Digital Business 5 (2025) 100114

Contents lists available at ScienceDirect

Digital Business

journal homepage: www.elsevier.com/locate/digbus

Rethinking bitcoin's energy use through sustainable digital business models and resources monetization: A multiple case study analysis

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ARTICLE INFO

Keywords:
Bitcoin mining
Emerging business models
Blockchain
Resources monetization
Sustainability

ABSTRACT

As Bitcoin (BTC) continues to gain traction, its energy consumption and potential environmental impact have sparked considerable debate within the scientific community. In this paper, we explore the theoretical underpinnings of BTC blockchain infrastructure and BTC mining as potent instruments for resource monetization, giving rise to innovative digital business models. In particular, we explore the complex relationship between BTC mining and sustainable energy practices, reframing BTC mining from an energy-intensive activity to a potential catalyst for sustainable value creation. Based on a sound methodological approach that relies upon case study analysis, grounded theory and Causal Loop Diagrams (CLDs) we investigate BTC mining's potential as a resource monetization instrument. According to the results, it is clear that BTC mining can absorb excess energy, balance energy grids and support renewable energy integration, ultimately contributing to environmental sustainability and economic efficiency. The findings suggest that BTC mining, when integrated with advanced technologies and unused energy from renewable or stranded sources, creates new business opportunities that align economic incentives with sustainability goals. The research contributes to the ongoing debate about BTC's environmental impact by offering an alternative perspective: that BTC mining can, under the right conditions, promote cleaner energy use and reduce the carbon footprint of energy production. The paper provides valuable insights for policymakers, industry stakeholders and researchers interested in the intersection of BTC mining industry and blockchain-based digital business models.

1. Introduction

The introduction of Bitcoin (BTC) in 2008, a decentralized digital currency, marked a significant moment in the evolution of financial technology. From a practical perspective, BTC presented the first successful implementation of blockchain technology, especially in solving the so-called double-spending problem (Nakamoto, 2008). BTC emerged not only as a novel means of public, distributed, global settlement infrastructure but also as a new investment class, attracting significant attention from diverse sectors. Apart from serving as a global monetary and settlement infrastructure, BTC also provides significant business opportunities. According to Qureshi and Xiong (2019), BTC's true value for corporations lies in its integration into a novel business model, which they call a "Bitcoin investment bank". Under such an approach, companies capitalize on BTC's volatility and related financial instruments, such as options and futures, to generate revenue through fees, spreads and hedging activities. This positions BTC not as a stable store of value, but as a dynamic asset capable of creating new business opportunities and revenue streams. Other studies highlight the potential of BTC to have a positive impact on human development, particularly by enabling new forms of value creation and economic opportunities. For instance, Sedliačik and Ištok (2023) identify a significant correlation between the frequency of BTC transactions and improvements in the Human Development Index (HDI), suggesting that BTC facilitates global economic inclusion. Besides, business and investor interest in BTC is evident in the substantial inflows to spot BTC exchange-traded funds (ETFs) representing the most successful ETF launch in the financial history. In addition, several corporations have adopted the so-called Bitcoin Standard, a financial strategy that allows companies to capitalize on their BTC holdings to enhance corporate performance and deliver significant

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https://doi.org/10.1016/j.digbus.2025.100114
Received 21 October 2024; Received in revised form 20 February 2025; Accepted 20 February 2025
Available online 25 February 2025
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shareholder value. MicroStrategy is one such example. All these factors underscore the increasing demand for BTC exposure among institutional investors through regulated investment vehicles.

The energy usage of the BTC network has been a prominent topic in academic literature over the last decade, particularly in studies examining its environmental impact (de Vries, 2018; Kakinuma, 2023; Proelss, Schweizer, & Sévigny, 2023; Rudd, Jones, Sechrest, Batten, & Porter, 2024; Truby, 2018). Recently, however, there has been a significant shift in the perceived environmental impact of BTC mining documented in the scientific literature. In particular, the BTC mining industry has sparked innovations in utilizing renewable energy sources and optimizing energy consumption (Lal, Niaz, Liu, & You, 2024; Velický, 2023). BTC mining also offers a potential solution to the problem of stranded energy sources by providing a flexible and portable demand for excess or otherwise wasted energy sources. According to industry-related reports, several opportunities exist with respect to BTC's unique properties that could be leveraged to support the transition to energy abundance across several sectors. For instance, in the oil and gas industry, capturing and using stranded gas for BTC mining helps reduce methane emissions. Instead of releasing methane through flaring or venting, which sends it directly into the atmosphere, the gas is burned more completely during the mining process. This lowers its global warming potential since methane has a much higher warming potential than carbon dioxide, making its reduction crucial for climate action. According to the latest Global Gas Flaring Tracker Report (World Bank, 2023), gas flaring in 2022 released 357 million tonnes of carbon dioxide equivalents (CO_2e). By reducing methane emissions from oil and gas operations, BTC mining can contribute to broader climate goals, aligning with initiatives like the Global Methane Pledge, which aims to reduce methane emissions by 30 % from 2020 levels by 2030. Therefore, the profitability of BTC mining provides an economic incentive for oil and gas producers to invest in the necessary infrastructure to capture and utilize stranded gas, leading to a significant reduction in methane emissions while portraying the BTC network as a sound environmental, social and governance (ESG) instrument.

Arguably, the potential of BTC mining to serve as an ESG instrument has to do with its capacity to serve as a potent resources monetization mechanism, as seen in Fig. 1. In particular, BTC mining connects physical energy sources to the BTC blockchain, highlighting emerging business models that capitalize on resource monetization. For example, energy sources such as stranded energy sources (resources that are geographically isolated or not economically viable to transport or utilize in traditional ways), wasted energy sources (energy that is produced but not utilized, often due to inefficiencies or lack of demand, like surplus energy from industrial processes) and renewable energy sources (sustainable energy sources such as solar, wind, or hydro power that are often location-agnostic, meaning they can be harnessed in various locations) can be used in BTC mining. These diverse physical energy sources feed into the process of BTC mining and are converted into computational work. It is worth noting that the integration of renewable energy with BTC mining is beneficial only when it incentivizes the production or utilization of renewable energy that might otherwise remain untapped or underutilized.

As depicted in Fig. 1, the computational work from BTC mining produces cryptographic energy, which is essential for maintaining and validating the BTC blockchain. Therefore, the BTC blockchain serves as a global settlement infrastructure to facilitate the transfer of value directly across the internet on a peer-to-peer (P2P) basis, without relying on traditional intermediaries, while supporting various applications, including financial transactions, payment solutions and decentralized applications (Burkett, 2023; Dasaklis & Malamas, 2023). The process of converting physical energy into cryptographic energy through BTC mining leads to the creation of new business models. We refer to the notion of cryptographic energy as the computational work performed during the BTC mining process to secure the network. It refers to the computational effort required to solve cryptographic puzzles rather than a direct physical or thermal form of energy. These digital business models are based on the monetization of previously untapped and/or wasted energy resources, thus they create economic value from sources that were once considered impractical or inefficient to use. As a consequence, using and leveraging diverse and location-agnostic energy sources for BTC mining, it is possible to create a decentralized, global infrastructure that not only sustains the BTC network but also promotes innovative business opportunities in the digital economy. This integration highlights the potential for BTC'S blockchain infrastructure to drive new economic paradigms by harnessing and monetizing physical resources in novel ways. To this end, circular or symbiotic business models could also be relevant in this context (Geissdoerfer, Pieroni, Pigosso, & Soufani, 2020; Rentería Núñez & Perez-Castillo, 2023). In particular, BTC mining has the potential to fully align with circular and symbiotic business models by repurposing waste energy, reducing resource inefficiencies, and creating new value streams. For example, by integrating with renewable energy sources, capturing waste heat and employing sustainable hardware practices, BTC mining operations can support the broader goals of sustainability, waste reduction and resources optimization.

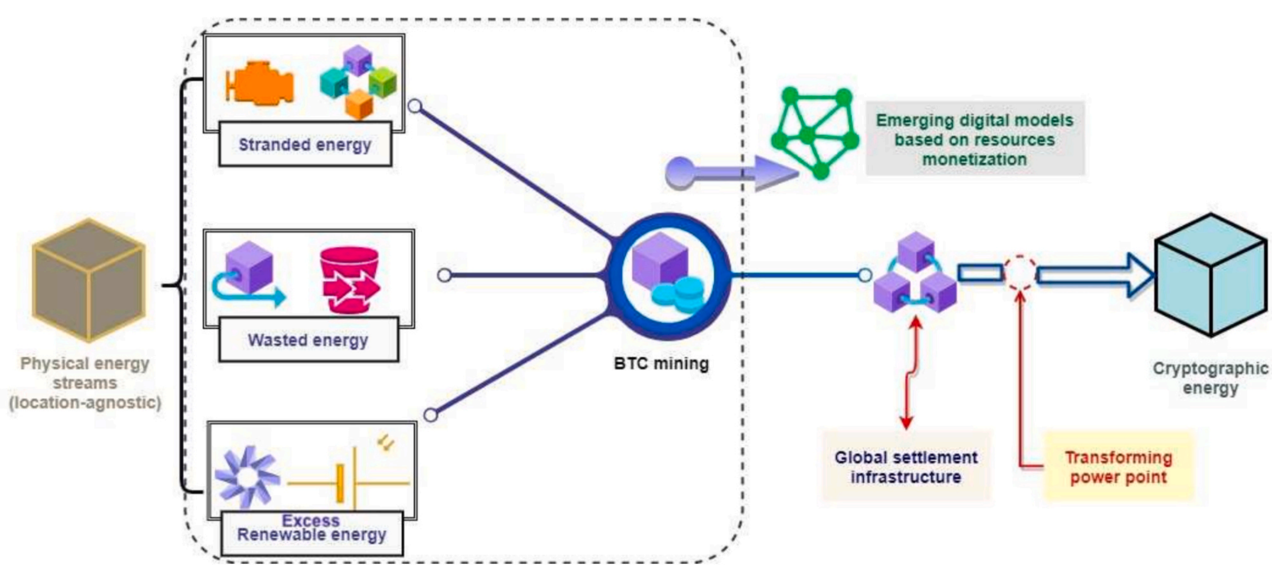

Fig. 1. Interrelations among bitcoin mining (energy usage), resources monetization and emerging digital business models.

The value brought forward by the BTC network and its blockchain infrastructure is often viewed through the lens of its energy requirements and environmental considerations. These factors have led to an ongoing debate in the scientific community regarding BTC mining's overall environmental impact and sustainability. While many studies emphasize the network's negative effects due to its energy consumption (Calvo-Pardo, Mancini, & Olmo, 2022; de Vries, 2018; Sapra, Shaikh, & Dash, 2023; Sarkodie & Owusu, 2022; Sharma, Sharma, Bamotra, & Gaur, 2023; Xiao, Cui, Xiang, Liu, & Zhang, 2023; Zhang, Chen, Lau, & Xu, 2023), other studies suggest its potential as an ESG tool (Lal & You, 2024; Lal et al., 2024; Bruno, Weber, & Yates, 2023; Velický, 2023; Hallinan et al., 2023; Niaz, Liu, & You, 2022,Niaz, Shams, Liu, & You, 2022). However, studies that focus on its environmental drawbacks often show inconsistencies, largely because they rely on two predominant methods for estimating BTC's energy consumption: the Cambridge Bitcoin Electricity Consumption Index (CBECI) and the Digiconomist Index. According to Sai and Vranken (2024), both the CBECI and Digiconomist models have significant limitations due to their reliance on unverified or generalized assumptions, such as uniform electricity costs and Productive Use of Energy (PUE) values. Additionally, both models face challenges related to the extrapolation of limited or outdated data, which can lead to inaccuracies in their estimates of BTC's energy consumption. These limitations highlight the need for more rigorous and empirically grounded approaches to model BTC's energy footprint. Besides, to fully understand what drives BTC's energy consumption and emissions, it is crucial to consider several interconnected factors that are often overlooked in most studies assessing BTC's environmental impact. According to McCook (2023), BTC's energy use and emissions are driven by a complex interplay of economic incentives (a process that secures the BTC network while rewarding miners with newly minted BTCs and transaction fees, motivating them to continue energy-intensive mining as long as it remains profitable), competitive market dynamics (characterized by near-perfect competition), technological advancements (these advancements have drastically improved the energy efficiency of mining operations, allowing miners to perform more calculations per unit of energy, thereby increasing the overall network hash rate), and the availability of energy resources (the geographic mobility of mining operations allows miners to move to areas with cheaper or surplus energy and this flexibility reduces costs and influences the environmental impact of BTC mining.). Based on this analysis the following research questions (RQ) are deemed relevant:

RQ1: How can BTC mining transform stranded energy sources into economically viable assets?

