023b; De Vries 2018). This situation creates a significant conflict between the cryptocurrency sector and global climate goals (Mora et al. 2018; Stoll et al. 2019).

Moreover, BTC mining is still largely powered by non-renewable energy sources such as coal and natural gas, further exacerbating carbon emissions (Jiang et al. 2021; Krause and Tolaymat 2018). The direct correlation between BTC's market value and energy consumption suggests that as BTC demand increases, so does

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its environmental burden (Stoll et al. 2019; De Vries 2018). Therefore, understanding the interplay between BTC's energy consumption, market dynamics, and environmental sustainability remains crucial.

By incorporating the SDGs framework, this study examines the dynamic effects of BTC's electricity consumption (BEC) and climate policy uncertainty (CPU) on GHG emissions. Utilizing advanced econometric methods such as dynamic stimulated autoregressive distributed lag (DARDL) and kernel-based regularized least squares (KRLS), developed by Hainmueller and Hazlett (2014), it provides a deeper analysis of the short- and long-term relationships between these variables. Unlike traditional approaches, this research considers both linear and nonlinear dynamics, offering a more comprehensive perspective on BTC's carbon footprint.

Additionally, BTC miners have increasingly adopted renewable energy sources such as solar, wind, and hydroelectric power to mitigate environmental concerns. While these alternatives help reduce mining costs and emissions, their intermittent nature and energy storage limitations remain significant challenges (Kuznetsova and Anjos 2020). This study contributes to the literature by examining the feasibility of integrating renewable energy into BTC mining operations and evaluating its role in achieving sustainability goals.

Thus, this study fills a critical gap in the literature by proposing practical strategies to align cryptocurrency mining with global sustainability goals. It not only investigates BTC's energy consumption and environmental impact but also explores potential solutions, including renewable energy adoption and alternative consensus mechanisms such as PoS.

In this context, the study consists of eight sections based on this theoretical framework. The first section introduces the study. The second section presents the literature review, while the third section addresses the research gap. The fourth section explains the methodology, followed by the fifth section, which details data, conceptual framework, and model specification. The sixth section presents the empirical findings, and the seventh section provides the discussion. Finally, the eighth section concludes with the conclusion, policy recommendations, limitations of the study, and future research directions.

2 | Literature Review: Theoretical and Empirical Studies

Blockchain technology is transforming many industries and business processes by providing a decentralized, secure, and transparent data-sharing system. However, the widespread use of this technology also brings certain environmental threats. Blockchain technology should not be considered solely as a new technological advancement; it should also be evaluated holistically by taking into account its environmental impact, energy consumption, and societal consequences (Sedlmeir et al. 2020).

One of the biggest criticisms of this technology is its environmental impact. The primary reason for this is the high electricity consumption of blockchain networks that rely on the PoW consensus mechanism. When combined with the use of fossil fuels, high energy consumption leads to environmental consequences and threatens the sustainability of energy resources (Kiayias et al. 2017).

Bublyk et al. (2023) in their research, estimated that BTC's energy consumption will reach a minimum of 142 TWh per year by 2026 and found that in 2022 alone, BTC mining caused at least 27.4 Mt of CO_2 emissions, harming the environment. Furthermore, a 95% correlation was found between IT sector spending, the energy consumption of BTC and Ethereum, and the total market capitalization of the cryptocurrency sector. The research identified BTC's energy intensity as a significant sustainability issue and suggested encouraging the use of renewable energy sources or residual energy sources such as natural gas.

Lu (2023) examined the environmental impact of cryptocurrencies and found that BTC mining consumes 150 TWh annually, exceeding the total energy consumption of countries like Norway and Argentina. This results in significant GHG emissions, intensifying the effects of climate change. Lu also highlighted Ethereum's transition to the PoS, which reduced its energy consumption by 99.9%, as an example of the need to adopt energy-efficient methods. However, to address the energy intensity issue of BTC's current PoW system, the study proposed implementing more efficient mechanisms such as Green-PoW or merged mining. Additionally, the study suggested that by promoting carbon credits and the use of renewable energy sources in crypto mining, a sustainable digital financial ecosystem could be created.

Siddik et al. (2023) analyzed the energy consumption and environmental impact of cryptocurrencies, finding that these systems have a significantly larger environmental footprint compared to traditional financial systems. Their research found that cryptocurrencies consumed 236 TWh of energy in 2021, which was 83% higher than the energy consumption of traditional monetary systems. Furthermore, crypto mining activities alone were responsible for 139 Mt of CO_2 emissions and an annual total water consumption of 3668 million cubic meters. The study emphasized that the energy consumption of BTC and other cryptocurrencies largely depends on the energy sources and regulatory policies of the countries where mining activities take place. For example, China's ban on crypto mining in 2021 reduced the carbon intensity of mining operations by 10% but led to a 73% increase in water consumption. The researchers recommended using more energy-efficient algorithms such as PoS and concentrating mining activities in low-carbon-intensive regions to reduce energy consumption and mitigate environmental impacts. The study concluded that the energy intensity of cryptocurrencies poses a major sustainability challenge and that integrating renewable energy sources is crucial to addressing this issue.

Miśkiewicz et al. (2022) analyzed the impact of cryptocurrency trading on economic growth, renewable energy consumption, and environmental degradation, providing a long-term perspective on these relationships. The study found that cryptocurrency trading positively influences gross domestic product (GDP), fixed capital formation, and globalization. However, it also

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discovered that crypto trading does not have a long-term relationship with the share of renewable energy in total energy consumption. The study highlighted the impact of cryptocurrencies on energy consumption and carbon emissions, noting that BTC's energy consumption has reached 204.50 TWh, which is equivalent to Thailand's annual energy consumption. Additionally, BTC mining's carbon footprint was measured at 114.06 Mt of CO_2, comparable to the carbon footprint of the Czech Republic.

Regarding e-waste, BTC transactions generate 34.36 kt of e-waste annually, a figure comparable to the amount of small IT equipment waste in the Netherlands. The study described cryptocurrency trading as creating a dilemma cycle—acting as a tool that supports economic growth and provides resources for green technology development while simultaneously contributing to increased energy consumption and environmental degradation. The researchers recommended implementing innovative technologies and energy-efficient mining protocols to reduce energy consumption and environmental damage. Additionally, they emphasized the need for green taxes and government policies to help reduce carbon emissions.

According to the Paris Climate Agreement, it is emphasized that global cooperation is necessary to address the climate crisis. However, the design of the BTC system, which generates high energy consumption, poses a threat to the implementation of global agreements (Truby 2018). While cryptocurrencies are a promising technology with numerous potential applications, their high energy consumption and carbon footprint present a significant threat to global warming (Mora et al. 2018; Corbet and Yarovaya 2020). The impact of BTC on carbon emissions is also a major concern.

In recent years, several studies have examined the effects of BTC's carbon emissions on climate change. Stoll et al. (2019) calculated that as of November 2018, BTC's annual electricity consumption was 45.8 TWh, with annual carbon emissions ranging between 22.0 and 22.9 Mt of CO_2. These results indicate that BTC's emissions are comparable to those of Jordan, Sri Lanka, or nearly Canada. De Vries (2018) reported that as of 2018, BTC's energy consumption resulted in a carbon footprint of 19.0–29.6 million metric tons of CO_2 (475 g CO_2/kWh). In this scenario, the average carbon footprint per transaction was estimated to be between 233.4 and 363.5 kg CO_2. By comparison, the carbon footprint of a VISA transaction is 0.4 g CO_2, while a Google search produces 0.8 g CO_2.

Sarkodie et al. (2023) observed that an increase in BTC transaction volume led to a 24% long-term increase in BTC's energy consumption and carbon footprint, while a dynamic shock in trading volume resulted in a 46.54% rise in BTC's energy consumption and carbon emissions. Kohli et al. (2023) found that BTC consumes as much energy as Sweden and that BTC's CO_2 emissions are similar to those of Greece. Additionally, a study conducted by Palta and Alsu (2013–2021) analyzed the relationships between energy expenditures, carbon emissions, GDP, and BTC production using panel data analysis. According to the panel data analysis, a long-term negative relationship was found between BTC production and carbon emissions, suggesting that BTC production may have a reducing effect on carbon emissions.

Kohli et al. (2023) stated that cryptocurrencies are one of the main factors contributing to an increased carbon footprint and that the energy consumption of a single BTC account is equivalent to the energy consumption of a refrigerator over 8 months. Gallersdörfer et al. (2020) measured the energy consumption of cryptocurrencies and BTC based on algorithms, current hash rates, and suitable mining devices, determining that BTC accounts for two-thirds of total energy consumption, while the remaining cryptocurrencies make up the other one-third. Additionally, Das and Dutta (2020) argued that BTC mining is unsustainable unless efficient mining practices and low-cost electricity sources are available. These studies highlight the scale of the energy consumption and carbon footprint issues caused by BTC. However, some projects, particularly Ethereum, are attempting to mitigate this issue by adopting more energy-efficient consensus mechanisms such as the proof of stake system.

The social and economic consequences of blockchain technology are also critical factors that need to be addressed. The adoption of this technology threatens certain traditional business models and institutions, which could lead to unemployment and income inequality. Additionally, concerns regarding data privacy and security have emerged with the use of blockchain-based applications. Therefore, blockchain technology must be carefully considered to maintain social and economic balance.

Discussions on BTC's energy consumption and environmental impact frequently take center stage, particularly due to criticisms of the energy-intensive PoW mechanism. However, this perspective focuses solely on PoW-based systems like BTC and does not sufficiently cover alternative blockchain consensus mechanisms. In particular, the advantages of the PoS mechanism in terms of energy efficiency are worth examining in this context. Recent data indicates that PoS-based systems consume significantly less energy compared to BTC.

Ethereum's transition to the PoS mechanism through the process known as "The Merge" clearly illustrates the extent of this difference. Before The Merge, Ethereum's annual energy consumption was approximately 70 TWh, whereas after the transition, its energy consumption decreased by 99.9%. Currently, Ethereum's annual energy consumption ranges between 963 kW and 33 kW, while energy consumption per transaction is measured between 0.02095 kWh and 0.000718 kWh (Ibañez and Rua 2023). When compared to BTC's energy consumption per transaction, which stands at 2.927 kWh, it becomes evident that Ethereum's environmental impact is several orders of magnitude lower.

Similarly, Solana, another blockchain utilizing the PoS mechanism, has managed to reduce energy consumption per transaction to 0.000517 kWh. Considering its high transaction throughput (TPS) capacity, Solana's energy efficiency presents a significant advantage. Other PoS-based platforms such as Hedera and Algorand also stand out with their remarkably low energy consumption levels. Hedera's energy consumption per transaction is recorded at just 0.000003 kWh, while Algorand's consumption per transaction is measured at 0.003411 kWh. These figures demonstrate that PoS-based blockchain systems offer far more sustainable alternatives in terms of energy efficiency compared to PoW-based systems like BTC. Additionally,

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comparisons with centralized financial systems such as VisaNet indicate that PoS-based systems can be competitive in terms of energy consumption. For example, VisaNet's energy consumption per transaction is approximately 0.00328 kWh, whereas many PoS-based blockchains consume even less energy than this (Ibañez and Rua 2023).

In this context, focusing solely on PoW-based mechanisms when evaluating BTC's environmental impact overlooks the energy efficiency advantages offered by PoS-based blockchains. For a more balanced assessment, a comprehensive comparison of the energy consumption and environmental impact of different consensus mechanisms is necessary. These comparisons will help us better understand the potential effects of technological innovations on environmental sustainability.

In the literature, studies on the environmental impacts of BTC mining have generally focused on energy consumption and carbon emissions, while the effects of CPUs on these processes have not been adequately addressed. In particular, the interaction between environmental damage caused by energy consumption and uncertainties in climate policies, as well as how this situation contributes to carbon emissions, has not been thoroughly examined in existing studies. Additionally, the years considered in these studies often coincide with the period when BTC's popularity increased.

Moreover, there is a notable lack of comprehensive evaluation regarding the impact of renewable energy use on the environmental sustainability of BTC mining and the feasibility of alternative mining mechanisms. In this regard, this study carefully explains the potential positive aspects of systemic changes. Furthermore, while analyzing the effects of BTC mining on carbon emissions, it aims to propose solutions to align these impacts with SDGs. The study particularly emphasizes the importance of promoting renewable energy sources, improving energy efficiency in mining technologies, and reducing CPUs.

In this respect, the study seeks to go beyond the limited energy- and environment-focused perspective in the existing literature, offering both an academic and practical contribution.

