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Cambridge
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UNIVERSITY OF CAMBRIDGE
Judge Business School

Cambridge Digital Mining Industry Report

Global Operations, Sentiment, and Energy Use

FIRST EDITION

Contents

Foreword

Traditional finance and the digital asset ecosystem are increasingly converging. This is most clearly demonstrated by the growing involvement of established investment firms, but also by landmark events such as the U.S. Securities and Exchange Commission's approval of spot Bitcoin ETFs last year that significantly broadened mainstream access to bitcoin and, subsequently, other cryptoassets. Looking at Bitcoin in particular, many large institutional investors, initially hesitant due to concerns about illicit activity and the environmental impact, now actively offer clients exposure to this still-nascent, yet increasingly prominent, asset class.

The Cambridge Centre for Alternative Finance (CCAF) has long recognised the disruptive potential inherent in digital assets. Since our inaugural "Global Cryptocurrency Benchmarking Study" in 2017, we have consistently dedicated resources to exploring this evolving landscape. This publication marks our thirteenth report focused on the digital assets ecosystem and blockchain technology.

One topic in relation to this novel technology that quickly drew significant public and academic attention was its environmental impact. Specifically, the energy-intensive nature of the Proof-of-Work consensus mechanism, most notably used by Bitcoin, has raised concerns about long-term sustainability.

These concerns are not new. Already over a decade ago, early research began examining this issue. Despite growing awareness, a persistent challenge has hindered a full understanding of the issue: the decentralised nature of networks like Bitcoin makes it exceptionally difficult to obtain reliable, granular data on energy consumption and the energy sources used by mining operators – both of which are central variables for a robust environmental impact assessment. This lack of primary data has led to widely varying estimates and ongoing debate between industry and academic sources. The CCAF responded to the need for greater transparency with the launch of the Cambridge Bitcoin Electricity Consumption Index (CBECI) in 2019, providing a hybrid top-down estimate of Bitcoin's electricity consumption, an initiative we have significantly expanded in scope since its inception. However, CBECI still relies on modelling and access to contemporary data; it does not capture the detailed, firm-level information necessary for a truly granular assessment.

This report directly addresses that remaining data gap. In an effort to reduce abstractions and rely more heavily on direct practitioner insights, the CCAF has undertaken a comprehensive study, surveying 49 digital mining firms who collectively represent nearly 48% of the implied Bitcoin network hashrate. The findings of this study offer unparalleled insights into operational structures, the ASIC market, industry sentiment, and, most notably, the environmental impact of digital mining operations. Key questions addressed include the geographical distribution of mining activity, the efficiency of deployed hardware, electricity consumption, greenhouse gas emissions, and more. For readers less familiar with the subject, an introduction to Bitcoin and digital mining is included to ensure the subsequent content can be fully appreciated.

We extend our sincere gratitude to all stakeholders who contributed to this report, whether by facilitating connections within the industry or by providing invaluable feedback. It is our hope that this in-depth examination of the digital mining landscape will serve as a useful reference on a variety of topics and help facilitate an evidence-based dialogue.

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This research was conducted as part of the Cambridge Digital Assets Programme (CDAP), and we are immensely grateful to the CDAP's institutional collaborators for their ongoing support. Their contributions are essential to our mission of providing the datasets, digital tools, and insights necessary to foster a balanced public dialogue about the opportunities and risks presented by the evolving digital asset ecosystem.

The CDAP is a public-private research collaboration built upon a representative cohort of institutions across the public and private sectors. We especially want to thank our founding members, whose vision and commitment were instrumental in establishing the programme.

We are also deeply indebted to numerous individuals who generously contributed their time and expertise to this project. In particular, we want to thank (in alphabetical order) Olzhas Amirov, Brian Dixon, Brian Estes, Dmitrii Stupin, and Peter Wall for their invaluable assistance in connecting us with professionals in the mining industry, and Margot Paez for her feedback on the survey questionnaire.

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Finally, and most importantly, we express our deepest gratitude to all the survey respondents across the globe who dedicated their time to participate in this extensive study. Their commitment to transparency has been instrumental to the success of this research. While not all respondents have chosen to be publicly named, their contributions are deeply valued.

49 Total Number of Participants

Alps Blockchain
argo blockchain
BIT DIGITAL NASDAQ: BTBT
BITDEER NASDAQ: BTDR
Bitfarms
BITFURY
BLOBB.IO
BLOCKFUSION
BLOCKWARE
CleanSpark America's Bitcoin Miner
cormint
CRYPTOHALL24
DMG BLOCKCHAIN SOLUTIONS
enegix
ez blockchain
GRIDLESS
HASHLABS
HEARST
HUT 8
IREN
MARA
MININGSTORE
RIOT
SATO TECHNOLOGIES
SOLUNA
Standard Hash
Summit MINING
synteq DIGITAL
XIVE

+20 Others

Executive Summary

From hobbyist communities to billion-dollar industrial operations, the digital mining industry has evolved at breakneck speed, and stands at the nexus of information technology and energy systems. Drawing on primary data from digital mining firms that collectively represented nearly half the computational power supplied to the Bitcoin network, this report offers timely and granular insights into the ecosystem. Our findings reveal an estimated annual electricity usage of Bitcoin mining activity at approximately 138 TWh, resulting in around 39.8 $MtCO_2e$ attributable GHG emissions. Survey results further indicate that the U.S. has solidified its position as the largest global mining hub (75.4% of reported activity), and show that while sustainable energy sources collectively represent the majority of the electricity mix (52.4%), natural gas constitutes the single largest source (38.2%). Moreover, mining firms reported regulatory uncertainty and energy prices as their primary concerns, and cited business and geographical diversification as key risk management strategies; lack of deployment opportunities and logistical challenges were identified as the primary factors impeding their growth.

The security of Bitcoin, the first and arguably most prominent cryptoasset, relies on a network of specialised computers, a global infrastructure of immense scale. This report offers an unparalleled insight into that infrastructure, analysing the dynamic and increasingly complex world of digital mining. Building upon the CCAF's Global Cryptoasset Benchmarking surveys (2017, 2019, and 2020)[1-3], which examined the wider cryptoasset ecosystem, this work provides a focused, industry-specific analysis of the digital mining landscape. Crucially, this report is based on insights directly obtained from companies that engage in digital mining via a comprehensive survey about their individual operations that captured nearly half (48%) of the computational power that secures the Bitcoin network. Access to this primary data marks a major milestone in our ongoing efforts to provide contemporary data and cutting-edge insights into the industry. It further signifies an alternative to the reliance on theoretical models or aggregated data from industry stakeholders such as mining pools, presenting results directly collected from the source – the firms who engage in the mining activity.

From its origins as a niche concept, Bitcoin has rapidly gained traction, attracting significant institutional interest and sparking debates about its role in the global financial system. This rise has been fuelled by its trusted crypto-economic incentive mechanisms, a capped supply of 21 million coins, and a diverse community ranging from grassroots enthusiasts to multinational corporations. Milestones such as Tesla's bitcoin investment in 2021 and the 2024 approval of spot Bitcoin ETFs by the SEC underscore a growing integration into mainstream finance. However, despite this remarkable growth, the cryptoasset market, with bitcoin at its forefront, remains relatively small and volatile compared to traditional asset classes such as gold and equities. This volatility and relative immaturity underscore the critical need to understand the digital mining ecosystem – the very foundation upon which Bitcoin's security and value proposition rest. Drawing on survey data from 49 digital mining firms (41% publicly listed, 59% privately held), with headquarters in 16 jurisdictions and operations spanning 23 different countries, we explore the operational intricacies, market dynamics, and environmental impact of this industry, offering unique insights into the challenges and opportunities that lie ahead.

Analysis of key operational data reveals significant year-over-year (YoY) improvements in mining efficiency, a notable concentration of mining activities in North America, and provides insights into hardware lifecycle and e-waste.

As of June 2024, the industry-wide ASIC (SHA-256) hardware efficiency is estimated at 28.2 J/TH, marking a 24% YoY improvement, closely aligning with top-down projections from our theoretical CBECI model. Annualised electricity consumption associable with Bitcoin mining is estimated at 138 TWh, representing a YoY increase of 17% and approximately 0.54% of global electricity consumption. Miners report a median electricity cost of $45/MWh and an all-in cost of $55.5/MWh, with electricity constituting more than 80% of their cash-based operational expenses. By the end of 2024, 11.1% of the current hashrate (61.8 EH/s) is projected to be phased out. Importantly, 86.9% of this decommissioned hardware is expected to be repurposed or recycled, with actual e-waste approximated at about 2.3 kilotonnes. The operations of miners surveyed appear to be heavily concentrated in North America, primarily the United States (75.4% of reported hashrate) and Canada (7.1%). While acknowledging a U.S.-centric respondent base that likely affects precise estimates of global activity, leading to over (such as the U.S.) and under (such as Russia) representation of certain countries, the survey nevertheless reveals directionally relevant developments such as emerging activity in South America and the Middle East, alongside ongoing operations in Northern Europe.

A detailed examination of the electricity mix and carbon footprint of Bitcoin mining reveals a primary reliance on sustainable energy sources, alongside ongoing efforts to mitigate environmental impact.

The survey indicates that miners' electricity mix is predominantly sustainable (52.4%), with renewables accounting for 42.6%. Hydropower constitutes the largest sustainable source (23.4%), followed by wind (15.4%), nuclear (9.8%), solar (3.2%), and other renewables (0.5%). Fossil fuels make up 47.6%, primarily natural gas (38.2%), which is also the single largest energy source, followed by coal (8.9%) and oil (0.5%). The estimated annual GHG emissions associated with Bitcoin mining are approximately 39.8 $MtCO_2e$, representing about 0.08% of global annual GHG emissions, although a more nuanced analysis suggests a potential range of 32.9 to 37.6 $MtCO_2e$. Notably, miners reported a total load curtailment of 888 GWh for the calendar year 2023, demonstrating their flexibility, and 70.8% of respondents stated that they are actively undertaking climate mitigation measures.

The Bitcoin mining sector is characterised by a highly concentrated hardware market dominated by a few key players, while the firmware landscape presents more diversity, reflecting varying degrees of vendor dependence. Survey results indicate that 98% of respondents' power capacity is dedicated to Bitcoin mining. The digital mining hardware market exhibits an oligopolistic structure, with the top three manufacturers – Bitmain, MicroBT, and Canaan – commanding over 99% market share. Bitmain alone holds an 82% share, underscoring significant vendor concentration. The firmware market presents a more fragmented landscape, with manufacturer-provided firmware (44.4%), Vnish (26.4%), and proprietary solutions (17.6%) being the most prevalent.

Facing a dynamic landscape shaped by technological advancements, market volatility, and evolving regulations, miners identified energy price fluctuations and regulatory uncertainties as their primary concerns. Business and geographical diversification were cited as their key risk management strategies, with limited deployment opportunities and logistical challenges as their main barriers to growth. Miners further demonstrated rather precise predictive capabilities regarding market developments.

Miners express at least high concerns about long-term energy price increases (57%), unfavourable governmental action at local or federal level (47%), and adverse BTC price developments (40%). Furthermore, miners named business diversification (64%), power hedging (60%), and geographical diversification (55%) as key risk management strategies. Hashprice hedging and cryptoasset collateralisation are perceived as less effective. The primary constraints to growth are identified as insufficient deployment capacity and logistical challenges such as ASIC supply bottlenecks and delivery delays, with 47% of miners seeing the former and 45% the latter as at least a high constraint – although access to debt (40%) and equity (36%) financing also pose a challenge. Industry participants projected a bitcoin price range of $60,000 to $150,000 by year-end (2024), with a median estimate of $80,500. Year-end (2024) implied network hashrate was anticipated to fall between 600 and 900 EH/s by 83% of respondents, with a median baseline estimate of 750 EH/s. These projections proved relatively accurate, with the actual year-end bitcoin price settling at $93,390 and the hashrate reaching 796 EH/s, indicating that miners were slightly too pessimistic about price, but quite precise on hashrate development.

