



Review

Bitcoin and Its Energy, Environmental, and Social Impacts: An Assessment of Key Research Needs in the Mining Sector

Murray A. Rudd ^{1,*}, Lee Bratcher ², Simon Collins ³, David Branscum ⁴, Matthew Carson ⁵, Shaun Connell ⁶, Elliot David ⁷, Magdalena Gronowska ⁸, Sebastien Hess ⁹, Austin Mitchell ¹⁰, Matt Prusak ¹¹, Kyle Schneps ¹², Maxim Serezhin ¹³, Scott A. Wolfe ¹⁴ and Dennis Porter ¹

- ¹ Satoshi Action Education, Portland, OR 97214, USA
 - ² Texas Blockchain Council, Richardson, TX 75081, USA
 - ³ Stackr Limited, Otautahi 9610, New Zealand
 - ⁴ Rebel Mining Company, Jackson, WY 83001, USA
 - ⁵ Hash House Tech, Wilmington, DE 19808, USA
 - ⁶ Lancium Technologies Corp, The Woodlands, TX 77380, USA
 - ⁷ Sustainable Bitcoin Protocol, Rehoboth Beach, DE 19971, USA
 - ⁸ PRTI Inc., Franklinton, NC 27525, USA
 - ⁹ Block Green AG, 6343 Rotkreuz, Switzerland
 - ¹⁰ Synota Inc., Columbus, OH 43219, USA
 - ¹¹ US Bitcoin Corp, Austin, TX 78741, USA
 - ¹² Foundry Digital LLC., Pittsford, NY 14534, USA
 - ¹³ Standard Power, Coshocton, OH 43812, USA
 - ¹⁴ Bitcoin Coalition of Canada, Toronto, ON M6H 3P2, Canada
- * Correspondence: murray@satoshiaction.org



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Abstract: In this study, we used a combination of AI-assisted analysis of social media discourse and collaboration with industry experts to delve into the key research needs associated with the Bitcoin mining industry. We identified primary threats, opportunities, and research questions related to the Bitcoin mining industry and its wider impacts, focusing on its energy use and environmental footprint. Our findings spotlight the industry's move towards increasingly greater energy efficiency and an emerging commitment to renewable energy, highlighting its potential to contribute to the coming energy transition. We underscore the transformative potential of emerging applications in the Bitcoin mining sector, especially regarding demand response, grid flexibility, and methane mitigation. We suggest that targeted research on Bitcoin can serve policymakers, private sector decision-makers, research funding agencies, environmental scientists, and the Bitcoin industry itself. We propose that filling key information gaps could help clarify the risks and benefits of Bitcoin mining by encouraging collaboration among researchers, policymakers, and industry stakeholders and conducting research that provides baseline peer-reviewed evidence surrounding Bitcoin's production and impacts. A collaborative approach could help mitigate the risks and realize the benefits of Bitcoin mining, including potentially positive and substantive contributions in alignment with the Sustainable Development Goals.

Keywords: bitcoin; bitcoin mining; energy transition; grid flexibility; key questions; research agenda; renewable energy

1. Introduction

Bitcoin, a decentralized open-source digital ledger, enables global peer-to-peer financial transactions [1]. Its Proof-of-Work (PoW) consensus mechanism rewards the 'miner' who solves a cryptographic challenge with the right to create the next transaction block. Once validated by decentralized node operators, the miner receives bitcoin (lower-case bitcoin denotes the currency; upper-case Bitcoin denotes the protocol) as a reward, plus transaction fees collected for that block. The PoW consensus mechanism safeguards the

ledger's integrity, creating a secure and immutable record of transactions. Attempts to falsify it are not only mathematically formidable but also extremely energy- and capital-intensive. Bitcoin miners are central to network security.

For newcomers to Bitcoin, several essential points are worth noting. Firstly, miners, ranging from individuals with a single computer to large-scale entities with thousands, provide computing power and security to the Bitcoin network. Secondly, tens of thousands of independent Bitcoin network node operators validate mining transactions, providing a balance of power between the compute and validation functions. Each node operator stores a copy of the globally distributed ledger, securing the network's integrity. Lastly, Bitcoin, distinctively decentralized, has no central authority or foundation and derives its power and security from its inherently decentralized design.

As of November 2023, the Bitcoin network reached a computation capacity of >500 exahash per second (<https://data.hashrateindex.com/network-data/btc> (accessed on 20 November 2023)), accounting for nearly 0.65% of global electricity consumption (<https://ccaf.io/cbnsi/cbeci/comparisons> (accessed on 20 November 2023)). Despite its numerous and innovative benefits [2], Bitcoin's energy-intensive production has become a point of criticism [3–7]. Some policymakers [8] and parts of the public [9,10] equate Bitcoin's global energy demand and contributions to climate change, even though these two factors are not necessarily correlated should mining prove to support the transition to renewable energy.

The foundation for informed Bitcoin policy decisions is currently limited, partly due to its nascent nature and partly due to conclusions drawn by researchers unfamiliar with Bitcoin's intricacies [11,12]. This underscores the urgent need for a comprehensive Bitcoin research program that spans environmental, applied, and social sciences [13]. The research should contextualize Bitcoin mining within the broader framework of energy production and socio-economic dynamics, catering to policymakers by providing high-level studies on Bitcoin mining's influence on energy systems and, as needed, in-depth case studies and modeling efforts. Much of the current knowledge resides with industry experts and experienced practitioners, so engaging them is crucial.

In this study, we explore research areas to enhance the understanding of bitcoin mining and its multifaceted impact on climate, energy systems, the environment, and society. Utilizing a twofold approach inspired by the horizon scanning field [14,15], our first step involved assessing a broad spectrum of publicly accessible broadcasts within Bitcoin's dynamic social media landscape. This discourse laid the foundation for AI-assisted identification and articulation of pivotal Bitcoin information needs and candidate research questions. Secondly, we collaborated with industry stakeholders to scrutinize the AI-generated research questions, add additional questions when necessary, and enrich the knowledge-building process. This paper aims to significantly contribute to an emerging Bitcoin research agenda that can help policymakers and other decision-makers make informed decisions and prioritize research needs.

2. AI-Assisted Exploration of Bitcoin Threats, Opportunities, and Research Questions

2.1. Overview

Our study centered on identifying perceived threats and opportunities ('issues') relevant to the Bitcoin mining industry and energy- and environment-focused policymakers. Our methodology involved:

1. Identification of Key Issues: We employed AI to extract prominent threats and opportunities related to mining from Bitcoin-oriented podcasts (this step replaced the solicitation of candidate research questions from the wider community in traditional key questions exercises).
2. Formulation of Candidate Research Questions: From these threats and opportunities, we further used AI assistance to develop a set of pertinent and compelling research questions ($n = 180$).

3. **Consultation with Industry Experts:** After a light-touch human review that further eliminated redundancies, we were left with 81 candidate research questions. We then engaged with experts from the Bitcoin mining, energy production, and support industries, inviting them to identify their priority information needs and engage in the manuscript review and editing process.

Our approach, engaging with seasoned industry professionals, helps to ensure high-level perspectives on the industry's information and research needs. Our participatory approach was preferred to traditional quantitative surveys, which likely would have garnered limited engagement. This strategy helped maintain focus on the key evidence vital for informed decisions concerning Bitcoin mining, as well as energy and environmental policymaking.

2.2. Identification of Pressing Bitcoin Mining Issues

2.2.1. Selecting Social Media Interviews

The Bitcoin-focused social media landscape is active and spirited, with a wide variety of interviews and discussions addressing topics such as mining, technological advance, and the broader societal impacts of Bitcoin mining and adoption. Our source pool of podcasts included interviewees ranging from high-profile senior executives to lesser-known but often very knowledgeable practitioners. Most of our content was derived from long-form interviews (<https://doi.org/10.6084/m9.figshare.24547774.v1>, accessed on 20 November 2023) for interview summaries and other Supplementary Materials).

We analyzed transcripts from 358 broadcast segments, amounting to 383 h of dialogue (Figure 1), at which point we reached a pre-determined cut-off date for analyses (to allow for the preparation of a short list of questions prior to a July 2023 workshop). These broadcasts, sourced from 59 broadcasters, afforded broad insight into the industry. While mining was a central theme, other Bitcoin-related subjects were also discussed. 301 out of 358 broadcasts occurred in the first half of 2023, so we captured current issues being actively discussed on Bitcoin-oriented social media.

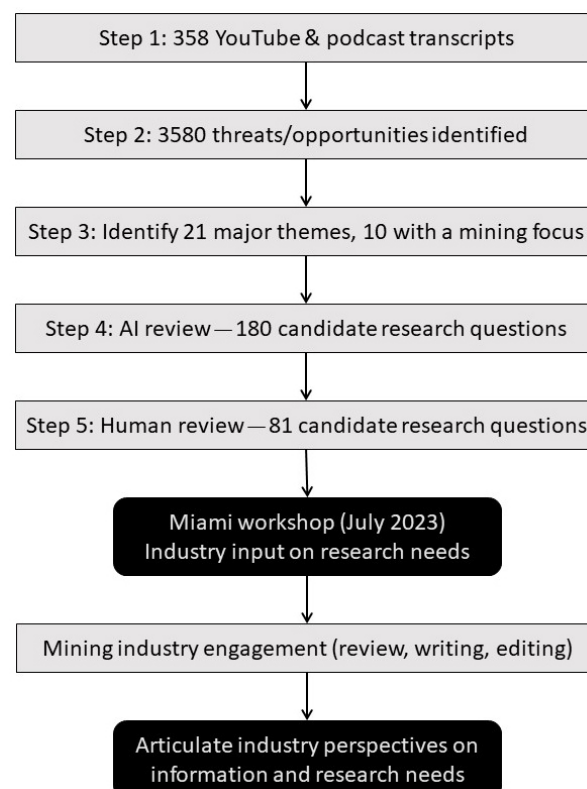


Figure 1. Steps in the Bitcoin issue identification process.

2.2.2. AI-Assisted Identification and Refinement of Issues

Rapid advancements in automated AI-assisted podcast transcription services over late 2022 and 2023 have made the analysis of long-form interviews and panel discussions simple and economical. Moreover, with the recent progress in Large Language Models (LLMs) and prompt engineering [16,17], complex parsing of transcriptions is now possible. Innovative use of LLMs opens up new possibilities for cross-cutting transdisciplinary research [18,19].

