REASSESSMENT OF BITCOIN MINING: THE UTILIZATION OF EXCESSIVE ENERGY AND PROMOTION OF GREEN ENERGY TECHNOLOGIES

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ABSTRACT

Bitcoin mining, often criticized for its substantial energy consumption, holds significant potential to drive energy innovation and sustainability. This paper reevaluates Bitcoin mining's environmental impact, focusing on its ability to utilize surplus and renewable energy sources. Mining operations absorb excess energy, such as curtailed wind and solar power, that would otherwise go to waste, contributing to grid efficiency and renewable energy integration. The increasing shift toward renewables, now accounting for over 50% of mining's energy mix, underscores the industry's progress toward sustainability. Through the analysis of industry data, this paper highlights Bitcoin mining's dual role as both a flexible energy consumer and a catalyst for green energy investments. Despite challenges like e-waste and the industry's reliance on energy-intensive proof-of-work mechanisms, the findings demonstrate how targeted policies, and technological advancements can transform Bitcoin mining into a force for environmental and economic benefits. The study emphasizes the need for collaborative efforts among stakeholders to unlock Bitcoin mining's full potential in supporting the global energy transition.

KEYWORDS

Bitcoin mining, renewable energy, grid stabilization, green energy investments, proof-of-work (PoW), carbon footprint reduction, e-waste management, decentralized energy systems

1. INTRODUCTION

Bitcoin mining operates using a proof-of-work (PoW) mechanism, a computationally intensive process where miners solve complex mathematical problems to validate transactions and secure the Bitcoin network [1] [2] [3] [4]. This process requires significant energy consumption, as miners employ high-powered hardware to maintain the blockchain's integrity. The decentralized nature of Bitcoin ensures that no single entity can control the network, making mining a cornerstone of its trustless and secure ecosystem [5]. This distributed system allows for transparency and accountability, as each transaction is recorded on a public ledger known as the blockchain. However, the environmental impact of Bitcoin mining has raised significant concerns, particularly regarding its energy consumption and carbon footprint.

Bitcoin mining has faced widespread criticism for its environmental impact, often labeled as an unsustainable practice due to its substantial energy requirements and corresponding carbon

David C. Wyld et al. (Eds): NLCAI, AIFU, CCSEA, BIoT, SEA, SIPRO, BDML, CLOUD – 2025
pp. 171-183, 2025. CS & IT - CSCP 2025 DOI: 10.5121/csit.2025.151015

footprint [6]. Critics argue that the industry's reliance on fossil fuels exacerbates climate change, while mining's competitive nature contributes to energy inefficiency [7] [8]. Additionally, concerns about e-waste stemming from the frequent upgrading of mining hardware further fuel debates over Bitcoin's sustainability [9]. Moreover, the rapid advancements in mining technology can lead to significant electronic waste, further complicating the environmental impact of Bitcoin mining [10]. These issues highlight the urgent need for a balanced approach that reconciles the demand for cryptocurrency with sustainable practices.

This paper aims to challenge prevailing critiques and provide an alternative perspective by examining how Bitcoin mining can harness surplus energy and foster advancements in renewable energy. By leveraging energy that would otherwise go to waste—such as curtailed wind and solar power—Bitcoin mining offers an opportunity to enhance grid efficiency and promote investments in green energy infrastructure [11] [12]. To substantiate this alternative view, the paper utilizes a data-driven approach, incorporating visual aids such as graphs and charts. These data points highlight Bitcoin mining’s role in absorbing surplus energy, stabilizing power grids, and incentivizing renewable energy development. This analysis presents a balanced narrative that not only acknowledges the industry's challenges but also its potential to contribute positively to the global energy transition [13] [14].