The Bitcoin mining industry stands at a critical juncture, with the traditional revenue model facing challenges, prompting miners to explore business diversification and innovative energy strategies to ensure their long-term sustainability.

The legacy miner revenue model, heavily reliant on the block subsidy, faces increasing pressure from recurring halving events. Diversification into high-growth sectors like HPC serving computationally intense AI workloads, leveraging existing infrastructure, is emerging as a key adaptive strategy. Innovative energy solutions, including the utilisation of otherwise flared natural gas, waste-heat recovery, and demand side response are also gaining traction. Hashprice hedging may also play a role in the future in managing financial risks; hedging energy prices already does, and is expected to stay a core risk mitigation strategy.

This report provides critical, data-driven insights into the evolving digital mining industry, highlighting its technical complexities, market dynamics, and environmental considerations. It serves as an essential resource for policymakers, industry stakeholders, and researchers navigating the multifaceted landscape of digital mining. By offering a granular perspective on the mining ecosystem's evolving practices, this report aspires to anchor the debate on robust, transparent data rather than speculation, and to inform grounded policy discussions. In doing so, it brings to the forefront the pressing considerations faced by policymakers, financial institutions, and industry practitioners, who must grapple with the delicate balance between harnessing Bitcoin's transformative potential and managing the externalities of large-scale computing operations. We hope that the data and analysis presented here will promote responsible industry practices, and guide future research on the pivotal roles of technology, geography, and sustainability in the next chapter of digital mining.

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I: What is Bitcoin?

Bitcoin, a revolutionary digital asset rooted in the cypherpunk movement and driven by a vision of individual financial sovereignty, challenges the very foundations upon which the traditional financial system is built.

Amid the turmoil of the global financial crisis in 2008, an enigmatic figure known as Satoshi Nakamoto (whose actual identity remains unknown), published a whitepaper titled "Bitcoin: A Peer-to-Peer Electronic Cash System".[4] The message "The Times 03/Jan/2009 Chancellor on brink of second bailout for banks" is recorded in Bitcoin's genesis block, leading to the common thesis that bitcoin was not just a response to the 2008 financial instability but also a critique of the centralised financial systems that dominate the global economy. By leveraging cryptographic principles and a decentralised network, Bitcoin represented the culmination of decades of cryptographic research and a new idea of a decentralised, apolitical monetary system as an alternative to the established financial order.

Bitcoin Fundamentals

Exploring Bitcoin's roots

Bitcoin's intellectual and ideological foundations can be traced back to the cypherpunk movement of the early 1990s. This movement, initiated by technologists and activists such as Timothy C. May, Eric Hughes, and John Gilmore, advocated for the use of cryptography as an instrument to protect individual freedom and privacy in the digital age. Their vision, encapsulated in texts like "A Cypherpunk's Manifesto",[5] was one where technology, particularly cryptography, could empower individuals to resist government surveillance and control.

The cypherpunks' efforts led to notable advancements in cryptographic technologies, such as Pretty Good Privacy (PGP), created by Phil Zimmermann, which popularised asymmetric (public-key) cryptography, and the evolution of Proof-of-Work (PoW) systems through implementations such as Adam Back's Hashcash. These innovations laid the groundwork for the creation of digital currencies that could operate without centralised control.

In the late 1990s, further advancements were made by Wei Dai and Nick Szabo with their respective proposals for b-money and Bit Gold. These systems introduced concepts critical to Bitcoin's eventual design, such as decentralised ledgers, cryptographic security, and digital scarcity. While neither system achieved widespread adoption, they provided the theoretical foundation Nakamoto would build upon in the creation of Bitcoin.

The technical architecture of Bitcoin

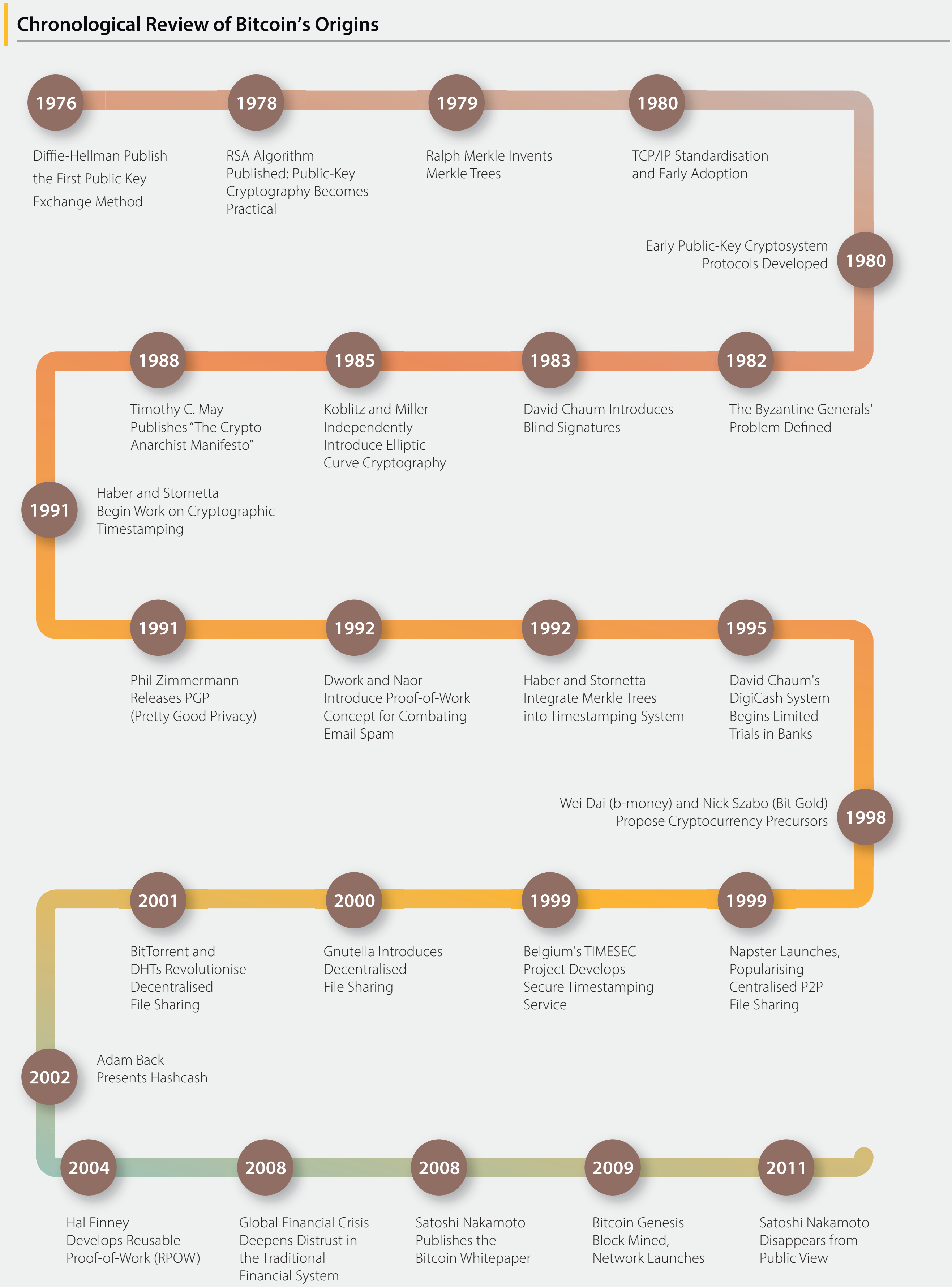
In keeping with its cypherpunk origins, Bitcoin (capitalised 'B') is more than just the digital currency bitcoin (small 'b', abbreviated as BTC). It is a decentralised, open-source software that allows anyone to propose technical upgrades to its codebase, or even forcibly make changes and create a new product (known as a 'hard fork'). However, the success of any fork depends entirely on whether users choose to adopt it. For those who want to learn more about the technical evolution of Bitcoin, Appendix B offers additional insights.

To understand how Bitcoin operates, it is essential to briefly elaborate on the underlying technology. The network's architecture represents a chain of blocks (hence 'blockchain'), and is a publicly distributed and immutable ledger that records all transactions in a chronological sequence of blocks, maintained by a decentralised network of nodes, each running Bitcoin software. There are no gatekeepers and anyone with internet access and a device capable of running the software can participate, either by running a node or using the existing infrastructure. This ensures that the ledger is both decentralised, transparent, and accessible to everyone. However, this open and permissionless nature also introduces potential vulnerabilities. One such vulnerability is a Sybil attack, where a malicious actor creates and controls a large number of pseudonymous identities (nodes) on the network. While a Sybil attack itself cannot directly alter past transactions or break Bitcoin's cryptography, it can be used to disrupt network operations, such as censoring transactions or attempting to influence consensus.

When it comes to security, the network's protocol rules ensure that only those possessing a secret key can make transactions and once a transaction is recorded, it is generally considered to be irreversible. This provides a high level of security and enables exchange of value in a trustless environment. Thus, it allows for transactions without the need for intermediaries.

The process of adding new blocks to the chain is known as 'mining', in which certain network participants, so-called 'miners' compete in a cryptographic challenge. The first miner to find a valid solution to this challenge earns the right to add a new block to the blockchain, and in return is awarded with newly minted bitcoins and transaction fees. The mining process requires substantial computational resources, which is a deliberate feature designed to secure the network against Sybil attacks and prevent double-spending.[7]

Figure 1: Shows a timeline that illustrates seminal milestones in cryptography, decentralised systems, and early digital currency experiments that paved the way for Bitcoin. Source: Adapted from Bashir (2023; [6])



The PoW mechanism is central to Bitcoin's security model. By requiring miners to commit significant financial resources, in the form of capital (such as electrical and data centre infrastructure, hardware purchases, etc.) and operational expenditures (such as electricity costs) the system ensures that altering the blockchain would require a prohibitive amount of computational power, making such attacks economically unfeasible. The decentralised process of mining is also a key pillar in ensuring that no single entity controls the network, and decisions about the protocol require the collaboration of a variety of stakeholders.

Once a block has been appended to the ledger and it reaches a certain depth in the chain, meaning it has a sufficient number of confirmations, all transactions within that block are considered practically irreversible. For instance, in Bitcoin, it is commonly recommended to wait for at least six confirmations, though finality is ultimately probabilistic and strengthens with each new block. In a PoW system, to alter or reverse transactions in an already confirmed block requires what is commonly referred to as a '51% attack', whereby the malicious actor(s) must control the majority of the network's hashrate. In so doing, they would need to re-mine the altered block and every subsequent block, essentially creating a competing chain that eventually becomes longer than the honest one. Achieving this is far from trivial and, in the case of Bitcoin, deemed unfeasible given the previously mentioned infrastructure requirements. However, for smaller networks, particularly those utilising a consensus algorithm similar to that of much larger networks, such scenarios may be at higher risk of materialisation.[8]

Even after a successful 51% attack, a last line of defence exists: the community, also known as 'layer-zero' or social consensus. This represents the off-chain governance aspect of blockchains, where human coordination plays a critical role. This is, however, a highly controversial approach, as it violates the fundamental principle of blockchain immutability. In essence, the community can agree to fork the chain at a block height preceding the attack, requiring all participants to update their nodes accordingly. This demands extensive public coordination. A prominent example is the aftermath of the DAO hack on Ethereum, where a vulnerability in a decentralised autonomous organisation (DAO) smart contract was exploited to drain a significant amount of Ether.[9] The Ethereum community ultimately decided to fork the chain, creating what is now known as Ethereum. The original, unaltered chain continues to this day as Ethereum Classic. However, this decision was highly controversial and sparked a heated debate about the core premise of blockchain immutability versus the community's right to intervene in exceptional circumstances.