For each of the 358 broadcasts, OpenAI’s ChatGPT-4 was tasked with identifying 10 AI-derived keywords, a concise summary, and the 10 most important threats and opportunities (‘issues’) discussed in the transcription. Note that the scope of material that we drew on for this study—3580 issues—was far in excess of the level typical for traditional horizon scanning exercises [20]. The full list of 3580 issues and prompts are available in the Supplementary Materials of <https://doi.org/10.6084/m9.figshare.24547774.v1> (accessed on 20 November 2023).

2.2.3. Extraction of Threats and Opportunities

Initiating the threats and opportunities identification process necessitated the establishment of a research context and the creation of a research persona for GPT-4. The context specified that the analysis would extract information for subsequent use by researchers conducting synthesis research on Bitcoin mining. The persona was described as a ‘senior academic researcher and full professor, highly acquainted with Bitcoin, and possessing a PhD focused on the social and technical implications of emerging technologies.’ This persona had a keen interest in aspects concerning Bitcoin’s social, environmental, political, economic, and governance impacts, as well as issues relating to computer science, technical developments in Bitcoin and Layer 2, finance, and law.

We asked ChatGPT-4 to identify issues using the prompt: “. . .list 10 important threats and/or opportunities—the most important issues—you discovered in this content. These threats and/or opportunities may (1) impact on Bitcoin mining, technology, or adoption, or (2) be environmental, economic, social, or governance impacts arising from Bitcoin mining, technology, or adoption”. Note that we focused GPT-4 entirely on identifying issues that were discussed within the transcription text, not on its general knowledge. We wanted the AI to extract important issues and then generate ‘candidate’ research questions based on those issues, mirroring the process in traditional key questions exercises, where a working group sorted and refined a pool of candidate questions supplied from the broader community. We requested the AI to summarize its internal rationale for its choices (Table 1).

Table 1. Verbatim response by GPT-4 on its process for conducting a “detailed review of the content [broadcast transcription], with a focus on recognizing any potential opportunities and threats that can affect Bitcoin mining and its associated impacts”.

Step	Details
“Initial Reading	The first step was to thoroughly read and understand the content, taking into account all the details. While reading, I considered the context, geographic location, and specificities of Bitcoin mentioned in the text.
Identification of Core Themes	After understanding the content, I identified the core themes in it [GPT-4 usually provided an interview-specific example here to illustrate the process for each transcript]
Threats and Opportunities	From these themes, I started identifying the threats and opportunities that they posed. The threats and opportunities were derived based on the positive or negative implications they might have for Bitcoin mining and its social, environmental, political, economic, and governance impacts. For instance, the possibility of changing the public perception of Bitcoin mining was seen as an opportunity, whereas the reliance on government incentives and subsidies was identified as a potential threat.
Impact Factors	For each identified threat or opportunity, I provided three supporting points that helped determine their inclusion. These points highlighted the elements that made these issues significant, or that had the potential to impact Bitcoin mining or its broader impacts.
Ranking and Selecting	After developing the preliminary list, the issues were ranked based on their overall potential impact. This ranking was based on the scale of their impact, their likelihood, and their relevance to the themes of Bitcoin mining and its broader impacts. This helped ensure that the most pertinent issues made it to the final list of 10.
Cross-Checking	Finally, I cross-checked the chosen issues against the content to ensure they are all strongly relevant to the given information.”

To illustrate GPT-4’s capability, we analyzed Peter McCormick’s interview with Troy Cross and Shaun Connell from What Bitcoin Did (www.whatbitcoindid.com/wbd619-troy-cross-shaun-connell, accessed on 20 November 2023). They discussed US Bitcoin mining and energy policy. GPT-4 identified 10 issues—threats and opportunities—from the broadcast transcriptions and, in Table 2, explains how they were selected.

Table 2. Verbatim response by GPT-4 about how it identified threats and opportunities (‘issues’) for Peter McCormick’s What Bitcoin Did interview with Troy Cross and Shaun Connell.

Issue	Rationale
“Complexity of Electricity Pricing	Different cost components: energy, transmission, distribution, and taxes; Varying costs from state to state; Difficulty for miners to accurately predict costs.
Lack of Capacity Charges in ERCOT	Encourages high energy prices; promotes strategic operation by miners, turning off during peak prices; unique market structure can create unpredictable scenarios.
Introduction of Nodal Pricing	Encourages load placement based on energy prices; influences miner operation location; could lead to strategic geographical clustering.
Effect of Weather Events on the Energy Market	The impact of Winter Storm Uri on energy prices and policies; potential for future events to disrupt operations; need for miners to adapt to weather-related volatility.
The Shift towards Efficiency in Bitcoin Mining	Miners adapting operations to market signals; aligning mining activities with grid reliability; shift from focusing solely on Bitcoin accumulation.
Opportunities for Demand Response in Bitcoin Mining	Potential for cost savings and grid support; role of miners in aiding grid reliability; the need for flexible operations in response to energy demand.
The Importance of Geographic Location in Bitcoin Mining	Influence on energy costs; effect on access to renewable energy; impact on grid integration and support.
Renewable Energy Credits (RECs) in Different Regions	Role in promoting renewable energy sources; potential costs for miners in areas lacking wind and solar; influence on overall mining operation costs.
High Energy Prices as a Disincentive for Miners	Influence on profitability; push for more efficient operations; potential for driving innovation in the sector.
Connection to Transmission Voltage	Possible cost savings by bypassing distribution infrastructure; impact on grid stability and resilience; dependence on specific geographic locations and infrastructure availability.”

2.2.4. Identifying the Most Important Themes across All Content

As of July 2023, neither GPT-3.5 nor GPT-4 could consistently and systematically sort issues due to restrictions on the context window size. Thus, we used a traditional text miner (QDA Miner version 5.0.11) to analyze the 3580 issues. Through keyword and phrase cluster analysis, we identified 21 themes, 10 of which were particularly relevant to mining. These 10 are detailed in Table 3.

Table 3. Keywords and phrases characterizing themes potentially most relevant for the Bitcoin mining industry.

Theme	Cluster Keywords and Phrases
Energy context	Electricity; energy
Environmental	Activism; activist; activists; carbon; climate; decarbonization; decarbonizing; emissions; environmental; environmentalism; environmentalists; environmentally; esg; footprint; green; high energy consumption; impact of bitcoin; mitigate; mitigated; mitigates; mitigating; mitigation; pollution; recs; remediation; sustain; sustainability; sustainable
Renewable energy	Geothermal; green energy; hydro; hydroelectric; hydroelectricity; hydropower; nuclear; ocean; oceanic; otec; renewable; renewables; solar; sustainable energy
Electricity for mining	Energy consumption; energy efficiency; energy intensive; energy sources; hashrate predictions; high energy; power consumption; power generation

Table 3. Cont.

Theme	Cluster Keywords and Phrases
Energy grids	Balancer; balancing; blackout; blackouts; curtailments; demand response programs; electrification; energy grid; energy infrastructure; energy policies; ercot; grid; grids; microgrids; power prices; ppas; puc; responsiveness
Site choice dynamics	Africa; African; Alberta; Argentina; Bhutan; California; Canada; China; Congo; Dubai; El Salvador; Electricity Price; Electricity Prices; Energy Costs; Energy Prices; Europe; Georgia; Iceland; Ireland; Kazakhstan; Korea; Logistical Challenges; Nordics; Oklahoma; Paraguay; Philippines; Political Stability; Quebec; Risk Profile; Russia; Siberia; South America; Taxation; Texas; US; USA; Varunga; Venezuela; Weather Events; Zimbabwe
Mining companies and strategies	ASIC; ASICs; bankruptcies; bankruptcy; bitcoin mining efficiency; Bitcoin mining hardware; bitdeer; bitmain; blockware; cleanspark; competition; competitive; competitiveness; cooling; crusoe; crusoe energy; efficient mining; energy efficiency in bitcoin mining; energy efficient; energy management; energy utilization; foreman; foundry; gridless; griid; hardware; hash; hashrate; hive; hive blockchain; hut 8; immersion; immersion cooling; iris; marathon; market competition; mining difficulty; mining efficiency; mining equipment; mining hardware; mining infrastructure; mining machines; mining power; mining rigs; mining technology; overclocking; pow; professionalization; resale value; rigs; riot; risk management; stronghold; terawulf; terrawulf; underclocking
Markets	Bear; Bitcoin market; Bitcoin price; Bitcoin prices; bull; consolidation; cycles; difficulty; economic viability; halving; halvings; investors; liquidate; liquidation; manipulation; market cycles; market downturns; market dynamics; mining profitability; price fluctuations; profitability; profitable; revenue; shareholders; speculators; squeeze; volatile; volatility
Nonrenewable and stranded energy	Flared; flaring; gas; hydrocarbon; methane; non-renewable energy; petroleum; stranded; vented; vespene; wasted
Support industry	Braiiins; derivative; derivatives; FTX; hedging; luxor; marketplace; marketplaces; markets; nft; nfts; nicehash; ordinal; ordinals

2.2.5. Refining Subthemes and Candidate Research Questions

Keywords characterizing the 10 relevant clusters were input into GPT-3.5 for deeper analysis (3580 issues—the list of issues was >125,000 words in length). It recognized 239 subthemes across the 10 themes and proposed two research questions for each. From these, we selected 10–20 questions per theme based on the number of related interviews (Table 4).

Note that we used GPT-4 for all analysis of individual transcripts, but due to mid-2023 constraints in loading large datasets to ChatGPT-4 (all our transcription analysis was done prior to the release of Code Interpreter), we used GPT-3.5 for synthesis. These are two entirely different modeling exercises, so mixing models had no impact on the quality or consistency of transcription analyses, for which we relied on GPT-4. GPT-3.5 was perfectly competent for generating research questions using output from GPT-4's individual analyses.