3 | Methodology

3.1 | Augmented Dickey and Fuller (1979) and Phillips and Perron (1988) Unit Root Tests

The study first examines the degree of integration or stationarity of the series using the augmented Dickey–Fuller (ADF) unit root tests proposed by Dickey and Fuller in 1979 and the Phillips–Perron (PP) unit root tests developed by Phillips and Perron in 1989. A common feature of ADF and PP unit root tests is that they do not account for structural breaks and non-linearity. The following regressions are carried out for the Dickey–Fuller (DF) unit root test:

$$\text{Model without constant and trend: } \Delta Y_t = \delta Y_{t-1} + u_t \tag{1}$$

$$\text{Model with constant and without trend: } \Delta Y_t = a_0 + \delta Y_{t-1} + u_t \tag{2}$$

$$\text{Model with constant and trend: } \Delta Y_t = a_0 + a_1 T + \delta Y_{t-1} + u_t \tag{3}$$

where Δ is the difference operator, a_0 is the constant term, T states the trend, while u_t is the error term, and t is time dimension. If there is an autocorrelation problem in the u_t error term, the above equation is transformed as follows:

$$\text{Model without constant and trend: } \Delta Y_t = \delta Y_{t-1} + \beta_i \sum_{i=1}^{m} \Delta Y_{t-i} + u_t \tag{4}$$

$$\text{Model with constant and without trend: } \Delta Y_t = a_0 + \delta Y_{t-1} + \beta_i \sum_{i=1}^{m} \Delta Y_{t-i} + u_t \tag{5}$$

$$\text{Model with constant and trend: } \Delta Y_t = a_0 + a_1 T + \delta Y_{t-1} + \beta_i \sum_{i=1}^{m} \Delta Y_{t-i} + u_t \tag{6}$$

The model is designed to eliminate the problem of autocorrelation, as the DF test does not work effectively in the presence of autocorrelation. ΔY_{t-i} term is performed in the model to eliminate the autocorrelation. By applying the DF test to this equation, the model takes the form of the extended DF (ADF) test based on autoregressive processes at different levels as well as the extended AR(1) process. In addition, the PP (1989) method, which has a non-parametric character, extends the assumption of the DF test equation regarding the error term and changes the ratio of the coefficient so that serial correlation does not affect the asymptotic distribution of the test statistic.

3.2 | Zivot and Andrews (2002) and Güriş (2019) Unit Root Tests

If we look at the development process of unit root tests, the development of tests with structural breaks is an important stage. In the first stage, unit root tests were developed in which structural breaks were determined exogenously. Later, however, Zivot and Andrews (2002) proposed a model in which the dates of structural breaks could be determined endogenously. Here, Phillips and Perron (1988) added structural break dates exogenously to the model when establishing the null hypothesis, but ZA now proved that it would be possible to select the structural break dates from within the series. The following models are created for the ZA unit root test (Zivot and Andrews 2002).

$$\text{Model (A): } \Delta y_t = \mu_1 + \alpha y_{t-1} + \beta_t + \theta_1 DU_t(\lambda) + \sum_{j=1}^{k} d_j \Delta y_{t-j} + e_t \tag{7}$$

$$\text{Model (B): } \Delta y_t = \mu + \alpha y_{t-1} + \beta_t + \gamma_1 DT_t(\lambda) + \sum_{j=1}^{k} d_j \Delta y_{t-j} + e_t \tag{8}$$

$$\text{Model (C): } \Delta y_t = \mu_1 + \alpha y_{t-1} + \beta_t + \theta_1 DU_t(\lambda) + \gamma_1 DT_t(\lambda) + \sum_{j=1}^{k} d_j \Delta y_{t-j} + e_t \tag{9}$$

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$$DT_t^{*} = \begin{cases} t - T_B & t > T_B \\ 0 & \text{otherwise.} \end{cases}$$

$$DU_t = \begin{cases} t & t > T_B \\ 0 & \text{otherwise} \end{cases}$$

Here, T_B represents the date of the structural break. The Δy_{t-j} term should be added in the model to ensure that the error term is free of autocorrelation. e_t represents the error term with no autocorrelation and normal distribution. Model A relates to the break in the mean, while Model B indicates the break in the slope. Model C is the equation that shows that a structural change modifies both the mean and the slope. When applying the ZA test, Model C is first estimated and the appropriate model is selected according to the significance of the parameters of the dummy variables DU and DT. If both dummy variables DU and DT are statistically significant, Model C is appropriate, if only DU is significant, Model A is appropriate, and finally, if only DT is significant, Model B is appropriate. However, although the ZA unit root test detects structural breaks endogenously without non-linearity, it uncovers sharp structural breaks due to the use of dummy variables in the model.

For this reason, unit root tests have been developed that take into account both soft breaks and nonlinearity. The Fourier Kruse (FKruse) unit root test is a non-linear unit root test with Fourier function developed by Güriş (2019). The FKruse unit root test procedure can be illustrated as follows:

$$y_t = \alpha_0 + \alpha_1 sin\left(\frac{2\pi k^{*} t}{T}\right) + \alpha_2 cos\left(\frac{2\pi k^{*} t}{T}\right) + v_t \tag{10}$$

where k^{*} is the optimum frequency and can be between 1 and 5; then, OLS is performed to estimate the equation and minimize the sum of the squares of the error terms. v_t is specified as the error term. v_t can be calculated using Equation (10) as follows:

$$v_t = y_t - \alpha_0 - \alpha_1 sin\left(\frac{2\pi k^{*} t}{T}\right) - \alpha_2 cos\left(\frac{2\pi k^{*} t}{T}\right) \tag{11}$$

The test statistics are computed by the following estimation using the error terms obtained in Equation (11):

$$\Delta v_t = \delta_1 v_{t-1}^3 + \delta_2 v_{t-1}^2 + \sum_{j=1}^{p} \varphi_j \Delta v_{t-j} + \varepsilon_t \tag{12}$$

After applying, if the null hypothesis of the existence of a unit root is rejected, it can be said that it is stationary around a deterministic function that breaks for the variables. All in all, it should be said that the null hypothesis of all unit root tests used in this study is that the series has a unit root, while the alternative hypothesis is that there is no unit root in the series.

3.3 | Dynamic Stimulated Autoregressive Distributed Lag Models (DARDL)

The ARDL cointegration test introduced by Pesaran et al. (2001) is a convenient method for variables with different degrees of integration. The traditional ARDL test is used to estimate long-run and short-run coefficients for variables of the form I(1) and I(0) I(1). Later, the augmented autoregressive distributed lag (A-ARDL) bound test was developed by Sam et al. (2019) for variables with integration degrees such as I(0) and I(1) I(0). In this study, the dynamic simulated ARDL model proposed by Jordan and Philips (2018) was run as the prerequisites for this test were provided. The feature of this model, and the reason for its selection, is that it can automatically stimulate, quantify, and represent the actual variation in an explanatory variable and its impact on the dependent variable, ceteris paribus (Sarkodie et al. 2019; Sarkodie and Owusu 2020). Figure 1 is given for analysis steps of the research.

4 | Data, Conceptual Framework, and Model Specification

This paper uncovers the nexus between BEC, CPU and BTC GHG emissions (BTCGHG) in the world, utilizing monthly data from 2015 to 2023. The theoretical model of this paper is based on the Environmental Kuznets Curve (EKC). As it is known, the EKC, which is generally considered to be parabolic, the dependent variable is created by modeling environmental variables, and the independent variables are GDP and the square of GDP (Dinda 2004; Stern 2004; Celik et al. 2024). However, in this study, the dependent variable was modeled as the GHG emissions variable of BTC mining, and the independent variables were BEC and the square of BEC. It is also included in the model to measure the impact of uncertainty in climate policy.

In this context, the mathematical and econometric model can be presented as follows:

$$\mathrm{lnBTCGHG} = \mathrm{f}(\mathrm{lnBEC}, \mathrm{lnBEC}\hat{}2, \mathrm{lnCPU}) \tag{13}$$

$$\mathrm{lnBTCGHG_t} = \alpha_0 + \alpha_1 \mathrm{lnBEC_t} + \alpha_2 \mathrm{lnBEC_t^2} + \alpha_3 \mathrm{lnCPU_t} + \mathrm{u_t} \tag{14}$$

where α_0 states the constant term, while u_t denotes the error term. In addition, $\alpha_1 ... \alpha_3$ denote the slope coefficients, “ln” indicates the natural logarithm, t subscript indicates time dimension. Within the framework of the above hypotheses, the expectations regarding the slope coefficients $(\alpha_1 > 0, \alpha_2 > 0, \alpha_3 > 0)$ in the model are that the independent variables considered could increase the BTCGHG. In this respect, the description of the variables is given in Table 1. Therefore, BTCGHG and BEC data were collected by the Cambridge Centre for Alternative Finance, while CPU data were obtained from https://www.policyuncertainty.com/. It should also be noted that global data are utilized in the analysis process of this study.

Moreover, Figure 2 indicates time change of variables at monthly frequency after 2015. Accordingly, with the popularity of cryptocurrencies over the years, the increase in energy consumption and the growth in GHG emissions caused by the increase in BTC production are clearly observable.

Furthermore, Table 2 demonstrates that the mean of lnBTCGHG is 2.81, while the mean of lnBEC is 3.47, the mean of lnBEC^2 is 13.63, and the mean of lnCPU is 5.09. It can also be seen that the

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FIGURE 1 | Analysis steps of the research Source: Constructed by authors.

TABLE 1 | Description of variables.

Variable	Code	Unit	Source
Bitcoin greenhouse gas emissions	BTCGHG	Terawatt	Cambridge Centre for Alternative Finance
Bitcoin electric consumption	BEC	Terawatt	Cambridge Centre for Alternative Finance
Climate policy uncertainty	CPU	Index	https://www.policyuncertainty.com/

standard deviation of lnBTCGHG is 1.23, the standard deviation of lnBEC is 1.25, the standard deviation of lnBEC^2 is 7.69, and the standard deviation of lnCPU is 0.43.

In continuation of descriptive statistics, Figure 3 displays the results of the correlation analysis. It can be said that the results of the correlation analysis are in line with expectations. Accordingly, a positive relationship was found between BEC and BTCGHG. Similarly, a positive relationship was found between CPU and BTCGHG. Another notable result is the high correlation between BTC production and BEC. The reason for this, of course, is that BTC production is directly dependent on electricity consumption.

5 | Empirical Findings

Table 3 indicates the results of the ADF, PP, Zivot ve Andrews (ZA), and FKruse unit root tests. The ADF and PP unit root tests are linear unit root tests without structural breaks. They may not give reliable results in the presence of structural breaks and non-linearity. Therefore, ZA with sharp structural breaks and without taking non-linearity into account and the FKruse unit root test with soft breaks and then taking non-linearity into account were considered first. ADF and PP