Cryptography is another cornerstone of Bitcoin's architecture. Each Bitcoin wallet is associated with a pair of cryptographic keys: a private key and a public key. This system is also known as public-key or asymmetric cryptography. The private key, known only to the wallet owner, is used to sign transactions, proving ownership of the bitcoins being spent. The public key, generated from the private key, is used to create a Bitcoin address, which can be shared with others to receive bitcoins. This system ensures that transactions are secure and that only the rightful owner of the bitcoins can authorise their transfer.

However, the advent of quantum computing poses a potential long-term challenge to existing cryptographic standards. Quantum computers, with their vastly superior computing power, could potentially break the encryption algorithms currently used in Bitcoin and other blockchain networks.[10] While this is generally not considered an immediate threat, the communities are actively researching and developing quantum-resistant cryptographic solutions to ensure the long-term security of blockchain networks.

Despite its strengths, Bitcoin's architecture is not spared from criticism. A major concern is the resource-intensive nature of PoW, frequently criticised for its environmental implications. Other criticism revolves around scalability, specifically the network's comparatively low transaction throughput. To address this issue, off-chain solutions such as the Lightning Network, which enables faster and cheaper transactions, have been proposed, but a trade-off between scalability and security remains.

Predictable issuance via a difficulty adjustment mechanism

To maintain a consistent rate of bitcoin issuance, the network employs a difficulty adjustment mechanism. On average, a new block is mined every 10 minutes. However, as more miners join the network and deploy greater computational resources, the time required to discover a valid block tends to decrease. To counter this, Bitcoin's difficulty level – essentially the complexity of the cryptographic challenge that miners must solve – is adjusted every 2016 blocks, which equates to approximately every two weeks.

In short, the difficulty adjustment ensures that, regardless of fluctuations in computational resources, Bitcoin's issuance rate remains relatively steady. If the computational power (also known as hashrate) increases, the difficulty rises. Thus, block production is slowed down to maintain a 10-minute average. Conversely, if miners withdraw computational power, the difficulty drops, allowing block discovery to speed up, which consequently stabilises the issuance rate. This mechanism ensures that Bitcoin's supply schedule remains predictable, independent of the level of miner participation.

Programmatic scarcity, a contrast to traditional monetary policy

Bitcoin's issuance mechanism stands in contrast to traditional fiat systems. While central banks have the ability to adjust money supply, potentially leading to concerns about inflation and debt levels, Bitcoin's issuance is governed by programmatic scarcity. This means that the total supply of bitcoins is capped at 21 million, a rule embedded in its underlying protocol. This fixed supply is one of Bitcoin's defining features and a key reason why it is often compared to precious metals like gold.

However, it is important to remember that while Bitcoin's protocol is designed with a fixed set of rules, these rules could technically be subject to change through consensus among network participants, although such changes are generally considered unlikely due to the potential disruption they could cause.[11]

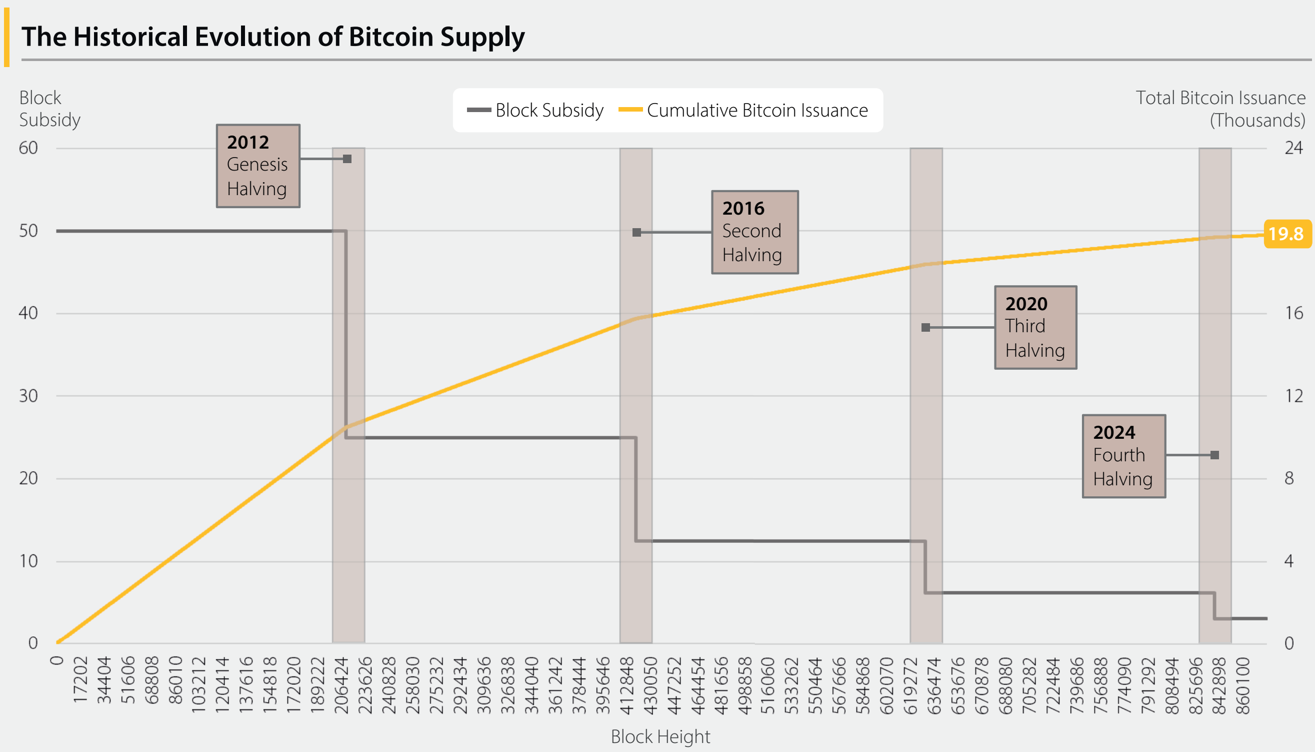
Bitcoin's issuance is designed to decrease over time. This gradual reduction is achieved through a process known as 'halving', where the block subsidy, i.e., the number of newly minted bitcoins awarded for mining new blocks, is reduced by 50% approximately every four years, or specifically after every 210,000 blocks. This event is a core tenet of Bitcoin's economic model, ensuring that its monetary inflation rate declines as it approaches the supply cap.

Figure 2 illustrates how the protocol enforced supply schedule works in practice, using the last four halving events as an example. Initially, when Bitcoin was launched in 2009, the block subsidy was set at 50 BTC. After the genesis halving (the first halving event) occurred at block height 210,000 in November 2012, the subsidy was reduced to 25 BTC. Subsequent halvings led to further reductions, to 12.5 BTC in July 2016, 6.25 BTC in May 2020, and 3.125 BTC in April 2024. Each future halving event will decrease the rate at which new bitcoins enter circulation further until block height 6,930,000 is reached, which marks the point at which Bitcoin reaches its maximum total supply of 21 million bitcoin. This is expected to occur around 2140. As of the end of 2024, more than 19.8 million bitcoins have already been mined.

Security implications of Bitcoin’s programmatic scarcity

Bitcoin’s supply schedule, defined by its fixed cap of 21 million coins and the halving mechanism, has significant implications for both its value and network security. As discussed earlier, the halving events – which occur approximately every four years – reduce

Figure 2: Bitcoin issuance per block (in BTC, left axis), in line with the Bitcoin protocol’s supply schedule, and the cumulative bitcoin issuance (in BTC, right axis) from the genesis block to block height 877,258 (mined on 31 December 2024). Source: Cambridge Centre for Alternative Finance



the block reward for miners by half, effectively decreasing the rate at which new bitcoins are put into circulation. This mechanism is integral to Bitcoin's inherent scarcity, contributing to its perceived value and the analogy of 'digital gold'.

However, the halving mechanism also presents challenges for network security. As the rewards for mining diminish, the immediate financial incentive for miners to contribute computational power to the network decreases. While a rise in bitcoin's value or an increase in network activity, which would likely lead to an increase in transaction fees, could offset these diminishing rewards, there is no certainty that this will occur. As the network's security is directly related to miner engagement, this uncertainty could create a vulnerability.

Approaching Bitcoin's final epoch

As Bitcoin approaches its final epoch, the block reward will eventually reach zero, meaning that the network will entirely rely on transaction fees to incentivise miners. This transition raises critical questions about the long-term sustainability of the network's security. The term 'security budget' refers to the total amount of resources, primarily financial, that are allocated to securing the Bitcoin network. This budget, largely composed of block rewards and transaction fees, is crucial for incentivising miners to participate in the network and protect it from attacks.

If transaction fees do not sufficiently compensate for the absence of block subsidy, there is a risk that miners may leave the network, reducing the security budget and making it more vulnerable to attacks. This could potentially lead to a 51% attack, where a single entity or a group controls a majority of the hashrate.

Recent developments in Bitcoin's ecosystem, such as the introduction of new token standards like Ordinals and Runes, could potentially increase overall transaction fees. These innovations might provide additional incentives for miners as the network gradually transitions from a block subsidy to a transaction fee-based economic incentive model. However, current transaction fee levels remain by far insufficient to sustain the network's security at today's standards. The success of these new developments in offsetting the future decline in block subsidy remains uncertain and will depend on broader adoption and market dynamics.

The debate around the security budget has been a point of contention within the Bitcoin community. Some suggest tail emissions may be a way forward to ensure continued incentives for miners.[12-14] Others fundamentally oppose the idea of changing the Bitcoin protocol, arguing that as adoption grows so will the demand for block space, leading to higher transaction fees and ensuring that miners remain incentivised to secure the network.[15-16]

Bitcoin's philosophy, Austrian economics as a key source of inspiration?

Austrian economist F.A. Hayek, in his work "The Denationalization of Money",[17] envisioned a future where private entities issued currency, arguing that competition among currencies would stabilise value and shield money from state intervention. Although Hayek's model involved competitive private currencies rather than a fixed supply, Bitcoin's capped issuance of 21 million coins addresses a similar Austrian concern: the risk of government-led monetary expansion, which proponents argue can lead to inflation, wealth erosion and economic instability.

Economists such as Ludwig von Mises, Murray Rothbard, and Milton Friedman argued that arbitrary expansion of money supply disrupts economic signals, leading to malinvestment and cycles of boom and bust. Bitcoin's decentralised nature and scarcity present what is likely the closest modern proxy to a private, global currency as Austrian and neoclassical economists might have envisioned.

The denationalisation of money: the good, the bad – and can Bitcoin fill the void?

The philosophical implications of Bitcoin are profound, as it challenges the traditional role of the state in the creation and regulation of money. With Bitcoin, monetary policy is not governed by central authorities but instead is enshrined in its protocol, which can only be amended via decentralised consensus. This design aligns closely with libertarian ideals of autonomy and censorship-resistance. Bitcoin's architecture allows users to transact without intermediaries or the risk of third-party interference, appealing to those who value financial privacy and independence.

For people in regions where access to the traditional financial system is restricted or where governments use financial control to suppress dissent, Bitcoin can function as a crucial link to the global economy and serves as a tool to enhance individual financial sovereignty. This means empowering individuals with greater control over their own finances, free from censorship or interference.

However, Bitcoin's philosophical underpinnings are not without criticism. Critics argue that the libertarian vision embedded in Bitcoin's architecture overlooks the importance of regulatory frameworks in maintaining economic stability and protecting consumers – functions that a decentralised currency like bitcoin cannot easily replicate. Furthermore, the absence of a central authority in Bitcoin means there is no recourse for users in cases of fraud, theft, or technical failures, potentially leading to significant financial losses.