Chat-GPT-3.5 narrowed the pool to 180 important research questions across all 10 themes. A light-touch human review was used to identify further redundancies and opportunities for combining questions, which resulted in a final list of 81 questions in 11 topic areas. This procedure mirrored that used for some human working groups conducting key question exercises, where project leaders undertake a preliminary edit prior to bringing a list of candidate questions to workshop participants [see [20] (Table 2)].

Table 4. Verbatim response by GPT-3.5 that for the ‘Energy Grids’ theme explains “a detailed step-by-step process of how the final research questions were identified, including the criteria used for sorting issues and questions, and other considerations that influenced the choices”.

Step	Details
“Compilation of Subthemes and Research Questions	The initial step involved compiling a list of 23 subthemes related to the ‘Energy Grids’ theme based on keyword analysis. These subthemes served as the foundation for generating research questions. A pool of 46 research questions was developed, with a minimum of two questions per subtheme.
Review of Pertinence and Relevance	Each research question was assessed for its pertinence and relevance to both the societal benefits and the Bitcoin mining industry. The questions were evaluated based on their potential impact, alignment with sustainability goals, industry applicability, and ability to contribute to academic research and knowledge advancement.
Consideration of GPT-4’s Prioritized Issues [from original YouTube and podcast transcripts]	While GPT-3.5 does not have direct access to GPT-4’s priorities, the previous discussions with GPT-4 [supplied to GPT-3.5 for context] provided valuable insights into important issues within the Bitcoin mining context. These insights were considered as part of the selection process to ensure consistency and coherence between the two models’ findings.
Evaluation of Academic Tone and Language	The language and tone of the research questions were carefully reviewed to ensure they adhered to the professional and academic standards expected in research settings. Clarity, conciseness, and adherence to the guidelines provided to GPT-4 were prioritized to maintain the integrity and quality of the research questions.
Consideration of Research Criteria	Several criteria were taken into account during the selection process. These criteria included the complexity of the research, data availability, research timeframe, potential benefits to society, generalizability of research results, policy feasibility, and relevance to the Bitcoin mining industry. Each research question was evaluated based on these criteria to determine its importance and priority.
Comparative Analysis and Prioritization	The pool of 46 research questions was further analyzed, and a comparative assessment was conducted to identify the top 20 questions that would serve as the highest research priorities. This analysis involved considering the relative importance of each question for both societal benefits and the Bitcoin mining industry. Questions were ranked based on their potential impact, feasibility, and alignment with the specified criteria.
Rationale and Justification	For each of the 20 final research questions, a rationale was provided to explain the thought process behind their selection. The rationale highlighted the specific aspects of the question that made it crucial for academic research, its potential benefits to society, and its significance for the Bitcoin mining industry. Considerations such as industry relevance, sustainability, risk mitigation, and technological advancements were addressed in the justifications.
Conclusion	This comprehensive step-by-step process ensured a systematic approach to identifying the final research questions, maintaining consistency with the GPT-4 context, and considering various criteria and industry-specific factors. The aim was to provide a balanced selection that both benefits society and has important implications for the Bitcoin mining industry while adhering to the academic standards required for rigorous research and scholarly publication.”

3. Industry Perspectives on High-Priority Issues and Research Needs

We discussed the AI-generated research questions at an open Bitcoin industry workshop (Mining Disrupt, 26 July 2023, Miami, FL, USA). After the workshop, industry representatives reviewed the questions and contributed to the manuscript. Once the manuscript draft was complete, it was circulated among a wider group of industry participants for review. Contributors who provided substantive input during the preparation of the draft manuscript were included in this paper as ‘review and editing’ co-authors.

In the material that follows, research questions identified by the AI are shown in tables, while the accompanying commentary for each section was developed by the co-authors. There was no obligation for co-authors to mention every AI-generated question nor to restrict themselves to questions in the tables. This level of freedom is similar to the freedom that breakout group participants have at in-person meetings. Participants in the key questions exercises are always free to accept or reject candidate questions or develop their own questions [14,21,22].

Our focus was on Bitcoin mining in this paper. We recognize that there are a variety of Bitcoin's impacts that are also important (e.g., the impacts on issues like financial inclusion and adoption, cybersecurity and crime, and macroeconomic and political implications), but those are beyond the scope of the current mining paper.

3.1. General Energy Use

This section explores questions pertaining to the complex interplay between Bitcoin mining and sustainable energy (Table 5). This kind of targeted research may help Bitcoin miners and policymakers make informed decisions on the optimal settings, locations, and terms for conducting business.

Table 5. Candidate research questions about general energy use issues.

Examples of AI-Generated Candidate Research Questions—General Energy Use	
1.	What strategies can be employed to minimize gas flaring, optimize the utilization of stranded energy sources, and integrate Bitcoin mining into oil and gas production operations while ensuring environmental sustainability?
2.	What are the most accurate methods for measuring the carbon footprint associated with the energy consumption of Bitcoin mining?
3.	What methods can be used to accurately measure and evaluate the economic and environmental benefits of renewable energy investments in mining operations?
4.	What are the key challenges and potential solutions for scaling renewable energy sources to meet the energy demands of large-scale Bitcoin mining operations?
5.	What benefits can be derived from integrating specific energy storage systems and demand-side management strategies with Bitcoin mining operations to optimize energy usage, grid interaction, and overall sustainability?
6.	How can the incentivization of renewable energy adoption in Bitcoin mining operations maximize social, economic, and environmental benefits?
7.	How can the Bitcoin mining industry optimize energy diversification for sustainable mining operations?

Bitcoin mining now holds significant influence in the energy landscape in some regions and is increasingly being used to monetize underused energy resources. As the Bitcoin network continues to grow, the industry will need to increasingly rely on lower-cost power to remain economically viable, particularly during bear markets when miners may face significant cash flow challenges.

From a mining supply and demand perspective, low-cost electricity, the most important input in bitcoin production, enables producers to increase production levels and reduce average costs (i.e., the supply curve shifts outward). Thus, the exploration of innovative strategies to access under-utilized energy sources and integrate Bitcoin mining may both enhance financial viability and valorize previously wasted energy resources [23]. Utilizing waste methane from abandoned oil wells, gas from operational oil wells that are venting methane, landfills, wastewater plants, and agricultural and forestry wastes to power mining operations may also help rapidly reduce greenhouse gas emissions, an important consideration given methane's potent greenhouse gas impact [24] and the urgent need to reduce CO₂e emissions [25–27].

Understanding the challenges and solutions related to employing renewable and carbon-free energy sources in large-scale mining operations is also important [28]. Integrating Bitcoin mining with intermittent solar and wind energy systems and electricity transmission grids [29] may expedite the expansion of renewable energy infrastructure and the initial and sustained investments needed for their grid interconnection [30].

Nuclear generation is also a well-suited generation partner for Bitcoin mining, given that nuclear power is baseload generation but still has a shutdown cycle of several weeks for refueling, though this shutdown cycle is manageable for Bitcoin mining. Nevertheless, it is also crucial to consider other factors like the predictability of 'excess' energy generation, generating capacity factors, and policy-driven financial incentives for energy production.

The accurate measurement of the emissions intensity of energy used by the Bitcoin network has historically been a critical point of contention. Thus, precise quantification

of Bitcoin mining's carbon footprint is fundamental for the industry's credibility and accountability [31]. This not only enhances transparency but also provides miners and policymakers with the essential knowledge to make informed decisions regarding energy consumption and emissions reduction. Furthermore, improving measurement and contextualization within inherently variable energy grids is vital.

3.2. Energy Grids

Table 6 introduces research questions concerning Bitcoin mining and its impact on energy grids. The current energy paradigm, characterized by decentralized energy grids and distributed energy resources, significantly steers the evolution of energy infrastructure. Industrial-scale Bitcoin mining, because of its unique qualities as a large flexible load, may be poised to contribute to transformative shifts in the energy sector, potentially solidifying Bitcoin mining's role as a foundational support for power grids [28] and catalyzing further transitions toward renewable sources and innovations [32]. Effectively identifying and navigating these types of grid management challenges requires research that can inform complex decisions about grid design and efficiency.

Table 6. Candidate research questions about energy grids.

Examples of AI-Generated Candidate Research Questions—Electricity Grids	
8.	What potential impacts does Bitcoin mining have on the stability and reliability of local energy grids, and how can energy grid actors collaborate to minimize power disruptions and ensure grid stability?
9.	How can decentralized energy grids and distributed energy resources be effectively integrated with Bitcoin mining operations to establish a resilient and secure mining network?
10.	Which pricing mechanisms can ensure fair and transparent energy costs for Bitcoin mining operations while incentivizing the adoption of renewable energy sources?
11.	What strategies can optimize the capacity planning and expansion of energy grids to effectively meet the growing energy demands of Bitcoin mining?
12.	What are the prominent challenges and barriers in modernizing energy grids for Bitcoin mining, and what strategies can be employed to overcome them?
13.	What are the most impactful energy efficiency strategies and demand response mechanisms that can be implemented in Bitcoin mining to contribute to grid stability?

Bitcoin mining's distinct flexibility has underscored its capability as an adaptable load with substantial implications for grid behavior [28]. In instances of high energy output or low market demand, Bitcoin mining operations can function as an energy load balancer, assimilating excess energy generated by renewable sources such as solar and wind. Rather than permitting this surplus to remain unused, being unprofitably curtailed by the generator, or relying on less efficient and more expensive storage methods, it can be channeled toward Bitcoin mining. This positions Bitcoin mining as a fully adjustable load [28], proficiently managing fluctuations in surplus energy while concurrently enhancing the economics of renewables by mitigating negative pricing, an increasingly prevalent issue in regions with abundant renewable energy resources [33,34].

Flexible Bitcoin mining operations that leverage advanced software control systems for quickly adjusting their load consumption can provide grid operators with a flexible resource that can be used for real-time energy load balancing or providing ancillary services such as frequency response (sudden drops in system frequency) and contingency reserves (back-up power in case a power plant trips offline). Bitcoin miners running on renewable energy have a faster response time to shut down compared to powering up fossil fuel 'peaker plants', therefore positioning Bitcoin mining as a better grid stability partner that does not require increased burning of fossil fuels during periods of extreme market demand. Bitcoin mining may also offer advantages in situations requiring power system flexibility [35,36] by rapidly offsetting any sudden fluctuations in system frequency, ensuring the grid's continuous operation. ASICs can be over- or under-clocked, though it is important to

recognize that they were engineered to have a constant 24/7 inflow of electrons and run without fault.