RQ2: What is the role of BTC mining in absorbing excess energy from energy-intensive industries and how does it contribute to grid balancing and stability?

RQ3: In what ways can emerging business models leverage BTC mining drive the adoption of renewable/stranded energy sources and support the transition towards sustainable energy practices?

Our paper seeks to contribute to this discourse by shifting the focus from the core environmental impact, such as CO_2 emissions and energy usage, to the emerging business models that leverage BTC's blockchain infrastructure and BTC mining to enhance energy efficiency and sustainability, especially taking into account the distributed nature of energy sources. While Treiblmaier (2023) highlights positive effects such as stranded energy utilization, our analysis contextualizes these within a broader framework that considers both economic incentives and environmental trade-offs. The paper's main contribution lies in developing a comprehensive theoretical framework that repositions BTC mining and the truly distributed BTC blockchain infrastructure as catalysts for sustainable value creation through resources monetization, rather than merely an energy-intensive process. Based on a multiple case study analysis combined with grounded theory and Causal Loop Diagrams (CLDs), we provide empirical evidence on how BTC mining can transform stranded energy sources into economically viable assets. Unlike prior studies that focused on isolated mechanisms (for example, fostering renewable energy or mitigating stranded energy waste), our framework integrates these elements into a cohesive model, capturing their interdependencies and dynamic feedback loops. This systems-thinking approach advances the discourse by offering a holistic understanding of BTC's role in sustainable energy practices. Therefore, our study shifts the focus from BTC mining's environmental challenges to the potential of emerging business models empowered by the BTC's blockchain infrastructure that leverages mining for enhancing energy efficiency and sustainability. This framework not only deepens the understanding of BTC mining's integration with renewable and stranded/wasted energy sources but also offers valuable insights for the development of sustainable, blockchain-based digital business models.

The remainder of this paper is structured as follows: Section 2 focuses on a comprehensive literature review that addresses the topic of BTC mining, especially elaborating on the environmental impact of BTC mining operations in terms of energy usage. In Section 3, the methodology that has been meticulously crafted for this study is presented. Sections 4 and 5 present the results of our study whereas Section 6 delves into the analysis and discussion of the results, fostering a rich dialogue around the main findings of our study. The paper ends with some concluding remarks.

2. Theoretical background and literature review

BTC mining is the process of validating transactions and, therefore, maintaining/updating the status of transactions on the BTC network. In other words, the participants in the BTC network, while not trusting each other, need to reach consensus on how new transactions will be added in the BTC blockchain (update the state of the blockchain). The participants (nodes) in the BTC network commonly accept and use the Proof-of-Work (PoW) consensus mechanism for reaching agreement. PoW is not inherently energy-intensive; however, in the BTC network, this distinction arises from BTC's popularity and the associated economic incentives, which drive high levels of mining activity involving the energy-intensive process of finding the correct nonce to create valid blocks. BTC mining also ensures the overall security of the BTC network by preventing the double-spending problem (Nakamoto, 2008). The BTC mining process is performed by thousands of computers around the globe that compete with each other ferociously to find a specific “nonce” value that results in a hash lower than a given target, as stipulated in the BTC protocol. The first miner to achieve this is rewarded with newly minted BTCs and the relevant transaction fees attached. This reward, however, decreases over time through a mechanism known as the “halving”. It is worth noting that BTC's block reward started at 50 BTCs in 2009 and halves approximately every four years, with the latest reduction in 2024 bringing the reward to 3.125 BTCs per block. Halving controls BTC's supply by reducing the rate at which new BTCs are created, ultimately aiming to reach a maximum supply of 21 million BTC around 2130. Mining difficulty, which adjusts approximately every two weeks (or 2016 blocks), helps maintain consistent block times by regulating the complexity of mining based on the network's total computational power. BTC mining difficulty is practically a dynamic, self-regulating mechanism that keeps block production on a ten-minute schedule interval while adapting to changes in the total number of miners and the overall BTC network's hash rate. By making the mining difficulty adaptive to the network's overall computational power, the BTC protocol prevents any single entity from gaining undue influence over the blockchain, therefore maintaining the security, integrity and trully distributed nature of the BTC blockchain. It is clear that BTC mining hash rate is a key security metric. In particular, the more hashing (computing) power in the BTC network, the greater its security and its overall resistance to attack from malicious actors. Although BTC's exact hashing power is unknown, it is possible to estimate it from the number of blocks being mined and the current block difficulty.

In recent years, several authors have focused on the multifaceted impacts of BTC mining, providing a rich discourse encompassing environmental, economic, technological and sustainability concerns. Obviously, at the centre of this discourse lies the significant environmental impact attributed to the process of BTC mining, namely its significant carbon footprint and energy consumption. Given these environmental concerns, technological innovation emerges as a potential solution to the high energy use problem of BTC mining. Several authors explore how advancements in mining hardware and computational efficiency could disrupt the status quo, arguing that profitability need not be at odds with planetary well-being. In the same vein, the push towards renewable energy sources and sustainability in BTC mining has become a significant research theme. As seen in Fig. 2, we have identified four (4) main streams of literature relevant to BTC mining and energy: 1) economic and environmental implications, 2) carbon footprint and energy consumption, 3) renewable energy and sustainability and 4) technological innovations and profitability. In the sequence we provide an analysis of all these streams of the literature and we also highlight discrepancies identified in the scientific literature concerning the environmental impact of BTC mining to further substantiate the motivation and contribution of our study.

2.1. Carbon footprint and energy consumption

The environmental impact of BTC mining has become a significant concern, particularly in relation to its carbon footprint and energy

Fig. 2. Classification of key themes in the literature relevant to bitcoin mining and its energy consumption and environmental impact.

consumption (Calvo-Pardo et al., 2022; de Vries, 2018; Sarkodie & Owusu, 2022; Xiao et al., 2023). The vast energy demands of BTC's PoW consensus mechanism have been widely scrutinized, as it requires substantial computational power, leading to high electricity consumption and, consequently, considerable greenhouse gas emissions (Sharma et al., 2023; Wendl, Doan, & Sassen, 2023; Zhang et al., 2023). Several studies have highlighted the rather alarming scale of these emissions that are usually compared to those of entire countries. Such a comparison underscores the severity of BTC's environmental impact (Sapra et al., 2023). Other researchers have examined the carbon emissions attributed to BTC mining across different regions. They note that the reliance on non-renewable energy sources further exacerbates the environmental implications of BTC mining (Ye et al., 2023). The above-mentioned environmental concerns have initiated a vivid debate in the scientific literature with respect to the sustainability of BTC and the urgent need for mitigation strategies of its environmental impact (Köhler & Pizzol, 2019). Energy consumption of BTC mining is strongly linked to various economic and environmental factors (Küfeoğlu & Özkuran, 2019; Marin & Dumitrescu, 2024). In particular, the dynamics of BTC prices, mining difficulty and technological advancements in mining hardware play a crucial role in determining the energy usage and carbon footprint of the BTC network (Ghosh & Bouri, 2022; Hsu, Lien, & Lee, 2023; Sapra & Shaikh, 2023; Sarkodie, Amani, Ahmed, & Owusu, 2023; Vranken, 2017). Transitioning to sustainable energy practices is not a straightforward process and several challenges exist, including the need for substantial investments and the balancing act between profitability and environmental responsibility (Hajiaghapour-Moghimi, Azimi Hosseini, Hajipour, & Vakilian, 2022). Besides, the interaction between market forces and energy consumption patterns in the BTC network is complex and predicting future trends requires sophisticated economic models and scenario analyses (Heinonen, Semenov, Veijalainen, & Hämäläinen, 2022). Policy and regulatory frameworks are of crucial importance, especially in addressing the environmental impact of BTC mining (de Vries, Gallersdörfer, Klaaßen, & Stoll, 2022). Governments and international bodies are increasingly recognizing the need for intervention to bring down the carbon emissions associated with cryptocurrencies (Jiang et al., 2021; Stoll, Klaaßen, & Gallersdörfer, 2019). Proposed measures include, among others, the implementation of carbon taxes, incentives for the use of renewable energy in mining operations and stricter regulations on energy consumption (Bukhari, Ansari, Yousif, Hassan, & Hassan, 2024; Chamanara, Ghaffarizadeh, & Madani, 2023; Sapra et al., 2023). Some authors emphasize the development and adoption of alternative consensus mechanisms, such as Proof-of-Stake (PoS), which are less energy-intensive and, therefore, are less harmful for the environment (in terms of their carbon footprint) (Ghosh & Bouri, 2022; Mathy, 2023; Sutherland, 2019; Zhang et al., 2023). Overall, the retrieved literature suggests that a combination of technological innovation, regulatory oversight and market-based incentives will be essential for the advancement of the cryptocurrency industry towards a more sustainable future (Truby, 2018).

2.2. Economic and environmental implications

The economic and environmental implications of BTC mining and the associated energy use have attracted significant attention in the scientific literature. In particular, several studies highlight the intricate relationship between the cryptocurrency market and global energy consumption (Baur & Oll, 2022; Maiti, Vukovic, & Frömmel, 2023; Su, Qin, Tao, & Umar, 2020). To this end, some studies focus on the bidirectional relationship between BTC prices/trade volume and energy consumption. Based on these studies, it becomes clear that rising BTC prices drive higher energy usage due to increased mining activity. As a consequence, the higher energy usage raises serious concerns regarding the environmental implications and overall sustainability of BTC mining operations (de Vries, 2021; Kumari, Mamidala, Chavali, & Behl, 2024; Long, Lucey, Zhang, & Zhang, 2023; Sarkodie, Ahmed, & Leirvik, 2022; Yuan, Su, & Peculea, 2022; Zheng, Feng, Zhao, & Chang, 2023). Another prevalent stream within the literature discusses how energy costs, often driven by both market conditions and regulatory factors, play a critical role in determining the profitability of BTC mining operations (Polemis & Tsionas, 2023). The findings of these studies suggest that the energy-intensive nature of BTC mining operations poses a substantial economic challenge, particularly in parts of the world where energy prices are high or where energy sources are principally non-renewable (Huynh, Duong, Burggraf, Luong, & Bui, 2022; Malfuzi, Mehr, Rosen, Alharthi, & Kurilova, 2020; Wu & Ding, 2023). Based on the retrieved literature, environmental concerns are closely linked to the economic dynamics of BTC mining (Bâra, Oprea, & Panait, 2024). For instance, the more BTC mining energy consumption escalates, the more its associated carbon footprint increases. This increase in both the energy consumption and the associated carbon footprint leads to significant environmental implications (Dogan, Majeed, & Luni, 2022). Several researchers have highlighted that the environmental impact of BTC mining is heavily affected by the type/mix of energy used. In particular, BTC mining operations powered by coal or other fossil fuels contribute more to greenhouse gas emissions than those utilizing renewable energy sources (Sibande, Demirer, Balcilar, & Gupta, 2023). However, despite the environmental challenges of mining operations, the BTC network has the potential to create economic value, especially when its carbon footprint is compared to other industries. Towards this direction, the authors of recent studies are beginning to recognize BTC mining as a new/emerging industry and advocate for continuous improvements in energy efficiency and a shift towards cleaner energy sources to mitigate its environmental impact (Liu et al., 2023). Finally, recent studies delve into the potential of BTC mining industry to contribute to methane mitigation by utilizing landfill gas (LFG) to power BTC mining operations. Specifically, the authors in a recently published article explore the scalability and economic viability of combining LFG-based electricity generation with BTC mining and they further highlight potential revenue streams and environmental benefits (Rudd et al., 2024).