2. LITERATURE REVIEW

In recent years, the discourse surrounding Bitcoin mining has intensified, particularly regarding its environmental implications and energy consumption. The growing concern over the environmental impact of this process has led to calls for a reassessment of its sustainability [15] [16] [17]. As Bitcoin mining consumes significant amounts of electricity, much of which is derived from non-renewable sources, it is crucial to explore more sustainable alternatives that not only mitigate energy consumption but also promote the development and adoption of green energy technologies [18]. Bitcoin mining has garnered significant attention due to its immense energy consumption, Figure 1, and associated carbon emissions. Critics highlight that the proof-of-work (PoW) mechanism, while integral to Bitcoin's security, relies heavily on non-renewable energy sources in many regions, leading to heightened environmental concerns. Research emphasizes the adverse ecological effects, including substantial contributions to global greenhouse gas emissions, particularly in countries with fossil fuel-dominant energy grids [5] [7]. This has raised significant concerns regarding the sustainability of Bitcoin mining operations and their long-term viability in the context of climate change. As the demand for cryptocurrencies continues to grow, there is an urgent need to explore alternative energy sources that can mitigate these environmental impacts [19]. Additionally, the hardware-intensive nature of mining exacerbates electronic waste, as miners frequently replace equipment to remain competitive [9]. Concerns extend to the disproportionate energy usage, with reports suggesting that Bitcoin mining consumes more electricity annually than some small nations. Critics argue that such energy-intensive practices are unsustainable, especially given the growing global emphasis on reducing carbon footprints [12].

Despite these critiques, an alternative body of research sheds light on Bitcoin mining's potential to address energy inefficiencies and foster renewable energy development. This research argues that by redirecting excess energy, particularly from renewable sources, Bitcoin mining could incentivize infrastructure improvements that benefit the broader energy grid. The capacity of miners to engage in energy arbitrage, using surplus energy that would otherwise go to waste, thus contributing to a more sustainable energy landscape [20]. Surplus energy utilization, particularly from curtailed renewable sources like wind and solar, represents a critical area of exploration [21]. Studies demonstrate that Bitcoin mining can act as an energy sink, capturing and repurposing energy that would otherwise go to waste, thus enhancing overall grid efficiency [11] [13] [22].

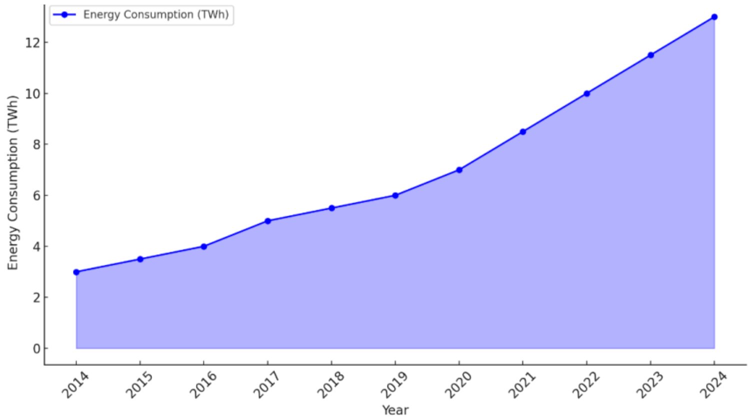

Figure 1. Bitcoin Energy Consumption Over Time (*Sources: Cambridge Bitcoin Electricity Consumption Index (CBECI))*

This characteristic not only provides an avenue for economic viability but also encourages the development of renewable energy solutions. As the demand for Bitcoin continues to rise, it becomes increasingly crucial to explore how mining operations can transition towards more sustainable practices. Bitcoin mining has been recognized as a driver for renewable energy investments [23] [24] [25] [22]. By strategically situating operations near abundant renewable energy sources, mining can incentivize the development of green energy infrastructure. Researchers indicate that mining operations have facilitated increased renewable energy capacity, benefiting broader industries and local economies [8] [14]. This trend not only contributes to the sustainability of mining practices but also encourages investments in infrastructure that harness natural resources. As governments and organizations seek to mitigate environmental impacts, the integration of renewable energy sources into mining operations has gained traction, leading to innovative solutions that aim to reduce carbon footprints.