The integration of Bitcoin mining into both regulated and deregulated power systems poses not only a technological challenge but also a strategic one, with impacts on the sustainability and efficiency of the wider energy system. Ensuring affordability and reliability in supplying electricity, a commodity that needs to be used immediately upon production, is pivotal. Electricity pricing schedules [37,38] and innovative power purchasing agreements are needed, ensuring equitable energy pricing for electricity users and producers, including Bitcoin miners, while incentivizing the uptake of clean energy. Efficiency is so important for power grid managers that, according to some internal reports, some curtailment service providers now offer Bitcoin miners financial incentives to upgrade computers running the current most energy-efficient ASICs, which helps reduce overall grid energy consumption.

The modernization of energy grids and the expansion of transmission capacity to meet Bitcoin miners' needs present challenges, extending from regulatory nuances [39] to the logistics of infrastructure development [40–42]. Transmission requirements are a key development issue for renewables, and Bitcoin might allow renewable facilities to generate value without grid buildout. This alone is a key attribute of Bitcoin mining that might enable it to be a true partner for renewables that are located in remote locations, allowing them to produce energy and generate revenue prior to grid transmission connections becoming operational [30].

It is important to acknowledge that highly flexible loads (i.e., 75% uptime) are quite distinctive compared to firm loads. Whereas a firm load perpetually draws energy from the grid without reciprocity, flexible loads offer grid operators a substantial degree of flexibility, aiding in the reliable flow of electricity to the market and the potential for integration of higher levels of renewables.

3.3. Bitcoin Mining Operations

Bitcoin mining companies must balance energy efficiency, profitability, network security, decentralization, and energy independence amidst fluctuating mining difficulties and hashrate (Table 7). This requires a context-specific understanding of energy consumption. Mining needs to be considered within the context of distinct regional energy grids, ensuring a precise representation of its energy utilization and environmental impact. Given the direct influence of electricity cost fluctuations on the profitability and economic viability of Bitcoin mining operations, research must explore how miners can adeptly mitigate these impacts and address the economic challenges posed by such variations.

Strategies and collaborative models that forge robust partnerships between Bitcoin mining companies and local energy providers (local distribution companies, retail electric providers, utilities, load-serving entities, and qualified scheduling entities who schedule the electricity into the grid) constitute another important research avenue. Such partnerships, vital for securing a sustainable and cost-effective energy supply, also dictate the resilience and strategic direction of Bitcoin mining operations. An in-depth exploration of partnership models across a spectrum of energy providers, from co-ops to major independent power producers, may illuminate how effective, sustainable partnerships across varied operational contexts can be created and sustained. In some cases, miners might vertically integrate (e.g., investing in energy production) to accrue greater control over their energy supply chain, enhance energy security, and mitigate costs.

Table 7. Candidate research questions about Bitcoin mining operations.

Examples of AI-Generated Candidate Research Questions—Bitcoin Mining Operations	
14.	How can mining companies strike a balance between energy efficiency, profitability, network security, decentralization, and achieving energy independence in Bitcoin mining operations?
15.	How can the Bitcoin mining industry optimize its operations to ensure a balance between profitability, environmental sustainability, and the challenges posed by fluctuating mining difficulty and hashrate?
16.	In what ways do fluctuations in electricity costs impact the profitability and economic viability of Bitcoin mining operations, and how can miners effectively mitigate these impacts?
17.	What strategies and collaborative models can be employed to establish strong partnerships between Bitcoin mining operations and local energy providers, promoting a sustainable and cost-effective energy supply?
18.	What practical measures and initiatives can be taken to implement responsible mining practices in Bitcoin mining operations, effectively managing and mitigating local environmental impacts while ensuring sustainable growth?
19.	What strategies can be employed to facilitate the transition of Bitcoin mining towards a circular economy, minimizing resource depletion and electronic waste generation?
20.	What are the most effective strategies for minimizing environmental pollution, resource depletion, and electronic waste in Bitcoin mining operations?
21.	What approaches can be taken to implement standardized reporting and verification mechanisms that enhance transparency in energy usage across mining operations?

The promotion of responsible mining practices, consonant with the principles of a circular economy and aimed at preventing resource waste and minimizing electronic waste [43], is both an ethical imperative and a strategic necessity for the industry's sustained viability. Research is needed to identify pathways through which the industry can navigate the intricacies of energy use, environmental impact, and sustainability while ensuring operations retain their profitability.

Incorporating variable pricing strategies, miners might leverage low electricity prices during off-peak hours and employ predictive analytics to ascertain optimal mining times. Moreover, diversifying energy sources through a blend of renewable and non-renewable energy could attenuate exposure to price fluctuations while concurrently addressing local environmental concerns, such as water usage and habitat disruption.

Given that Bitcoin is a network technology with each computer having its own media access control (MAC) ID as well as its own IP address, understanding IT systems management is important. Often, companies will choose to design systems to stringent Service Oriented Company (SOC) compliance frameworks such as SOC 1 for monetary and payment transfer systems and SOC 2 for network and IT systems. Maintaining systems integrity is critical to maintaining the flow of hashrate to a mining pool.

To augment transparency and accountability, miners might consider collecting and sharing data on their operations, inclusive of real-time energy consumption, energy source mix, and environmental impact metrics. Joining industry associations or engaging in working groups focused on sustainable mining practices can facilitate access to best practices, knowledge sharing, and collective problem-solving for environmental and operational challenges.

3.4. Geographic Distribution of Bitcoin Mining

The exploration of Bitcoin mining's geographic distribution highlights vital considerations for energy use, environmental sustainability, and interactions with various sectors, providing valuable insights for miners and policymakers (Table 8). Bitcoin mining is likely to concentrate in areas with very reliable and abundant energy, which may not coincide with areas of high energy demand.

Table 8. Candidate research questions about the geographic distribution of Bitcoin mining.

Examples of AI-Generated Candidate Research Questions—Geographic Distribution of Bitcoin Mining	
22.	How does spreading out Bitcoin mining affect energy use, environmental impact, and its connections to energy-heavy industries, taking into account both positive and negative outcomes?
23.	How does the geographical distribution of Bitcoin mining operations, nodes, and their impact on network robustness enhance sustainability?
24.	How do geopolitical factors, political stability, and local regulations shape the selection of Bitcoin mining sites and their implications?
25.	What are the key infrastructure requirements needed to support large-scale Bitcoin mining operations and foster the growth and stability of the industry?
26.	What is the impact of varying energy costs, electricity prices, and their regional differences on the profitability and sustainability of Bitcoin mining operations?
27.	How do climate conditions, weather events, and their long-term effects impact the operational resilience and viability of Bitcoin mining sites?
28.	How does water availability influence the selection of Bitcoin mining sites, and what strategies can mining operations implement to ensure responsible water use and conservation?

Astute management significantly determines the beneficial and detrimental repercussions of Bitcoin mining. The intersections between Bitcoin mining and other energy-intensive industries raise questions regarding competition and compatibility, providing distinct challenges and opportunities that require research. Additionally, factors such as varying energy costs, electricity tariffs, climatic variations, and water availability exert a notable influence on mining site choices and profitability [44–46].

A crucial aspect deserving exploration is the role of geographic distribution in maintaining network security. The possible impact of geographic centralization on risk and security is pivotal. For example, while Texas has become a mining hub due to its favorable conditions, does this concentration effectively consolidate these miners into a single entity? Alternatively, do the distinct characteristics of each firm provide enough differentiation to collectively enhance network resilience?

Geopolitical nuances, political stability, and regional regulations substantially guide Bitcoin mining location choices, molding the industry’s global footprint and influencing miners’ decisions [47]. Bitcoin’s openness and mining present intriguing questions related to geopolitics and network credibility, especially considering nations under stringent sanctions, such as North Korea, Russia, and Iran, can enter the market and reap returns. Does this situation merely showcase Bitcoin’s intrinsic equity as an open protocol? Or does it indicate a potential risk of ideological decay, possibly hindering its adoption by entities adhering to the US-centric world order?

3.5. Local and Regional Impacts of Bitcoin Mining

Examining the local and regional effects of Bitcoin mining requires context-dependent analysis. The research questions laid out in Table 9 may help unpack Bitcoin’s impact on local energy markets, the environment, and communities, including the issue of revenue diversification and resilience in rural regions.

The infrastructure demands of large-scale Bitcoin mining operations are significant. Bitcoin miners provide a very large-scale, point-specific load that can consume as much as 50 MW of power within five acres. This highly energy-dense footprint allows for a minimally intrusive physical presence. At the same time, the large power density allows for the possibility of miners becoming new anchor tenants, helping to revitalize existing industrial facilities into Bitcoin data centers that use existing on-site infrastructure. For example, an old paper mill in the Pacific Northwest, a carpet mill in the USA Southeast, or a steel mill in the USA Midwest might be re-purposed, and the high voltage substation and grid connectivity used instead of building new substation and power lines that could be disruptive to the local landscape. Industrial properties can sit undeveloped for years, if not

decades, causing potential community decline through the ‘broken windows syndrome’ process of neglect-led decline.

Table 9. Candidate research questions about the local and regional impacts of Bitcoin mining.

Examples of AI-Generated Candidate Research Questions—Local and Regional Impacts of Bitcoin Mining	
29.	What is the impact of Bitcoin mining on local and regional energy markets?
30.	How does Bitcoin mining impact the environment in specific ways in different regions?
31.	How does Bitcoin mining impact local communities economically, socially, and environmentally?
32.	What is the influence of the geographical distribution of Bitcoin mining activities on regional economies, including economic diversification opportunities, job creation, and entrepreneurship in mining site regions?
33.	In what ways can miners promote responsible and inclusive practices, mitigate negative consequences, and harness the transition to renewable energy for regional economic development?
34.	What measures can policymakers and stakeholders take to encourage a geographically balanced distribution of mining activities and minimize strain on local energy infrastructure?
35.	What are the essential attributes of an ideal labor force for Bitcoin mining operations, and how can local talent in mining site regions be effectively utilized and developed?
36.	How does the integration of Bitcoin mining investments with local infrastructure development contribute to the sustainable growth of the regional economy?
37.	What are the social impacts and community-level benefits associated with the adoption of renewable energy in Bitcoin mining regions?