2.3. Technological innovations and profitability

The relevant literature on technological innovations and profitability in BTC mining focuses on the critical role advancements in mining technology play in shaping the economic viability and sustainability of BTC mining operations. As more participants join the network and the hash rate increases (i.e., BTC mining becomes increasingly competitive) the efficiency and effectiveness of mining hardware have emerged as key determinants of profitability. The diminishing returns on investment due to the escalating difficulty of the BTC network present a significant challenge, as older hardware becomes obsolete more quickly, necessitating continuous upgrades to remain profitable (Yazıcı, Olcay, & Arkalı Olcay, 2023). It should be noted, however, that even though newer hardware is more energy-efficient on a per-hash basis, this does not equate to a net reduction in energy consumption due to the incentive structure of BTC mining. Another point of interest in the relevant literature is the relationship between energy consumption and profitability in BTC mining operations. The high energy demands of mining operations, mainly attributed to the PoW consensus mechanism, have made energy costs one of the most critical factors influencing profitability in BTC mining operations. Several studies suggest that miners must locate their mining operations in regions with lower energy costs or adopt more energy-efficient technologies to maintain profitability, especially in the face of volatile BTC prices (Das & Dutta, 2020; Jabłczyńska et al., 2023).

2.4. Renewable energy and sustainability

The integration of renewable energy sources within BTC mining operations has also emerged as a critical topic in the scientific literature, especially in light of potentially decarbonizing BTC's mining operations

(Rech, Yan, Bagonza, Pinter, & Musa, 2022). Several researchers have explored the potential of harnessing renewable energy sources, such as wind, solar and green hydrogen, to power BTC mining operations (Lal et al., 2024; Lal & You, 2024; Lal, Zhu, & You, 2023) or balancing the grid (Bruno et al., 2023). These studies suggest that, by utilizing surplus renewable energy, BTC mining could reduce its environmental impact while also providing financial incentives for the development of renewable energy infrastructure (Velický, 2023). Other studies in the literature indicate that BTC mining could be strategically deployed in regions with high renewable energy production, thus offering a viable solution to manage energy oversupply while promoting economic viability in renewable energy projects (Hallinan et al., 2023; Niaz, Liu, & You, 2022,Niaz, Shams, et al., 2022; Bastian-Pinto, Araujo, Brandão, & Gomes, 2021). It should be noted, however, that while there is optimism about the potential for BTC mining to support renewable energy expansion, the feasibility of such approaches is often questioned (de Vries, 2019; Goodkind, Berrens, & Jones, 2022). In particular, several factors seem to affect the potential of BTC mining to support renewable energy expansion. For instance, economic viability is closely related to the cost of renewable energy, the efficiency of mining hardware and the volatility of both BTC prices and energy markets (Tiwari, Abakah, Rehman, & Lee, 2023). Apart from economic-related aspects, policy and regulatory aspects are also a prominent theme in this stream of literature. Specifically, several researchers argue that without the appropriate regulatory frameworks, the environmental benefits of integrating renewable energy sources with BTC mining operations may not be fully realized (Bastian-Pinto et al., 2021). Finally, the social and ethical dimensions of BTC mining, in particular the ones related to ESG criteria, are increasingly being considered by many researchers (Kakinuma, 2023; Proelss et al., 2023).

According to the above analysis of the relevant literature, several discrepancies with respect to the BTC's mining environmental impact are worth noting. For example, the literature presents conflicting views with respect to the BTC's carbon footprint. In particular, some studies emphasize the significant emissions comparable to entire countries, while others suggest that the impact could be less severe or even that BTC mining could serve as an ESG instrument. Another area of discrepancy could be found in the intersection of BTC mining and renewable energy. For instance, while some studies are optimistic about renewable energy reducing BTC's carbon footprint, other studies highlight challenges such as the mismatch between energy supply variability and mining demands, suggesting renewable energy alone may not solve the issue. The scientific literature diverges also on the economic viability of using renewable energy for BTC mining, with some studies seeing potential in surplus energy utilization, while other studies cite high costs and market volatility as major barriers. In addition, while some authors suggest that advanced mining technologies can improve energy efficiency, other authors question whether these innovations can keep pace with the increasing network difficulty and energy consumption. Finally, the economic viability of BTC mining is debated, with discrepancies depending on geographic context; regions with low-cost or abundant renewable energy may find BTC mining profitable, while high-cost areas may struggle to sustain operations. All these discrepancies in the scientific literature along with the inconsistencies identified in several papers and overlooked factors influencing BTC's energy consumption and emissions that are not fully addressed in previous studies (McCook, 2023; Sai & Vranken, 2024), represent a promising area for research. To this end, our paper provides empirical evidence on how BTC mining could leverage excess renewable and stranded/wasted energy sources to support sustainable, blockchain-based digital business models and value creation.

3. Methodology

The objective of this paper is to develop a comprehensive theoretical framework specific to BTC mining and its potential to serve as a sound resource monetization instrument giving rise to innovative digital business models. In particular, given the nascent nature of BTC mining and the relatively limited body of research in comparison to more established fields, the creation of robust theoretical frameworks and guidelines is expected to open new avenues for profitable and sustainable business approaches that are crucial for enhancing organizational reputation, competitive advantage and long-term sustainability. To achieve this objective, a sound methodological approach has been designed, drawing parallels from both the multiple case study analysis approach suggested by Eisenhardt and Graebner (2007); Kshetri (2016) and grounded theory-based methodologies which builds upon analyzing interrelations among key thematic areas and developing Causal Loop Diagrams (CLDs). Such an integrated methodological approach is pivotal for understanding the interrelationships within BTC mining configurations and for validating theoretical frameworks that explain contemporary trends in current research and practice. The adoption of such a quantitative approach (use of CLDs) to complement our qualitative research is inspired by similar studies that have been employed in the field of management (De Boeck et al., 2023).

Overall, our methodology is grounded in the principle that the complexities of phenomena are best understood within their specific contexts, a concept supported by Mcdowall and Short (2012). According to Lewis (2015), case studies facilitate a detailed exploration of practical implementations over time by gathering data from multiple sources, thus enabling comprehensive descriptions of case narratives and recurring patterns. The use of case study design is fundamental to theory formation and is well-aligned with the application of CLDs, as it allows for the integration of predefined constructs that guide theoretical inquiries (Eisenhardt, 1989). This integrated approach plays a critical role in theory testing by enabling comparisons between theoretical frameworks and empirical data, thereby enhancing the accuracy, depth and comprehensiveness of the findings (Eisenhardt, 1989).

To enhance the generalizability of the findings derived from this research and the reliability of the proposed theoretical framework, we incorporate the methodology of multi-case study analysis. The analysis of multiple cases for the extraction of broader conclusions is a recognized approach that has been gaining increasing interest in the social sciences. As noted by Baxter and Jack (2010), the multi-case analysis methodology allows for the combined analysis of different dimensions by focusing on capturing similarities and differences. In this way, it significantly enhances the in-depth review of case studies and supports the development of reliable theoretical frameworks based on the principles of collective knowledge. These characteristics are notably distinct from the analysis of single case studies, where the scope, generalizability and documentation of research questions are constrained to more simplistic interpretations (Vannoni, 2015). In line with the objectives of this research and the comparative advantages of multi-case study analysis methodologies, the following section outlines the key features of the overall methodology and substantiates their contribution to the development of the theoretical framework. Overall, the phases of the methodology consist of a) the selection of cases, b) the identification of key dimensions of analysis, c) the development of CLDs, which capture the dynamic interaction between variables, and finally, d) the validation and generalization of the proposed theoretical framework. By following these steps, we are able to provide a robust and domain-specific theory that facilitates the core dynamics identified to be relevant within the BTC mining field and emerging digital business models.

Case study analysis also aligns perfectly with grounded theory as there is significant interplay between these two methods, especially in the context of qualitative research methodologies (Dahwa, 2024). In particular, their interplay lies in their shared emphasis on context, iterative data collection and analysis and the generation of theory grounded in empirical data. For instance, grounded theory provides a structured way to conceptualize the insights derived from case studies, allowing for a more rigorous and systematic theory-building process. In addition, grounded theory provides a systematic set of coding and analysis mechanisms that can be applied to the rich, detailed data produced by case studies. This ensures that emerging concepts and theories are grounded in empirical evidence rather than pre-existing frameworks (Fernandez & Lehmann, 2011; O'Connor, 2012). Besides, when applied together, grounded theory coding techniques can refine the data from case studies, moving from raw descriptions to higher-order categories and concepts. This allows the researcher to abstract broader patterns from specific cases (Fernandez & Lehmann, 2011; O'Connor, 2012). Finally, grounded theory introduces the notion of theoretical sampling, where cases are selected based on their potential to inform the development of theory. This is highly compatible with case study research, particularly when multiple cases are used to explore the variations and patterns across different contexts (Fernandez & Lehmann, 2011).

3.1. Locating and selecting case studies

The principles governing case selection in multiple case study research share similarities with sampling, where the primary objective is to ensure that the selected cases accurately reflect the target population and demonstrate significant variations across key dimensions relevant to the theoretical framework (Seawright & Gerring, 2008). However, unlike traditional sampling, the rationale in multiple case studies focuses on substantively representing a target population rather than relying solely on statistical analysis (Greene & David, 1984). Practical considerations, such as time constraints and financial resources, also notably influence the case selection process (Seawright & Gerring, 2008).

To collect a representative sample for identifying and capturing the dynamic interaction between BTC and sustainable business models, we adopted a dual approach. Specifically, we implemented the extreme and diverse case selection methods, following the model proposed by Seawright and Gerring (2008). The extreme case selection approach is used to determine the boundaries between the interaction parameters by assessing the impact of these parameters concerning the achievement of best and worst practices, respectively. The systematic assessment of these boundaries allows for an in-depth exploration of case studies, with parameters falling within the predefined limits. Aligning with predefined approaches, as recommended by Seawright and Gerring (2008), we applied the diverse case method to identify organizations that utilize BTC mining as a source of profitability improvement based on the resource monetization approach. At the same time, to select the most targeted sample possible, we primarily evaluated the dynamic interaction between variables such as economic benefits, contribution to optimizing environmental impact (particularly through reducing the carbon footprint and the integration of renewable energy sources), the degree of utilization of new mining technologies, contribution to the maturation of technologies and variables assessing resource use efficiency. Combining the above, we designed an extensive and detailed search for case selection, ensuring the evaluation of BTC mining methods both in terms of their contribution to society and the environment, as well as their added technological, economic and business value.

For conducting our research, we relied upon secondary data sources. Such sources provide comprehensive insights into BTC mining practices and their integration into sustainable business models. In particular, we focused on: a) relevant company reports detailing BTC mining projects and b) news articles and case studies that document specific BTC mining projects and their socio-economic and environmental impact. These qualitative data sources allowed us to capture a comprehensive view of BTC mining across different contexts and to identify recurring themes and key variables. Such an approach was deemed relevant for several reasons: BTC mining is a nascent and rapidly evolving field and ongoing projects and initiatives are often documented in publicly available reports rather than academic literature, b) secondary data provides detailed case narratives that are crucial for identifying patterns and variables across different BTC mining projects and c) using secondary data ensures that our findings are empirically grounded while also being generalizable across diverse contexts.

By leveraging a variety of platforms, including company websites, social media, and technical publications, we maintained the relevance and accuracy of our research, thereby enhancing the reliability of our findings. Mapping the interrelationships among the identified key variables, such as economic benefits, environmental impact, and technology adoption, is a critical component of our analysis. By enhancing this dual approach with practical considerations including data availability, time constraints and financial resources, we managed to locate twenty-two (22) relevant cases for our research, in terms of reflecting the target population and exhibiting significant variations within the predefined limits that allow the development of a well-structured and grounded theoretical framework (a comprehensive description of the selected case studies may be seen in the Appendix). The collected sample has also significant impact on the documentation of the proposed theoretical framework, specifically due to its extensive nature in comparison to relevant works identified in the literature (Eisenhardt & Graebner, 2007). The eligibility criteria created for case screening and selection included:

- **Operational scale**: Representing a range of scales from small to large enterprises to explore how scale influences sustainability practices and business model innovation.
- **Geographical diversity**: Ensuring representation from various regions to understand the impact of local environmental, regulatory, and energy-related factors on BTC mining and subsequent value creation.
- **Technological innovation drivers**: The focus was placed on cases with significant advancements in energy efficiency, integration of renewable energy and reduction of environmental impacts to examine the role of BTC mining in business model creation.
- **Sustainability implications**: Selecting cases committed to sustainability, such as the use of renewable energy and efforts to minimize environmental footprints, to study the balance between profitability and environmental responsibility.