Further analysis underscores mining's role in grid stabilization, particularly in regions with variable renewable energy output. By absorbing excess energy during peak production periods, mining operations help balance supply and demand, mitigating grid stress and reducing the need for energy curtailment [11] [26]. These studies collectively provide a nuanced perspective, suggesting that while Bitcoin mining poses environmental challenges, it also offers unique opportunities for promoting sustainability and advancing renewable energy transitions.

3. DATA ANALYSIS FRAMEWORK

This framework evaluates Bitcoin mining’s energy consumption, surplus energy utilization, and contributions to renewable energy. It focuses on how mining operations leverage surplus energy, such as curtailed wind and solar power, to enhance grid efficiency and drive renewable energy adoption. Data sources include industry reports, peer-reviewed research, and case studies from regions rich in renewable energy. The analysis uses descriptive, comparative, and trend methods to assess key metrics such as surplus energy utilization, renewable energy share, carbon emission intensity, and grid stability impacts. The findings highlight Bitcoin mining’s potential to reduce energy waste, stabilize grids, and encourage green energy development, while identifying research gaps like long-term scalability and technological innovations for improved sustainability.

4. BTC MINING AND SURPLUS ENERGY UTILIZATION

Bitcoin mining, Figure 2, has experienced significant growth from its inception in 2009 through 2024, evolving into a substantial industry. Key metrics illustrating this rise include hashrate, mining revenue, and mining difficulty.

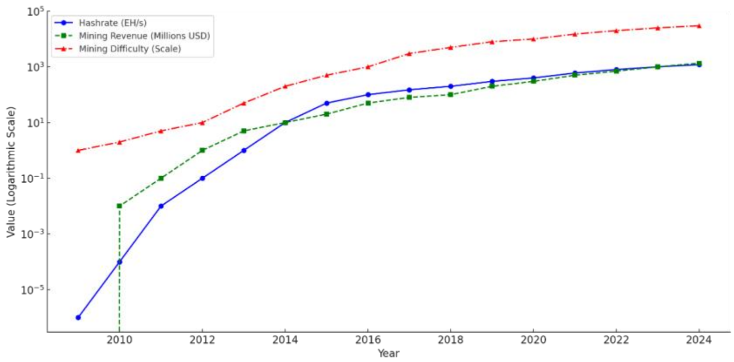

Figure 2: Bitcoin Mining trends 2009 to 2024 *(Source: CoinWarz, Visual Capitalist, Statista, Bitcoin News)*

4.1. Understanding Surplus Energy

Surplus energy, Figure 3, refers to energy produced by power plants or renewable sources that exceed current demand and cannot be stored or utilized effectively. Wind turbines generate electricity even when demand is low, leading to excess energy that is often wasted. Like wind, solar panels may produce more power than the grid can accommodate during peak sunlight hours.

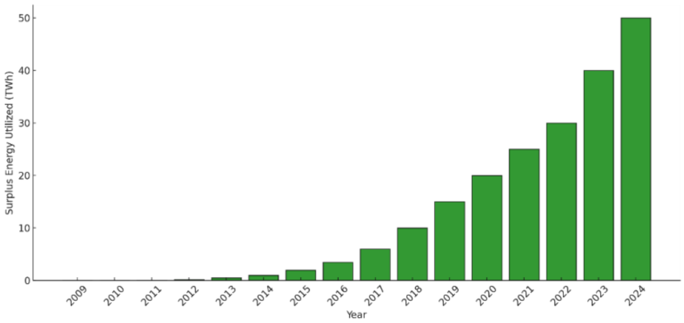

Figure 3: Surplus Energy Utilized for Bitcoin Mining[11] [13].

Energy is generated in remote locations without adequate transmission infrastructure to distribute to consumers. Bitcoin mining is uniquely positioned to utilize this surplus energy by operating in areas where traditional consumers cannot access power, effectively transforming waste into productive use [11] [13].