Having an economically viable local industrial base also offers the potential for indigenous communities to increase the degree of sovereignty they hold over economic development, social impacts, and their own financial independence.

Accurate forecasting of the influence of Bitcoin mining on electricity prices is often the focus of local and state-level politicians. Policymakers need to develop strategies that ease the burden on local energy supplies and market prices and create smart power use and pricing strategies for both wholesale and retail electricity customers [37].

By encouraging economic diversification, job creation, and entrepreneurial efforts, Bitcoin mining might enhance regional development [48]. While mining activities can drive economic growth, create jobs, and diversify economies, they may also demand more from infrastructure and impact local communities across social, economic, and environmental dimensions [29,49]. Noise generated by Bitcoin mining operations is an important, yet sometimes overlooked, factor that may become a local issue.

Regional economic impact models are sometimes used to assess spillover effects of new industrial investments, but they have their limitations, especially when arbitrary multipliers are used in input–output models [50]. Refined multi-account assessment methodologies can provide valuable insights beyond financial and employment impacts [51]. In areas like Texas, where Bitcoin mining is a major industry, it might also be possible to use computable general equilibrium models [52] to assess mining’s regional and national economic impacts. Life cycle analysis, which is commonly used in energy research [53,54], has also been applied in studies on Bitcoin mining in China [43,55] and the United States [56], but rigorous research in multiple locations would be valuable.

The future of Bitcoin mining likely involves finding ways to monetize waste heat, especially as the industry becomes highly competitive. Bitcoin mining has shown that waste heat from data centers can be reused for other firms within a local circular economy. Options include district heating [2,57] and alternative uses such as heating greenhouses and lumber drying. Projects in Sweden and Norway, where waste heat from hydropower-based Bitcoin mining is used for district heating, avoid the need to burn wood chips or fossil fuels while also increasing economic returns for the hydropower-generating facilities.

The geographical spread of Bitcoin mining activities can significantly shape regional economic landscapes, suggesting a need to explore both opportunities for revitalization as well as the strength of enduring impacts of Bitcoin mining once miners leave a region. This ‘boomtown’ phenomenon has been studied in the Bitcoin mining context [49], and there are likely many places where understanding Bitcoin’s impact on rural development

dynamics would be extremely useful for policymakers. Research may involve comparing the environmental and economic impacts relative to the departure of other industrial-scale operations, the impacts of Bitcoin mining on local human capital, and the role of expanded grid infrastructure for future high-technology industries.

Exploring the opportunity cost of electricity is needed in the Bitcoin mining context. The global market for low-cost, stranded power will likely have multiple actors, including hydrogen producers, AI data centers, and other industries. Evaluating whether allocating electricity to mining is the most valuable option requires considering factors such as economic returns, environmental impact, and societal priorities. In some cases, the opportunity cost may suggest that diverting electricity to alternative uses with broader benefits is more advantageous. Such analyses would require comprehensive economic cost-benefit analyses in support of regulatory actions and infrastructure investments [e.g., [58]].

3.6. Security and Risk Management

Navigating security issues spanning physical and cyber domains is key for Bitcoin miners. The research questions outlined in Table 10 probe into various facets of security, from the indispensability of decentralization to confronting potential threats. The essence of decentralization is woven into the very fabric of Bitcoin's design [1,59]. Excessive consolidation of core network attributes such as hashrate or the geographic distribution of mining could jeopardize the network's security and utility. The network's security grows with energy use, yet the optimum energy consumption for bitcoin's security is still undetermined [60]. Furthermore, mining pools play a central role in fostering decentralization and fortifying network security, particularly given their influence on consensus-building within the network. Understanding the implications of consolidation is vital to safeguard the resilience and stability of the Bitcoin network [61].

Table 10. Candidate research questions about security and risk management.

Examples of AI-Generated Candidate Research Questions—Security and Risk Management	
38.	How does consolidation affect mining decentralization, competition, and the overall security of a diverse and resilient Bitcoin mining ecosystem?
39.	What are the most effective ways for mining pools to contribute to the decentralization and security of the Bitcoin network?
40.	How can mining companies enhance the security and resilience of their operations within the Bitcoin mining ecosystem, protecting facilities, equipment, and data against physical and cyber-attacks?
41.	How can miners effectively address financial privacy concerns related to mining activities while ensuring compliance with legal, regulatory, and privacy requirements?
42.	What critical infrastructure components and measures should be implemented in energy grids supporting Bitcoin mining to enhance resilience against natural disasters, cyber-attacks, and other potential disruptions?

Addressing risks such as mining centralization, potential 51% attacks, cartel formations, limited ASIC manufacturers, hard forks, and coordinated efforts by major entities to launch attacks (e.g., the theorized 'Satoshi's heel' type attack) is crucial. Even theoretical attacks that may seek to destabilize the network regardless of associated costs merit scrutiny [62].

Ensuring the safety of facilities, hardware, and data from physical and cyber threats is vital for maintaining the continuity of mining endeavors. Moreover, adroitly navigating through the intricate challenges posed by balancing financial privacy concerns with legal and regulatory obligations demands scrutiny. Significant bottlenecks in supply chains could restrict the availability of essential infrastructure components. Conducting research into the robustness, vulnerabilities, and alternative strategies within the supply chain could help build understanding and mitigate potential mining hurdles.

Moreover, the interdependent relationship between Bitcoin mining and energy grids is crucial to the discourse on security. Bitcoin mining could potentially fortify the security of energy supply through in-depth integration with energy grids and infrastructure enhancements. Deciphering how Bitcoin intertwines with tangible energy infrastructure to

amplify security is crucial for miners, grid operators, and regulatory entities, ensuring a coordinated, secure, and resilient operational landscape.

3.7. Innovation

Ongoing technological innovation within Bitcoin mining highlights diverse research needs crucial for both miners and policymakers (Table 11). The Bitcoin mining industry revolves around the optimization of energy consumption and reducing the energy intensity inherent in manufacturing specialized mining hardware [63,64]. ASICs can be managed at the chip level, potentially opening up possibilities for increasing energy efficiency at the data center scale by 5% or more. Collaborative efforts among researchers, mining operators, and hardware and software manufacturers are vital, serving as catalysts to spur innovation within the Bitcoin mining ecosystem. Such collaborations might pave ways to identify and implement technological advancements, thereby enhancing energy efficiency while concurrently fostering industry-wide growth and sustainability.

Table 11. Candidate research questions about innovation.

Examples of AI-Generated Candidate Research Questions—Innovation	
43.	What technological innovations, strategies, and approaches can optimize energy consumption, reduce energy intensity in manufacturing specialized mining hardware, and drive the evolution of the Bitcoin mining industry?
44.	What measures can be taken to expedite the adoption of promising technological advancements, optimization algorithms, and energy-efficient solutions in Bitcoin mining?
45.	How can collaboration between researchers, mining operators, and hardware manufacturers foster innovation and drive advancements in the Bitcoin mining ecosystem?
46.	How can energy storage technologies be optimized to ensure a reliable power supply from intermittent renewable energy sources, enhance energy grid stability and reliability, and minimize the carbon footprint of Bitcoin mining operations?
47.	How does continuous innovation in support services impact the efficiency and competitiveness of Bitcoin mining operations?
48.	To what extent can Bitcoin miners accurately model and predict the future hashrate growth of the Bitcoin network?
49.	What opportunities exist for mining companies to leverage data analytics, advanced technologies, and energy grid optimization techniques?
50.	How do hash power marketplaces affect the profitability and efficiency of Bitcoin mining?

Exploration and refinement of energy storage technologies is one area of need for renewable energy production [65] and Bitcoin mining [66]. Battery storage works to reduce emissions by charging when energy is cheaper and discharging, or using, that stored energy when it is more expensive, which often happens when less efficient thermal power plants set the price. From a grid operator’s short-run supply and demand perspective, energy storage is a measure that pushes out the renewable energy supply curve (more energy becomes available due to the flexibility that energy storage provides), while Bitcoin mining affects the demand curve, shifting it rapidly inwards as mining operations shut down in response to market price signals or the negotiated terms in pre-defined power purchase agreements (i.e., they receive mandatory shut-down notices that they abide by in order to secure long-term favorable electricity pricing). The combination of increasing energy supply via energy storage (pushing supply up and prices down) and Bitcoin mining (reducing demand and prices) can work in tandem to control price spikes in electricity markets. Together, they may also prevent the need for deploying fossil fuel peaker plants during times of extreme weather events. There is a need to explore how the dynamics of energy storage and mining interact and their potential for reducing reliance on fossil fuels during peak loads.

Investigating new partnerships with energy producers and those who manage power grids is worth exploring, particularly when it comes to creating innovative agreements and working arrangements in a unique field like Bitcoin mining. The ability to effectively respond to energy demands and create optimal power grids or patterns of energy use through these partnerships is a largely unexplored area but one that could have a wide-reaching impact.

Finding new ways to cool mining computers could lead to improvements in how efficiently and sustainably they run. Mining outputs include both desired Bitcoin and unwanted waste heat, so finding and using innovative cooling strategies is crucial. Understanding how these cooling technologies work in different climate conditions is also important. Bitcoin-driven advances in computer cooling technology provide positive spillover impacts in other industries that need advanced cooling technologies.

Innovation-focused research highlights the key role of technological advances in shaping the Bitcoin mining sector. The critical points here include the need for efficiency, sustainability, collaboration, and the use of the latest manufacturing, computing, and grid management technologies to navigate the various challenges and opportunities in the Bitcoin mining landscape. Exploring these aspects is crucial for managing miners, as well as for policymakers responsible for balancing trade-offs between human well-being, economic development, and sustainability in the face of rapid technological innovation [67].

3.8. Corporate Operations and Strategy

Navigating through the strategic corporate decisions in Bitcoin mining entails balancing profitability, sustainability, and ethical considerations. Research questions outlined in Table 12 delve into the nuances of how corporate decisions shape enduring success. Focal areas such as custodial management, investment strategies, and fiscal approaches are central for miners aiming to safeguard assets and create value. Encouraging accountability and transparency among mining firms can help build needed trust among a wide array of stakeholders, from investors to local communities.