Additionally, bitcoin does not fit the traditional definition of money, which typically includes serving as a medium of exchange, a unit of account, and a store of value. While bitcoin has exhibited some characteristics of each of these functions, it faces challenges in fulfilling all of them simultaneously. For example, its price volatility can hinder its use as a unit of account and medium of exchange, while its scalability limitations can impede its widespread adoption for everyday transactions.

Critics further point to the network's slow transaction processing times, occasionally leading to congestion and high transaction fees, as another major factor that makes Bitcoin unsuitable for everyday transactions. While this argument generally finds broad acceptance,[18] opinions diverge on whether this can be overcome with technological solutions that increase scalability: for example, by utilising the Lightning Network that settles transactions off-chain, but still leverages Bitcoin's security.

Bitcoin's Road to Institutional Acceptance

In the early days of Bitcoin, controversies repeatedly flared up

Bitcoin's origins are intertwined with some of the most controversial aspects of its early use. It was initially traded in niche circles, where its potential as a decentralised, censorship-resistant currency was recognised. One of the earliest platforms to facilitate bitcoin trading was Mt Gox, an exchange that originally started as a marketplace for trading "Magic: The Gathering" cards before pivoting to Bitcoin in 2010.

By 2013, Mt Gox had become the world's largest Bitcoin exchange, handling up to 70% of all Bitcoin transactions at its peak.[19] However, the exchange's dominance ended abruptly in 2014 when it filed for bankruptcy after it lost approximately 850,000 BTC of clients' deposits, reportedly due to a series of hacks and poor management. This event severely damaged the credibility of both Bitcoin and the broader cryptoasset market, causing significant price declines and prompting many to question the viability of digital currencies.

Simultaneously, Bitcoin was gaining notoriety on the dark web, particularly through the Silk Road marketplace. Silk Road facilitated anonymous transactions for illegal goods, with bitcoin serving as its primary currency. The FBI's shutdown of Silk Road in 2013 and the subsequent arrest of its founder further associated Bitcoin with illicit activities, damaging its early reputation.

The first steps towards mainstream adoption, emergence of crypto-native exchanges and real-world use cases

The collapse of Mt Gox and the notoriety of Silk Road underscored the need for secure and regulated platforms for trading and using bitcoin. This led to the rise of crypto-native exchanges, such as Bitstamp, Kraken, and Coinbase, which provided more reliable and user-friendly platforms for buying, selling, and storing bitcoin.

The entrance of legitimate actors played a crucial role in driving bitcoin's mainstream adoption, making the cryptoasset more conveniently accessible for a less tech-savvy audience. As Bitcoin's infrastructure improved, so did its use cases. Beyond speculation, Bitcoin began to be used for remittances, as it enables the seamless transfer of value across borders, often at a much lower cost and faster speed than traditional remittance services.[20] This was particularly evident in countries where hyperinflation and capital controls made it difficult for citizens to preserve their wealth. In these contexts, Bitcoin became a lifeline, offering a way to store value and engage with the outer world.

As Bitcoin's utility became more apparent, a few forward-thinking companies began to experiment with accepting bitcoins as payment. In 2014, companies like Dell, Microsoft, and Overstock.com started accepting bitcoin, signalling the first wave of corporate adoption. These early adopters saw Bitcoin not just as a payment method but as a way to attract tech-savvy customers.

In 2021, Tesla's involvement in Bitcoin further accelerated its adoption. When Tesla announced it had purchased $1.5 billion worth of bitcoin and would begin accepting it as payment,[21] it marked a significant milestone in Bitcoin's journey toward mainstream acceptance. Although Tesla later suspended Bitcoin payments due to environmental concerns, the event was a clear indicator of the growing interest in Bitcoin from major corporations.

The corporate adoption of Bitcoin was not just limited to payments. Companies like MicroStrategy made headlines by adopting bitcoin as a treasury reserve asset, investing billions of dollars in bitcoin as a hedge against inflation and currency devaluation, further solidifying its place in the financial ecosystem.[22]

The digital asset ecosystem becomes more diverse, though bitcoin continues to dominate

While the cryptoasset market has become increasingly diverse, bitcoin's dominance, albeit fluctuating, remains a key indicator of market sentiment and evolution. Historically, bitcoin has been emblematic of the cryptoasset market, often viewed as a bellwether for the entire sector. Since its inception, bitcoin's dominance – measured by its share of total market capitalisation – has shifted (see Figure 3), reflecting broader market trends, investor sentiment, and the emergence of alternative cryptocurrencies and tokens (altcoins). While bitcoin remains the leading cryptoasset by market value (calculated as circulating supply multiplied by price), the dynamics of its dominance have evolved significantly, especially with the rise of altcoins and new blockchain applications.

In its early days, bitcoin was practically the only major cryptoasset, maintaining a market share above 80%. As the sole significant cryptoasset, bitcoin's dominance remained unchallenged for quite some time. However, this began to change around 2015 with the advent of the ICO boom, which brought a plethora of new tokens and blockchain projects. These emerging tokens offered various functionalities beyond what Bitcoin's protocol capabilities could support, such as smart contracts on Ethereum or privacy features on Monero and Zcash. This proliferation of tokens eroded bitcoin's dominance, driving market share down to 32.5% during the 2017 bull run. This diffusion of utility beyond Bitcoin's function as a decentralised store of value signalled the onset of a more segmented market, where no single blockchain network could claim dominance across all use cases. It also created a sense that there was a new product space (blockchain), instead of only a new product (bitcoin).

Bitcoin's dominance is not solely a function of market cycles; it also reflects its increasing integration into mainstream finance, driven by both institutional interest and broader macroeconomic trends. Figure 3 shows that bitcoin's dominance stood at approximately 56% in 2024, highlighting a gradual upward trend since 2022. A likely catalyst for this growth was the introduction of spot Bitcoin ETFs in major markets such as the U.S. and Hong Kong, which gave institutional investors access to the underlying asset rather than exposure through proxies, such as mining firms. This development marked a notable shift, given that institutional investors had traditionally been sceptical of cryptoassets due to concerns around illicit activity, regulatory ambiguity, and other risks. The approval of spot Bitcoin ETFs by the SEC may have not only opened the market to a wider audience but also legitimised Bitcoin further, reinforcing its dominant position. This increasing institutional acceptance aligns with broader

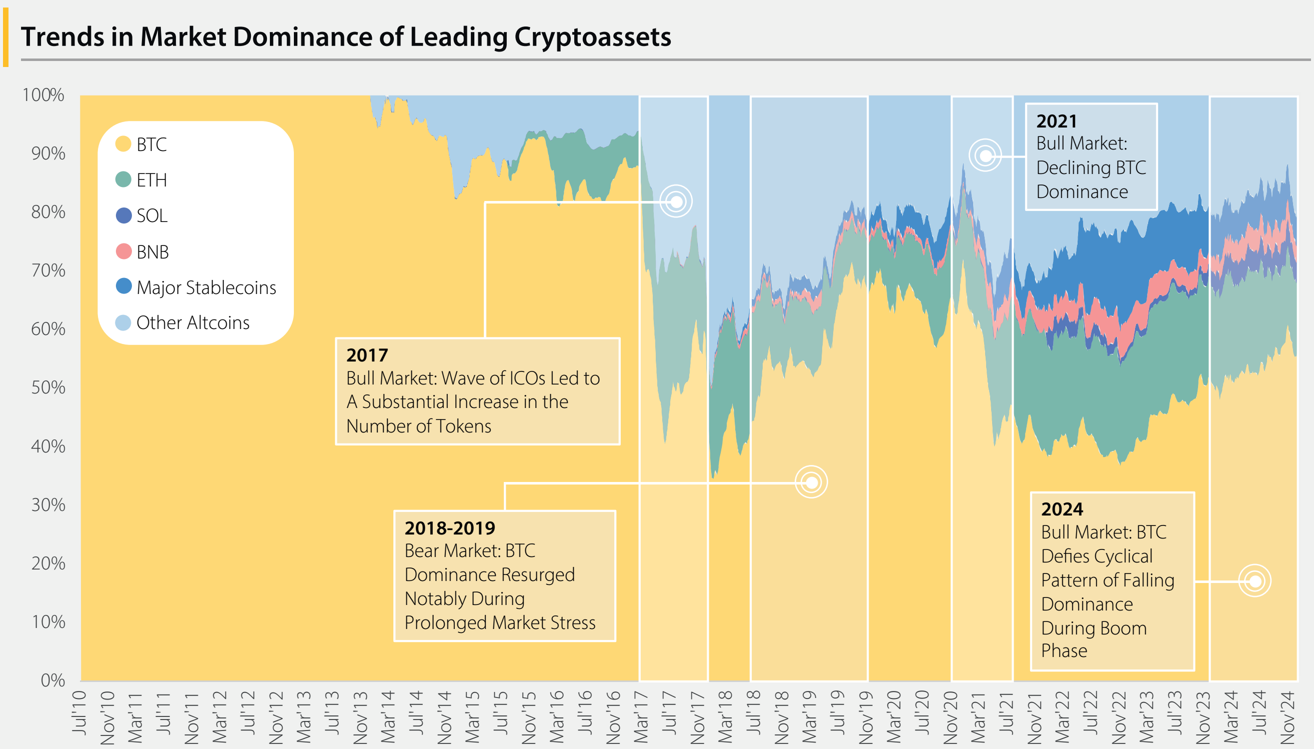


Figure 3: Market dominance (in %) of leading cryptoassets from 18 July 2010 to 31 December 2024, using a 14-day moving average.
Data source: Coin Metrics [23], TokenInsight [24]

macroeconomic trends. For example, in the early days of the COVID-19 pandemic, bitcoin's value surged, likely indicating a flight to safety among investors, with gold similarly reaching all-time highs. Institutional players, including Tesla, MicroStrategy, and Square, further validated bitcoin's standing by integrating it into their treasuries. These developments, both at the institutional level and within broader market dynamics, likely bolstered confidence and contributed to gains in market dominance.

Overall, bitcoin's dominance reflects more than just market cycles; it captures investor sentiment, technological progress, and macroeconomic influences. Analysing this trend reveals that during bullish phases, risk appetite grows, leading to increased capital flows into altcoins, NFTs, and DeFi projects, with bitcoin's dominance contracting. Conversely, in bearish markets, capital seems to return to bitcoin, as participants likely seek refuge in its stability and liquidity.

The institutional rise of crypto-native firms

As Bitcoin and the crypto-ecosystem matured and expanded, so did the businesses built around it. Crypto-native firms like Coinbase, which went public in 2021, became symbols of the growing legitimacy and institutionalisation of Bitcoin. Coinbase's IPO was a landmark event, as it signalled the integration of cryptoasset businesses into the traditional financial markets.