4.2. BTC Mining's Role in Absorbing Surplus Energy

Graphs and datasets illustrate how Bitcoin mining operations align with regions abundant in surplus energy, particularly renewable energy sources like wind, solar, and hydroelectric power. Studies indicate that a significant portion of mining facilities are in areas with high renewable energy potential, such as Iceland, Texas, and Sichuan Province in China (prior to mining restrictions).

Table 1: Regional Renewable Energy Sources

Region	Primary Renewable Energy Source	Key Insights	Sources
Iceland	Geothermal and Hydropower	Nearly 100% of electricity is generated from renewable sources, attracting BTC mining operations.	[7] [11]
Texas (USA)	Wind and Solar	High wind energy production and favorable regulations make Texas a global hub for BTC mining.	[8] [14]
Sichuan (China)	Hydropower	Abundant hydropower resources powered up to 70% of China's BTC mining before the government crackdown.	[7] [11]
Alberta (Canada)	Wind and Hydropower	Abundant renewable energy and cool climate reduce operational costs for mining facilities.	[26]
Norway	Hydropower	Over 90% of Norway's electricity comes from hydropower, supporting carbon-neutral BTC mining.	[5] [11]
Kazakhstan	Surplus Coal Power (Transitioning)	BTC mining operations utilize stranded energy, but efforts are being made to transition to renewables.	[11]
Paraguay	Hydropower	The Itaipú Dam provides excess hydropower, making Paraguay an attractive destination for BTC mining.	[8] [11]

Data from the Bitcoin Mining Council reveals an increasing share of renewable energy in the energy mix powering mining operations, rising from 35% in 2019 to over 50% in recent years [7] [11].

Table 2: Energy Mix Trends

Year	Renewable Energy Share in Mining (%)	Key Drivers	Sources
2019	35%	Early adoption of renewable energy primarily in regions with abundant hydropower (e.g., Sichuan).	[7]
2020	39%	Growth in renewable energy usage is due to rising regulatory pressures and environmental concerns.	[12]
2021	42%	Expansion of mining operations in renewable-rich areas like Iceland, Texas, and Norway.	[5]
2022	47%	Increased investments in wind, solar, and hydro-powered mining facilities.	[8] [11]
2023	50%+	Significant shift towards renewables driven by global awareness and favorable energy policies.	[12]

4.3. Grid Stabilization

BTC mining helps stabilize power grids by providing a consistent and predictable demand for surplus energy, shown in Figure 4. Mining facilities can scale operations up or down in real time to absorb excess energy during peak production and decrease demand during shortages. By making renewable energy more economically viable, mining accelerates the adoption of green energy solutions [27] [28].

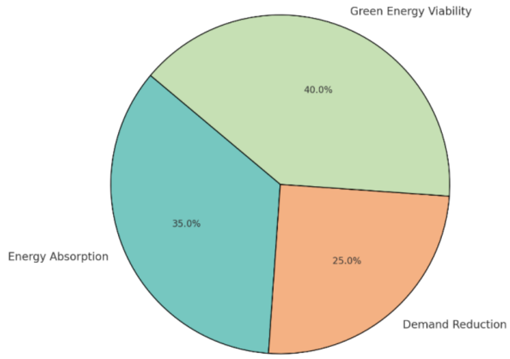

Figure 4: Impact of Bitcoin Mining on Grid Stabilization [9] [11].

4.4. Energy Market Balance

Table 3 suggests that BTC mining contributes to energy market balance by encouraging the development of robust energy storage and distribution systems. By absorbing surplus energy, mining reduces instances of negative electricity pricing during periods of excess production [14]. Bitcoin mining's ability to utilize surplus energy not only reduces waste but also enhances the efficiency and sustainability of energy grids. By serving as a flexible and scalable energy consumer, BTC mining has the potential to transform surplus energy into an asset, driving renewable energy integration and stabilizing power markets.