Human resources and personnel operations also need significant research. Training workers in mining regions and transforming untrained individuals into proficient data center technicians, for instance, is vital for sustaining successful mining operations. Further, mergers and acquisitions (M&A), foreseen to play a pivotal role amidst industry consolidation, warrant an in-depth exploration.

Bitcoin miners, characterized by their pronounced price sensitivity regarding electricity pricing and their active management of energy risks, find innovations like Bitcoin and hashrate derivatives markets attractive. Derivatives markets, which enable Bitcoin miners and energy suppliers to hedge their transactions, reflect practices employed by firms in traditional commodities markets.

The sustainability of Bitcoin mining operations is intrinsically intertwined with various factors: the persistent stability of the network, the fiat valuation of Bitcoin, and the efficacy of their mining hardware. Exploring alternative hedging strategies, such as diversifying into mining other cryptocurrencies or utilizing their computing facilities for alternative high-performance computing tasks, suggests additional research needs. This exploration might address questions related to the trade-offs between enhanced operational resilience provided by diversification strategies and the profitability of the foundational Bitcoin mining business.

Finding the right balance between management systems and the different interests of various stakeholders is a key challenge. Miners have to manage the needs and expectations of different groups; research could help address various challenges in the Bitcoin mining industry, ranging from managing risks and financial strategies to considering ethical aspects and sustainable practices.

Table 12. Candidate research questions about corporate operations and strategy.

Examples of AI-Generated Candidate Research Questions—Corporate Operations and Strategy	
51.	How can miners effectively manage and mitigate risks associated with the custodial management of mining assets?
52.	How can mining companies adopt effective approaches to optimize investment and financing strategies for long-term growth?
53.	How can mining companies enhance transparency and accountability in their operations to foster trust among stakeholders?
54.	How can mining companies effectively address and navigate supply chain disruptions that impact their mining operations?
55.	What measures can mining companies implement to effectively address social, ethical, and environmental considerations in Bitcoin mining?
56.	What is the impact of the growing Bitcoin derivatives market on miners' risk management strategies, profitability, and regulatory considerations?
57.	How can miners effectively utilize hedging strategies to mitigate price volatility risks?
58.	How can the integration of ordinal marketplaces with Bitcoin mining be leveraged to boost revenue generation for miners?
59.	What is the impact of mining taxation policies on the profitability, sustainability, and economic implications of mining activities?
60.	How can mining companies adopt governance mechanisms and structures to balance stakeholder interests and ensure fair decision-making?
61.	What effective strategies can miners employ to mitigate risks and challenges when liquidating Bitcoin holdings during market downturns, ensuring profitability and long-term sustainability?

3.9. Financial Sector

Understanding the relationship between Bitcoin mining and the financial sector requires a detailed look at its economic, environmental, and strategic aspects, providing important insights for both miners and policymakers. Addressing research questions relating to the interaction between the traditional finance sector and Bitcoin mining (Table 13) could shed light on the economic, environmental, and regulatory facets of the industry, aiding miners in decision-making and assisting policymakers in crafting multifaceted policies and regulations.

Developing precise methodologies and metrics is vital to accurately compare Bitcoin mining's energy consumption with traditional financial systems. For instance, discerning what proportion of global electricity demand from Bitcoin miners provides demand response, compared to the traditional financial system—a 'firm load' that solely consumes electricity—would be useful. Such evaluations could be indispensable for miners documenting their environmental impact.

The entrance of mainstream financial institutions into the Bitcoin arena influences market liquidity, price stability, and the overarching trajectory of the mining sector. Market liquidity in the Bitcoin sphere is critical, affecting price consistency, trading volume, and susceptibility to market manipulation. Market volatility can significantly impact miners' revenues, underscoring the necessity for astute risk-mitigation strategies and operational finesse. Furthermore, financial institutions and utility companies must adeptly assess the economic viability of Bitcoin mining firms, especially as mainstream entities increasingly invest in the mining sector. The addition of secondary markets (e.g., ETFs, futures trading, etc.) also adds complexity that Bitcoin mining, investment, and insurance firms all need to understand and account for in their business planning.

Considering accounting standards for Bitcoin, notable efforts towards standardization and their current unfavorable terms is also critical. The present accounting context, as highlighted by proponents like Michael Saylor, dissuades firms from incorporating bitcoin into their balance sheets. Progress is being made (<https://www.cpajournal.com/2023/09/25/fasb-takes-on-crypto/>, accessed on 20 November 2023), but financial services research focusing on accounting is warranted. Research is also needed on the impacts of banks increasingly restricting access to commercial banking services for mining companies. Such moves in the financial sector also suggest that research exploring mining company mobility jurisdictional arbitrage warrants attention.

Table 13. Candidate research questions about the financial sector.

Examples of AI-Generated Candidate Research Questions—the Financial Sector	
62.	How can methodologies and metrics be developed to accurately compare the energy consumption of Bitcoin mining with alternative [legacy] financial systems?
63.	What is the impact of market volatility and understanding market cycles on the profitability, strategic decision-making, and operational choices of Bitcoin miners?
64.	What strategies can financial institutions employ to assess the economic viability and risk factors of Bitcoin mining investments and engage with the mining industry?
65.	What effects does the adoption of Bitcoin by mainstream financial institutions have on market liquidity, price stability, and the overall development of the Bitcoin mining industry?
66.	How can ESG factors be effectively incorporated into the governance and operations of Bitcoin mining to promote sustainable and socially responsible practices?
67.	How does market liquidity impact price stability, trading volume, and market manipulation risks in the Bitcoin mining industry?
68.	What role can miners play in fostering a more liquid and resilient [Bitcoin] market ecosystem?

3.10. Bitcoin Policy and Regulation

Navigating through the multifaceted impacts of Bitcoin mining requires policy- and governance-oriented research (Table 14). Policymakers are tasked with crafting policies and regulations that ensure responsible energy sourcing and sustainable growth in the sector. Bitcoin miners, on the other hand, face the significant challenge of maneuvering through complex, multi-layered regulatory frameworks, amplifying the need for regulatory clarity. Nonetheless, due to the challenges of keeping up with the swift pace of technological advancements and bureaucratic competition, policy coherence—the alignment of policies and regulations across diverse departments and agencies [68]—in the digital asset arena is low.

One governance theme revolves around incorporating renewable energy into Bitcoin mining [28,31,34]. Given the widespread concern about Bitcoin mining’s environmental impact [8], identifying effective strategies and incentives to expedite the transition to renewable energy sources becomes paramount. Carbon offsetting is progressively emerging as a pivotal topic within sustainable Bitcoin mining discussions [69]. Institutional involvement in Bitcoin, from entities like BlackRock and Fidelity Investments, is growing despite the environmental risks posed by Bitcoin mining, which have been a barrier due to ESG mandates. While these institutions are seeking approval for Bitcoin ETFs in the US, indicating a rising interest in Bitcoin as an asset class, concerns about its environmental impact persist. A possible solution involves developing policies or market mechanisms that encourage miners to use verified clean energy sources. The success of Energy Attribute Certificate markets in supporting renewable energy financing and validating clean energy use claims might offer a model to incentivize sustainable practices in Bitcoin mining, enhancing its appeal to institutional investors without sacrificing Bitcoin’s intrinsic qualities.

An additional dimension needing exploration pertains to the ongoing debate concerning Bitcoin’s classification as a commodity versus a security. Regulatory frameworks and policies significantly pivot upon this classification, influencing various aspects of Bitcoin mining, from operational prerequisites to financial reporting and compliance mandates. Thus, exploring the implications of these classifications becomes crucial for both miners and policymakers.

Examining broader implications, such as aligning Bitcoin mining with Sustainable Development Goals (SDGs) [70], also demands attention. Gaining an understanding of the potential economic, social, and environmental repercussions of intertwining Bitcoin with SDGs is vital to augmenting Bitcoin mining’s visibility and traction among key policy agencies and organizations that influence the international energy and environmental research agenda.

Table 14. Candidate research questions about Bitcoin policy and regulation.

Examples of AI-Generated Candidate Research Questions—Bitcoin Policy and Regulation	
69.	How can evolving regulatory frameworks effectively balance innovation, security, and environmental concerns while fostering sustainable development and reducing the carbon footprint of mining activities?
70.	What strategies, methods, and measures can be employed to incentivize and accelerate the adoption of renewable energy in Bitcoin mining operations?
71.	How can effective strategies and technologies for carbon offsetting be implemented in Bitcoin mining operations to reduce environmental impact and contribute to global sustainability initiatives?
72.	What policy frameworks, regulatory approaches, and incentive structures can be implemented to promote sustainable development and responsible energy sourcing in Bitcoin mining operations?
73.	How can mining companies navigate multi-level regulatory frameworks and policies while addressing complex challenges and promoting sustainable practices aligned with environmental and social goals?
74.	What are the regulatory, economic, and sustainability implications of transitioning energy grids in Bitcoin mining to diverse low-carbon sources, and how can policy frameworks support this transition?
75.	How can the potential economic, social, and environmental impacts of integrating Bitcoin align with Sustainable Development Goals best be maximized?

3.11. Bitcoin Awareness, Education, and Research

Understanding the Bitcoin mining industry demands a focus on collaboration, innovation, and responsibility, all of which are highlighted by the research questions in Table 15. Research on the educational sector itself may help to develop impactful formal training programs for high schools, technical colleges, and undergraduate and graduate university programs. Research on the dynamics of knowledge mobilization across the science-policy interface [71,72] will be needed if Bitcoin is to provide policymakers with the kind of information they need. Such research may need to consider factors such as policy windows, advocacy coalitions, and other methodologies that assess knowledge mobilization pathways in academic and policy networks [73–76].

Undertaking research on the perceptions of members of the public [77] and government agencies regarding Bitcoin mining’s energy use is needed. It is possible to prioritize research needs among industry, academic, and government stakeholders [78]. This would not only inform policymakers about the likely support or opposition to particular mining developments or regulatory initiatives but may help pro-actively build awareness about how best to foster responsible Bitcoin mining practices.

Table 15. Candidate research questions about Bitcoin awareness, education, and research.