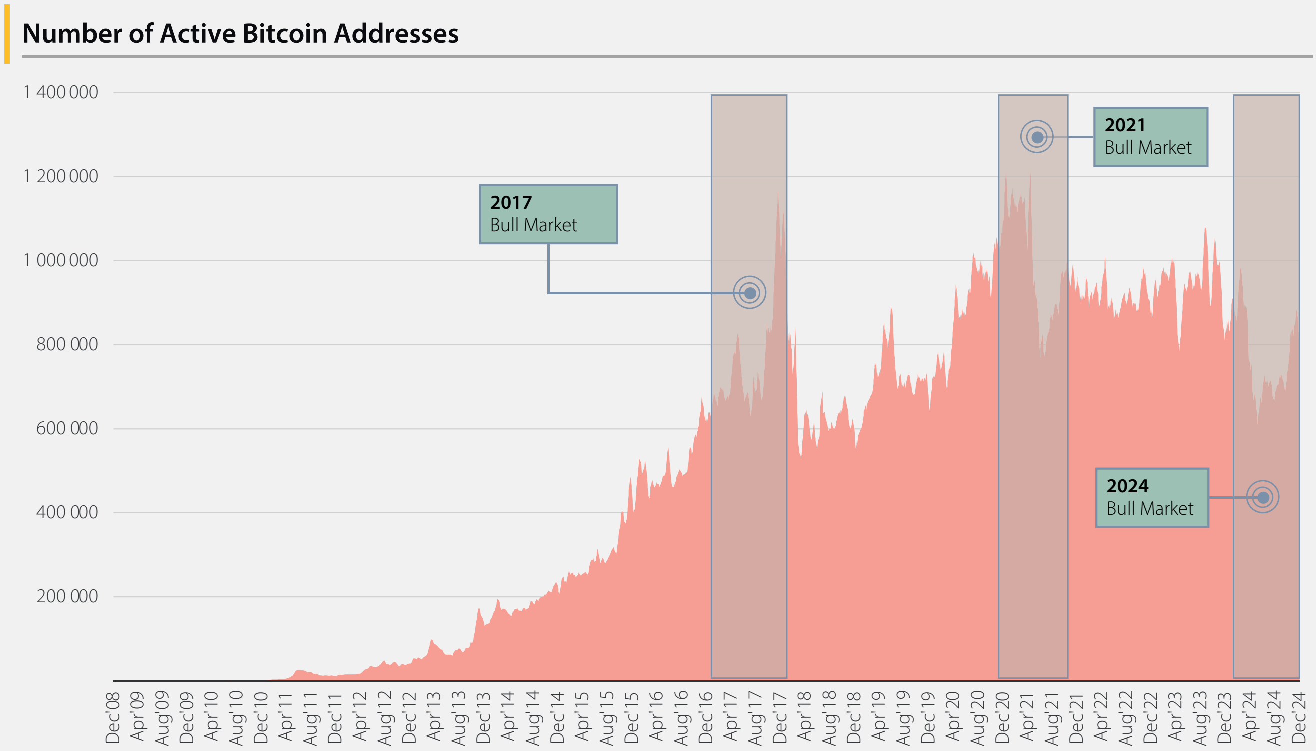
At the same time, more traditional financial institutions began to offer Bitcoin-related products. Fidelity, one of the largest asset managers in the world, launched a digital assets division in 2018. Similarly, Morgan Stanley, JP Morgan, and Goldman Sachs began offering Bitcoin crypto-related products and services, marking a significant shift in institutional attitudes towards Bitcoin.

Activity on the Bitcoin network grew as well. However, while active addresses – a key metric of network usage – once indicated rapid growth, recent trends show a plateau between 2020 and 2024, with numbers largely oscillating between 0.8 to 1 million (see Figure 4) – with the exception of a sharper drop in the first half of 2024 that subsequently recovered. This flattening may reflect a shift in Bitcoin's use, particularly among institutional investors.

Heightened regulatory scrutiny as part of the digital assets ecosystem's maturing process

As digital assets increasingly gained in popularity, public entities around the world began to take notice. A true wake-up call was the planned launch of Facebook's Diem project (originally Libra) in 2020 [26] that prompted many governments and regulators to accelerate their efforts to regulate the ecosystem. Regulatory frameworks began to take shape with some governments and regulators taking a more cautious approach than others.

Figure 4: Sum of unique Bitcoin addresses that were sending or receiving BTC on any given day from 9 January 2009 to 31 December 2024, using a 14-day moving average. Data source: Coin Metrics [25]



In 2023, the European Union introduced the Markets in Crypto Assets Regulation (MiCA), which was implemented in stages and aimed to create a harmonised regulatory environment across all member states. Although not specific to Bitcoin, MiCA provided clarity on the treatment of digital assets, establishing rules for issuers, service providers, and investors, thereby fostering a more stable and predictable market environment.

China took a more prohibitive stance, banning financial institutions from dealing with Bitcoin transactions in 2013 and further cracking down on the ecosystem in 2021. Despite these restrictions, China continued to develop its digital yuan, a state-controlled central bank digital currency, which is a tool that enables governments to embrace the digital world, while still maintaining control, as compared to the decentralised ethos of, for example, Bitcoin.

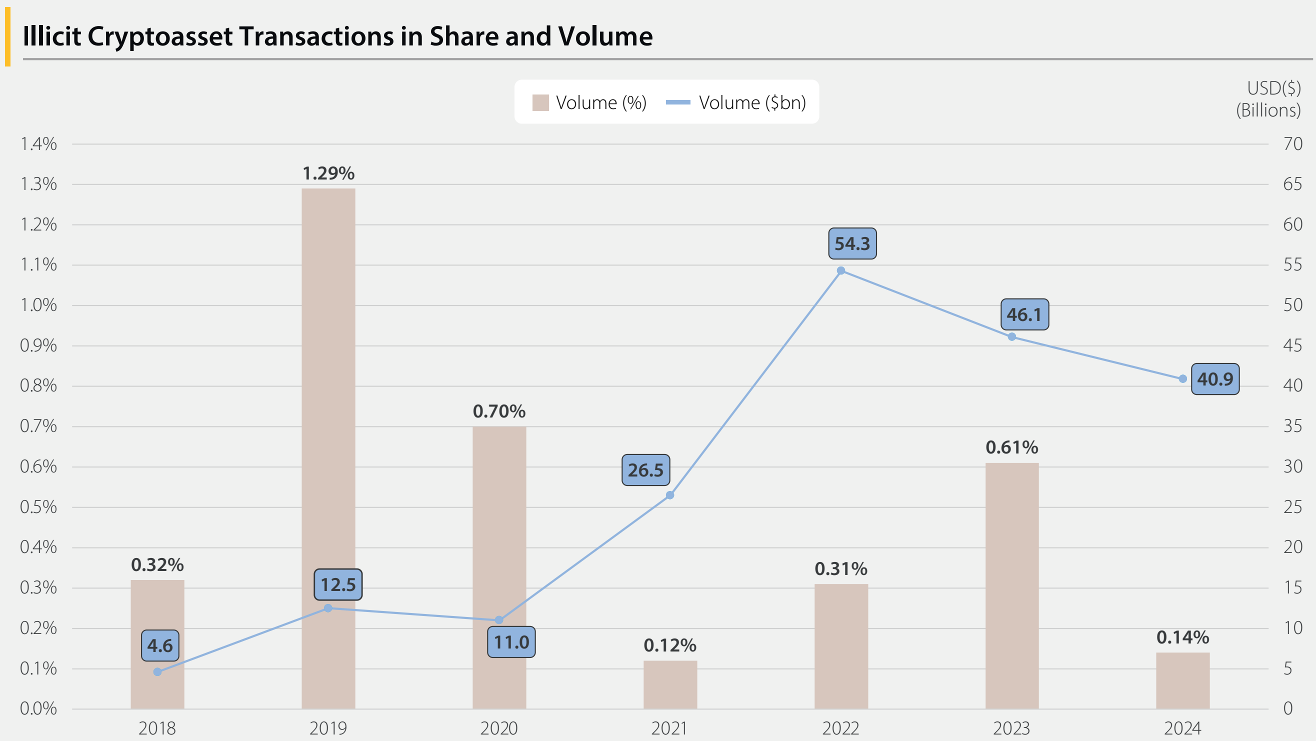
On the other hand, some countries have fully embraced Bitcoin. El Salvador made headlines in 2021 by becoming the first country to adopt bitcoin as legal tender.[27] The following year, the Central African Republic took a similar step,[28] but reversed the legal tender status about a year after adoption.

Illicit activity in the digital assets ecosystem

As institutional acceptance and regulatory clarity have grown, Bitcoin has largely shed its image as a primary facilitator of illicit activity. Although illicit transactions continue to occur, their scale is much smaller than the debate surrounding it would suggest.[29] The share of illicit transactions reached an all-time low of 0.12% in 2021. Although it increased to 0.63% in 2023, it dropped again notably in 2024 to 0.14%, reflecting one of the lowest levels recorded in recent years (see Figure 5). This reduction is attributed to both increased adoption of cryptoassets for legitimate purposes and proactive law enforcement efforts. Nevertheless, in absolute terms, illicit activity remains substantial, totalling $40.9 billion in 2024 – which Chainalysis considers the lower bound. This highlights a persistent challenge for the industry and regulators alike. Readers seeking further information on the regulatory landscape of cryptoassets and digital mining are referred to the CCAF's dedicated studies on the subject.[30-31]

Observing the illicit flows by asset type, stablecoins have emerged as the preferred means for illicit actors, notably surpassing bitcoin and all other asset types

Figure 5: Share of illicit transaction on total transaction volume (in %, left axis) and illicit cryptoasset transaction volume (in USD, right axis) from 2018 to 2024. Data source: Chainalysis (2024-2025; [32-33])



combined. This preference is driven by their price stability and the relative financial accessibility they offer, especially to users in sanctioned jurisdictions. However, stablecoin issuers can freeze assets when suspicious activity is detected, adding a layer of regulatory intervention that may deter some illicit actors.

The types of crypto crime have also changed in recent years, characterised by a shift in priorities and increasing sophistication. While some forms of illicit activity, such as those associated with darknet markets and certain types of fraud shops, showed signs of decline, others, including theft and various scams, remained significant challenges. Ransomware persisted as a notable threat, despite some successes in law enforcement disruption, and DeFi platforms continued to be attractive targets for theft, alongside centralised services.[33] Hacking remains a critical concern, with sophisticated groups, for example North Korea's Lazarus Group, employing advanced techniques such as cross-chain bridges and newer mixers to obfuscate funds and evade detection, demonstrating the ongoing adaptation of laundering tactics.[34] The increasing use of emerging technologies, such as artificial intelligence (AI), in scams and fraud also marked a concerning trend.[35]

Bitcoin derivatives as a stepping stone to mainstream finance

The growing acceptance and resilience of bitcoin fuelled demand for financial derivatives, bridging the gap between the cryptoasset and traditional financial markets. A key development was the introduction of bitcoin futures contracts in 2017, offered by the Chicago Mercantile Exchange (CME),[36] which provided institutional investors with their first regulated route to gain exposure to bitcoin, marking a crucial step towards wider acceptance.

Previously, institutions had been wary due to concerns about Bitcoin's regulatory ambiguity, potential for illicit use, and market manipulation. The regulated nature of futures contracts, overseen by established exchanges, helped to mitigate some of these risks, providing a framework with greater oversight and investor protection.

Building on this, in October 2021, the SEC approved the first bitcoin futures-based exchange-traded fund (ETF) – the ProShares Bitcoin Strategy ETF (BITO).[37] This landmark event signified a shift in regulatory acceptance, offering a wider range of investors easier access to the market through a familiar and regulated investment vehicle.

The success of futures-based ETFs paved the way for the next major development. In January 2024, the SEC approved Block ETFs – funds that hold the underlying asset directly. This triggered a substantial influx of institutional capital, reflected in a rapidly growing assets under management (AUM), a key metric representing the total market value of assets managed by an investment fund.

Examining the AUM of spot ETFs specifically provides a concrete example of this institutional inflow. Figure 6(a) shows the increase in AUM (in BTC) of spot ETFs from 10 January 2024 to 31 December 2024. Holdings surged from 0.62 million to 1.11 million BTC, marking a significant increase of 79% over the year. Observing AUM from a U.S. dollar perspective (see Figure 6(b)), the increase becomes even more pronounced, rising from $29 billion to $104 billion (+259%), with this rise not only reflecting the increase in BTC holdings but also being driven by a rise in BTC price from $48,818 to $93,390 over the same period.