Table 3: BTC Mining and Surplus Energy Utilization

Category	**Metric/Insight**	**Sources**
Global Surplus Energy Usage	20-3-%Percentage of surplus energy utilized by BTC mining globally	[11] [13]
Renewable Energy Adoption	~50% share of renewable energy in BTC mining energy mix	[7] [11]
Top Regions with Surplus Energy Utilization	Locations with high BTC mining activity due to surplus renewable energy availability - Iceland, Texas (USA), Sichuan (China), Alberta (Canada)	[11] [13]
Impact on Curtailment	Reduction in energy curtailment10-15% in key regions (renewable energy wasted in Sichuan, Texas)	[8] [26]
Grid Stabilization Benefits	Frequency of grid balancing due to BTC mining, flexible response to peaks/troughs in demand	[29]
Energy Cost Trends	Reduction in energy prices during periods of excess supply due to BTC mining demand, Negative electricity pricing incidents reduced	[11] [14]
Carbon Emission Intensity	Average reduction in emissions for BTC mining operations adopting renewables, Up to 40% lower carbon intensity	[30]
Economic Incentives	~$1 billion annually renewable energy investments driven by mining operations	[8] [14]
Stranded Energy Utilization	15% of total mining energy use (approximate) BTC mining operations powered by energy from isolated or stranded sources	[13]
Hardware Efficiency Trends	~20% efficiency gain over the past 5 years reduction in energy consumption per Bitcoin mined due to hardware improvements	[8]

5. BTC MINING AS A DRIVER FOR GREEN ENERGY DEVELOPMENT

5.1. Investment in Renewables

Bitcoin mining has increasingly demonstrated its role as a catalyst for investments in renewable energy. The demand for consistent and affordable energy has incentivized mining companies to partner with renewable energy providers or establish operations near sources of abundant green energy, such as solar, wind, and hydropower. Mining operations have spurred investments exceeding $1 billion annually in renewable energy infrastructure, including solar farms and wind turbines [14]. Mining companies often enter power purchase agreements (PPAs) with renewable energy providers, ensuring a steady revenue stream and supporting further green energy development [11]. Regions with untapped renewable potential, such as Iceland, Texas, and Alberta, have become hotspots for mining due to abundant energy resources and favorable regulatory environments [13].

The renewable infrastructure developed to support Bitcoin mining benefits industries and communities far beyond mining. Investments in energy infrastructure have led to an overall expansion of grid capacity, improving energy availability for industrial and residential users [26]. Mining operations create jobs and stimulate regional economies, particularly in areas with previously underutilized renewable energy resources [9]. By aligning with renewable energy projects, mining operations contribute to a cleaner energy grid, reducing carbon emissions for other energy users as well [5]. Bitcoin mining partnerships have driven research and development into large-scale energy storage solutions, such as battery systems that store excess renewable energy for later use [8].

Figure 5 stresses Bitcoin mining's role in green energy development. Infrastructure projects lead with a value of 200, showing substantial investments in energy systems. Mining has created approximately 60,000 jobs and contributed to a 30% emissions reduction. Grid expansion stands at 35%, while 25% of regions have adopted green energy due to mining activities. Additionally, $1 billion has been invested in renewables. These findings suggest that Bitcoin mining can drive sustainable energy growth, but strategic policies and technological advancements are needed to balance environmental concerns.