3.2. Applying grounded theory and the development of CLDs

Building upon the initial selection of case studies, this phase delves deeper into the analysis by applying grounded theory approaches to define key-variables and further identify the interrelationships among then within the context of BTC mining and sustainable digital business models. The objective is to achieve a more granular understanding of the variables at play by incorporating multiple descriptive variables that emerge from the retrieved data sources.

Data quality remains a key driving factor in this process, as emphasized in the literature (Golder, 2000; Gottschalk, 1950; Mason, McKenney, & Copeland, 1997). High-quality data is essential for ensuring accurate research outcomes, which necessitates careful evaluation of sources, consideration of the temporal relationship between events and validation through multiple channels (Gottschalk, 1950). To enhance the reliability of our findings, we employed triangulation-based approaches, to systematically collect information from diverse sources that reinforce the robustness of such analyses (Constantino, D'Amato, & Pellegrino, 2009). This method aligns with established guidelines on maintaining data integrity and impartiality (Wang & Strong, 1996), while also mitigating biases by prioritizing external, credible sources over self-reported data (Eppler, 2006; Price & Shanks, 2005).

Given the nascent and rapidly evolving nature of BTC mining, continuous evaluation of data sources is crucial to ensure that our analysis accurately reflects the latest industry developments and technological innovations (Eppler, 2006; Wang & Strong, 1996). Exemplifying interrelationships between key-variables and factors involved, presents a crucial step in fostering theory development. Researching under this scope, we identified and incorporated case-specific descriptive variables derived from the retrieved cases, enabling a more detailed examination of the contextual factors influencing each case. Such an augmented analysis was reinforced by tracing data origins and identifying primary sources (Eppler, 2006). This rigorous methodological approach established a solid foundation for exploring BTC mining's potential to drive sustainability and foster innovation in digital business models.

For identifying the key variables and the interrelationships among them in the broader context of BTC mining, the selected case studies are analyzed using coding techniques based on the principles of grounded theory. In particular, we: a) conducted open coding to identify key variables across different BTC mining projects, b) applied selective coding to group related variables into higher-level themes (e.g., resource monetization, environmental impact, regulatory frameworks), and c) built categories and key concepts to develop the theoretical framework. By focusing on thematic areas such as economic benefits, the growth rate and adoption of technological advancements and the efficiency of resource utilization, we identified the relevant variables by applying coding techniques using MaxQDA 2022, following all the relevant steps of qualitative analysis within the framework of grounded theory, as recommended in the literature (MAXQDA Research Blog, 2020; Rädiker, 2023). The steps employed to implement the grounded theory are summarized as follows:

1. Coding the data: Assigning codes, presenting specific keywords or labels, to segments of the qualitative data (i.e. text) that help in content identification and easily location. This step facilitates both open coding (creation of new codes) and selective coding (definition of higher-level codes).
2. Customizing the code system: Creating a structured system, that hierarchically sorts the codes into parents, codes and sub-codes. In this manner a “code tree” is created, that helps both in the organization and grouping of coded segments into related concepts.
3. Category building with creative coding: Grouping similar concepts into categories during the selective coding phase. This involves the use of MAXQDA's Creative Coding function, which allows researchers to freely move and sort codes into meaningful groups to form new categories.

As part of the next step in the methodological process, the identified variables and themes were mapped using CLDs to visualize interrelationships and feedback loops. In essence, the outputs from the qualitative analysis serve as inputs for the development of CLDs, through which the interfaces and dynamic interactions between the key variables are depicted. Therefore, the secondary data allowed us to trace causal connections between variables such as energy usage, profitability, regulatory changes and community impact, which are central to BTC mining's role in sustainable business models. Together, grounded theory provides detailed qualitative data and the main conceptual frameworks, while CLDs graphically represent the system dynamics created around BTC mining.

CLDs are a foundational tool in systems dynamics modeling, essential for visualizing and analyzing the feedback loops that shape the behavior of complex systems. In the context under consideration, CLDs are used to map the dynamic interactions, namely interrelationships, among key-variables previously identified. These diagrams distinguish between reinforcing loops (R), which amplify changes within the system and balancing loops (B), which counteract changes to maintain system stability. Building on the groundwork laid in the previous phase, where key-variables and their interrelationships were mapped, the development of CLDs in this phase allows us to visualize how these variables interact to form feedback loops. For example, energy consumption might interact with regulatory pressures and technology adoption to create a balancing loop that mitigates environmental impact. Similarly, interactions between economic benefits and resource efficiency could form a reinforcing loop that drives profitability and further investment in BTC mining technologies. Following such an approach, the development of CLDs is guided by the central themes identified in the multi-case analysis, such as resource monetization, energy grid stabilization, sustainable mining innovations, and synergistic community and industry integration. These themes provide a context-specific framework for developing CLDs, thus enabling to integrate the identified variables in a holistic perspective that reflects the real-world dynamics of BTC mining and business-related implications.

As a last step that ensures the integrity and reliability of our analysis, we employed the Holsti Coefficient technique, based on which we manage to measure the reliability of the coded segments and assess the efficiency in qualitative data classification. This metric is specifically designed to measure the agreement rate achieved when two or more scientists are independently coding the same content. The formula to calculate this coefficient is given in Eq. 1, in which $N_{agreements}$ represents the number of coding agreements and $N_{Coder\ A}$ and $N_{Coder\ B}$ are the total coding decisions made by the involved coders.

$$\text{Holsti Coefficient} = \frac{2 \times N_{agreements}}{N_{Coder\ A} + N_{Coder\ B}} \tag{1}$$

In our case, two researchers conducted the qualitative analysis of the case studies. The first researcher identified ten (10) key-variables whereas the second identified eight (8) key-variables. Seven (7) key variables were commonly identified by the researchers during the coding process. At the end, consensus was reached for a final set of nine (9) key-variables to be used. Using Eq. (1), the Holsti Coefficient has a value of approximately 0.78. The value reflects a good level of inter-coder reliability, suggesting substantial agreement between the coders. While there are some differences in the key variables identified by each researcher, a Holsti Coefficient of this magnitude generally signifies a robust qualitative analysis with a high degree of inter-coder reliability.

Overall, the proposed methodology aims at systematically analyzing and synthesizing research findings to create a new theoretical framework that describes and explains the dynamics between key variables in BTC mining. The use of CLDs to represent these dynamics assists in evaluating the drivers for the development of sustainable models. These models not only extend the communities' capacity to generate profits through collectivity but also promote societal fairness and well-being. Indeed, these variables are key components in the development of the theory, explaining how digital business models bring to the forefront the ability to achieve profitability in a sustainable manner.

4. Multiple case study analysis

This section represents the core implementation stage of the proposed methodology. Specifically, we present the research insights identified by analyzing the sample of the case studies collected. The techniques adopted to better deliver the systematic coding, classification and synthesis of the results are aligned with the grounded theory principles. After the extensive coding and analysis of the case studies, we managed to classify the retrieved cases, based on four broader themes: resource monetization, energy grid stabilization, sustainable mining innovations, and synergistic community and industry integration. After the theme-based classification, the findings within each theme were critically synthesized by evaluating their implications for technological advancements and their contributions to the creation of innovative digital business models empowered by both BTC mining and the BTC blockchain infrastructure.

4.1. Resources monetization

This class presents case studies that demonstrate the conversion of unused, excess, or hazardous resources into revenue via the process of BTC mining. The following cases highlight the utilization of assets that might otherwise be stranded, such as flared gas, surplus natural gas, or residual renewable energy. Additionally, it is important to emphasize the transformation of these resources into business opportunities via mining operations. Furthermore, the primary emphasis is in presenting business models and technical solutions that not only enhance the efficiency and profitability of resource consumption for BTC mining, but also provide financial benefits while mitigating environmental harness. The inclusion of case studies under this class exemplifies a trajectory from underutilized or wasted resources to substantial financial gains, namely by means of including BTC mining activities, thus highlighting its pioneering role in energy market transformation. Ultimately, cases in this class highlight the capacity of enterprises to advance sustainability by transforming perceived expenses or environmental concerns into sources of income, thus connecting financial security with the preservation of the environment.

Delving into the applications of this class, it is evident that major oil and gas enterprises are actively engaged to BTC mining, showcasing several projects on both pilot and full-operating scale. Given the challenges and pressure faced by such enterprises regarding their carbon emissions, it is clear that BTC mining provides a sector-wide strategy to improve environmental and economic viability by creating additional revenue streams. Aligning to this strategy, ExxonMobil, in collaboration with Crusoe Energy, has implemented a pilot project in North Dakota where excess natural gas from oil wells is redirected from flaring to BTC mining (ExxonMobil, 2022a, 2022b). ConocoPhillips has undertaken a similar pilot project in the Bakken region of North Dakota, where excess natural gas is captured and redirected to power BTC mining (ConocoPhillips, 2022). Synthesizing the results reported, it is implied that such initiatives have significant contribution in greenhouse gas emissions' reduction, by meeting almost net zero emissions target while also have proven profitable, generating BTC worth several million dollars.

Another interesting application aimed to exploit the use of flared gas came from Siberia and the Gazprom Neft, the oil subsidiary of Gazprom. Its project involves capturing flared gas and converting it into electricity for mining operations. The corresponding pilot-scale application showcased that company successfully mined 1.8 BTCs using 49,500 cubic meters of gas, demonstrating the profitability of this method while reducing environmental impact (Gazprom Neft, 2023). Additionally, Standard BTC capitalizes on stranded natural gas from oil wells, which is typically flared due to the lack of infrastructure for transport. This interesting approach serves also as a paradigm that the wasted energy could be utilized and converted into electricity for off-grid BTC mining, thus reducing emissions in the whole production process by monetizing a previously untapped resource (Braiins, 2022).

Another interesting venue identified is aimed to mitigate the harness of waste reached as solid or gas forms. A significant portion of cases targets methane emissions, a significant environmental concern, and coal waste. For instance, Vespene Energy captures methane from landfills to generate electricity for BTC mining, preventing harmful emissions and turning waste into a valuable resource (Vespene Energy, 2024). Similarly, Stronghold Digital Mining uses waste coal to produce energy for mining, addressing environmental issues and supporting land reclamation. By converting these waste products into energy, these companies demonstrate how waste can be transformed into economic and environmental benefits (Stronghold Digital Mining, 2024). Greenidge Generation has transitioned from coal to natural gas, incorporating carbon offset programs to reduce its impact while exploring renewable energy integration (Greenidge, 2024). Extending beyond waste management and energy production enterprises, Gabbani's project is an innovative initiative in the food industry, combining thermal energy from food production with solar power for sustainable BTC mining. This project not only delivers promising results but also aligns with Switzerland's Plan B agenda, demonstrating the synergy between the food industry and renewable energy in cryptocurrency mining (Gabbani, 2023).

4.2. Energy grid stabilization

This class consists of case studies that demonstrate the efficacy of BTC mining operations in providing support and stability to electricity networks. The criteria for selection include the provision of cases in which BTC mining contributes to demand response methods or functions as an “interruptible load”, hence offering adaptability to energy grids via the adjustment of energy consumption in response to changes in grid demand or surplus energy availability. This class highlights the role of mining in facilitating the use of renewable energy during periods of reduced demand, hence enhancing the overall efficiency and dependability of renewable energy sources. The rationale for including these case studies is rooted in their capacity to enhance grid stability and optimize energy efficiency. BTC mining may serve as a versatile demand solution, contributing to the equilibrium between energy supply and demand, the optimization of renewable energy use, and the improvement of grid management methods. Therefore, case studies under this class demonstrate the potential of BTC mining in facilitating the shift towards sustainable energy practices and achieving larger sustainability objectives.

Three case studies have been select that exemplify the potential of BTC mining to act as a grid stabilizer or an “interruptible load” by supporting demand response strategies. At first, the RIOT Platforms paradigm, which utilizes the abundant wind and solar resources in Texas, to adjust its energy consumption in real-time, responding to grid demand fluctuations. This approach helps stabilize the grid, especially during high-demand periods like heatwaves, by reducing strain and optimizing energy use (Riot Platforms, 2024). Similarly, Blockfusion leverages hydroelectric power produced by Niagara Falls to ensure a renewable and cost-effective energy supply while employing demand response strategies to support the local grid, by modulating grid pressure during peak periods, enhancing overall resilience of the system (CPower Energy, 2024). Paving the way for large-scale applications, the MintGreen-Lonsdale Energy Partnership in North Vancouver, Canada, utilizes waste heat from BTC mining for district heating, converting 96 % of mining electricity into thermal energy. This not only reduces greenhouse gas emissions but also provides a reliable heating source, balancing energy loads and improving grid stability during periods of reduced demand (District Energy, 2022).