Examples of AI-Generated Candidate Research Questions—Bitcoin Awareness, Education, and Research	
76.	How can the Bitcoin industry foster proactive engagement with key actors to facilitate knowledge sharing, drive research and development initiatives, and exert influence on policy decisions?
77.	In what ways can collaborative partnerships between mining companies and academia or research institutions promote innovation and foster responsible mining practices in the Bitcoin ecosystem?
78.	What effective strategies can be implemented through education and awareness initiatives to promote energy-conscious behaviors, encourage responsible practices, and accelerate the widespread adoption of renewable energy solutions within the Bitcoin mining community?
79.	How can meaningful collaboration between environmentalists and the Bitcoin mining industry be cultivated to address environmental concerns and promote sustainable mining practices?
80.	How does the social perception of Bitcoin mining’s energy consumption influence Bitcoin acceptance and hinder widespread adoption?
81.	What proactive measures can miners take to enhance Bitcoin’s reputation and ensure its long-term viability as a trusted and stable store of value?

In the context of education, there is a need for training at both technical and university levels. Bitcoin mining requires network engineers, electrical technicians, data center construction specialists, and infrastructure systems professionals. A unique dynamic of Bitcoin mining is its ability to create technical and mechanical jobs for those without advanced

degrees. This strongly distinguishes Bitcoin's PoW mechanism from Proof-of-Stake cryptocurrencies, which rely on staking rewards that largely accrue to token holders. Initiatives, such as Bitcoin mining engineering fellowships for high school graduates in some urban areas, offer technical training and access to jobs for those typically without access to higher education. Research on the design and effectiveness of such programs could help document and optimize impacts on disadvantaged communities.

Within higher education, new initiatives are being developed to educate students about Bitcoin mining and adoption, but these are currently isolated, and there is a clear need for more advancements in Bitcoin-oriented educational opportunities for both students and faculty. In situations where there is insufficient demand for Bitcoin courses within individual institutions, online programs that could be used for specialty teaching may be possible. For example, the Saylor Academy offers a variety of undergraduate courses with strong Bitcoin relevance, as well as professional development courses explicitly focused on Bitcoin. Other options for university training support might include independent study options facilitated by industry groups, thus allowing MSc-level students to gain direct experience through independent Bitcoin study and research projects.

Cross-cutting research is vital for building understanding about Bitcoin mining impacts: the industry's complexity requires cooperation that transcends traditional academic boundaries [13]. There is a clear need for transdisciplinary research [79,80] that is problem-focused and involves sustained interaction and mutual learning among researchers, miners, and policymakers. Such transdisciplinary collaboration takes time and funding, allowing participants from disparate backgrounds and epistemic communities to learn the language of other sectors and disciplines prior to being able to fully participate in synthesizing concepts and methodologies [81,82]. Direct researcher and industry engagement with policymakers may also increase the likelihood that relevant research is later recognized and utilized in policy and regulatory decisions.

3.12. Outside-the-Box Research Questions

Beyond the 81 candidate questions, we used the AI to generate 212 speculative questions about Bitcoin mining and energy grid transitions in a zero-emission global economy. Recall that for research needs presented above, we focused GPT-4 on identifying only threats and opportunities identified within transcriptions. It is also possible to widen the focus of the AI-assisted question-generation process. We additionally asked GPT-4 to, in two steps, draw on its general knowledge and anticipate other Bitcoin mining questions that may not have made our current list but that might become important over the next several years and to speculate about emerging Bitcoin-oriented possibilities that, "if successful, could have a massive impact on Bitcoin and the transition to a zero carbon emissions global economy?".

Table 16 presents nine notable questions that our AI identified. These explore both existing and emerging technologies, speculating on their importance in the next decade. While some of these questions build upon existing technologies, others concentrate on newly emerging trends, with the AI speculating about their growing significance over the coming decade.

Table 16. Highly speculative AI-generated research questions.

Examples of AI-Generated Candidate Emerging and Speculative Research Questions
<ul style="list-style-type: none"> • How can Bitcoin mining operations leverage space-based solar power to achieve a sustainable and virtually unlimited energy supply, eliminating the need for traditional energy-intensive mining processes? • What are the potential implications of developing advanced carbon capture and storage (CCS) technologies specifically designed for capturing emissions from Bitcoin mining operations, and how can this contribute to a carbon-negative mining industry? • Can the concept of energy harvesting from ambient sources, such as kinetic or thermal energy, be harnessed to power Bitcoin mining equipment, reducing the reliance on grid-connected nonrenewable energy sources? • How will advancements in quantum computing impact the security and cryptographic algorithms used in Bitcoin mining, and how can the mining industry prepare for potential vulnerabilities? • How can Bitcoin mining operations optimize the energy efficiency of mining hardware in real-time using artificial intelligence and machine learning algorithms, reducing energy consumption while maintaining computational performance? • How might the development of advanced energy storage technologies, such as next-generation batteries or supercapacitors, enhance the utilization of intermittent renewable energy sources for Bitcoin mining? • How can Bitcoin mining operations integrate blockchain-enabled energy trading platforms to incentivize the rapid adoption of renewable energy sources, allowing individuals to directly trade excess renewable energy for Bitcoin? • What are the potential environmental and economic benefits of leveraging blockchain-based smart contracts to enable automated energy demand response programs in Bitcoin mining operations? • How can Bitcoin mining operations leverage advancements in decentralized, community-owned mining operations powered by renewable energy sources, empowering local communities and creating new economic opportunities?

4. Discussion

4.1. Overview

Our goal in this paper was to identify important Bitcoin research questions that, if answered, could provide credible evidence and an accurate knowledge base for policy-makers, enabling them to make well-informed decisions. We drew from the extensive Bitcoin discourse on social media, encompassing comprehensive interviews with mining CEOs, to insights from adept, albeit less-recognized, developers and practitioners. Utilizing AI-assisted analysis, major threats and opportunities related to Bitcoin mining and its consequences were quickly identified and extracted. Industry experts then reviewed the questions, identified gaps, and provided context regarding research needs.

By actively engaging with industry experts in the co-production of this paper, we aimed to ensure our AI-assisted findings were attuned to the perspectives of the Bitcoin mining industry. The industry perspective is one of several that policymakers will need to consider when deliberating potential interventions and balancing the interests of multiple stakeholders. It will also be possible in the future to conduct similar analyses for topics including the effects of Bitcoin technical development on adoption and policy options, macroeconomic and geopolitical influences on Bitcoin's role in trade and banking, and the impacts of widespread Bitcoin adoption on financial inclusion, particularly for marginalized and underprivileged communities. All of these might be used to develop a 'menu' of research needs that could be used by policymakers wanting to identify the 'low-hanging fruit' in the context of their jurisdictions and mandates.

Traditional approaches to key questions and horizon-scanning exercises sometimes involve prioritizing research needs through surveys of academics, policymakers, and industry representatives [78,83]. In other instances, initial key questions research can be used to help structure follow-on workshops that dive into specific research questions. For example, an ecotoxicology research initiative [84] followed up a key questions exercise with a workshop that produced four peer-reviewed articles, each illustrating core concepts across the main themes initially identified in the key questions exercise [85]. This methodology might be effectively applied to explore Bitcoin research needs in more depth, contributing to publications and encouraging new research collaborations.

It is worth noting that the AI-generated questions are sometimes quite generic in nature, a challenge similarly seen in many in-person key questions exercises [14]. Achieving a balance between ensuring broad, jargon-free relevance and specific, context-focused utility

requires finesse. Wisz et al. [86] tackled the problem of generic questions by outlining a process for framing the questions initially at a very high level, minimizing jargon, and crafting questions in a clear, uniform manner. They then outlined factors such as perceived threats, target audiences, geographical region, time frame, and policymakers' objectives to craft context-specific, actionable research questions that were subsumed by the high-level covering question. As an illustration, a broad question like "How does Bitcoin mining impact local communities?" can be refined for a specific context: "Given the expected growth of Bitcoin mining in rural Texas and its potential effects on electricity prices and job opportunities, how might State agencies act to ensure that employment benefits offset potential increases in household electricity expenses for citizens of West Texas?"

4.2. Methodological Limitations

Horizon scanning and key questions exercises traditionally involve systematic gathering of candidate research priorities from experts across academia, industry, and policy sectors, usually culminating in a collaborative workshop [14]. Our approach uses the strengths of the AI—analyzing a much wider range of background material that would be feasible in traditional key questions exercises—to help accelerate and provide depth relative to the traditional methodology. The advent of advanced AI capabilities offers a potential reconfiguration of the traditional approach, albeit with potential complications across four dimensions (Figure 2).

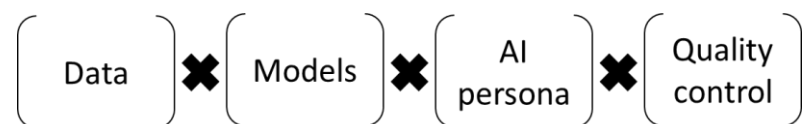


Figure 2. Areas of potential AI analysis limitations.

4.2.1. Data Limitations

Unlike traditional semi-structured interviews, which involve a limited number of directed interviews with selected experts or stakeholders [87], podcast interviews are unbounded and can range in their content and quality. Not all participants are necessarily experts, which might introduce biases or misinformation. Nonetheless, by utilizing 383-h of transcripts from these interviews, we believe that a comprehensive set of mining-relevant threats and opportunities were captured.

While most podcast interviewees held a strong pro-Bitcoin stance, the AI's analytical methodology aided in mitigating biases. For instance, even if a participant emphatically denied climate change, the AI still recognized climate change as a significant issue due to its prominence in the discourse. Consequently, the AI generated and assessed research questions with regard to their potential impact, alignment with sustainability goals, industry applicability, and ability to contribute to academic research and knowledge advancement. Recall, from Table 4, that each research question considered "the specific aspects of the question that made it crucial for academic research, its potential benefits to society, and its significance for the Bitcoin mining industry. Considerations such as industry relevance, sustainability, risk mitigation, and technological advancements were addressed in the justifications".

By pooling all 3580 issues, we were able to ensure that issues that were widely discussed were represented in the research questions. Conversely, issues that were 'fringe' or drew on misinformation were unlikely to have any impact on the broad selection of important issues.