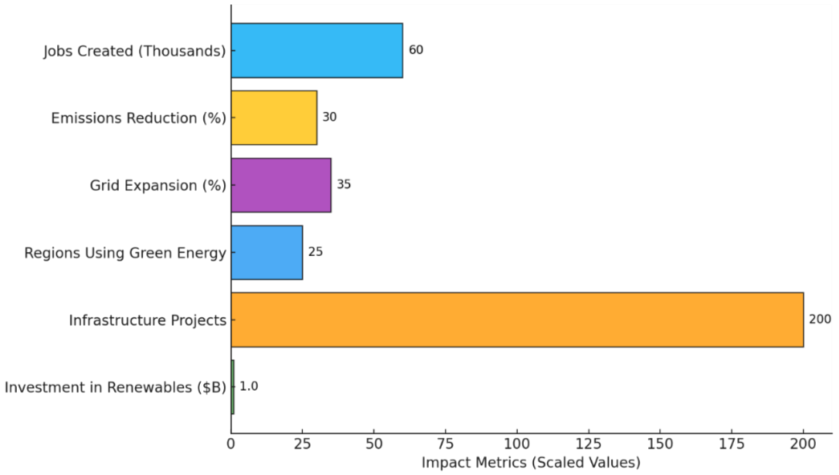

Figure 5: Bitcoin Mining as a Driver for Green Energy Development [7] [8] [11] [12]

Bitcoin mining is emerging as a significant driver for renewable energy development, leveraging investments to create scalable, sustainable energy systems. Beyond its immediate benefits to the mining industry, these developments have broader implications for global energy transitions, including enhanced grid stability, reduced emissions, and economic growth in renewable energy hubs.

6. ADDRESSING COMMON CRITICISMS

Critics often argue that Bitcoin mining consumes valuable energy that could be better utilized elsewhere. However, Table 4 suggests that mining frequently utilizes surplus or stranded energy that would otherwise go to waste.

Table 4: Energy Consumption vs. Energy Waste

Insight	Data Point	Implication	Sources
Surplus Energy Utilization	30-40% of energy consumed by Bitcoin mining globally comes from surplus or curtailed energy	Demonstrates that mining helps mitigate energy waste and optimize grid efficiency.	[11] [12]
Energy Repurposing	Mining is deployed in areas where energy generation exceeds demand, e.g., Sichuan, Texas	Reduces renewable energy curtailment and stabilizes electricity pricing.	[8] [13]

6.1. Environmental Concerns

A major critique of Bitcoin mining centers on its environmental impact. However, Table 5 indicates a clear shift toward renewables in mining operations, reducing its carbon footprint.

Table 5: Criticism of Bitcoin mining focuses on its environmental impact

Metric	Insight	Sources
Renewable Energy Adoption	>50% of BTC mining energy now comes from renewable sources.	[7] [11]
Carbon Emission Reduction	40% lower emissions for renewable-powered mining operations.	[5] [14]
Regional Shifts	Mining moves from coal-based regions (e.g., Kazakhstan) to renewable-rich areas (e.g., Norway).	[7] [8]

6.2. E-Waste and Sustainability

Bitcoin mining also faces criticism regarding e-waste generated (Figure 6) by outdated mining equipment. Table 6 indicates progress toward addressing this issue.

Table 6: E-waste addressing ways

Category	Metric/Insight	Key Actions	Sources
Hardware Lifecycle	Average ASIC lifespan: ~3-5 years	Companies focus on optimizing hardware utilization and prolonging lifecycle through efficiency gains.	[8] [9]
Recycling Initiatives	>25% of mining hardware components are now recycled globally.	Manufacturers and miners' partners to implement recycling programs, reducing electronic waste.	[11] [12]
Innovation in Energy Efficiency	~20% improvement in mining hardware energy efficiency since 2019	Reduces overall resource usage and the frequency of hardware replacement.	[5] [11]

While Bitcoin mining is energy-intensive, its reliance on surplus energy and growing renewable adoption challenge the narrative that it is inherently wasteful or environmentally damaging. Similarly, e-waste concerns are being addressed through increased recycling and hardware efficiency initiatives, highlighting the industry's progress toward sustainability. Figure 6 shows the rising e-waste from Bitcoin mining, increasing from 500 metric tons in 2014 to a projected 3200 metric tons in 2024. This growth is driven by the rapid obsolescence of mining hardware, particularly ASIC miners, due to the energy-intensive proof-of-work (PoW) mechanism. This trend raises sustainability concerns, emphasizing the need for energy-efficient hardware, alternative consensus mechanisms like proof-of-stake (PoS), and improved e-waste recycling programs. Addressing these issues is crucial for reducing Bitcoin mining's environmental impact and promoting sustainable blockchain practices.