4.3. Sustainable mining innovations

Within this particular class, the selection criteria include the use of renewable energy sources and state-of-the-art technology to sustainably and efficiently fuel BTC mining operations. It is anticipated that the case studies will demonstrate advancements in cooling systems, energy management strategies, and the incorporation of energy sources such as solar, wind, hydroelectric, and geothermal power to facilitate mining operations. Moreover, the primary objective is to address the consequences of BTC mining by advocating for sustainable mining techniques and demonstrating the industry's commitment to environmentally friendly methods. We illustrate the potential of technological breakthroughs, intelligent energy usage, and sustainable ways in facilitating environmentally and financially viable mining operations.

Building upon the criteria described above, several interesting themes are reached. Firstly, the growing number of applications using surplus hydroelectric power for BTC mining, particularly in Africa, where two large-scale initiatives are noteworthy. In Northern Kenya, a small hydroelectric dam, initially built to power a village, now supports a BTC mining operation, utilizing excess energy to generate additional income and promote local economic development (UnHerd, 2024). Meanwhile, in Virunga National Park, Democratic Republic of Congo, BTC mining powered by hydroelectric energy provides vital funding for wildlife conservation, demonstrating how mining can support environmental efforts in regions rich in renewable energy but with limited economic opportunities (MIT Technology Review, 2023). In a similar vein, Gridless leverages surplus hydroelectric power in rural Africa to power its mining operations, creating incentives to expand local energy infrastructure and bringing electricity to under-served communities, thereby supporting sustainable development (Gridless Compute, 2024).

Extending beyond the applications located in wider Africa but maintaining the same scope, both Genesis Mining and Gryphon Digital Mining run projects that exemplify sustainable BTC mining through the exclusive use of renewable energy sources. Specifically, Genesis Mining Bot (2024) reports the utilization of Iceland's abundant geothermal and hydroelectric energy, benefiting from low-cost renewable power and a cool climate that reduces cooling costs for equipment. Similarly, the case of Gryphon Digital Mining relies entirely on renewable energy, primarily hydroelectric, through strategic partnerships, reinforcing its commitment to ESG principles (Gryphon Digital Mining, 2024). Both cases illustrate how leveraging local renewable resources can minimize environmental impact and reduce operational costs in BTC mining.

The second renewable energy pillar focuses on utilizing geothermal, solar, and wind energy sources for BTC mining. Interestingly Cointelegraph (2024) recently reported that in El Salvador, the government is pioneering the use of geothermal energy from volcanoes to mine BTC as part of its broader strategy to adopt BTC as a national currency. This initiative leverages the country's abundant geothermal resources, providing a sustainable and innovative energy source for BTC production. Meanwhile, Chainergy in Europe is currently implementing a pilot-scale project powered entirely by solar energy, integrating blockchain technology with solar power and developing storage solutions to efficiently manage energy supply and demand (Chainergy, 2024). Similarly, Argo Blockchain's Texas facility benefits from the state's substantial wind and solar energy resources. By exploiting the potential of energy-efficient practices, as a key factor for sustainable growth, the company focuses on becoming a leader in the cryptocurrency mining operations. To this end, its strategies are streamlined to the commitment of sustainability and reduced carbon footprint, which revolves around the utilization of renewable energy sources (Argo Blockchain, 2024).

The first significant operating project that integrates nuclear power into BTC mining, namely the Terawulf Nautilus Cryptomine project, is developed in the USA, specifically in Pennsylvania. This facility, a collaboration between Terawulf and Talen Energy, operates nearly 8000 rigs entirely on nuclear energy, advancing the industry towards carbon-free operations and demonstrating the viability of zero-emission energy sources in large-scale mining (PR Newswire, 2021; TeraWulf, 2024).

4.4. Synergistic community and industry integration

The case studies under this class focus on illustrating the successful integration of BTC mining with other sectors, communities, or economic strategies, resulting in mutually beneficial outcomes that extend beyond just financial advantages. The selection criteria prioritize projects that demonstrate a community-centric approach, while also highlighting relationships across several sectors. For example, several initiatives demonstrate the use of waste heat generated from mine to promote local economic growth or integrate mining operations into comprehensive energy solutions for cities. The primary objective is to foster economic development by enhancing the sustainability of supply chains and stimulating economic growth via the establishment of creative partnerships centered on BTC mining. These case studies are selected based on their wide-ranging benefits to communities, industry and the environment, rather than only their financial effect.

The pivotal role of community-centric approaches in transforming grid-powered networks and integrating them into large-scale industrial applications is highlighted in the following cases. As reported in Farmers Journal (2022) Irish farmers pioneer a promising project which showcase how BTC mining can utilize biogas generated from cow dung. By capturing methane emissions from manure and converting them into electricity, Irish farmers power mining rigs, providing a renewable energy source and creating an additional income stream that exemplifies the contribution of advanced technologies in economic resilience and community sustainability.

Aligning to the above, the Bitfury Dutch BTC Mining Operation in the Netherlands capitalizes on the country's established renewable energy network, predominantly relying on wind and solar power. This operation adheres to European environmental standards, supporting the local economy and significantly reducing the carbon footprint of BTC mining (Taipei Times, 2022).

By synthesizing the information analyzed above, we can draw the broader picture regarding the applications operating at both pilot and full-scale levels across various industries. A common theme in most cases is the use of energy from waste, flared, untapped, and residual sources; forms of energy that typically remain underutilized and are often discarded without the potential for reuse in high-value production processes. The increasing capability of technologies associated with BTC miners to harness such energy sources highlights the transformative role of BTC mining technologies in enhancing the value and quality of the output produced. These factors collectively paint a portrait of innovative, technology-intensive business models emerging through the maturation of technologies that reinforces the already growing reputation of BTC and its truly distributed blockchain infrastructure. These developments appear to play a crucial role in attracting investment and stimulating entrepreneurial activity in sectors related to BTC mining. Table 1 summarizes the main applications identified in the above classes and the emerging, sustainable-oriented business models that deemed relevant to BTC mining operations.

From a business development standpoint, the emergence of new business models is fundamentally based on the documentation of their value proposition and the assessment of how they can be differentiated in contrast to existing models. A detailed examination of Table 1 reveals the contribution of BTC mining on added-value proposition, in two sustainability-oriented pathways: (a) upgrading the power of degraded sources and residuals (b) exploiting the synergistic potential of both infrastructures and communities, towards viable mining solutions. Both of these patterns are aligned with ESG goals, demonstrating proven added value derived from energy-degraded and environmentally harmful sources. Building upon our grounded and in-depth analysis, we provide practical guidelines for incorporating BTC mining as a core element of emerging business models:

- **Integrate renewable and stranded energy sources in BTC mining process**: Sustainable mining innovations often leverage renewable energy sources like wind, solar, hydroelectric, and geothermal along with stranded energy sources (like gas flaring) to minimize environmental impact and operational costs.
- **Prioritize circular economy and community synergy**: Models that integrate BTC mining with local industries or community needs can create synergies that benefit both the environment and the economy.
- **Investing on technological innovations**: The implementation of advanced cooling systems, real-time energy management and decentralized modular mining solutions contribute significantly to reducing the carbon footprint and enhancing the operational efficiency of BTC mining activities.

5. On the development of a new theoretical framework

As mentioned earlier, our methodology extends beyond the synthesis and classification of findings into thematic units, aiming instead at the proposal of a comprehensive theoretical framework. This framework seeks to identify opportunities for innovative business models that emerge in the context of BTC mining, particularly focusing on the potential for reducing environmental footprint. To achieve the research objective, we integrate information and findings derived from the synthesis of the multiple case studies. Specifically, we elaborate on the identified themes and, through the application of grounded theory techniques and critical evaluation of parameters, propose higher-level descriptive key-variables. These key-variables serve to describe the main themes within the field and the interrelationships among them. This approach supports the theory-building process guided by classical

Table 1
Synthesis of case studies identified through a value proposition lens.

Class	Key-thematic elements (No. of cases)	Scope and Value Proposition	Implementation paradigms
Resource monetization	Residual oil and gas (2); Stranded/flared/untapped energy (3); Waste-related approaches (3)	Building upon repurposing strategies to create new revenue streams while mitigating the CO_2 emission and other harmful effects.	Supplying miners with redirected flared gas; generating electricity through the use of waste and stranded resources; combining waste with energy from renewable sources.
Energy grid stabilization	Pressure-releasing role of BTC mining, that enhances the resilience of the energy production systems (3)	Harness of renewable energy sources and waste heat to reduce strain on grids during peak periods, and providing additional utility services that enhance resilience and sustainability while generating revenue.	Platforms to dynamically adjust energy consumption in mining operations; mechanisms to convert the wasted energy of mining operations into useful heat power.
Sustainable mining innovations	Renewable energy sources utilized: Geothermal (2); Hydroelectric (4); Solar/wind (2); Nuclear (1)	Advancing the environmental viability by feeding energy surplus, mainly produced by renewable sources, to BTC mining processes. Streamlines profitability with global carbon reduction goals.	Developing mechanisms to convert abundant renewable energy resources into electricity to supply the miners, based on the exploitation of local climate conditions.
Community-integrated applications	Minimization of waste through circular economy approaches (1); Local networking that capacities abundant of renewable energy sources (1)	Leveraging circular economy principles, these models turn waste and local renewable resources into electricity for BTC mining, creating new income streams and reducing environmental impact.	Synergies among communities, for the collective management and processing of their waste, aimed at transforming it into electricity to power miners.

theories of system dynamics and modeling.

In particular, the key-variables foster the development of CLDs, a key component for studying influences and developing the theoretical frameworks. Following an extensive research of the selected case studies, we developed a total of nine (9) key-variables to describe the main themes analyzed in the previous section. The specific key-variables identified include: Environmental impact, Profitability, Energy utilization, BTC mining efficiency, Technological innovation, Regulations, BTC reputation, Community integration and Resources' availability. These high-level key-variables aim to model the broader dimensions that compose the dynamic evolution of BTC mining and the emergence of related business models within the field.

The in-depth study of the interrelationships among these key-variables leads to the development of six (6) loops, which serve as central descriptive elements for the substantiation of the theory. These loops are classified into reinforced (R) and balanced (B), in accordance with system dynamics standards, as explained in Section 3. The relationships governing the loops are subsequently described and additional explanatory variables are proposed for the key variables. Such explanatory variables and rates are crucial for the quantitative assessment of the phenomenon's evolution, enabling evaluation across multiple cases. By researching on the interrelationships among the identified key-variables we managed to reach out the following high-level loops:

- **(R1) Energy utilization and Environmental impact**: Increased energy utilization in BTC mining leads to a higher environmental impact. The higher environmental impact can drive up costs or regulatory burdens, reducing profitability. Reduced profitability can limit further energy utilization, but when profitability improves, energy utilization also increases, creating a reinforcing loop.
- **(R2) BTC mining efficiency and Technological innovation**: Advancements in technological innovation improve BTC mining efficiency. Higher mining efficiency attracts more investments, which in turn fosters further technological innovation. This creates a reinforcing cycle of continuous improvement in mining efficiency and profitability.
- **(R3) Investments and Community integration**: As investments in technologies increase, there is a significant encouragement for active community participation, which accelerates the integration of BTC mining technologies. The active communities engagement aligns with symbiotic protocols, enhances profit margins and ensures a reduced environmental footprint, thus generating strong investment interest in the sector. Attracting investment essentially serves as fuel for directing more research efforts towards the development and exploitation of technologies related to BTC mining, thus creating an reinforcing loop of operational growth centered around BTC mining.
- **(B1) Regulations and Resources' availability**: Rapidly increasing reputation of BTC push the boundaries of existing regulatory frameworks, a factor that potentially limits the availability of resources for utilization purposes. In this sense, the expansion of large-scale BTC mining operations is hindered; and a balancing loop that controls the growth of the mining operations with respect to available resources is created.
- **(B2) BTC reputation and Resource availability**: Decreasing resource availability reflects a negative impact on BTC mining reputations, mainly due to scarcity and sustainability-related concerns. Reducing community engagement, as result of negative reputation, would hinder the demand and expansion of BTC mining operations, thus balancing the utilization rates to maintain a sustainable growth.
- **(B3) Energy entropy and Environmental impact**: Higher energy entropy, resulting from inefficient energy use, can trigger grid-interactive energy buffering strategies to optimize energy use. This buffering reduces energy utilization and minimizes environmental impact, balancing the system by mitigating negative environmental effects while maintaining operational efficiency.