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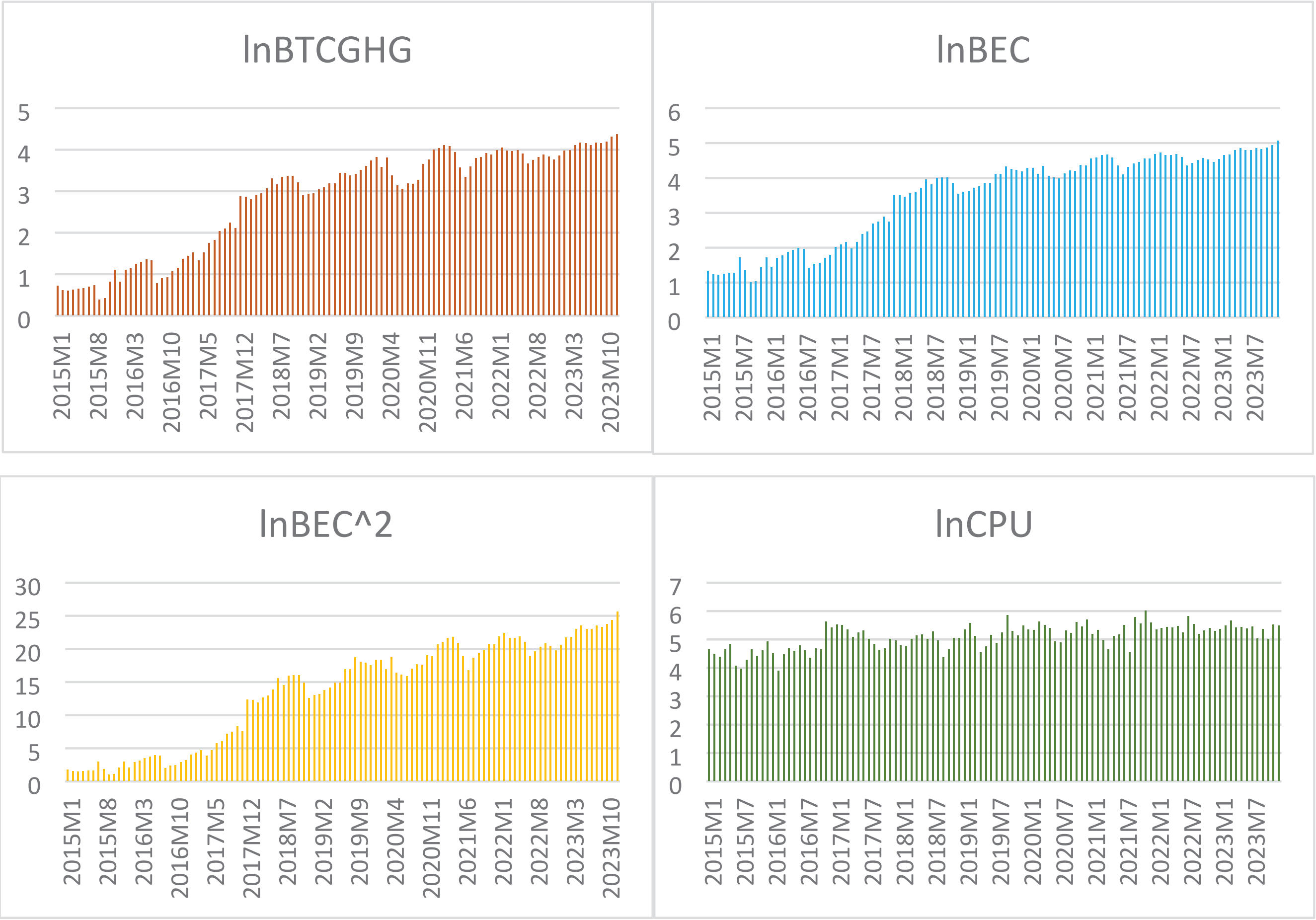

FIGURE 2 | Time change of variables at monthly frequency after 2015.

TABLE 2 | Descriptive statistics of the variables.

Variable	Obs	Mean	Std. dev.	Min	Max
lnBTCGHG	108	2.814343	1.237212	0.392042	4.379398
lnBEC	108	3.475775	1.250535	1.004302	5.059172
lnBEC^2	108	13.63037	7.698112	1.008622	25.59522
lnCPU	108	5.094411	0.431667	3.894375	6.019296

unit root test results indicate that lnCPU is stationary at the level, while other variables are stationary at their first differences. Furthermore, ZA unit root test results also reveal that lnBECKARE and lnCPU are stationary at the level, while lnBTCGHG and lnBEC are stationary at their first differences. Finally, Figures 4 and 5 illustrate the results of the quantile-based ADF and PP unit root tests proposed by Adebayo and Ozkan (2024). It can be said that these results are in line with the results of the traditional unit root tests. The results of the unit root test indicate that ARDL is a suitable method for estimating the coefficients, since the results of the unit root test point to a mixed integration of the variables.

Before evaluating the dynamic ARDL test results, the quantile on quantile regression (QQR) introduced by Sim and Zhou (2015) results are examined. The QQR approach is used for bivariate analysis, combining QR and nonparametric estimations (Adebayo and Acheampong 2022; Somoye et al. 2024). Figure 6 illustrates the results of Quantile on quantile regression analysis. According to the results in Figure 6a, it is observed that BEC increases BTCGHG at different quantile levels. In particular, it is found that a 1% increase in BEC at the upper quantile level increases BTCGHG by approximately 10%–15%. Next, Figure 6b demonstrates that BEC^2 increases BTCGHG predominantly at different quantile levels. Finally, Figure 6c indicates that the rise in CPU leads to growth in BTCGHG by 15%–20% at the upper quantile level, while at the lower quantile level, CPU has a neutral effect on BTCGHG.

Following the QQR results, Figure 7 illustrates the results of Wavelet quantile regression (WQR). Hence, Figure 7a illustrates the relationship between BTCGHG and BEC using

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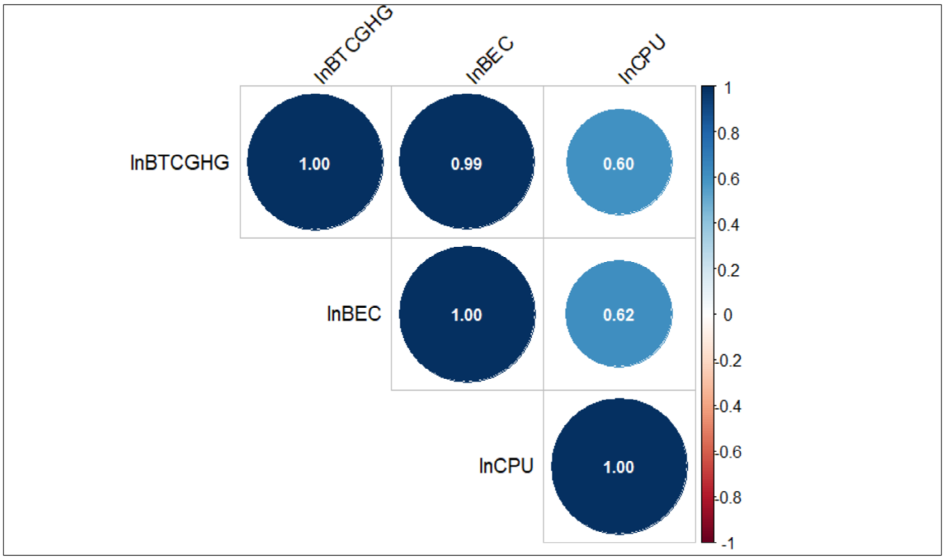

FIGURE 3 | Correlation analysis results.

TABLE 3 | Results of unit root tests.

Panel A. Results of unit root tests with no structural breaks and nonlinearity

	ADF		PP	
	Level	**1st diff.**	**Level**	**1st diff.**
Variable	***t*-Statistic**	***t*-Statistic**	***t*-Statistic**	***t*-Statistic**
lnBTCGHG	−1.16 (0.68)	−10.12 (0.00)***	−1.16 (0.68)	−10.12 (0.00)***
lnBEC	−1.17 (0.68)	−11.16 (0.00)***	−1.16 (0.68)	−11.14 (0.00)***
lnBEC^2	−0.66 (0.85)	−10.91 (0.000)***	−0.63 (0.85)	−10.91 (0.00)***
lnCPU	−4.46 (0.00)***	—	−4.32 (0.00)***	—

Panel B. Results of unit root tests with structural breaks and nonlinearity

Variable	**Zivot and Andrews (2002)**	**Breakpoints**	**Fourier Kruse (2019)**
lnBTCGHG	−4.26	2017 M5	6.99
lnBEC	−4.48	2017 M6	8.6
lnBEC^2	−5.22**	2017 M12	9.17
lnCPU	−7.36***	2017 M11	21.48***

Note: (*) significant at 10%, (**) significant at 5%, and (***) significant at 1%.

the wavelet quantile regression (WQR) method introduced by Adebayo and Ozkan (2024). It can be seen that BEC has a positive impact on BTCGHG for all periods. In particular, in the long term, an increase in BEC leads to an increment in BTCGHG by 1.10%. Figure 7b also demonstrates the relationship between BTCGHG and BEC^2. According to this result, the increase in BEC^2 also contributes to the rise in BTCGHG in the short, medium, and long term. Figure 7c also depicts the link between BTCGHG and CPU. According to this, an increase in CPU leads to an increment in BTCGHG in the short, medium, and long term.

When ARDL test results are monitored, first of all, the results of the bounds tests in Table 4 reveal that the values of the calculated *F*-statistic and *t*-statistic are greater than the critical values at the 1% significance level. Accordingly, the null hypothesis that there is no cointegration between variables is rejected. Therefore, cointegration relationships are detected between variables. In short, these results state that the selected variables have a long-run relationship and move together.

Table 5 indicates the results of the dynamic ARDL simulation. First, the results of the F-test statistic indicate that the model is statistically significant. Accordingly, it can be seen that the increase in lnBEC has a positive effect on lnBTCGHG in both the short and long term. A 1% increase in lnBEC raises lnBTCGHG by 0.64% in the short term and 0.33% in the long term. In addition, a 1% increase in lnBTC^2 rise in lnBTCGHG by 0.05% in the short term. In other words, the increase in energy consumption has led to an increase in GHG es. On the

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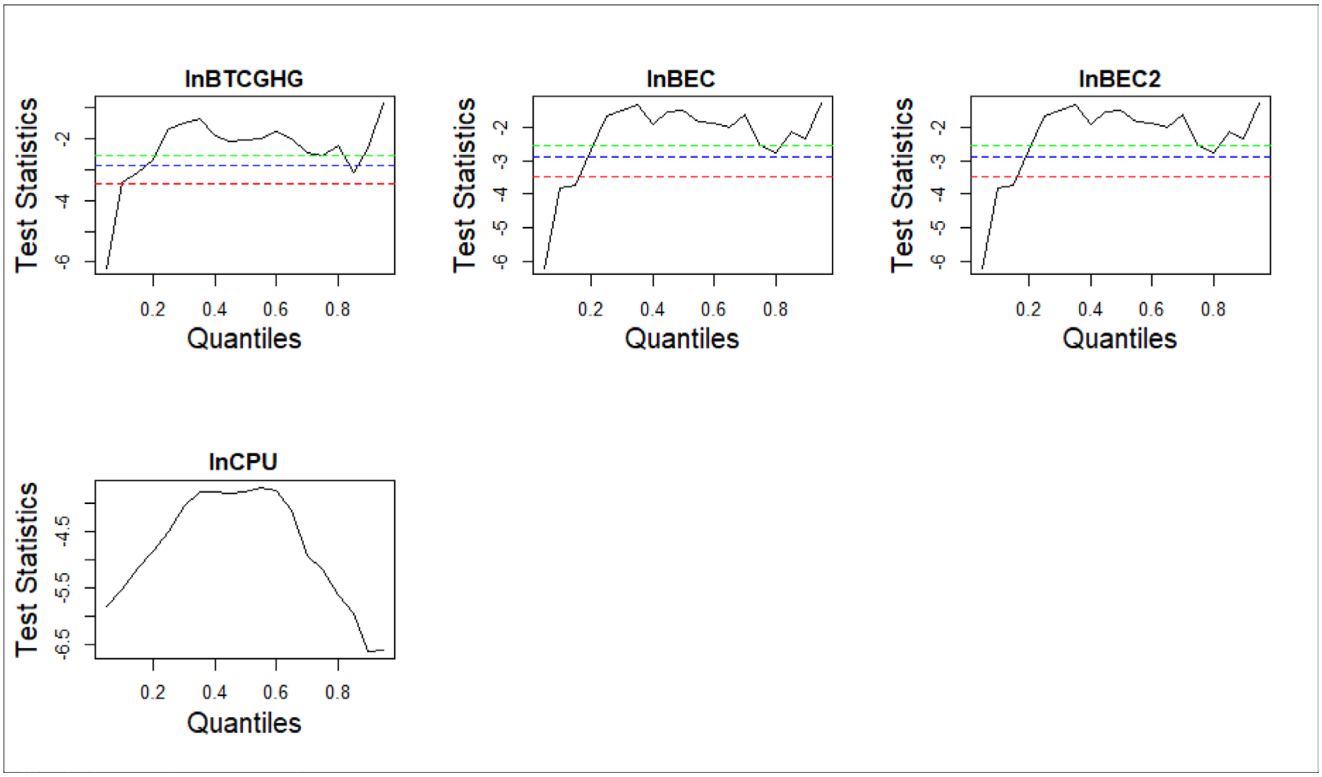

FIGURE 4 | Results of the quantile ADF unit root test.