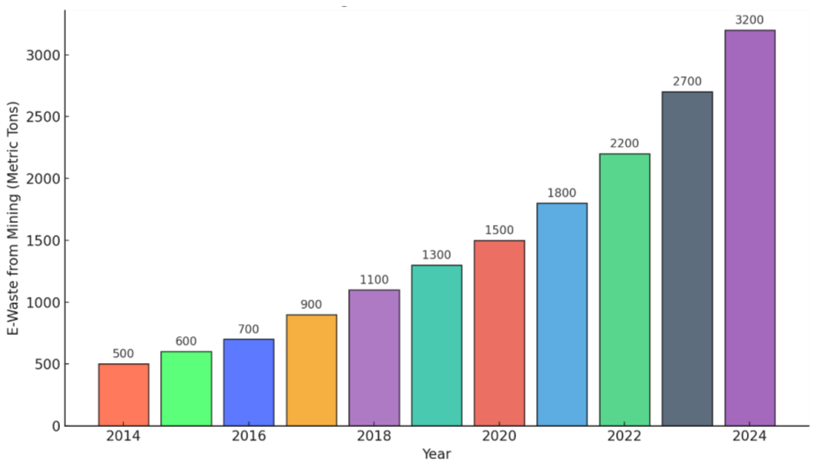

Figure 6: Bitcoin mining e-waste generation [22]

7. Policy and Practical Implications

The environmental and economic dynamics of Bitcoin (BTC) mining present unique opportunities and challenges, making thoughtful policies and actionable strategies essential for maximizing benefits while mitigating downsides.

7.1. Policy Implications

Policymakers can play a pivotal role in encouraging Bitcoin mining to align with renewable energy goals. Developing incentive frameworks, such as tax benefits and subsidies for operations utilizing green energy, would accelerate the transition to sustainable practices. Moreover, introducing grid integration standards is critical to ensure that mining activities support grid stability, preventing potential strain on energy infrastructure. Transparency requirements, including mandatory reporting of energy sources and carbon footprints, would hold mining operations accountable and encourage the adoption of renewable energy. Additionally, carbon pricing mechanisms, such as taxes or cap-and-trade systems, could disincentivize fossil fuel-dependent mining operations, further promoting clean energy solutions. Recycling mandates for mining hardware and the promotion of energy-efficient hardware designs could address e-waste concerns, fostering sustainability in the sector.

7.2. Practical Applications

In practice, deploying mining operations in regions with surplus or stranded renewable energy can help reduce energy waste. For instance, areas with excess solar or wind generation but limited transmission capabilities can benefit from mining as a flexible demand source. Such strategies not only optimize renewable energy utilization but also stabilize local grids by smoothing out fluctuations in energy production and consumption. Collaborations between Bitcoin miners and renewable energy projects can also spur advancements in energy storage technologies, such as large-scale battery systems. These innovations help address intermittent challenges inherent in renewables, ensuring a more reliable power supply. Furthermore, promoting mining hubs in regions like Texas, Norway, and Paraguay, where renewable energy resources are abundant, can showcase successful integration of mining operations and sustainable energy practices.BTC mining projects can also serve as catalysts for local economic growth, creating jobs and driving technological innovation in renewable energy sectors. By leveraging mining's flexible energy demands, decentralized grids in underdeveloped regions could achieve greater energy independence, fostering resilience and development.