Elaborating on the loops that describe the dynamic evolution of BTC mining, we undertake an extensive study of the case studies under examination to identify or develop descriptive variables for all the key variables mentioned. This grounded approach allows for a granular assessment of the influencing parameters. By adopting this analytical research method, we opt to make a significant contribution to the overall evaluation of the phenomenon. The full set of high-level variables and loops is presented in the following CLD (see Fig. 3).

Several key business-related insights derived from the case studies are reflected in the CLD, as seen in Fig. 3. For instance, profitability is a key variable in R1 (Reinforcing Loop 1) and is directly influenced by BTC Mining Efficiency and Energy Utilization. The underlying case studies examined demonstrate that profitability is a critical driver for adopting sustainable BTC mining practices. This is captured in the CLD by showing that higher mining efficiency and lower environmental impact increase profitability, creating a feedback loop that incentivizes further investment in sustainable technologies. The same holds for Technological Innovation and Investments, which are central to loops R2 and R3. The case studies show that business models focused on technological innovation and investment in renewable energy solutions create a positive feedback loop. This is already reflected in the CLD, where Technological Innovation drives Mining Efficiency and attracts further investments.

Delving into the interrelationships identified above, we opt to provide a new theoretical framework that carefully integrates all the major themes in BTC mining operations, thus shaping a fruitful area for further research, policy-making and strategic planning, in a systemic manner.

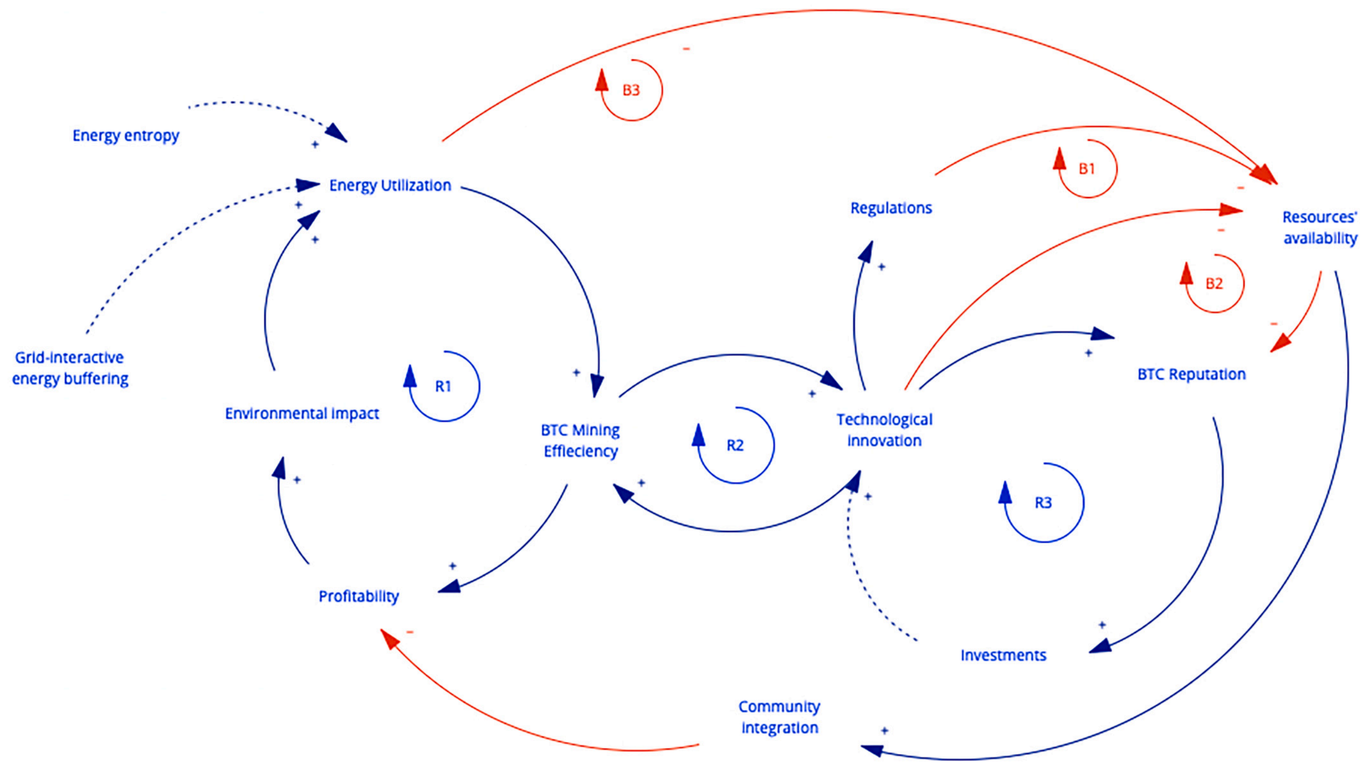

Fig. 3. Causal Loop Diagram based on the interrelationships identified.

Our model reveals that the sustainability and profitability of BTC mining relies upon a careful balance between factors such as energy utilization and BTC mining efficiency, technological innovation, and community integration. Specifically, it is observed that advancements in mining technology, leading to increased computational capacity, and community support can lead to more efficient, sustainable, and profitable mining practices. BTC mining efficiency specifically refers to the effectiveness of mining operations, largely determined by advancements in computational capacity and energy-agnostic embodied in the current generation of miners. Efficient miners consume less energy per unit of computational power by using stranded or other energy sources of high entropy/low quality, thereby reducing costs, environmental impact and increasing profitability.

On the other hand, BTC mining-specific constraints seem to play a moderating role to the above reinforced scenarios. Key considerations include regulatory pressures, the reputation of BTC, which is pivotal for growing the existing network and provide large-scale applications and resource availability, which act as a constraint since the existing technology cannot handle resources of very low quality, and focuses on using higher quality sources (i.e. gas) which are not infinite. Also, the impact of technological innovation on sustainability remains a key concern. In this sense, energy entropy plays a critical role here as it represents the disorder or waste generated from energy use in BTC mining operations. High energy entropy negatively impacts the environment and profitability, pushing the system towards finding ways to reduce waste. This is where grid-interactive energy buffering becomes significant; it refers to the ability of the mining infrastructure to interact with the energy grid, smoothing out consumption spikes and enhancing overall energy efficiency. By buffering energy use, mining operations can reduce peak demand on the grid, minimize entropy, and potentially lower costs, supporting profitability and sustainability.

The development of tech-intensive ecosystems appears to be the key component in addressing the aforementioned limitations. In this sense, the creation of modern financial instruments to support investments in the BTC mining sector is of critical importance. Continuous funding and the integration of the community could lead to cutting-edge technological and socially reinforced models. These models, based on digital technologies, would provide higher computational power with lower energy consumption. This reinforces the efficiency of BTC mining by enabling the extraction of less power per hash rate, significantly increasing profitability while also reducing the emissions associated with mining. Furthermore, investments are also crucial for fostering community integration, as mining operations that invest in local communities are more likely to gain social license to operate, creating a reinforcing loop that sustains growth. However, balancing these factors is essential, as over-utilization of resources can lead to scarcity, increased energy entropy, and regulatory push-backs.

Overall, technological innovation seems to be the catalyst in terms of promoting BTC mining and enhancing its sustainability promising features. By strategically investing in technological advancements, miners would be capable of utilizing higher entropy sources, a key-feature of preventing energy grid destabilization, while also enhancing profitability and reducing environmental costs. To this end, specific regulations and policies, must be refined to better support the integration of BTC miners in the existing grid power distribution networks. Also, it is evident that the community integration is vital for the enrichment of the existing policies. Considering the above dynamics, we conclude that fostering sustainability in BTC mining lies in strategically managing these interconnected variables to achieve a balanced growth, which based on community affairs promotes the environmental integrity and societal welfare.

6. Discussion

BTC mining has been criticized in the scientific literature, particularly in early publications, for its environmental impact due to high energy consumption. However, the findings of this paper illustrate that when integrated with stranded and unused renewable energy sources, BTC mining can transform into a tool for promoting energy efficiency and sustainability, as documented previously in the grey literature

(Sandner, 2020). In particular, our analysis contributes to the theoretical understanding of BTC mining and the underlying BTC blockchain infrastructure as transformative mechanisms within the energy ecosystem that give rise to sustainable digital business models. By framing BTC mining as a tool for resource monetization, our results highlight the potential of the BTC network to serve as a public, distributed infrastructure for sustainable energy utilization and economic efficiency. Therefore, by leveraging previously wasted or inaccessible energy sources (like stranded natural gas or excess renewable energy), BTC mining can support grid stability and enhance energy utilization, while simultaneously creating economic value. Such a key characteristic reframes BTC mining not as an isolated energy-intensive activity, but as a flexible mechanism that can complement sustainable energy practices and the creation of innovative digital business models.

Blockchain-based models have attracted significant attention due to their potential to reshape conventional business paradigms and drive organizational transformation and digital transition. During the last years, several researchers have thoroughly examined blockchain-related applications through various theoretical standpoints, highlighting critical areas such as economic, strategic, operational, behavioral and implementation considerations (Hanafizadeh & Alipour, 2024; Treiblmaier & Rejeb, 2023). By focusing on all these aspects, blockchain research emphasizes the need for a variety of theoretical frameworks to fully grasp the potential of this new technology, including investigations into the optimal instances, methods and reasons to employ decentralized solutions (Hanafizadeh & Alipour, 2024). In the case of metaverse, the decentralized structure of blockchain has been recognized for its capacity to promote sustainable governance and facilitate stakeholder capitalism, driven by fundamental characteristics such as a creator economy, continuous synchronous virtual environments, decentralization, interoperability and a digitized perspective (Sze, Salo, & Tan, 2024). The same holds for the sharing economy, where blockchain technology could redefine it, making it more equitable, efficient and user-driven (Tan et al., 2024; Tan & Salo, 2023). These features open avenues for innovative collaboration and governance models, suggesting that the integration of blockchain can be a catalyst for sustainable value exchange in cyber-physical domains (Aslam, Lai, Kim, & Treiblmaier, 2024; Sze et al., 2024). The importance of blockchain technology also stems from its capacity to improve profitability, productivity and efficiency, key determinants that force organizations to reassess how they create, deliver and capture value (Marikyan, Papagiannidis, Rana, & Ranjan, 2022). However, the limited research on different types of blockchain networks, especially the respective effects on business model innovation, indicates a need for more in-depth analyses to be carried out (Marikyan et al., 2022). To bridge these gaps, structured frameworks have emerged to guide businesses in tailoring blockchain configurations, therefore, enabling more robust and adaptive business models that leverage the unique attributes of this technology for achieving long-term competitive advantage (Upadhyay, 2024).

This research further expands the body of knowledge in blockchain technology by demonstrating that BTC's PoW mechanism can be adapted to serve as a driver for energy redistribution and efficiency when linked to unused renewable and stranded energy sources while giving rise to new digital business models. In this way, our study intersects blockchain technology, business economics and sustainability theories, promoting the idea that BTC's blockchain can be leveraged to create business value beyond traditional financial applications. These insights are valuable for policymakers, industry stakeholders and researchers exploring the convergence of BTC mining and blockchain technology, energy and sustainability, highlighting a path towards blockchain-enabled business models.

6.1. Blockchain-based business model implications

The developed CLD showcases interrelationships among key variables (like energy utilization, profitability, regulations, community integration, etc.) that synchronously shape the environmental, economic and social dynamics of BTC mining. These dynamics create the necessary conditions for emerging digital business models to thrive. In particular, the CLD identifies drivers and constraints that influence the sustainability and profitability of BTC mining by highlighting feedback loops that explain how BTC mining practices evolve in response to technological, regulatory and market changes. Such an approach sets the systemic framework for new business models to emerge, depending on how key variables interact with each other.