Figure 7(a) and (b) illustrate the monthly funding flows into and out of spot Bitcoin ETFs. The data shows a continuous inflow of BTC, with 11 out of 12 months showing net inflows. The only net outflow was recorded in April 2024. The figures also reveal a significant shift in market share between ETF issuers. Notably, Grayscale (GBTC) converted from a trust to an ETF structure in January 2024, which accounts for the high initial AUM. However, the market has become more fragmented since then, with BlackRock (IBIT) and Fidelity (FBTC) showing significant gains.

That said, bitcoin's growth trajectory suggests it may continue to capture a larger share of the global financial market. With a growing base of both retail and institutional investors and increasing mainstream acceptance, Bitcoin has positioned itself as a distinct asset class. Its unique attributes set it apart not only from traditional investments like stocks, bonds, and commodities, but also from other crypto-native assets, hinting at a future where Bitcoin continues to carve out its own niche in the evolving financial landscape.

Figure 6: (a) Assets under management (AUM) of various spot Bitcoin ETF issuers (in BTC); (b) AUM of various spot Bitcoin ETF issuers (in USD), from 1 January 2024 to 31 December 2024. Source: CCAF Blockchain Analytics by @alexneu_btc on Dune dashboard [38]

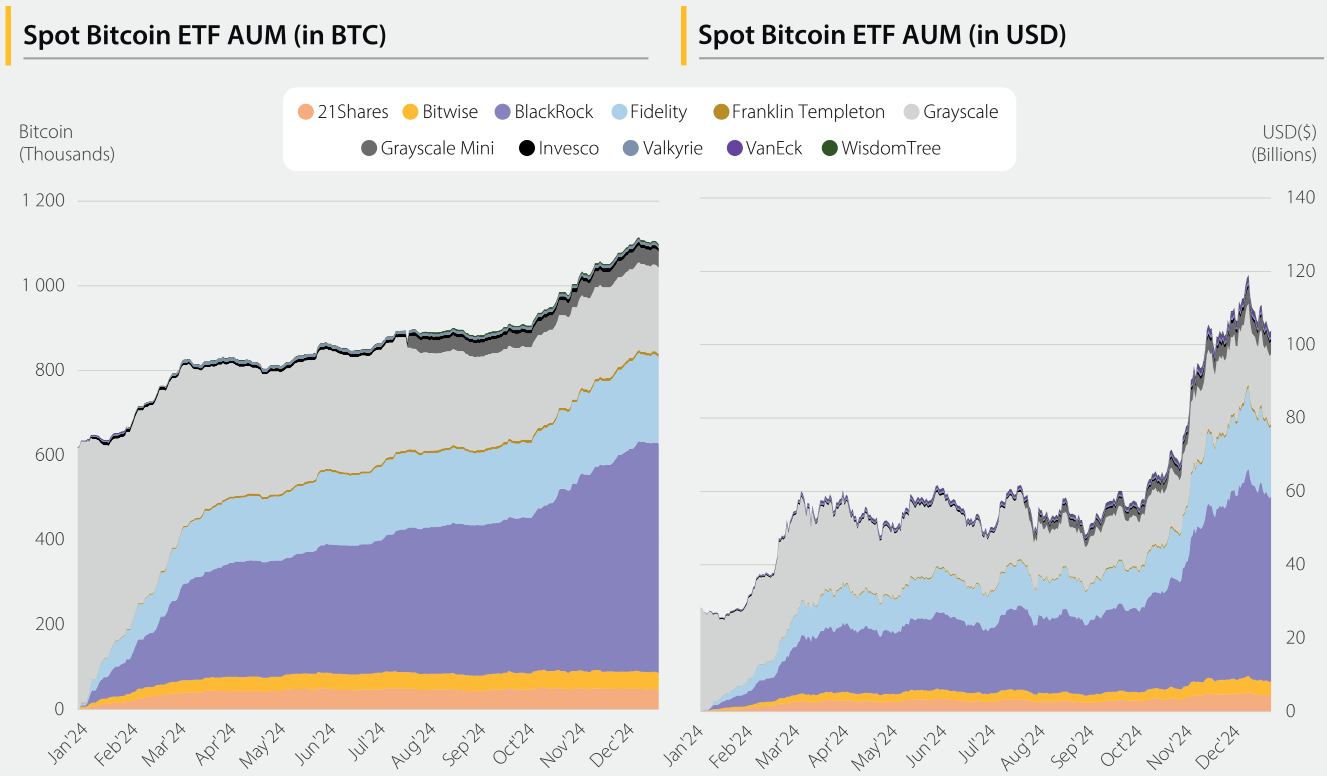
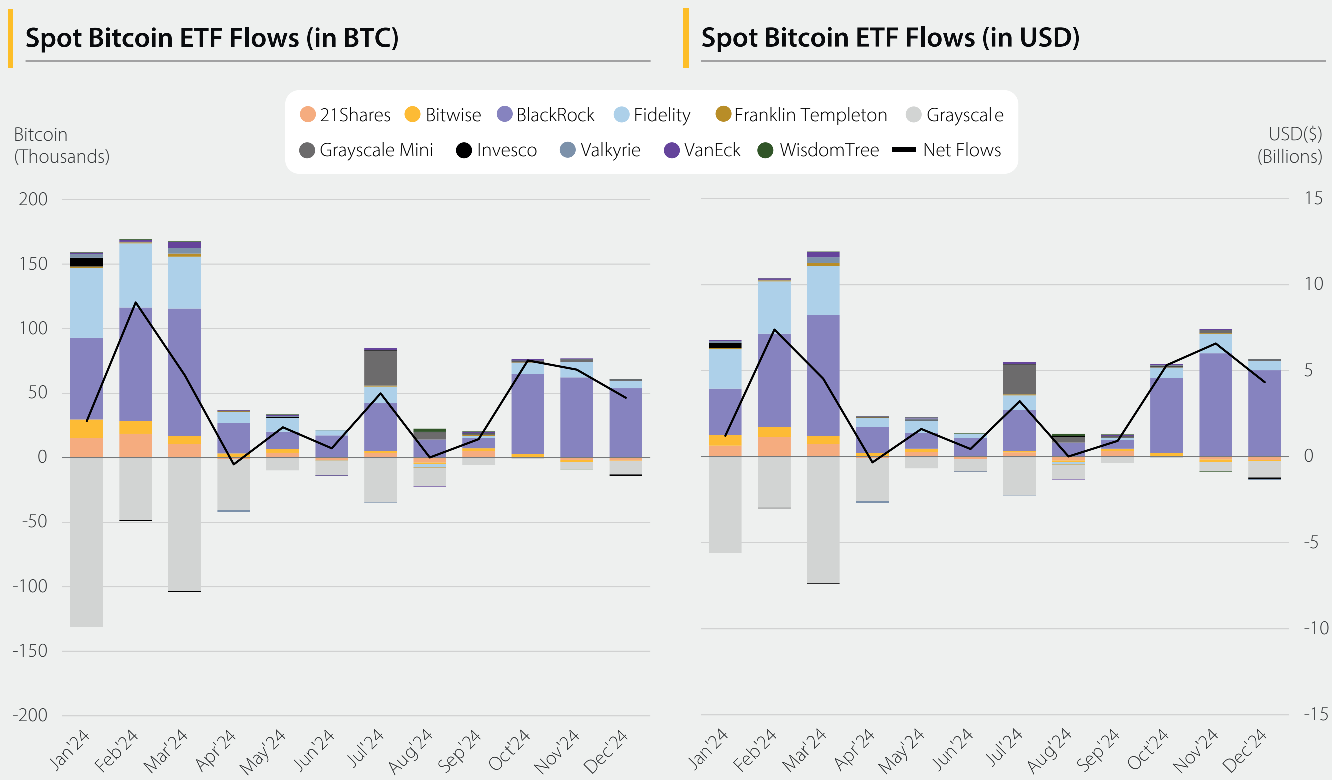


Figure 7: (a) Spot Bitcoin ETF flows (in BTC) by issuer; (b) Spot Bitcoin ETF (in USD) by issuer, with both charts including a line indicating net flows, from 1 January 2024 to 31 December 2024. Source: CCAF Blockchain Analytics by @alexneu_btc on Dune dashboard [38]



Bitcoin as an Asset Class, Market Value and Asset Correlations

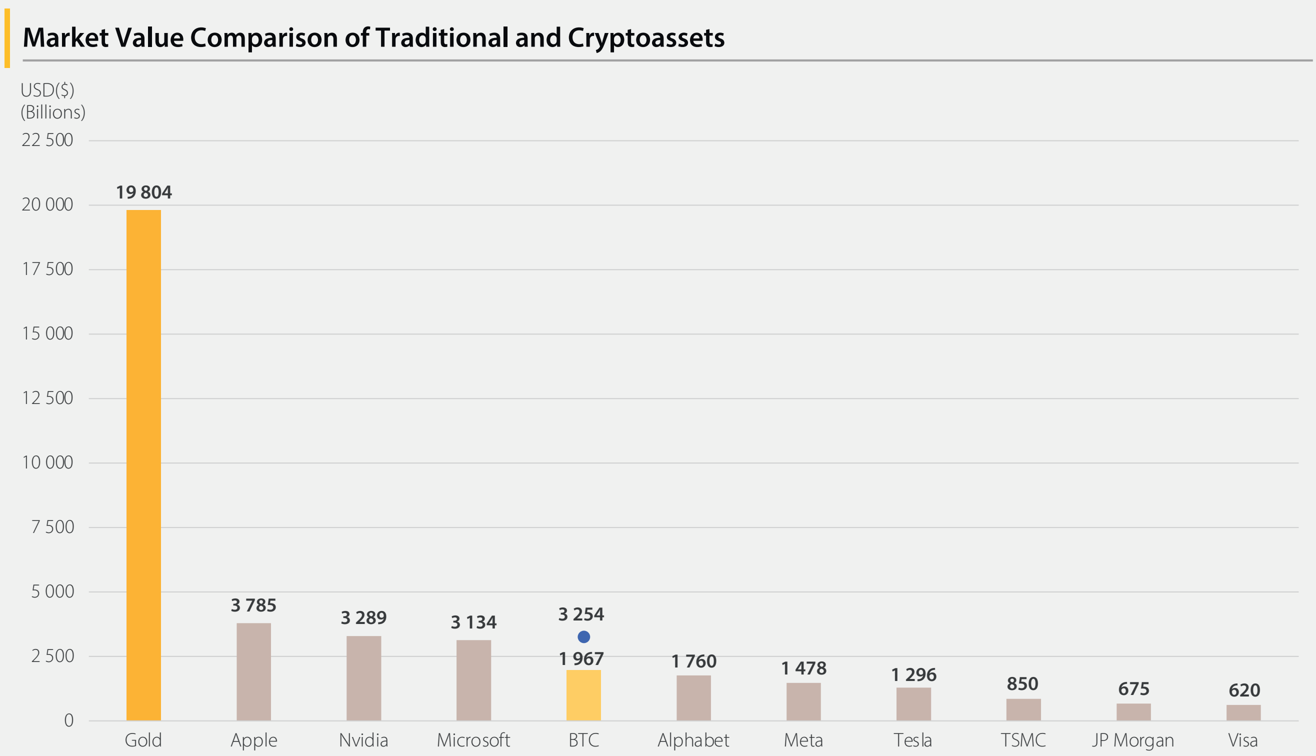
Bitcoin's market value, currently estimated around $2 trillion, has expanded considerably from its modest beginnings in the early 2010s. As Figure 8 illustrates, bitcoin would now rank amongst some of the world's largest companies by market value, surpassing the market capitalisation of tech giants such as Alphabet ($1.76 trillion), Meta ($1.5 trillion), Tesla ($1.3 trillion), and TSMC ($0.85 trillion), and traditional financial service providers such as J.P. Morgan ($0.68 trillion) and Visa ($0.62 trillion).