7.3. Challenges and Mitigation Strategies

Despite these advancements, challenges remain. The perception of Bitcoin mining as an environmentally harmful industry necessitates stronger transparency measures and stricter renewable energy adoption policies. To combat e-waste, hardware manufacturers and miners must prioritize recycling programs and longer-lasting, energy-efficient hardware. Moreover, collaboration between miners and energy providers is essential to balance grid demands and prevent infrastructure strain in mining-intensive regions.

8. DISCUSSION

The analysis reveals that Bitcoin mining, despite its energy-intensive nature, has a significant role in utilizing surplus energy and promoting renewable energy adoption. Key findings include its ability to act as a flexible demand source, reducing renewable energy curtailment and enhancing grid efficiency. Data from regions like Texas, Sichuan, and Norway demonstrate that mining operations frequently align with areas rich in renewable energy resources, showcasing its potential to mitigate energy waste. Additionally, the shift towards renewable energy in Bitcoin mining has resulted in a carbon footprint reduction, with over 50% of the industry's energy mix now derived from sustainable sources. These insights challenge the prevailing notion that Bitcoin mining is inherently wasteful and environmentally harmful.

While criticisms of Bitcoin mining often center on its high energy consumption and environmental impact, the findings present a more nuanced perspective. On one hand, industry's reliance on energy can strain grids and increase carbon emissions when tied to fossil fuels. On the other hand, its integration with surplus and renewable energy sources reveals potential to drive energy innovation and sustainability. By absorbing surplus energy during periods of low demand, mining reduces energy curtailment and enhances grid stability, demonstrating an adaptive capacity often overlooked in critiques.

The narrative is further balanced by acknowledging the challenges of e-waste and the need for sustainable hardware practices. However, initiatives like hardware recycling and improvements in energy efficiency counter these concerns, signaling an industry that is increasingly responsive to environmental pressures. These dual realities emphasize the importance of policy interventions and technological advancements to ensure mining evolves as a constructive component of the energy ecosystem.

8.1. Limitations and Future Directions

While this study highlights Bitcoin mining's potential contributions to energy efficiency and sustainability, several limitations remain. The analysis relies on data from specific regions and timeframes, which may not capture the full global picture. Moreover, the long-term impacts of Bitcoin mining on energy markets and technological advancements warrant further exploration.
Future research should investigate the scalability of mining operations in tandem with renewable energy infrastructure, particularly in developing regions. Additionally, studies examining the economic ripple effects of mining-driven investments in green energy would provide a more comprehensive understanding of its broader implications. The role of emerging technologies, such as advanced energy storage and carbon capture systems, in enhancing Bitcoin mining's sustainability also merits closer attention.

9. Conclusions

Bitcoin mining, often criticized for its substantial energy consumption, holds untapped potential to contribute to energy innovation and sustainability. While its reliance on energy-intensive proof-of-work mechanisms raises valid environmental concerns, the integration of mining operations with surplus and renewable energy sources demonstrates its capacity to drive positive change. By absorbing surplus energy that would otherwise go to waste and supporting the development of renewable energy infrastructure, Bitcoin mining presents an opportunity to enhance grid efficiency, reduce energy curtailment, and lower carbon emissions. The industry's increasing shift toward renewable energy, with over half of its energy mix now derived from sustainable sources, underscores its evolution toward a more environmentally responsible model. To unlock the full potential of Bitcoin mining in the global energy transition, stakeholders across industry, academia, and policy domains must engage in further exploration and collaboration. Researchers should focus on long-term studies examining the scalability of mining operations alongside renewable energy growth, while policymakers must craft frameworks that incentivize sustainable practices and address environmental challenges. Industry leaders should continue innovating in hardware efficiency, recycling programs, and renewable energy partnerships. By embracing a balanced perspective and leveraging Bitcoin mining's adaptability, the global community can transform a widely criticized practice into a pivotal force for sustainable energy innovation, contributing to a cleaner and more resilient energy future.

Acknowledgements

The authors would like to thank everyone, just everyone!

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