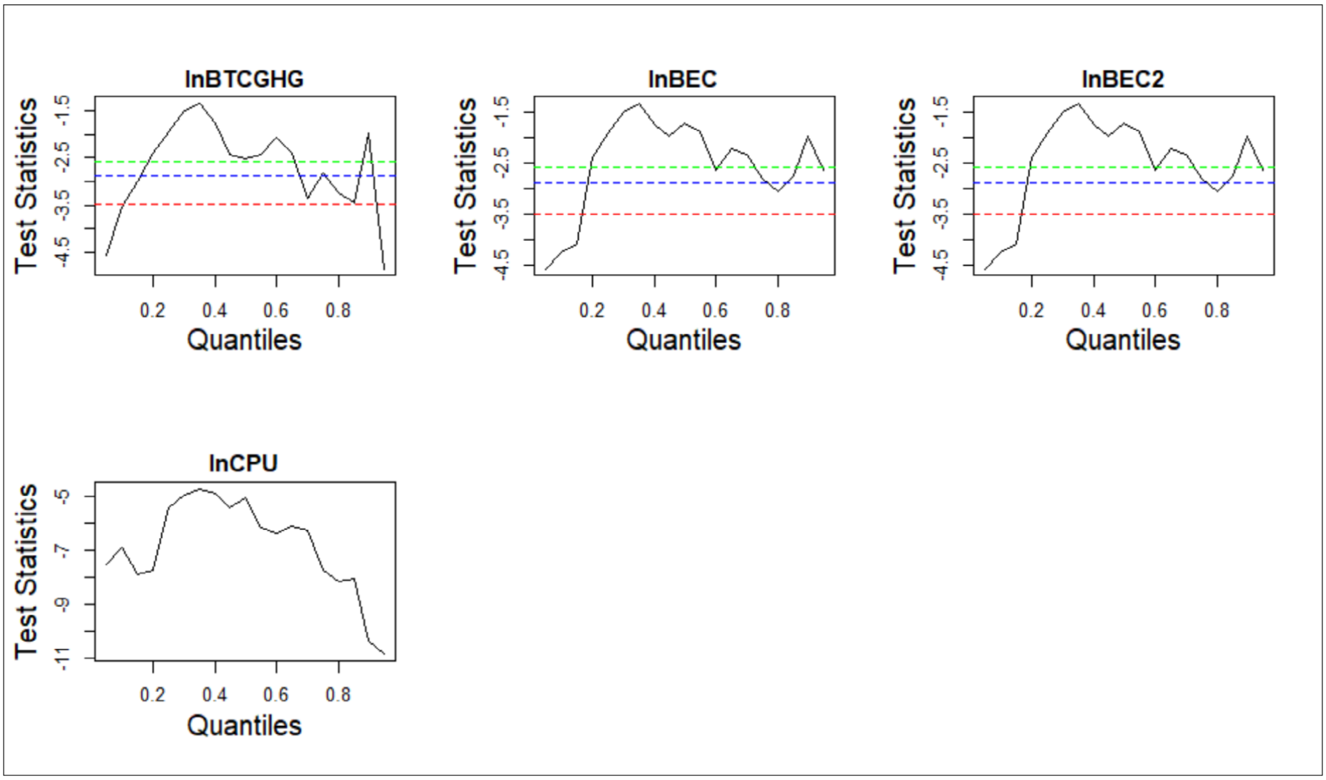

FIGURE 5 | Results of quantile PP unit root tests.

other hand, it is noted that the *R*-squared is 0.847. This result indicates that the independent variables have high explanatory power for the dependent variable. Likewise, the results of the diagnostic tests show that there is no problem with autocorrelation and heteroskedasticity at a statistically significant level of 1%.

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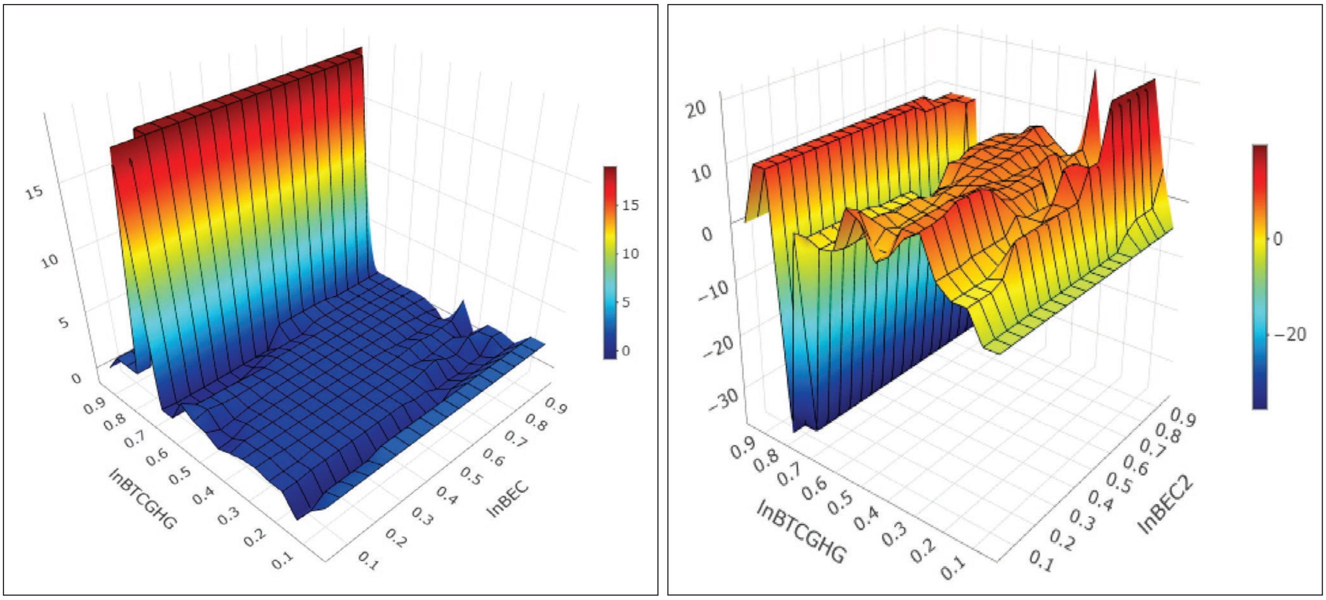
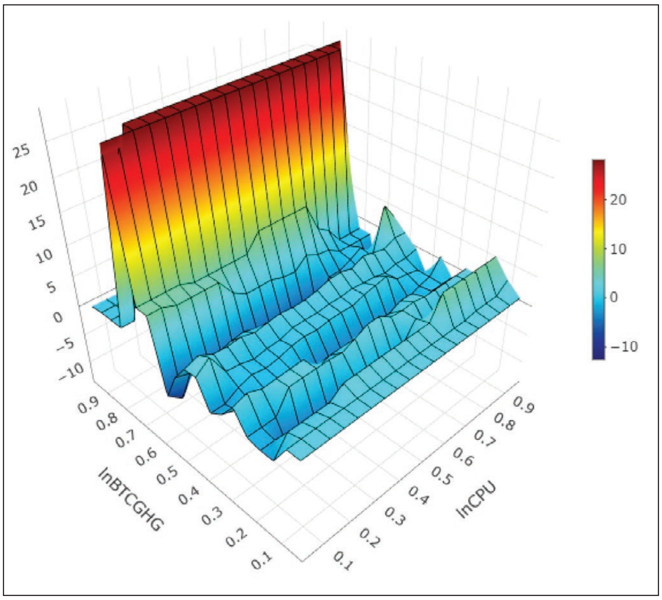


a) BTCGHG and BEC

b) BTCGHG and BEC^2



c)BTCGHG and CPU

FIGURE 6 | Quantile on quantile regression analysis results.

Following that, the estimated short and long-term effects of 1% positive and negative shocks that may occur in any period in the independent variables used in the study's model (BEC, BEC2, CPU) on BTC GHG emissions were simulated applying the dynamic ARDL simulation model. The graphs obtained as a result of the simulation are visualized in Figure 8. The graphs on the left in Figure 8 display the effect of a 1% negative shock on lnBTCGHG, while the graphs on the right show the effect of a 1% positive shock on lnBTCGHG. Looking at the upper plots, it can be revealed that a 1% negative shock to lnBEC significantly reduces lnBTCGHG in the short-term and then reaches a constant long-term value of about 1.8. Nevertheless, a 1% positive shock in lnBEC significantly increases lnBTCGHG in the short term and then reaches a constant long-term value of about 3.6. It is also simulated that 1% negative and positive shocks in lnBEC^2 have no direct impact on lnBTCGHG in the short and long term. However, a 1% negative shocks in lnCPU significantly reduces lnBTCGHG in time and a 1% positive shock in lnCPU rises in BTCGHG in time. To sum up, it has been concluded that increases in BEC increase BTC GHG emissions and ultimately increase environmental degradation. On the contrary, a decreases in BEC have been found to lower the amount of BTC GHG emissions. In addition, as CPUs diminish, the amount of BTC GHG Emissions decreases, while as CPUs grow, the amount of BTC GHG emissions increases accordingly.

Table 6 indicates the pointwise derivatives using KRLS. The goodness of fit of the KRLS model is 0.994, which means that 99% of the variation in BTC GHG emissions can be explained

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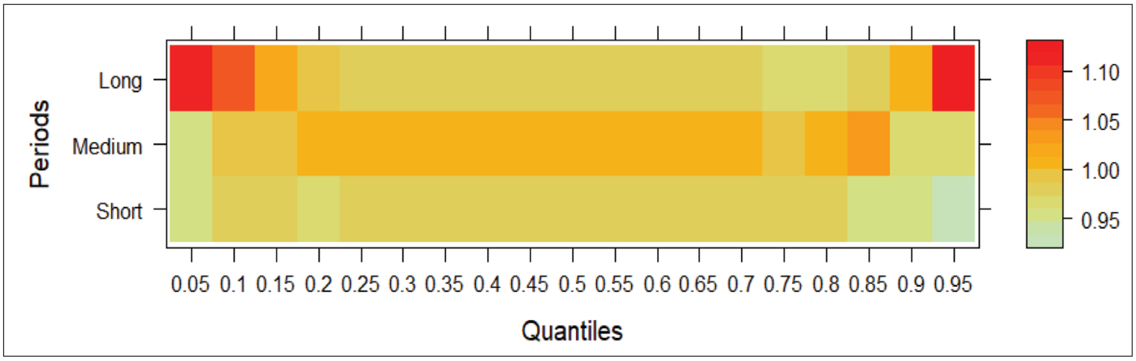
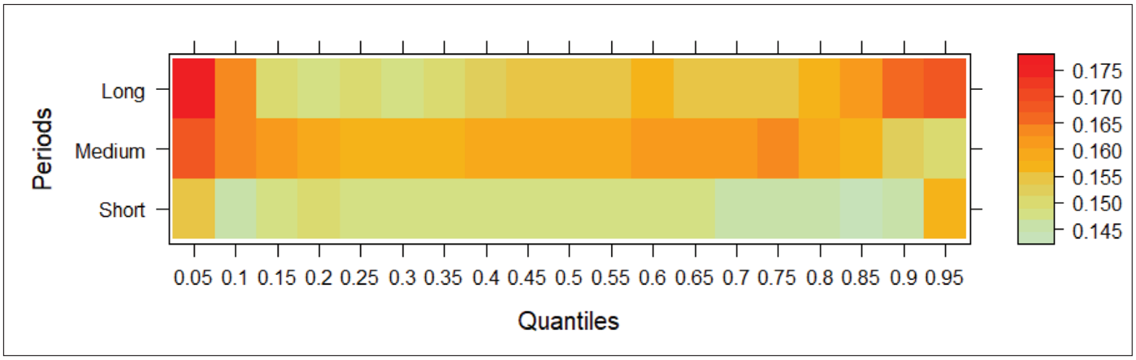
a) BTCGHG and BEC



b) BTCGHG and BEC^2



c) BTCGHG and CPU

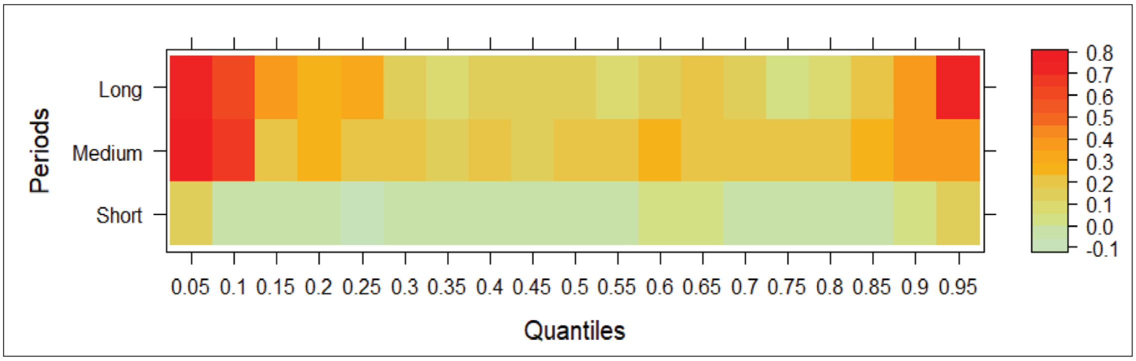


FIGURE 7 | WQC results.