However, despite these significant gains, bitcoin's market value remains relatively small when compared to the broader financial landscape. In terms of real-world analogues, bitcoin is often compared to gold, both positioned as stores of value and hedges against inflation. However, the estimated $19.8 trillion valuation of the gold market exceeds bitcoin's market value many times over. This disparity only widens when we look at traditional financial sectors: global equities command a market capitalisation of approximately $114.8 trillion,[41] while global debt markets reach $250 trillion,[42] with real estate even dwarfing debt and equity markets by a fair margin ($379.7 trillion).[43]

Nonetheless, bitcoin's unique characteristics continue to fuel its appeal as a nascent asset class. Unlike traditional financial instruments, bitcoin operates on a decentralised, peer-to-peer network, offering distinct advantages that are increasingly attractive to a range of investors. As Bitcoin's role within the global financial ecosystem grows, its market value is expected to increase, particularly as institutional adoption accelerates. Recent developments, such as the approval of spot ETFs in major markets like the U.S. and Hong Kong, have bolstered Bitcoin's standing, providing a gateway for institutional and more conservative retail investors to gain exposure through familiar, regulated products. This influx of institutional interest could channel significant liquidity into bitcoin and lay the groundwork for future growth.

In terms of market value, bitcoin has made significant strides, yet it still trails considerably behind traditional financial assets. Looking ahead, both Bitcoin and the broader digital asset ecosystem are likely to encounter challenges, whether regulatory or technical, that could impact their growth trajectory. While bitcoin's volatility has moderated over time, it likely remains a concern for many traditional institutional investors, some of whom remain unconvinced of Bitcoin's value proposition. Although the store of value narrative has gained traction and become heavily intertwined with Bitcoin's identity, some veteran investors remain sceptical.[44]

Figure 8: Market value of gold and the market capitalisation of major public companies compared to the total market value of cryptoassets and bitcoin (in USD) as of 31 December 2024. The total market value of gold has been computed using the following assumptions: above ground stock of 216,265 tonnes (2024 year-end estimate) and a gold price of $2.641 per ounce. Source: Analysis conducted by the authors, data obtained from Refinitiv Eikon [39], Coin Metrics [23], TokenInsight [24], and World Gold Council (2025; [40])



Bitcoin's evolving role: a diversifier, hedge, or something new?

As Bitcoin solidifies its position as a distinct asset class, its relationship with traditional financial assets provides valuable insights into its behaviour and potential role in investment portfolios. From 2019 to 2024, bitcoin's role within global financial markets has evolved significantly, displaying shifting correlations with traditional asset classes like equities, precious metals, commodities, and the U.S. dollar. By analysing its relationship with these assets (see Figure 9), we gain insight into how bitcoin may be perceived and utilised by investors. However, correlation does not imply causation, and these relationships are not static. Still, they provide valuable perspectives on bitcoin's behaviour across market cycles and its potential role as a portfolio diversifier.

A varying relationship between bitcoin and equities

Bitcoin's relationship with equities is highly variable and appears to be influenced by broader market sentiment. In 2019, a slightly negative correlation with equity indices like the S&P 500 (-0.12) and Nasdaq (-0.10) suggested a degree of independence. However, the COVID-19 pandemic in 2020 marked a shift, with correlations rising to 0.45 (S&P 500) and 0.47 (Nasdaq) as global equity markets experienced unprecedented volatility. This alignment with risk assets during market stress recurred in 2022.

Between 2021 and 2023 inclusive, correlations showed considerable fluctuation: 0.25 (S&P 500) and 0.26 (Nasdaq) in 2021, significant increases in 2022, followed by a decline in 2023 to 0.16 (S&P 500) and 0.19 (Nasdaq). The lower correlations in 2023 coincided with reports of increased institutional interest in Bitcoin, potentially driven by the desire to attract a tech-savvy audience or as a long-term strategic play. The trend of modest, positive correlation continued into 2024, suggesting that while bitcoin may behave like a risk asset during crises, it maintains enough independence to serve as a potential portfolio diversifier during stable periods.

Ambivalence in the correlation between bitcoin and gold

Bitcoin is often compared to gold as a modern store of value, yet its correlation with the metal has been relatively weak, averaging 0.12 over the six-year horizon. This relationship has fluctuated in response to broader economic conditions and bitcoin's own speculative nature. For instance, during bitcoin's sharp rally in 2021, its correlation with gold briefly turned negative (-0.06), underscoring diverging performance with bitcoin acting more as a speculative play on rising crypto market sentiment rather than a stable hedge.

This ambivalent role is further reinforced by bitcoin's performance during geopolitical events. During crises such as Russia's invasion of Ukraine in 2022, gold rallied as a safe haven, while bitcoin's correlation with gold remained weak (0.11). Following Iran's missile attack on Israel on 1 October 2024, traditional safe havens like gold (+1.2%) and geopolitically-sensitive industrial resources like crude oil (+3.5%) saw upward momentum, while bitcoin's price declined (-3.8%). This dichotomy suggests that bitcoin's potential to fully assume the role of digital gold remains largely theoretical: it has yet to reliably function as a hedge against geopolitical uncertainty in the way that precious metals do. Interestingly, political events such as the recent U.S. election highlighted bitcoin's role as a risk-on asset with BTC rising (+8.9%), in contrast to gold's decline (-2.7%) and outpacing S&P 500's gains (+2.5%).

Figure 9: Annual correlation matrices computed using daily log returns for bitcoin (BTC), major stock indices (S&P 500, NASDAQ, Dow Jones Industrial Average), commodities (Gold, Silver, WTI Crude Oil) and the U.S. Dollar Index (DXY), and daily log differences of yields for the 10-Year U.S. Treasury bond. Correlations represent Pearson correlation coefficients, calculated separately for each calendar year (1 January to 31 December) from 2019 through 2024. Source: Analysis conducted by the authors, data obtained from Coin Metrics [45] and Refinitiv Eikon [39]

Correlation Comparison of Bitcoin with Major Traditional Financial Assets

2019

	BTC	S&P 500	Nasdaq	DJIA	Gold	Silver	Oil (WTI)	USD	10Y US T-Bond
BTC	1.00								
S&P 500	-0.12	1.00							
Nasdaq	-0.10	0.96	1.00						
DJIA	-0.13	0.96	0.89	1.00					
Gold	0.21	-0.27	-0.28	-0.28	1.00				
Silver	0.11	-0.13	-0.12	-0.15	0.80	1.00			
Oil (WTI)	-0.03	0.32	0.30	0.33	-0.07	0.01	1.00		
USD	-0.13	0.08	0.09	0.09	-0.41	-0.29	-0.01	1.00	
10Y US T-Bond	-0.13	0.55	0.52	0.56	-0.51	-0.35	0.17	0.15	1.00

2020

	BTC	S&P 500	Nasdaq	DJIA	Gold	Silver	Oil (WTI)	USD	10Y US T-Bond
BTC	1.00								
S&P 500	0.45	1.00							
Nasdaq	0.47	0.96	1.00						
DJIA	0.42	0.98	0.91	1.00					
Gold	0.28	0.15	0.20	0.13	1.00				
Silver	0.31	0.23	0.26	0.21	0.77	1.00			
Oil (WTI)	0.09	0.19	0.19	0.18	0.05	0.11	1.00		
USD	-0.07	-0.01	0.01	-0.02	-0.26	-0.31	-0.03	1.00	
10Y US T-Bond	0.21	0.60	0.54	0.60	-0.08	0.01	0.14	0.25	1.00

2021

	BTC	S&P 500	Nasdaq	DJIA	Gold	Silver	Oil (WTI)	USD	10Y US T-Bond
BTC	1.00								
S&P 500	0.25	1.00							
Nasdaq	0.26	0.89	1.00						
DJIA	0.21	0.89	0.63	1.00					
Gold	-0.06	0.08	0.11	0.04	1.00				
Silver	0.05	0.16	0.16	0.13	0.77	1.00			
Oil (WTI)	0.08	0.39	0.26	0.46	0.03	0.12	1.00		
USD	-0.10	-0.22	-0.22	-0.20	-0.46	-0.39	-0.14	1.00	
10Y US T-Bond	0.04	-0.03	-0.11	0.08	-0.15	-0.04	0.18	0.15	1.00

2022

	BTC	S&P 500	Nasdaq	DJIA	Gold	Silver	Oil (WTI)	USD	10Y US T-Bond
BTC	1.00								
S&P 500	0.58	1.00							
Nasdaq	0.61	0.97	1.00						
DJIA	0.52	0.96	0.89	1.00					
Gold	0.11	0.12	0.09	0.10	1.00				
Silver	0.17	0.21	0.18	0.20	0.81	1.00			
Oil (WTI)	0.15	0.10	0.06	0.09	0.37	0.32	1.00		
USD	-0.30	-0.47	-0.42	-0.48	-0.47	-0.43	-0.18	1.00	
10Y US T-Bond	-0.05	-0.08	-0.07	-0.08	-0.23	-0.15	-0.03	0.12	1.00

2023

	BTC	S&P 500	Nasdaq	DJIA	Gold	Silver	Oil (WTI)	USD	10Y US T-Bond
BTC	1.00								
S&P 500	0.16	1.00							
Nasdaq	0.19	0.94	1.00						
DJIA	0.14	0.89	0.72	1.00					
Gold	0.11	0.00	0.01	0.01	1.00				
Silver	0.11	0.12	0.11	0.12	0.80	1.00			
Oil (WTI)	-0.05	0.13	0.03	0.19	0.04	0.11	1.00		
USD	-0.13	-0.26	-0.26	-0.19	-0.48	-0.55	-0.15	1.00	
10Y US T-Bond	-0.06	-0.03	-0.09	0.02	-0.45	-0.33	0.17	0.38	1.00

2024

	BTC	S&P 500	Nasdaq	DJIA	Gold	Silver	Oil (WTI)	USD	10Y US T-Bond
BTC	1.00								
S&P 500	0.35	1.00							
Nasdaq	0.32	0.92	1.00						
DJIA	0.35	0.82	0.63	1.00					
Gold	0.06	0.16	0.11	0.16	1.00				
Silver	0.12	0.24	0.23	0.17	0.75	1.00			
Oil (WTI)	-0.09	0.03	0.07	0.01	0.19	0.26	1.00		
USD	-0.03	-0.11	-0.09	-0.10	-0.31	-0.29	0.00	1.00	
10Y US T-Bond	-0.08	-0.07	-0.08	-0.04	0.03	0.01	0.17	0.04	1.00