Our analysis demonstrates that BTC mining can play a vital role in emerging digital business models that capitalize on resource monetization. Based on real-world examples and case studies coupled with system dynamics approaches, it becomes evident that BTC mining opens new pathways for creating value from otherwise unusable energy, especially when paired with surplus or stranded energy resources. These findings clearly challenge and move us beyond outdated perspectives in the scientific literature, which describe BTC mining solely as an energy-intensive mechanism (de Vries, 2019; de Vries et al., 2022).

Technological advancements combined with unused renewable energy sources could make BTC mining more sustainable and efficient. The value proposition of this type of emerging business models could relate to zero-carbon mining through renewable energy sources (e.g., hydro, geothermal, solar), continuous technological improvements to increase mining efficiency and alignment with ESG principles to attract investments. All these innovative business models have the potential to promote clean energy adoption and enhance environmental sustainability. These models highlight the economic and environmental benefits of integrating BTC mining with excess energy form renewable sources, demonstrating that mining can be both profitable and sustainable.

Community-driven BTC mining business models, leveraging local renewable resources and waste management solutions to support sustainability, also present a certain value proposition, especially through circular economy practices that turn waste into energy for BTC mining and community partnerships that create new revenue streams and economic opportunities.

BTC mining can act as a demand-response mechanism for energy grids, helping to stabilize them during periods of excess energy production or peak demand. To this end, the value proposition of business models relying upon this may relate to BTC mining operations providing grid flexibility by adjusting energy consumption based on grid demand, the reduction of grid instability during peak hours, and the creation of financial incentives for renewable energy projects. BTC mining's ability to act as a flexible load and incentivize renewable energy development supports the transition to a more sustainable energy system. This transition is a crucial aspect of the circular economy, which aims to shift away from linear, fossil fuel-based energy systems towards renewable, circular alternatives.

Finally, business models leveraging stranded energy sources (like excess natural gas, waste energy, or renewable energy) to power BTC mining operations also present additional value. The core idea is to convert unused or wasted energy into economic value through the monetization of previously untapped resources, the reduction of carbon footprint by utilizing waste energy and the support for grid stability and energy efficiency. Our findings fully align with and extend recent theoretical studies that emphasize BTC mining's potential as a powerful resource monetization instrument for otherwise wasted energy sources (Rudd et al., 2024). BTC mining operations can bring employment and revenue to remote communities, especially in areas where renewable energy projects are located and far from the established grid. This supports local economic development, a key aspect of sustainable circular economies. Therefore, by creating value from local renewable resources, BTC mining can help foster more self-sufficient and resilient local economies.

6.2. Implications for academia

Several implications for the academic community can be drawn from our analysis. Arguably, by repositioning BTC mining as a tool for sustainable value creation rather than solely an energy-intensive activity, our novel perspective opens several avenues for further research, especially into how the BTC network can be integrated with renewable energy systems and other sustainability initiatives to make them more profitable, as suggested in recent studies (Bastian-Pinto et al., 2021; Bruno et al., 2023). To this end, we call for rigorous assessments relying on established techniques, such as Life Cycle Assessment (LCA).

In addition, our approach partly addresses inconsistencies in the academic literature, such as varying estimates of BTC's carbon footprint, by setting a precedent for rigorous, empirically grounded research—requirements also emphasized in recent studies (McCook, 2023; Sai & Vranken, 2024). Therefore, the insights derived from our analysis call for more standardized methods to evaluate the environmental and economic impacts of BTC mining. Furthermore, the development and evaluation of emerging business models that leverage stranded or excess renewable energy sources invite further exploration into how blockchain and BTC mining can be integrated into broader economic and environmental value chains. Such a research roadmap aligns perfectly with the exploration of community-integrated applications and circular economy principles through BTC mining, highlighting how decentralized technologies can support local economies and enhance resource efficiency.

From a methodological point of view, the use of a multi-case study analysis combined with Grounded Theory and CLDs provides a methodological framework that can be replicated or extended in similar research areas. The systems-thinking approach offers a holistic method for examining complex interdependencies in technology-driven industries like the BTC mining industry. To this end, the integration of insights from environmental science, economics, blockchain technology and energy systems positions this paper as a foundation for interdisciplinary collaboration. Finally, based on our analysis, we challenge the dominant narrative that portrays BTC mining as inherently harmful to the environment by offering a balanced and evidence-based view. This approach fosters academic discourse to move beyond polarized debates and towards more constructive analyses of BTC's role in sustainability.

6.3. Implications for practitioners

From a managerial perspective, the findings offer a clear road map for industries and energy stakeholders looking to optimize energy usage through BTC mining and the BTC blockchain infrastructure. For instance, managers in energy-intensive industries, particularly those dealing with renewable energy or excess production, can utilize BTC mining to absorb surplus energy, providing an additional revenue stream while enhancing grid stability. BTC mining and the BTC blockchain provide an efficient and disruptive solution for utilizing stranded energy sources like natural gas that would otherwise be flared or excess renewable energy that cannot be stored. By harnessing these untapped resources, BTC mining can play a pivotal role in diversifying and stabilizing the global energy landscape, as documented in some latest industry-specific reports (World Bank, 2023).

Moreover, this study suggests that integrating BTC mining with renewable energy projects can improve the financial viability of these projects, encouraging further investments in clean energy. Energy sector managers can consider BTC mining as part of a diversified energy strategy, using it as a tool to reduce waste, balance energy production and consumption and ultimately create sustainable business models. Finally, policymakers and energy regulators can rely upon the derived insights to design frameworks that incentivize sustainable mining practices, thus aligning BTC mining operations with broader environmental goals. All of the above findings clearly define an emerging industry—the BTC mining industry—with immense potential for creating business value in the digital economy.

Despite the significant potential of BTC mining to act as a potent resource monetization instrument, practitioners and industry experts are faced with several challenges. Arguably, one of the primary challenges is economic viability, especially the high initial investment costs associated with transitioning to sustainable BTC mining practices. For instance, while several projects presented earlier demonstrate potential profitability from using excess natural gas, the upfront costs of setting up BTC mining operations and the necessary infrastructure can be significant. Ensuring consistent profitability given the fluctuating BTC prices and mining difficulty also poses a financial risk, which can deter investors and BTC mining operators from adopting these approaches. This prerequisite, along with the shift towards more efficient mining hardware, has also been highlighted in previous studies (Yazıcı et al., 2023). Another critical challenge is scalability. Although some BTC mining projects presented earlier show considerable promise, replicating these models on a larger scale or in different geographic areas can be difficult due to varying energy profiles, regulatory frameworks and infrastructure requirements. Additionally, integrating Bitcoin mining with current energy infrastructure necessitates operational modifications and technological know-how, which can be challenging, especially for smaller Bitcoin mining companies. Last but not least, policy and regulatory uncertainties continue to be major obstacles. All parties involved in the BTC mining sector may find their operating environment unpredictable due to the constantly changing legislation governing both mining and environmental policies. Policymakers play a key role in shaping frameworks that incentivize sustainable BTC mining practices and align them with broader environmental goals.

6.4. Limitations and future research

Although the paper provides valuable insights into the potential of BTC mining and emerging blockchain-enabled digital business models, some limitations should be kept in mind. For instance, the primary methodology employed in the paper is case study analysis. While case studies provide detailed and context-rich insights, they are inherently limited in their generalizability (Flyvbjerg, 2006). In particular, the specific conditions, locations and implementations described in the case studies may not be universally applicable. For example, the success of using excess natural gas for BTC mining in certain regions may not be replicable in regions with different resources and/or regulatory environments. It should be noted, however, that the final list of eligible case studies was geographically diverse.

The use of CLDs also presents some limitations worth mentioning. Case studies may highlight correlations without establishing clear causal relationships, making it difficult to accurately depict causality in the CLD. Besides, determining the direction of influence between variables can be challenging, especially in complex systems with reciprocal relationships. Many systems exhibit nonlinear behaviors that are challenging to depict with simple causal arrows. Complex interactions can lead to emergent behaviors not easily inferred from individual components in the CLD. Therefore, incorporating quantitative aspects into the analysis of interrelationships among CLDs presents a promising direction for future research.

Our analysis relies on qualitative data from case studies without providing extensive quantitative metrics to support the derived insights. For example, while the paper discusses the economic benefits and environmental impacts of various projects, it does not consistently present detailed data on energy consumption, emission reductions, financial performance, or efficiency improvements. Arguably, the absence of comprehensive quantitative data limits the ability to rigorously assess the actual impact and scalability of these projects. The case studies examined in the paper are based on relatively recent and possibly short-term projects. This temporal limitation means that the long-term sustainability and economic viability of these projects have not been fully tested or proven. Changes in technology, energy markets, and regulatory frameworks over time could significantly impact the outcomes and feasibility of these projects—aspects not fully captured by the current analysis. By taking these aspects into account, especially by focusing on longitudinal studies that incorporate both qualitative and quantitative data, future studies could provide a more rigorous assessment of the scalability and long-term sustainability of BTC's potential to create value.

As the proposed theoretical framework is based on techniques inspired by grounded theory and multiple case study analysis, a triangulation approach would enrich the reliability of our theoretical framework (Farquhar, Michels, & Robson, 2020). Given that the proposed theoretical framework pertains to a cutting-edge field, the number of studies, research papers, and, correspondingly, experts from the business and academic communities, is significantly limited. This severely hinders the possibility of implementing any valid triangulation method. However, as the creation of new relevant literature proliferates and more researchers become involved in this fascinating scientific domain, future studies could capitalize on both scientific and grey literature to evaluate the framework's alignment with the key aspects of BTC mining and its ability to create value in the form of new digital business models.

7. Conclusions

BTC mining has the potential to play a significant role in enhancing the sustainability of the energy supply chain through several key mechanisms, as extensively discussed in this paper. In essence, BTC mining can transform wasted energy into a valuable digital asset, closing a loop in the energy resource cycle. By utilizing excess renewable energy or untapped energy sources, BTC mining contributes to a more efficient use of resources. This aligns with the circular economy principle of maximizing resource utilization and minimizing waste. Based on the analysis, the emerging theory points to the idea that the sustainable progression of BTC mining depends on maintaining a dynamic balance, where technological, regulatory, social and environmental factors are carefully orchestrated.

Our analysis provides an alternative perspective on BTC mining by framing it as a potential enabler of creating sustainable digital business models. In particular, through the efficient use of stranded or surplus energy, BTC mining can serve as a practical tool to reduce waste, stabilize energy grids and drive the adoption of renewable energy. Therefore, contrary to prevailing narratives that focus primarily on BTC's environmental impact, our analysis highlights the potential of BTC mining to facilitate the transition to cleaner energy systems while promoting economic efficiency through innovative digital business models. These models capitalize on otherwise untapped energy resources, such as excess natural gas, flared gas and surplus renewable energy, showcasing BTC mining's capacity to drive value creation in a sustainable manner.

CRediT authorship contribution statement

Thomas K. Dasaklis: Writing – original draft, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Ioannis T. Thomaidis:** Writing – review & editing, Methodology. **Panagiotis G. Giannopoulos:** Visualization, Software, Methodology, Data curation. **Giannis T. Tsoulfas:** Writing – review & editing.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

We sincerely thank the Guest Editor for their time and support throughout the review process. We also extend our gratitude to the two anonymous reviewers for their insightful and constructive feedback.