TABLE 4 | ARDL bounds cointegration test.

***f*-test**	**10% critical value**		**5% critical value**		**1% critical value**	
f-stat: 5.527	2.72	3.77	3.23	4.35	4.29	5.61
***t*-test**	**10% critical value**		**5% critical value**		**1% critical value**	
t-stat: −4.614	−2.57	−3.46	−2.86	−3.78	−3.43	−4.37

by the independent variables in the model. Accordingly, the results of the KRLS test prove that a 0.38% increase in lnBEC leads to a raise in lnBTCGHG, while a 0.06% increase in lnBEC^2 contributes to a rise in lnBTCGHG. Overall, an increase in BEC results in an upward trend in BTC GHG emissions. The results of the robustness estimation (robust OLS, FMOLS, and VAR analysis) presented in Table 7 also show consistency with the relevant values. In particular, the variance decomposition results evidence that the influence of the independent variables on the GHG emissions of BTC is much higher as the time period becomes longer. Therefore, looking at the 10th time period, approximately 79.2% of BTC GHG emissions are caused by IT, while approximately 10.10% of BTC GHG emissions are caused by CPU. In addition, about 7.8% of BTC GHG emissions are affected by BEC, while about 2.56% of BTC GHG emissions are affected by BEC^2.

Next, the marginal effect of the independent variables on the dependent variable were considered. Figures 9–11 depict the marginal effects of the independent variables. First, Figure 9

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TABLE 5 | Estimates of the dynamic simulated ARDL model.

	Coef.	SE	*p*
$\ln BTCGHG_{(t\text{-}1)}$	−0.357***	0.077	0.000
ΔlnBEC	0.649***	0.105	0.000
$\ln BEC_{(t\text{-}1)}$	0.338***	0.083	0.000
ΔlnBEC^2	0.050***	0.017	0.000
ΔlnCPU	0.026	0.023	0.272
lnBEC^2 $_{(t\text{-}1)}$	0.001	0.006	0.856
$\ln CPU_{(t\text{-}1)}$	0.019	0.023	0.416
Constant	−0.286**	0.124	0.024
Observation	108		
F-statistics (*p*-value)	0.000***		
R-squared	0.847		
Root MSE	0.069		
Diagnostic tests			
Heteroskedasticity Test Breusch-Pagan-Godfrey	1.53 [0.16]		
B–G LM Test	4.65 [0.01]		
Cusum	Stabil		
Simulations	1000		

Note: ***states statistically significant at the 1% level, while **denotes statistically significant at the 5% level. Simulations = 1000. B–G LM test denotes Breusch–Godfrey Serial Correlation LM Test.

indicates the marginal effect of BTC electricity consumption on lnBTCGHG. Accordingly, as BEC increased, the amount of BTC GHG increased up to a threshold. However, after the threshold it partially decreased and then became stable. In addition to this result, as shown in Figure 10, when the square of BTC energy consumption increased, there was a linear increase in the amount of BTC GHG. Finally, in Figure 11, as CPU increased, the amount of BTC GHG showed an upward trend. However, after a certain threshold, there was a decrease in the amount of GHG emissions. A general overview of the results obtained can be seen in Figure 12.

6 | Discussion

Studies on the environmental impacts of BTC mining primarily focus on the high energy consumption of the PoW consensus mechanism and the resulting GHG emissions. BTC mining has been criticized for its significant energy and electricity consumption, which negatively impacts the environment due to its reliance on fossil fuels. Stoll et al. (2019) examined this issue in detail and reported that in 2018, BTC mining contributed to 22 Mt of CO_2 emissions globally. This amount is equivalent to the annual carbon emissions of some small countries, highlighting the environmental impacts of BTC's fossil fuel-based energy consumption on global warming and environmental degradation. De Vries (2018) echoed a similar view, emphasizing the negative environmental impacts of BTC mining. According to the Cambridge Centre for Alternative Finance (2023a), BTC mining consumes over 100 TWh of energy per year, which is comparable to the annual energy consumption of countries like Argentina. Since this energy consumption is largely dependent on fossil fuels, it poses a significant barrier to combating climate change (Mora et al. 2018).

However, some researchers argue that the environmental impacts of BTC mining could be more positive. They suggest that advancements in mining technology and the transition to renewable energy sources could mitigate these effects. Similarly, Shahbaz et al. (2020) claimed that technological innovations could optimize energy consumption and positively affect environmental outcomes.

As an alternative to PoW's high energy consumption, Ethereum's transition to PoS system is regarded as a significant example of reducing environmental impacts. Sedlmeir et al. (2020) argued that the PoS mechanism consumes significantly less energy compared to PoW and suggested that BTC could similarly reduce its environmental damage by making a similar transition. However, they also pointed out that this transition could present technical and ideological challenges for BTC. Kirikkaleli and Adebayo (2021) also found a relationship between the use of renewable energy and economic growth that supports environmental sustainability. Neagu (2019) research on economic complexity and environmental sustainability further supports the argument that the correct application of technology can reduce environmental harm.

In conclusion, discussions surrounding the environmental impacts of BTC mining are shaped by differing perspectives. On one side, there is criticism regarding BTC's environmental harm due to its high energy consumption and dependence on fossil fuels. On the other side, some argue that transitioning to renewable energy and technological advancements could mitigate these environmental impacts. In this context, adopting new technologies and consensus mechanisms that optimize BTC's energy consumption, particularly transitioning from the PoW system to the PoS system, as we have highlighted in our study, will be crucial to making cryptocurrency mining more sustainable.

Studies on the environmental impacts of BTC mining have mostly focused on general metrics such as energy consumption and carbon footprint. However, regional differences and their effects on environmental sustainability have not been examined in sufficient depth. In particular, the types of energy sources used in BTC mining are closely related to the energy infrastructures and regulations of different countries. However, analyses in this context have generally remained limited, and a comprehensive comparison of the regional impacts of BTC mining has not been conducted. For example, in 2020, China accounted for 73% of BTC mining. However, due to government bans and regulations on BTC mining, this share dropped to 21% by 2022. As a result, BTC mining has largely shifted to countries such as the US and Kazakhstan. The share of BTC mining in the US increased by 34%, while Kazakhstan's share rose by 10%. This shift has also affected the energy mix

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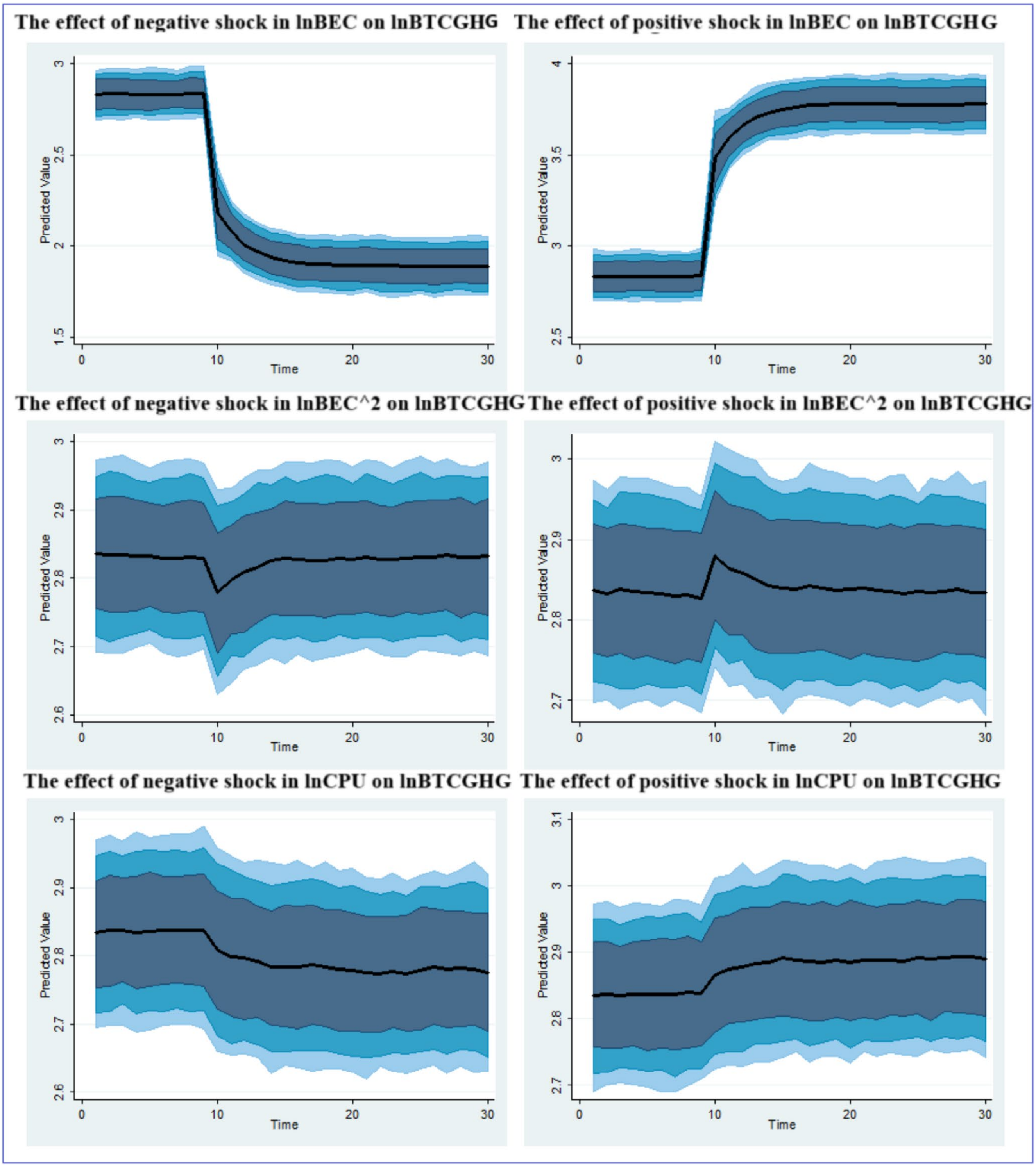

FIGURE 8 | The negative and positive shock of lnBEC, lnBEC^2, and lnCPU on lnBTCGHG.

used in BTC mining. Following China's exit from mining, the share of coal in the global BTC network's energy supply decreased from 53% in 2020 to 46% in 2022. Nevertheless, the global BTC network remains highly dependent on fossil fuels. For instance, in Kazakhstan, BTC mining relies primarily on energy produced from fossil fuels such as coal and natural gas. Due to its low electricity costs (70% cheaper), Kazakhstan has attracted significant investments in BTC mining (Cambridge Centre for Alternative Finance 2023b).

The US has become the second-largest country for BTC mining, with mining activities varying across different states. For example, Georgia (31%), Kentucky (11%), Texas (10.9%), and New York (9.8%) are the largest BTC mining hubs in the country (Cambridge Centre for Alternative Finance 2023b). Since there is no federal regulation banning BTC mining in the US, state-level energy policies contribute to variations in the environmental impacts of mining. States like Georgia focus more on renewable energy sources, whereas Kentucky

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TABLE 6 | Pointwise derivatives using KRLS.

lnBTCGHG	Avg.	SE	t	$p > t$	P25	P50	P75
lnBEC	0.389***	0.011	36.915	0.000	0.303	0.369	0.405
lnBEC^2	0.063***	0.002	38.031	0.000	0.050	0.069	0.080
lnCPU	0.023	0.033	0.692	0.491	−0.081	0.027	0.106
Diagnostic							
Lambda	0.196	Sigma	3.000	R^2	0.994	obs	108
Tolerance	0.108	Eff. df	13.600	Looloss	1.337		

***States statistically significant at the 1% level.

TABLE 7 | The results of robustness tests.