4.2.2. AI Models

Data collection commenced on 24 May 2023, utilizing ChatGPT-4 for its proficiency in analyzing transcripts. Although alternative adept LLMs emerged during our data collection period, GPT-4 was consistently used to ensure analytical consistency. Different models,

utilizing varied parameters, might identify diverse threats and opportunities, but it is yet to be determined if they would lead to significantly different research priorities. Our results, scrutinized in detail by industry experts, co-authors of this paper, suggest that the majority of core issues were indeed identified during the AI's screening. Future research is, however, needed to assess whether different LLMs would identify substantially different threats and opportunities or formulate a divergent set of research questions.

4.2.3. AI Model Persona

For consistency, a single AI persona was utilized throughout the data collection (refer to Section 2.2.2). The persona significantly influenced the model's outputs, introducing a potential for bias. Future research might explore using a collection of agents, each with a varied industry-, academic-, or policy-relevant persona, investigating and testing the impact of persona on research outcomes. That, however, was outside the scope of our current paper.

4.2.4. Quality Control

AI analysis requires continual oversight. The AI occasionally 'forgot' content it had previously uploaded because of content window limitations, misinterpreted prompting instructions, or identified threats or opportunities not initially discussed in the uploaded content. Ensuring the quality of outcomes required vigilance and verification in real-time: every response for every transcript was monitored by the lead author. With appropriate follow-up prompting (see <https://doi.org/10.6084/m9.figshare.24547774.v1>, accessed on 20 November 2023), we were virtually 100% successful in keeping the AI focused and on topic.

4.2.5. Human Biases

This paper, crafted by co-authors deeply engaged in the Bitcoin industry and in tune with current challenges, suggests a significant range of information needs in the space and an urgent need for peer-reviewed Bitcoin research. Such information could inform policymakers as well as provide invaluable information for Bitcoin miners and investors. Despite striving for objectivity and employing AI to mitigate potential biases from Bitcoin social media sources, our priorities might still reflect an industry bias. Nonetheless, even if this was the case, we suggest that this paper has value for policymakers and decision-makers simply by illuminating industry perceptions regarding key information voids that require attention. Industry suggestions about research needs are, obviously, only one of many sources of information that policymakers consider when making decisions.

4.3. Implications for AI-Assisted Horizon Scanning Research in Other Fields

Our study highlights the potential for new AI-assisted approaches to horizon scanning research [14,15], extending well beyond Bitcoin. Additionally, instead of relying on a single-persona method, current AI technology now allows for the development and use of diverse personas to participate in AI discussions, assessing the quality of different research queries. Such an approach, often referred to as the 'mixture of experts' [88], may function as an artificial version of the traditional Delphi method [89] and could facilitate consensus-building regarding emerging threats, opportunities, and research opportunities and priorities. Additionally, recent AI innovations offer the possibility to radically accelerate the potential for real-time information sharing during human conversations [90]. This could prove pivotal in tracking emerging risks and opportunities in near real-time horizon scanning efforts.

4.4. Aligning Bitcoin Research with SDG Goals

While international initiatives like the Sustainable Development Goals (SDGs) [70,91] may not be on the radar screen for all Bitcoin mining firms, aligning mining research with the SDGs might spotlight its multifaceted impacts and strategic role in addressing global

challenges. This approach may help elevate Bitcoin's role in energy transition research. Bitcoin's decentralized nature intersects with several of the 15 SDGs, notably through potential contributions to renewable energy adoption (SDG 7), industry, innovation and infrastructure (SDG 9), and climate action (SDG 13). To illustrate, Figure 3 shows possible relationships between research questions, the topics in which we grouped them, and the SDGs (to be very clear, this is speculative and for illustration only—research would be needed to confirm the relationships).

Central to the narrative of Bitcoin mining's potential is to catalyze renewable energy integration and facilitate and accelerate the build-out of renewable energy facilities and infrastructure. By creating demand for excess energy, it could stimulate investments in renewable projects and help balance energy grids. Additionally, its innovative use of flared gas in oil and gas operations aligns with climate action, showcasing a possible proactive approach to reducing CO₂e emissions and exemplifying a circular economy model.

We anticipate that for mining, SDGs 7, 9, and 13 could be of major importance and that mining may also substantively contribute to SDG 12 (responsible production and consumption). Relatively more modest impacts are likely to affect a number of other SDGs. Bitcoin mining's influence extends to local communities, potentially revitalizing rural areas and fostering advancements in education and technical training (SDG 4), as well as contributing to sustainable cities (SDG 11). Furthermore, Bitcoin's broader adoption could enhance financial inclusivity (SDG 1) and reduce inequalities (SDG 10), offering accessible financial resources across genders (SDG 5).

Several of these SDGs will figure much more prominently in future key questions exercises focusing on Bitcoin adoption and financial inclusion, macroeconomic and geopolitical context, and policy and regulation. However, realizing these benefits necessitates evidence-based validation of Bitcoin mining's impacts on global sustainability, economic goals, and human well-being. This potential alignment with the SDGs underscores the need for rigorous exploration into the likelihood and viability of benefits accruing to those who most need them.

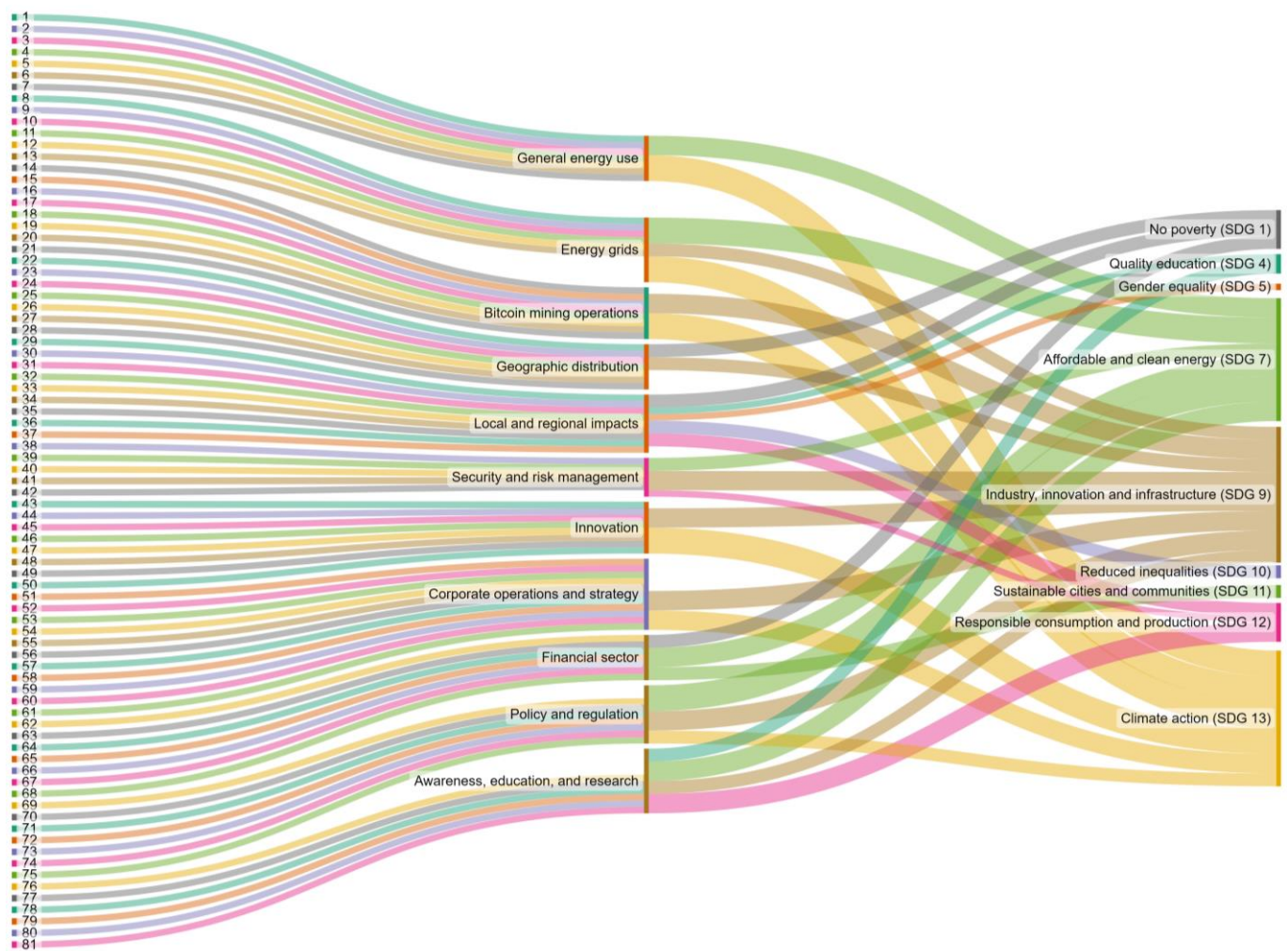


Figure 3. Stylized pathways of the potential impact of Bitcoin research on SDGs.

5. Conclusions

Our paper brings to light crucial research priorities from the perspective of the Bitcoin mining industry. We recognize, however, that our mining focus is only one of the viewpoints relevant to Bitcoin-oriented policy decisions. There are also Bitcoin-oriented research gaps with important implications for human well-being. For example, there is an urgent need for Bitcoin-oriented research relating to financial inclusion and resilience in economically and politically stressed regions internationally. Research is also needed regarding the macroeconomic and geopolitical interplay that could arise in the face of widespread Bitcoin adoption, as well as on matters specifically relating to governance and policy development.

The Bitcoin-oriented research questions that we identified in this article provide the first part of a ‘menu’ of information needs that we feel could be important to policymakers and other decision-makers. Given the broad interests of society, we acknowledge that only some of the research questions that we identified may be implemented.

As the Bitcoin ecosystem evolves, the need for clear, credible research becomes increasingly important. By identifying and addressing the key research questions highlighted in this study, the combined efforts of academics, Bitcoin-oriented companies, and government agencies might help clarify Bitcoin’s role in our evolving digital economy and its impact on human and environmental well-being.

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