Appendix A

#	Case study profile description	Implementation strategy
1	ExxonMobil implements a pilot program to repurpose excess natural gas from oil wells for Bitcoin mining. Traditionally flared due to limited infrastructure, this gas is now redirected to power mining data centers, significantly reducing greenhouse gas emissions and creating a new revenue stream. The initiative highlights ExxonMobil's commitment to sustainability by turning waste into a valuable asset while aligning with global environmental goals.	Through a partnership with Crusoe Energy Systems, ExxonMobil uses mobile data centers near oil sites to convert surplus gas into electricity for cryptocurrency mining. Initially launched in North Dakota, the program employs advanced technologies for efficient operations and plans scalable expansions to locations like Nigeria, Germany, and Argentina. This approach integrates innovation with market trends, optimizing resources and supporting economic growth.
2	ConocoPhillips engages in a pilot initiative in the Bakken region of North Dakota, selling excess natural gas to Bitcoin miners. Traditionally, this surplus gas would be flared due to the lack of infrastructure for effective utilization. By redirecting it to power Bitcoin mining operations, ConocoPhillips reduces greenhouse gas emissions associated with flaring and transforms waste into a valuable resource.	ConocoPhillips supplies excess natural gas to a third-party Bitcoin mining company operating in proximity to its oil extraction sites. This collaboration enables the efficient conversion of surplus gas into electricity for cryptocurrency mining. The initiative aligns with ConocoPhillips' objective to eliminate routine flaring by 2025, demonstrating a commitment to environmental sustainability and resource optimization.
3	Gazprom Neft, Russia's state-owned oil major, has conducted a pilot project in West Siberia to utilize associated petroleum gas (APG) for cryptocurrency mining. Traditionally, this gas is flared due to the lack of infrastructure for its utilization. By converting APG into electricity to power Bitcoin mining operations, Gazprom Neft reduces greenhouse gas emissions and transforms a waste product into a valuable resource.	In collaboration with a small Russian mining operation called Vekus, Gazprom Neft deployed a mobile data center equipped with 150 units of Bitmain's Antminer S9 ASICs at one of its drilling sites in Khanty-Mansiysk. Over a month, this setup mined 1.8 Bitcoin using 49,500 cubic meters of gas. The success of this pilot has prompted Gazprom Neft to consider expanding the project to other sites, aiming to reduce flaring and enhance resource utilization.
4	Standard Bitcoin, a company specializing in off-grid Bitcoin mining, utilizes stranded and flared natural gas to power its operations. Stranded gas refers to natural gas deposits in remote locations that are not economically viable to transport to markets, while flared gas is a byproduct of oil production that is often burned off due to safety and logistical reasons. By converting these underutilized energy resources into electricity for Bitcoin mining, Standard Bitcoin transforms waste into a valuable asset, contributing to environmental sustainability and resource optimization.	Standard Bitcoin deploys mobile, modular infrastructure equipped with Bitcoin mining hardware to remote oil and gas extraction sites. These setups capture stranded or flared natural gas directly at the source, converting it into electricity to power the mining equipment. This approach allows for flexible and efficient utilization of otherwise wasted energy resources, aligning with the company's goal of minimizing environmental impact while maximizing operational efficiency.

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#	Case study profile description	Implementation strategy
5	Vespene Energy mitigates methane emissions from landfills by converting captured methane into electricity to power off-grid Bitcoin mining operations. This approach transforms harmful emissions into a productive resource, supporting sustainability and reducing environmental impact.	The company installs modular systems at landfill sites to capture methane, which is then converted into electricity for mining equipment. This decentralized solution leverages otherwise wasted resources, aligning energy generation with environmental objectives.
6	Stronghold Digital Mining transforms coal refuse, a major environmental hazard in Pennsylvania, into electricity for Bitcoin mining. This process mitigates issues like acid mine drainage and uncontrolled fires while reclaiming polluted land.	The company operates reclamation facilities that use advanced technology to convert coal waste into power. The byproduct, beneficial use ash, is used to restore the land, creating a closed-loop system that addresses both energy and environmental challenges.
7	Greenidge Generation Holdings Inc. operates a vertically integrated cryptocurrency datacenter and power generation facility in Upstate New York. The company converted a former coal-fired power plant into a natural gas-powered facility, significantly reducing greenhouse gas emissions. Greenidge provides a clean, reliable power source to New York's energy grid and utilizes its electricity for Bitcoin mining operations.	Greenidge employs advanced technology to ensure efficient and environmentally responsible operations. The facility operates entirely on natural gas, resulting in reduced greenhouse gas emissions. Greenidge has worked closely with the local community to ensure its operation is both environmentally sound and a critical piece of infrastructure serving the community's energy needs and driving economic growth in the region.
8	Gabbani, a Lugano-based hospitality company, has launched an innovative project that repurposes excess energy from its food production facilities to power Bitcoin mining operations. This initiative combines sustainable energy practices with cryptocurrency mining, enhancing energy efficiency and contributing to Lugano's status as a leading European blockchain hub.	Gabbani installed a 100 kW solar panel system at its production facility, generating renewable energy for its operations. Excess energy produced during food manufacturing is redirected to a state-of-the-art Bitcoin mining system, effectively utilizing surplus power that would otherwise go to waste. This approach integrates traditional food production with advanced technology, promoting sustainability and energy independence.
9	Riot Platforms is a leading Bitcoin mining company operating North America's largest facility by developed capacity. The company focuses on large-scale, vertically integrated mining operations, contributing significantly to the Bitcoin network's security and transaction processing.	Riot employs advanced mining technologies and infrastructure to optimize efficiency and output. The company strategically locates its facilities to leverage cost-effective energy sources, ensuring sustainable and profitable operations. Riot's vertical integration allows for direct control over its operations and management of input costs, enhancing operational efficiency.
10	Blockfusion has transformed a decommissioned coal-fired power plant in Niagara Falls, New York, into a clean-energy-powered data center focused on cryptocurrency mining. By leveraging advanced technology and flexible energy loads, Blockfusion contributes to grid stability and environmental sustainability.	In collaboration with CPower and technology partner Optimal Blockchain Mining (OBM), Blockfusion participates in demand response programs, automatically adjusting its energy consumption in near real-time to support grid stability. The integration of OBM's Foreman software and CPower's virtual power plant platform enables seamless automation, allowing Blockfusion to power down operations within 10 min of receiving grid notifications.
11	MintGreen, a Canadian cleantech cryptocurrency miner, has partnered with Lonsdale Energy Corporation to supply heat to the city of North Vancouver, using waste heat from Bitcoin mining. This initiative aims to provide an innovative and low-carbon heating solution for the city's district energy system.	MintGreen's proprietary "Digital Boilers" recover over 96 % of the electricity used for Bitcoin mining in the form of thermal energy. This recovered heat is then integrated into North Vancouver's district energy system, providing a reliable and clean heating baseload for the city's buildings.
12	In Bondo, a remote village in Malawi, a micro-hydro scheme has been implemented to provide electricity to approximately 1800 homes. This initiative has significantly improved residents' quality of life, enabling activities such as studying after dark and food refrigeration. To fund the operation, the project utilizes excess energy to mine Bitcoin, creating a sustainable revenue stream that supports the community's energy needs.	The project employs three turbines to harness the region's abundant rainfall, generating renewable electricity for the village. Excess energy not immediately consumed is directed towards Bitcoin mining operations, ensuring efficient use of resources and providing financial support for the maintenance and expansion of the energy infrastructure.
13	Virunga National Park in the Democratic Republic of Congo has initiated a Bitcoin mining project to generate revenue for conservation efforts. By utilizing the park's abundant hydroelectric resources, this initiative aims to provide financial stability amid challenges such as political instability and reduced tourism.	The park operates a Bitcoin mining facility powered by hydroelectric energy from its rivers. This setup ensures a sustainable and eco-friendly mining process, aligning with the park's conservation goals while creating a new income stream.
14	Gridless is a Kenyan-based company that integrates Bitcoin mining with renewable energy solutions in rural Africa. By partnering with mini-grid energy generators, Gridless monetizes excess energy, ensuring financial viability for energy providers and promoting sustainable electrification in underserved communities.	Gridless collaborates with small-scale renewable energy producers, such as hydro and solar plants, to utilize surplus electricity for Bitcoin mining. This approach provides a consistent revenue stream for energy producers, enabling them to expand infrastructure and offer affordable electricity to local communities. Additionally, Gridless employs its proprietary Gridless OS, a real-time optimization system that coordinates Bitcoin miners' operations based on current mini-grid parameters, enhancing efficiency and grid stability.
15	Genesis Mining, established in 2013, is a leading cloud-based cryptocurrency mining service provider. The company offers clients access to Bitcoin and altcoin mining contracts, utilizing multipool techniques to manage and convert mined altcoins into Bitcoin. Genesis Mining has a global presence, with facilities in Iceland and Sweden, and serves over 2 million customers across more than 100 countries.	Genesis Mining operates large-scale mining farms that leverage renewable energy sources, such as geothermal energy in Iceland and hydropower in Sweden, to ensure efficient and sustainable mining operations. By utilizing advanced hardware and software solutions, the company provides a user-friendly platform for clients to participate in cryptocurrency mining without the complexities of managing physical hardware.
16	Gryphon Digital Mining is a U.S.-based Bitcoin mining company committed to sustainability by powering its operations with 100 % renewable energy, primarily hydroelectric power.	The company operates state-of-the-art facilities, such as the Massena facility in New York, with a hash rate of 0.91 EH/s. By leveraging advanced mining technology and strategic site selection, Gryphon maximizes efficiency while minimizing environmental impact.
17	El Salvador has mined a total of 474 Bitcoin, valued at $29 million, using geothermal energy from the Tecapa volcano since 2021. This initiative aligns with the country's adoption of Bitcoin as legal tender and its commitment to renewable energy sources.	The state-owned power plant allocates 1.5 MW (MW) of its 102 MW production to cryptocurrency mining, utilizing 300 mining processors powered by geothermal energy from the Tecapa volcano. This approach leverages the country's volcanic activity to sustainably power Bitcoin mining operations.
18	Chainergy has developed a sustainable solution that utilizes stranded renewable energy to power modular data centers, delivering high-performance computing for blockchain and AI applications.	In their pilot project, Chainergy deployed an EcoDC mobile data center at an anaerobic digestion biogas facility. This setup consumes excess power generated by the biogas plant, effectively utilizing energy that would otherwise be wasted.
19	Argo Blockchain is a cryptocurrency mining company operating facilities in Quebec, Canada, and Texas, USA. Their Baie Comeau facility in Quebec spans over 40,000 square feet, utilizing 15 MW of power sourced from 100 % renewable hydroelectric energy. In Texas, the Helios facility, now owned and operated by Galaxy Digital Holdings, is a 125,000 square foot Bitcoin mining center with a power capacity of 180 MW, primarily utilizing wind energy.	Argo focuses on deploying adaptable and efficient data centers, leveraging inexpensive renewable energy sources in North America. This strategy enables the company to maintain profitability even during cryptocurrency market downturns. The Helios facility employs immersion-cooling technology, enhancing operational efficiency in hot and dusty environments.

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#	Case study profile description	Implementation strategy
20	TeraWulf is a U.S.-based energy infrastructure company specializing in developing and operating fully integrated, sustainable facilities that support Bitcoin mining and AI/high-performance computing (HPC) applications. The company operates the Lake Mariner facility in New York, which is 100 % owned by TeraWulf and utilizes 91 % zero-carbon energy, primarily hydroelectric power. As of the third quarter of 2024, the Lake Mariner facility has 195 MW of operational capacity, achieving a hash rate of 10.0 EH/s.	TeraWulf's vertically integrated model focuses on leveraging low-cost, zero-carbon power sources to achieve environmentally sustainable Bitcoin mining at an industrial scale. The company is committed to achieving a power cost target of $0.035/kWh, which is 30 % less than the industry average. Additionally, TeraWulf is expanding its operations to include AI and HPC applications, with a 2 MW pilot project, "The WULF Den," nearing completion, and a 20 MW co-location pilot project, "CB-1," on track to be operational by the end of 2024.
21	In Ireland, a collaborative initiative has been established where livestock farmers integrate Bitcoin mining operations with anaerobic digestion (AD) plants. This approach utilizes surplus electricity generated from biogas production, which cannot be exported to the grid, to power Bitcoin mining equipment. By repurposing waste into energy and subsequently into cryptocurrency, farmers create a circular economy model that enhances sustainability and generates additional income streams.	The AD plant generates biogas through the decomposition of organic matter, which is then converted into electricity. Due to grid constraints, excess electricity is directed to on-site Bitcoin mining operations, ensuring continuous energy utilization and enhancing the plant's economic viability.
22	In the Netherlands, a tulip farm near Amsterdam has integrated Bitcoin mining into its operations to utilize the excess heat generated by mining rigs. This innovative approach addresses the high energy consumption associated with cryptocurrency mining by repurposing the heat for agricultural use.	The farm has installed six Bitcoin mining servers within its greenhouse. These servers perform complex computations to mine Bitcoin, producing significant heat as a byproduct. The heat is then used to maintain optimal temperatures for tulip cultivation, reducing the need for traditional gas heating methods. The servers are powered by solar energy generated from panels installed on the greenhouse roof, enhancing the sustainability of the operation.

Data availability

Data will be made available on request.

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