			Variance decomposition of LNBTCGHG					
Variable	**Robust OLS**	**FMOLS**	**Period**	**S.E.**	**LNBTCGHG**	**LNBEC**	**LNBEC_2**	**LNCPU**
LNBEC	0.925***	0.971***	2	0.24	99.39	0.09	0.12	0.40
LNBEC^2	0.009**	0.002	4	0.32	92.65	2.17	0.83	4.35
LNCPU	0.018	0.01	6	0.39	86.52	4.68	1.51	7.29
C	−0.622***	−0.646***	7	0.42	84.20	5.71	1.81	8.28
R^2	0.994	0.995	8	0.45	82.32	6.57	2.07	9.03
Adjusted R^2	0.994	0.995	9	0.47	80.79	7.26	2.32	9.63
Sum squared resid	0.828	0.835	10	0.49	79.52	7.82	2.56	10.10

Note: ***states statistically significant at the 1% level, while **denotes statistically significant at the 5% level. Lag length was selected as 2 for VAR analysis.

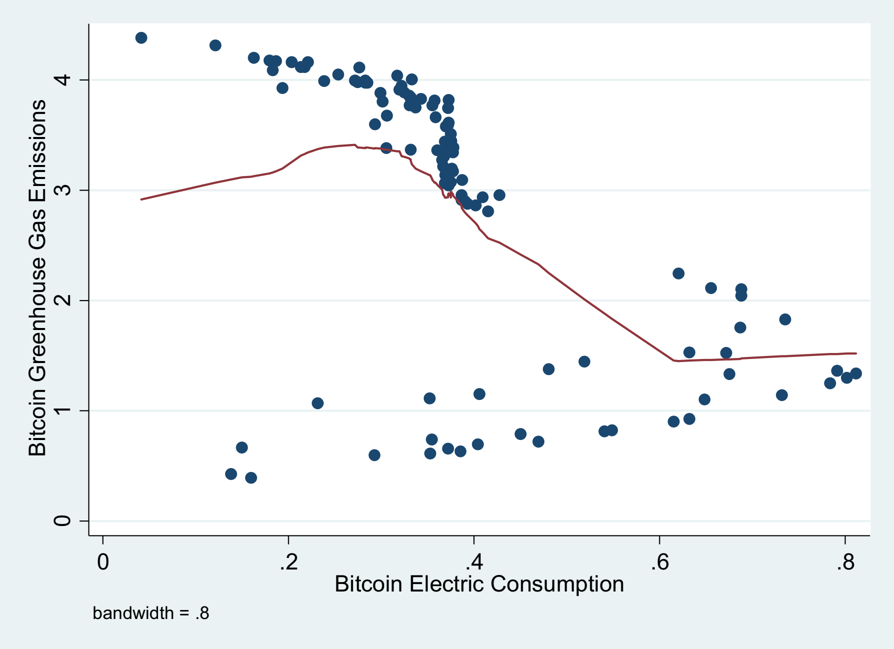

FIGURE 9 | Representation of the pointwise marginal effect of Bitcoin electric consumption.

relies on coal-based energy, leading to higher carbon emissions. Similarly, Russia is another major BTC mining hub. The amount of electricity used for BTC mining in Russia is equivalent to 37% of the US's BTC mining electricity consumption and 17% of China's. Malaysia continues BTC mining based on fossil fuel energy production, while countries like Canada, which have greater access to renewable energy sources, have a significant advantage in reducing their carbon footprint. On

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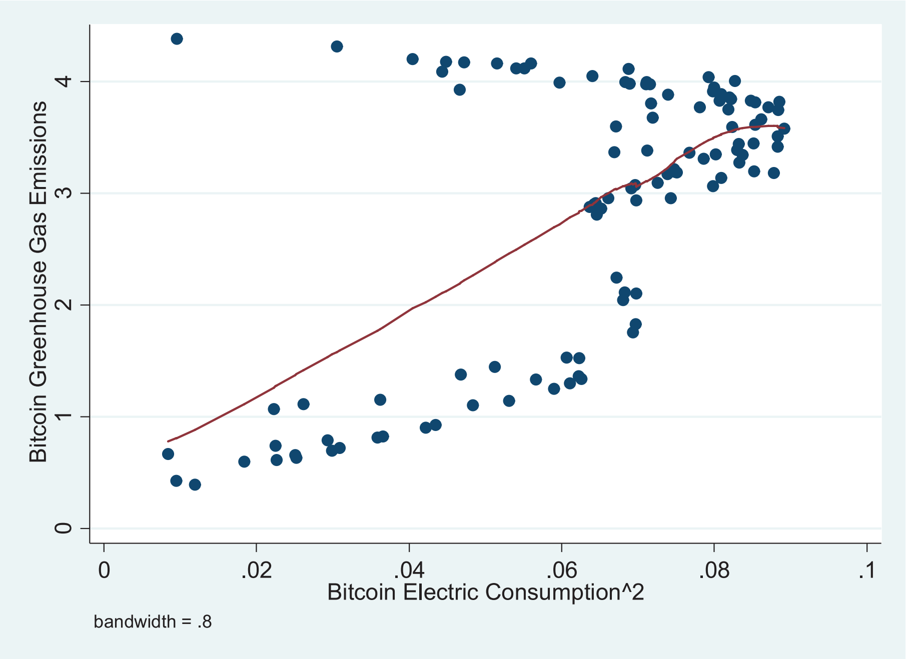

FIGURE 10 | Representation of the pointwise marginal effect of Bitcoin electric consumption squared.

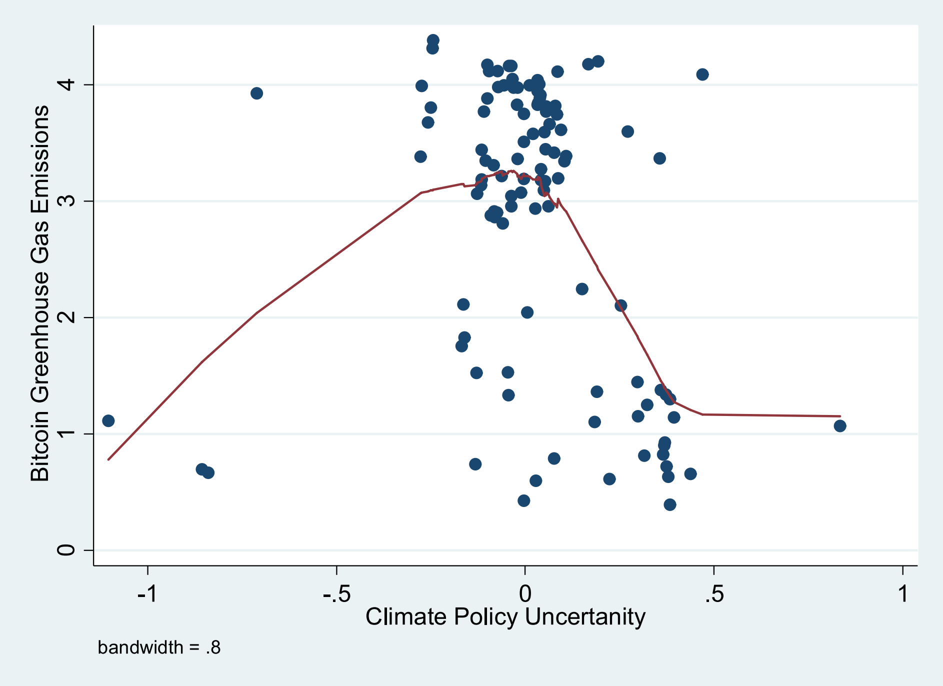

FIGURE 11 | Representation of the pointwise marginal effect of climate policy uncertainty.

the other hand, Kazakhstan has become an attractive BTC mining hub due to low energy costs, but this poses serious threats to environmental sustainability.

The results indicate that comprehensive changes in regulatory frameworks are needed to reduce the environmental impacts of BTC mining. In this context, tax incentives could be introduced to encourage mining activities to shift toward renewable energy sources, while carbon taxes could be implemented to discourage fossil fuel use. Policies requiring local governments to transparently report energy consumption would not only improve the traceability of environmental impacts but also promote energy efficiency.

Additionally, the widespread adoption of more energy-efficient consensus mechanisms, such as Proof of Stake, should be encouraged, and regulations should be developed to minimize the impact of mining operations on local energy infrastructures.

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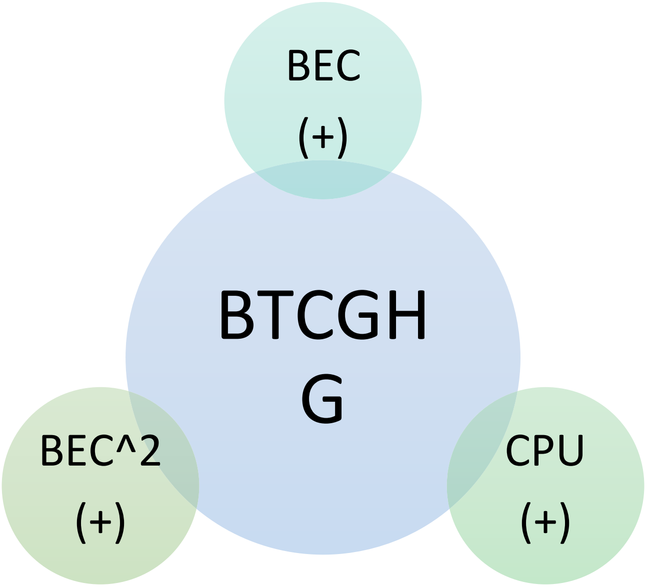

FIGURE 12 | General overview of the results obtained.

Establishing carbon tracking protocols through international cooperation would also be a crucial step in aligning BTC mining with environmental sustainability.

In order to effectively mitigate the environmental impacts of BTC mining, proposed solutions must go beyond general reductions in energy consumption and instead adopt a stakeholder-specific approach. Financial institutions and investment funds, for example, could develop green crypto investment portfolios that prioritize companies powered exclusively by renewable energy. This would also enable environmentally conscious investors to align their assets with Environmental, Social, and Governance (ESG) principles. Regulatory bodies could implement carbon taxes targeting high-emission mining operations and offer tax incentives to encourage the use of clean energy sources. In decentralized regulatory environments like the US, state-level mandates on energy transparency and source reporting could significantly reduce regional disparities in carbon emissions. Environmental organizations and civil society groups may also play a vital role by establishing real-time, publicly accessible digital platforms to monitor energy usage in mining operations, thereby increasing accountability (Mora et al. 2018; Gallersdörfer et al. 2020). Furthermore, an internationally recognized green certification system for mining companies could incentivize sustainable practices across the industry. A compelling example of environmentally conscious transformation is Ethereum's 2022 shift to the PoS consensus mechanism, which reportedly reduced its energy consumption by 99.95% (De Vries 2018). In this light, achieving environmental sustainability in BTC mining will depend not only on technological innovation but also on comprehensive institutional and regulatory reforms.

Technological advancements aimed at mitigating the environmental impact of BTC mining can play a significant role. In particular, the integration of more efficient mining hardware and renewable energy has great potential to reduce this impact. New Application-Specific Integrated Circuit (ASIC) machines can significantly improve the energy efficiency of mining equipment, which could be effective in reducing the environmental footprint of the BTC network. Additionally, low-energy consensus models can be implemented to limit the environmental damage caused by BTC mining.

Such innovative solutions are not only attractive from an engineering perspective but also economically viable, potentially transforming BTC mining into a more sustainable business model. Furthermore, the adoption of innovative technologies can serve as a proactive measure against regulations and create a significant opportunity to reduce the environmental impact of BTC mining. These technological advancements will not only help mitigate environmental harm but also enable BTC mining to become more sustainable.

7 | Conclusion, Policy Recommendations, Limitations of the Study, and Future Studies

7.1 | Conclusion

Global warming and climate change are among the most pressing issues facing the world today. Global warming and climate change threaten the entire ecosystem. The main cause of global warming and climate change is the increased utilization of fossil fuels, especially with the second industrial revolution. There are many sectors and man-made reasons for the increase in the use of fossil fuels, particularly in the industrial sector. Based on the net-zero emissions target set by the UN Sustainable Development and Climate Summits, all factors that negatively affect GHG and carbon dioxide emissions should be comprehensively examined. In recent years, the development of blockchain technology and cryptocurrencies has also had some impact on the climate. In particular, the aim was to analyze the impact on GHG emissions of the electrical energy consumed in BTC and BTC mining, which have the largest transaction volumes in cryptocurrency markets. In this context, the empirical results obtained indicate that the electrical energy consumed in BTC production significantly increases BTC GHG emissions. In addition, it is concluded that CPU also increases BTC GHG emissions, while decreasing CPU decreases GHG emissions.

7.2 | Policy Recommendations

The environmental impacts of BTC mining, particularly due to its high energy consumption and GHG emissions, present significant challenges to global sustainability goals. Much of this environmental degradation stems from the PoW consensus mechanism, which requires large amounts of energy to secure the BTC network and verify transactions. This process is often criticized for its reliance on fossil fuels, as it increases global carbon emissions and hampers efforts to combat climate change (Mora et al. 2018; Stoll et al. 2019). Despite the technological and financial advancements that BTC and other cryptocurrencies have brought to the global economy, the environmental costs associated with mining should not be ignored.

Today, many projects compete with BTC, and it is noteworthy that these projects are generally more environmentally friendly

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compared to BTC. For example, alternative blockchain projects such as Cardano, Tezos, and Polkadot use more efficient and eco-friendly consensus mechanisms like PoS instead of BTC's energy-intensive PoW mechanism. These projects not only reduce energy consumption but also offer solutions to enhance transaction speed and efficiency. Additionally, Cardano consumes 1.6 million times less energy than BTC, making it a significantly more sustainable option. Moreover, Ethereum's transition to PoS has been a major step toward energy efficiency and has set an example for other blockchain projects. By significantly reducing its annual energy consumption, Ethereum has minimized its environmental impact. Similarly, projects like Ripple and Flow also prioritize energy efficiency, making blockchain technology more accessible to a broader user base. Ripple processes transactions with much lower energy consumption compared to BTC, while Flow operates 200,000 times more efficiently than BTC (Alzoubi and Mishra 2023).

In this context, focusing solely on BTC presents a narrow perspective on the development and potential of blockchain technology. The advancements in other cryptocurrencies and the industry-wide transformation should not be limited to evaluations based only on BTC's energy efficiency and environmental impact. The cryptocurrency world is shaped by various innovative blockchain projects that go beyond BTC and drive the sector forward.

Addressing the negative environmental impacts of BTC mining and aligning the cryptocurrency sector with global climate goals requires significant policy changes. One of the most effective solutions to this issue is transitioning from PoW to a more energy-efficient consensus mechanism, such as the PoS system. The main reason discussed in our study is that this transition reduces both electricity consumption and GHG emissions. As seen in Ethereum's recent transition, this change requires significantly less computational power and energy, leading to a reduction in energy consumption of over 99% (Sedlmeir et al. 2020). A similar transition for BTC should be supported by both regulatory pressures and industry incentives. Governments and regulators should encourage research and development of PoS and other low-energy alternatives and support the adoption of these technologies through tax reductions, subsidies, or other policy measures.

In addition to transitioning to energy-efficient systems like PoS, the cryptocurrency mining industry should be encouraged to adopt renewable energy sources. Currently, a significant portion of BTC mining is concentrated in regions where electricity production heavily relies on fossil fuels, particularly coal and natural gas. This situation contradicts commitments to reducing carbon emissions and transitioning to clean energy under the Paris Agreement (UNFCCC 1998). Policymakers should implement stricter regulations requiring a certain percentage of mining operations' energy sources to come from renewables. In countries where BTC mining activities are prevalent, such as the US and Kazakhstan, laws should be introduced to promote the use of renewable energy in mining operations. To accelerate the transition of miners to solar, wind, or hydroelectric power, financial incentives such as grants, subsidies, or tax credits could be provided (Truby 2018).

Iceland serves as a significant example of successful international policies aimed at reducing the environmental impact of BTC mining and other cryptocurrencies. The country effectively utilizes geothermal and hydroelectric energy sources to generate power, thereby supporting the high energy consumption of mining activities. Additionally, there are strong claims that geothermal energy could be the future of BTC mining (Kumar 2021). This approach minimizes the carbon footprint while making renewable energy usage more attractive through tax incentives provided by the local government to mining companies. Iceland's strategy serves as a model for other countries in regulating cryptocurrency mining.

Furthermore, the Moonlite Project, established in 2017, presents a remarkable example. Moonlite is committed to using 100% renewable energy for mining BTC and other cryptocurrencies. Operating in Iceland, the project relies on wind, geothermal, and hydroelectric power for its mining operations. Additionally, Iceland's cold climate eliminates the need for cooling, making mining more efficient.

Canada's Quebec province also promotes environmentally friendly BTC mining by leveraging renewable energy sources. The province supports growth in this sector by offering tax credits and subsidies for renewable energy investments to mining companies. However, in regions like Quebec, where energy costs are low, mining activities tend to concentrate, while the use of eco-friendly energy aims to help reduce the carbon footprint (Atkins et al. 2021).

In conclusion, the renewable energy-based policies of countries like Iceland and Canada, along with Ethereum's transition to PoS and projects like Moonlite, offer concrete and practical solutions to mitigate the environmental impact of BTC and other cryptocurrency mining activities. These examples provide valuable references for achieving sustainability goals in the cryptocurrency sector and contribute to the development of a more environmentally friendly crypto ecosystem.

To ensure the environmental recommendations for cryptocurrency mining are truly impactful, it is essential that they go beyond general principles and offer specific, enforceable, and measurable strategies for policymakers. In countries with high mining activity such as the US, Kazakhstan, and China—licensing frameworks could mandate that at least 70% of the electricity used in mining operations comes from verified renewable sources. Mining firms that meet or exceed this threshold could qualify for fiscal incentives such as a 20% corporate tax reduction, carbon offset credits, or infrastructure subsidies (Popkova et al. 2023). In parallel, mandatory annual reporting on carbon emissions and energy sourcing by crypto mining facilities verified through independent audits would enhance transparency and enable more responsive regulatory oversight.

Given the cross-border nature of cryptocurrency networks, such national regulations must be complemented by international cooperation. For instance, as outlined in the European Union's 2023 Markets in Crypto-Assets (MiCA) regulation, mandatory environmental disclosures for mining operations should become a global standard. In addition, multilateral platforms such as the International Renewable Energy Agency (IRENA) or the G20 Energy Working Group could spearhead the development of a "Green Mining Certification" system. This framework would establish a shared set of criteria based on energy efficiency, renewable sourcing, and emissions thresholds, helping to identify and

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promote environmentally responsible mining operations across jurisdictions (Zetzsche et al. 2021). These measures would not only support global climate goals but also enhance the legitimacy and sustainability of the broader blockchain ecosystem.

Future research directions and emerging trends in cryptocurrency mining hold significant importance in terms of environmental sustainability. The increasing number of “carbon-neutral” or zero-carbon emission projects represents a key trend supporting sustainability efforts in this field. A deeper investigation of these developments will help us understand how the cryptocurrency mining sector can undergo a transformation to reduce its environmental impact.

Additionally, topics such as new energy-efficient solutions in blockchain technology and its integration with technologies like artificial intelligence and machine learning are gaining importance as future research areas. Studies should explore how these new technologies can be utilized to optimize mining processes and develop more sustainable alternatives. Another critical research direction in terms of environmental sustainability is the integration of cryptocurrency mining with other industries and potential changes in industrial applications. Research on how such innovative developments can play a role in reducing the environmental impact of the cryptocurrency sector could make significant contributions to the literature.

In conclusion, international cooperation is crucial in addressing the global environmental challenges posed by BTC mining. Given the decentralized nature of the cryptocurrency sector, coordinated efforts among countries will be essential to developing standardized environmental regulations for mining operations. This could include establishing global emission standards for cryptocurrency mining, creating green certifications for mining equipment, and fostering partnerships between governments, private companies, and environmental organizations to promote sustainable mining practices.

7.3 | Limitions of the Study and Future Studies

One of the main limitations of the study is the time period covered. At the same time, another limitation is that only BTC with the largest transaction volume was selected among the cryptocurrencies. In this context, the relevant restrictions can be revised in the future.

Future research should focus on how this technology can achieve environmental sustainability by seeking ways to overcome current energy efficiency issues. In particular, how blockchain can be aligned with environmental sustainability goals should be open to discussion from both technological and political perspectives.

One of the biggest areas of debate regarding the reduction of blockchain technology's energy consumption and environmental impacts is the development of alternatives to the current PoW consensus mechanism. Ethereum's transition to the PoS system sets an example by significantly reducing energy consumption.

Another important topic concerning the sustainability of cryptocurrency mining is the use of renewable energy sources. Currently, a significant portion of BTC mining relies on fossil fuel-based energy sources, leading to environmental pollution. The integration of renewable energy sources, particularly clean energy alternatives such as solar, wind, and hydroelectric power, into mining activities is proposed as a critical solution to mitigate this issue. Future research could develop proposals on how this transition can be managed technically and economically.

Government regulatory frameworks are also a key factor in reducing the environmental impacts of blockchain technology. More research should be conducted on how regulatory and financial policy tools can be used to reduce the energy consumption of blockchain technologies. In addition to tools such as carbon taxes and emissions trading systems, regulations mandating the use of renewable energy in mining activities should be discussed. It is suggested that such regulations can not only make mining activities more sustainable but also internalize environmental externalities. Tools such as carbon pricing and green energy incentives could be decisive in this process.

Furthermore, technological innovations hold significant potential for improving the energy efficiency of blockchain technology. By developing more efficient mining equipment, energy consumption can be optimized. Technological advances in this direction could enable mining processes to be carried out with devices that consume less energy. Research in this area could find technological solutions to address sustainability challenges in regions where energy-intensive mining activities take place.

In addition to the environmental impacts of blockchain technology, its socio-economic effects should not be overlooked. Particularly in regions where cryptocurrency mining is concentrated, studies on its impact on local economies could provide important insights into the societal and economic outcomes of this technology. The effects of blockchain-based applications on labor markets, income distribution, and traditional business models should be further discussed in terms of societal balance.

In conclusion, future studies on the environmental impacts of blockchain technology will provide important insights into how technological developments aimed at improving energy efficiency, the integration of renewable energy sources, and regulatory interventions by governments will take shape. These studies will help determine the steps that need to be taken for blockchain technology to contribute to a sustainable future.

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References

Adebayo, T. S., and A. O. Acheampong. 2022. “Modelling the Globalization-CO_2 Emission Nexus in Australia: Evidence From Quantile-On-Quantile Approach.” *Environmental Science and Pollution*

10991719, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/sd.3471 by Istanbul Gelisim Universitesi, Wiley Online Library on [15/08/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Research 29, no. 7: 9867–9882. https://doi.org/10.1007/s11356-021-16368-y.

Adebayo, T. S., and O. Ozkan. 2024. "Investigating the Influence of Socioeconomic Conditions, Renewable Energy and Eco-Innovation on Environmental Degradation in the United States: A Wavelet Quantile-Based Analysis." *Journal of Cleaner Production* 434: 140–321. https://doi.org/10.1016/j.jclepro.2023.140321.

Alzoubi, Y. I., and A. Mishra. 2023. "Green Blockchain–A Move Towards Sustainability." *Journal of Cleaner Production* 430: 139541. https://doi.org/10.1016/j.jclepro.2023.139541.

Andersson, K., X. Chen, C. Esposito, and E. Rondeau. 2020. "IEEE Transactions on Sustainable Computing, Special Issue on Cryptography and Data Security in Sustainable Computing (Part 1)." *IEEE Transactions on Sustainable Computing* 5, no. 2: 160.

Arfelli, F., I. Coralli, D. Cespi, et al. 2024. "The Environmental Stake of Bitcoin Mining: Present and Future Challenges." *Applied Sciences* 14, no. 20: 9597. https://doi.org/10.3390/app14209597.

Atkins, E., L. Follis, B. D. Neimark, and V. Thomas. 2021. "Uneven Development, Crypto-Regionalism, and the (Un-) Tethering of Nature in Quebec." *Geoforum* 122: 63–73. https://doi.org/10.1016/j.geoforum.2020.12.019.

Bublyk, Y., O. Borzenko, and A. Hlazova. 2023. "Cryptocurrency Energy Consumption: Analysis, Global Trends and Interaction." *Environmental Economics* 14, no. 2: 49. https://doi.org/10.21511/ee.14(2)0.2023.04.

Cambridge Centre for Alternative Finance. 2023a. "Bitcoin Electricity Consumption Index." https://cbeci.org.

Cambridge Centre for Alternative Finance. 2023b. "Cambridge Bitcoin Electricity Consumption Index (CBECI)." https://ccaf.io/cbnsi/cbeci.

Celik, A., A. Kostekci, and A. A. Alola. 2024. "Carbon Neutrality Implication of Material Productivity, Total Factor Productivity and Renewable Energy Uptake in the Nordics." *Ecological Indicators* 160: 111813. https://doi.org/10.1016/j.ecolind.2024.111813.

Corbet, S., and L. Yarovaya. 2020. "The Environmental Effects of Cryptocurrencies." *Cryptocurrency and Blockchain Technology* 1, no. 149: 60807. https://doi.org/10.1515/9783110660807.

Das, S. R., and A. Dutta. 2020. "Bitcoin's Energy Consumption: Is it the Achilles Heel to Miner's Revenue?" *Economics Letters* 186: 108530. https://doi.org/10.1016/j.econlet.2019.108530.

De Vries, A. 2018. "Bitcoin's Growing Energy Problem." *Joule* 2, no. 5: 801–805.

Dickey, D. A., and W. A. Fuller. 1979. "Distribution of the Estimators for Autoregressive Time Series With a Unit Root." *Journal of the American Statistical Association* 74, no. 366a: 427–431. https://doi.org/10.1080/01621459.1979.10482531.

Dinda, S. 2004. "Environmental Kuznets Curve Hypothesis: A Survey." *Ecological Economics* 49, no. 4: 431–455. https://doi.org/10.1016/j.ecolecon.2004.02.011.

Gallersdörfer, U., L. Klaaßen, and C. Stoll. 2020. "Energy Consumption of Cryptocurrencies Beyond Bitcoin." *Nature Sustainability* 3, no. 10: 739–746. https://doi.org/10.1016/j.joule.2020.08.005.

Güriş, B. 2019. "A New Nonlinear Unit Root Test With Fourier Function." *Com-Munications in Statistics-Simulation and Computation* 48, no. 10: 3056–3062. https://doi.org/10.1080/03610918.2018.1473591.

Hainmueller, J., and C. Hazlett. 2014. "Kernel Regularized Least Squares: Reducing Misspecification Bias With a Flexible and Interpretable Machine Learning Approach." *Political Analysis* 22, no. 2: 143–168. https://doi.org/10.1093/pan/mpt019.

Hossain, M. I., and T. Steigner. 2024. "Balancing Innovation and Sustainability: Addressing the Environmental Impact of Bitcoin Mining." https://arxiv.org/abs/2411.08908.

Ibañez, J. I., and F. Rua. 2023. "The Energy Consumption of Proof-Of-Stake Systems: Replication and Expansion." arXiv preprint arXiv:2302, 10.48550/arXiv.2302.00627.

Jiang, S., Y. Li, Q. Lu, et al. 2021. "Policy Assessments for the Carbon Emission Flows and Sustainability of Bitcoin Blockchain Operation in China." *Nature Communications* 12, no. 1: 1–10.

Jordan, S., and A. Q. Philips. 2018. "Cointegration Testing and Dynamic Simulations of Autoregressive Distributed Lag Models." *Stata Journal* 18, no. 4: 902–923. https://doi.org/10.1177/1536867X1801800409.

Khosravi, A., and F. Säämäki. 2023. "Beyond Bitcoin: Evaluating Energy Consumption and Environmental Impact Across Cryptocurrency Projects." *Energies* 16, no. 18: 6610. https://doi.org/10.3390/en16186610.

Kiayias, A., A. Russell, B. David, and R. Oliynykov. 2017. "Ouroboros: A Provably Secure Proof-Of-Stake Blockchain Protocol." In Annual International Cryptology Conference (357–388). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-63688-7_12.

Kirikkaleli, D., and T. S. Adebayo. 2021. "Do Renewable Energy Consumption and Financial Development Matter for Environmental Sustainability? New Global Evidence." *Sustainable Development* 29, no. 4: 583–594. https://doi.org/10.1002/sd.2159.

Kohli, V., S. Chakravarty, V. Chamola, K. S. Sangwan, and S. Zeadally. 2023. "An Analysis of Energy Consumption and Carbon Footprints of Cryptocurrencies and Possible Solutions." *Digital Communications and Networks* 9, no. 1: 79–89. https://doi.org/10.1016/j.dcan.2022.06.017.

Krause, M. J., and T. Tolaymat. 2018. "Quantification of Energy and Carbon Costs for Mining Cryptocurrencies." *Nature Sustainability* 1, no. 11: 711–718.

Kumar, S. 2021. "Review of Geothermal Energy as an Alternate Energy Source for Bitcoin Mining." *Journal of Economics and Economic Education Research* 23, no. 1: 1–12.

Kuznetsova, E., and M. F. Anjos. 2020. "Challenges in Energy Policies for the Economic Integration of Prosumers in Electric Energy Systems: A Critical Survey With a Focus on Ontario (Canada)." *Energy Policy* 142: 111429. https://doi.org/10.1016/j.enpol.2020.111429.

Lu, E. 2023. "The Environmental Implications of Cryptocurrencies." *Journal of High School Science* 7, no. 3: 2–4.

Lu, Y., Z. A. Khan, M. S. Alvarez-Alvarado, Y. Zhang, Z. Huang, and M. Imran. 2020. "A Critical Review of Sustainable Energy Policies for the Promotion of Renewable Energy Sources." *Sustainability* 12, no. 12: 2078. https://doi.org/10.3390/su12125078.

Masanet, E., N. Lei, and J. Koomey. 2024. "To Better Understand AI's Growing Energy Use, Analysts Need a Data Revolution." *Joule* 8, no. 9: 2427–2436. https://doi.org/10.1016/j.joule.2024.07.018.

McNally, K. F., and H. Kolivand. 2024. "Comparative Analysis of Bitcoin Mining Machines and Their Global Environmental Impact." *EAI Endorsed Transactions on Scalable Information Systems* 11: 5954. https://doi.org/10.4108/eetsis.5954.

Miśkiewicz, R., K. Matan, and J. Karnowski. 2022. "The Role of Crypto Trading in the Economy, Renewable Energy Consumption and Ecological Degradation." *Energies* 15, no. 10: 3805. https://doi.org/10.3390/en15103805.

Mora, C., R. L. Rollins, K. Taladay, et al. 2018. "Bitcoin Emissions Alone Could Push Global Warming Above 2°C." *Nature Climate Change* 8, no. 11: 931–933. https://doi.org/10.1038/s41558-018-0321-8.

Neagu, O. 2019. "The Link Between Economic Complexity and Carbon Emissions in the European Union Countries: A Model Based on the Environmental Kuznets Curve (EKC) Approach." *Sustainability* 11, no. 17: 4753.

Orun, A., and F. Kurugollu. 2023. "The Lower Energy Consumption in Cryptocurrency Mining Processes by SHA-256 Quantum Circuit

10991719, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/sd.3471 by Istanbul Gelisim Universitesi, Wiley Online Library on [15/08/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Design Used in Hybrid Computing Domains." https://doi.org/10.48550/arXiv.2401.10902.

Pesaran, M. H., Y. Shin, and R. J. Smith. 2001. "Bounds Testing Approaches to the Analysis of Level Relationships." *Journal of Applied Econometrics* 16, no. 3: 289–326. https://doi.org/10.1002/jae.616.

Phillips, P. C. B., and P. Perron. 1988. "Testing for a Unit Root in Time Series Regression." *Biometrika* 75, no. 2: 335. https://doi.org/10.2307/2336182.

Popkova, E. G., A. V. Bogoviz, S. V. Lobova, N. G. Vovchenko, and B. S. Ve Sergi. 2023. "Blockchain, Sürdürülebilirlik ve Temiz Enerji Dönüşümü." *Küresel Geçişler* 5: 64–78. https://doi.org/10.1016/j.glt.2023.04.002.

Pouresmaieli, M., M. Ataei, A. N. Qarahasanlou, and A. Barabadi. 2023. "Integration of Renewable Energy and Sustainable Development With Strategic Planning in the Mining Industry." *Results in Engineering* 20: 5–6.

Sam, C. Y., R. McNown, and S. K. Goh 2019. "An Augmented Autoregressive Distributed Lag Bounds Test for Cointegration." *Economic Modelling* 80: 130–141.

Sarkodie, S. A., and P. A. Owusu. 2020. "How to Apply the Novel Dynamic ARDL Simulations (Dynardl) and Kernel-Based Regularized Least Squares (Krls)." *MethodsX* 7: 101160. https://doi.org/10.1016/j.mex.2020.101160.

Sarkodie, S. A., M. A. Amani, M. Y. Ahmed, and P. A. Owusu. 2023. "Assessment of Bitcoin Carbon Footprint." *Sustainable Horizons* 7, no. 100: 060. https://doi.org/10.1016/j.horiz.2023.100060.

Sarkodie, S. A., V. Strezov, H. Weldekidan, E. F. Asamoah, P. A. Owusu, and I. N. Y. Doyi. 2019. "Environmental Sustainability Assessment Using Dynamic Autoregressive-Distributed Lag Simulations—Nexus Between Greenhouse Gas Emissions, Biomass Energy, Food and Economic Growth." *Science of the Total Environment* 668: 318–332. https://doi.org/10.1016/j.scitotenv.2019.02.432.

Sedlmeir, J., H. U. Buhl, G. Fridgen, and R. Keller. 2020. "The Energy Consumption of Blockchain Technology: Beyond Myth. Business & Information." *Systems Engineering* 62, no. 6: 599–608. https://doi.org/10.1007/s12599-020-00656-x.

Sedlmeir, J., J. Lautenschlager, G. Fridgen, and N. Urbach. 2022. "The Transparency Challenge of Blockchain in Organizations." *Electronic Markets* 32, no. 3: 1779–1794. https://doi.org/10.1007/s12525-022-00536-0.

Shahbaz, M., C. Raghutla, M. Song, H. Zameer, and Z. Jiao. 2020. "Public-Private Partnerships Investment in Energy as New Determinant of CO_2 Emissions: The Role of Technological Innovations in China." *Energy Economics* 86: 104664. https://doi.org/10.1016/j.eneco.2020.104664.

Siddik, M. A. B., M. Amaya, and L. T. Marston. 2023. "The Water and Carbon Footprint of Cryptocurrencies and Conventional Currencies." *Journal of Cleaner Production* 411: 137268. https://doi.org/10.1016/j.jclepro.2023.137268.

Sim, N., and H. Zhou. 2015. "Oil Prices, US Stock Return, and the Dependence Between Their Quantiles." *Journal of Banking and Finance* 55: 1–8.

Somoye, O. A., M. Seraj, H. Ozdeser, and M. Mar'I. 2024. "Modelling the Connection Between Energy Intensity, Renewable Energy, Globalization, Technological Innovation and CO_2 Emissions: A Quantile–On–Quantile Technique." *Geological Journal* 59, no. 4: 1322–1336. https://doi.org/10.1002/gj.4930.

Sovacool, B. K., P. Upham, and C. G. Monyei. 2022. "The "Whole Systems" Energy Sustainability of Digitalization: Humanizing the Community Risks and Benefits of Nordic Datacenter Development." *Energy Research & Social Science* 88: 102493. https://doi.org/10.1016/j.erss.2022.102493.

Stern, D. I. 2004. "The Rise and Fall of the Environmental Kuznets Curve." *World Development* 32, no. 8: 1419–1439. https://doi.org/10.1016/j.worlddev.2004.03.004.

Stoll, C., L. Klaaßen, and U. Gallersdörfer. 2019. "The Carbon Footprint of Bitcoin." *Joule* 3, no. 7: 1647–1661. https://doi.org/10.1016/j.joule.2019.05.012.

Truby, J. 2018. "Decarbonizing Bitcoin: Law and Policy Choices for Reducing the Energy Consumption of Blockchain Technologies and Digital Currencies." *Energy Research & Social Science* 44: 399–410. https://doi.org/10.1016/j.erss.2018.06.009.

UNFCCC. 1998. "Kyoto Protocol to the United Nations Framework Convention on Climate Change." https://unfccc.int/kyoto_protocol.

UNFCCC. 2021. "United Nations Climate Change." https://unfccc.int/annual-report-2021.

UNFCCC. 2023. "UN Climate Change Conference—United Arab Emirates." https://unfccc.int/cop28.

UNFCCC. 2024. "UN Climate Change Conference Baku." https://unfccc.int/cop29.

United Nations. 2015. "Paris Agreement." https://unfccc.int/documents.

Zetzsche, D. A., F. Annunziata, D. W. Arner, and R. P. Buckley. 2021. "The Markets in Crypto-Assets Regulation (MiCA) and the EU Digital Finance Strategy." *Capital Markets Law Journal* 16, no. 2: 203–225. https://doi.org/10.1093/cmlj/kmab005.

Zivot, E., and D. W. K. Andrews. 2002. "Further Evidence on the Great Crash, the Oil-Price Shock, and the Unit-Root Hypothesis." *Journal of Business & Economic Statistics* 20, no. 1: 25–44. https://doi.org/10.1198/073500102753410372.

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