A stock-to-flow comparison of bitcoin and precious metals

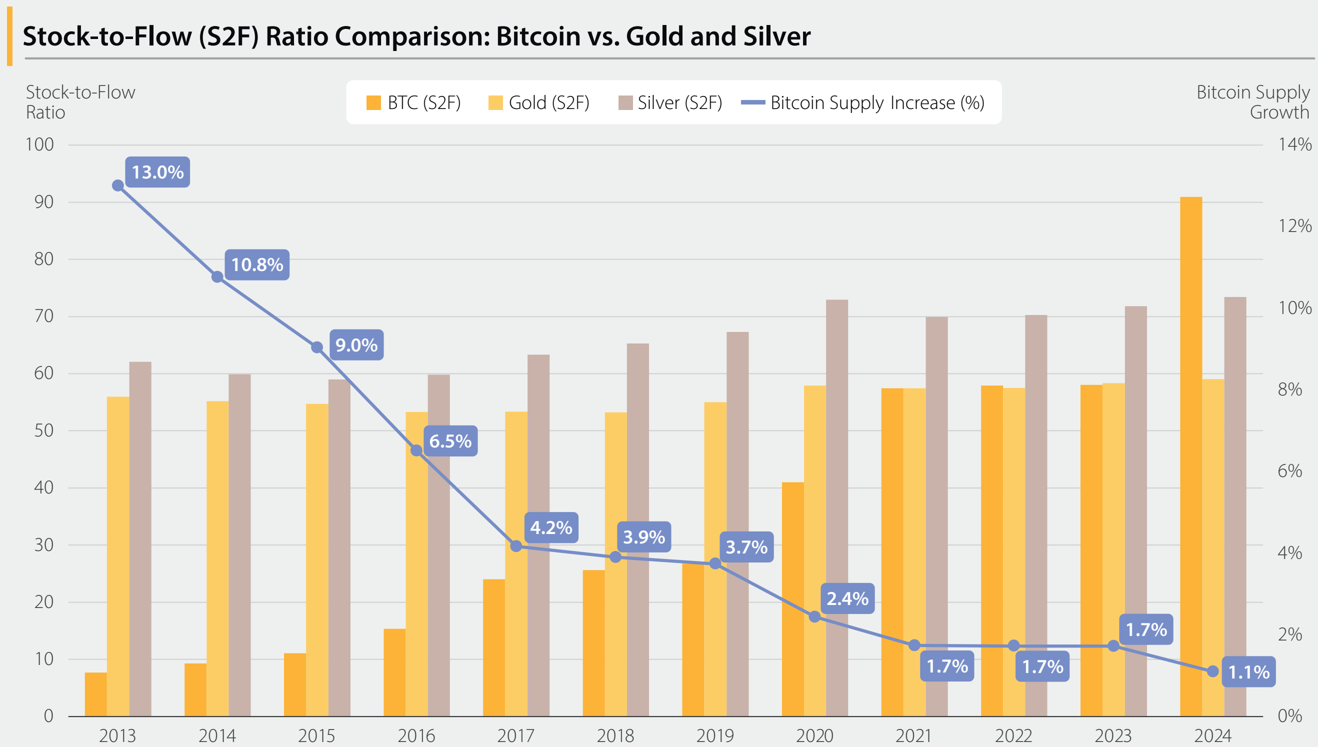
An interesting metric frequently used to compare bitcoin to precious metals is the stock-to-flow (S2F) ratio. This ratio compares the total circulating supply of an asset to the rate at which new units of said asset enter the market within a given year. In the case of bitcoin, the 'flow' is determined by the Bitcoin protocol's issuance policy (see Figure 2) and the number of blocks mined annually. The 'stock' represents all existing bitcoins in circulation (19,803,729 as of December 2024).

A high S2F ratio is generally seen as a positive attribute for an asset aspiring to be a store of value. This is because a high ratio indicates relative scarcity – the amount of new supply entering the market is small compared to the existing supply. This scarcity, when coupled with increasing demand, can create upward pressure on price, leading to price stability or even appreciation. However, it is essential to acknowledge that the relationship between the S2F ratio and price is not straightforward. While scarcity plays a role, it is not the sole determinant of price. A multitude of other factors can influence bitcoin's price, including market sentiment, regulatory developments, technological advancements, and even the loss or inaccessibility of existing bitcoins.

Figure 10 displays the S2F ratio of bitcoin in comparison to the precious metals gold and silver, which have historically often served as a store of value and means of payment. Contrasting the ratios, it becomes apparent how starkly bitcoin's S2F ratio has changed, driven by the predefined flow decreases following halving events.

While in 2013, close to the second halving, bitcoin's S2F ratio (8) was considerably lower than that of gold (56), after the latest halving in April 2024, the ratio surged to 91 – a more than 10-fold increase – turning the tables and now stands more than 50% higher than that of gold (59). The chart also illustrates the yearly increase in total BTC supply, which declined from 13% to 1.1% (2013 – 2024).

Figure 10: Annual stock-to-flow (S2F) ratios for bitcoin, gold, and silver (left axis), and Bitcoin's annual supply growth rate (in %, right axis) from 2013 to 2024. S2F calculations: Silver uses stock approximations from Nieuwenhuijs (2019) for 2013, with subsequent years derived from annual mine production data from The Silver Institute. Gold stock (2024 year-end estimate) and annual mine production data are from the World Gold Council; historical stock figures are calculated using the 2024 (year-end) estimate as a baseline, adjusted for annual production. Source: Analysis conducted by the authors, data obtained from Coin Metrics [46], Nieuwenhuijs (2019; [47]), The Silver Institute (2025; [48]), and World Gold Council (2025; [40,49])



Bitcoin’s relationship to fixed income and energy commodities

Bitcoin appears to stand apart from traditional asset classes like energy commodities and fixed income, demonstrating a low correlation with both. This independence highlights its unique position within the broader financial landscape.

Using oil as a proxy for energy commodities, bitcoin's correlation has remained near zero (0.03) over the past six years. This underscores bitcoin's detachment from the supply-demand dynamics that typically drive oil prices. The 2020 pandemic highlighted this contrast vividly: while oil prices rebounded sharply as demand recovered during the first half of the year, bitcoin's price rose more gradually, but experienced a much sharper price increase later in 2020, buoyed by factors like central bank liquidity and institutional interest[50]. This divergence suggests that bitcoin responds more to macroeconomic trends and investor sentiment than to traditional economic cycles linked to industrial activity.

Bitcoin's correlation with U.S. Treasury yields is complex. The network’s decentralised nature and absence of fixed returns contribute to a degree of independence from the yield-driven dynamics of the bond market, often leading to low or negative correlation. This supports bitcoin's appeal as a potential portfolio diversifier. However, periods of market stress, broader macroeconomic factors, and growing institutional interest can increase the correlation.

Bitcoin as hedge against monetary inflation

Bitcoin's potential to serve as a hedge against monetary inflation is often linked to its negative correlation with the U.S. dollar. A negative correlation suggests that when the dollar weakens, bitcoin tends to strengthen, and vice versa. However, this relationship is more complex than it initially appears.

Over the past six years, the correlation between bitcoin and the dollar has oscillated within a range, from -0.3 to -0.03, averaging around -0.13. While this indicates a general tendency towards an inverse relationship, it also highlights the nuanced nature of their interaction. The idea that a strong dollar always leads to poor bitcoin performance is an oversimplification. Factors like market liquidity and investor time horizons likely play a crucial role alongside currency movements.

During periods of loose monetary policy and heightened fears of monetary debasement, bitcoin's inverse relationship with the dollar tends to be more pronounced, suggesting that investors may view bitcoin as a safe haven from fiat currency devaluation during such times. However, recent observations, such as in 2024, indicate a weakening of this inverse correlation. This highlights that bitcoin's performance is also influenced by broader global economic conditions and idiosyncratic events within the crypto market itself, as exemplified by the FTX collapse.

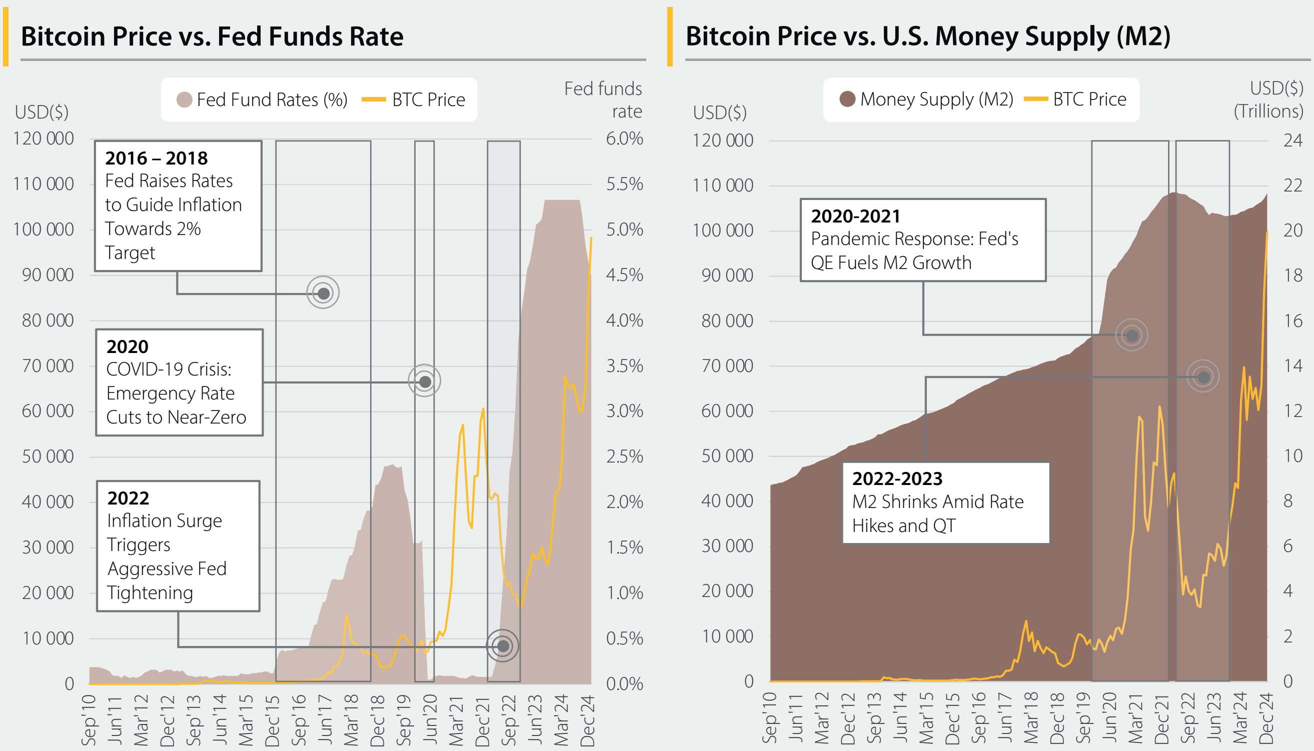
The influence of monetary policy on bitcoin returns

The increasing interconnectedness of traditional financial markets and cryptoassets is evident. Recent periods of historically low interest rates have fuelled investor demand for higher-yielding assets, with bitcoin emerging as a great beneficiary. Bitcoin's substantial rally in 2021 highlighted its responsiveness to an environment of ultra-accommodative monetary policy, suggesting it disproportionately benefited from the rapid decline in interest rates and significant increase in money supply, even more so than many traditional risk-on assets.

Figure 11(a) illustrates the relationship between bitcoin price and interest rates. Bitcoin's substantial rise during the pandemic aligned with a near-zero interest rate environment, as the Federal Reserve's expansionary policies injected liquidity into financial markets, fuelling demand for speculative assets like bitcoin.

Conversely, bitcoin's price downturn in 2018-2019 and its stagnation in 2022 align with periods of rising rates, as tightening monetary conditions dampened demand for high-risk investments. Interestingly, despite elevated rates in 2023 and 2024, bitcoin exhibited resilience and demonstrated a strong recovery amidst relatively high rates. However, this development was not unique to bitcoin; many high-growth assets, including technology stocks, displayed similar resilience, suggesting that investor confidence in selected growth and speculative sectors persisted even under stricter monetary conditions. The evolution of bitcoin price in this context underscores its sensitivity not only to interest rates but also to broader liquidity conditions shaped by monetary policy (see Figure 11(b)).

Figure 11: (a) bitcoin (BTC) price (in USD, left axis) versus the Fed funds rate (in %, right axis)); (b) bitcoin (BTC) price (in USD, left axis) versus U.S. money supply (M2) (in USD, right axis), from 1 September 2010 to 31 December 2024. Data source: Coin Metrics [45], Board of Governors of the Federal Reserve System (2025; [51])



This sensitivity to liquidity conditions became particularly apparent during the economic shifts following the COVID-19 pandemic. In response to the pandemic's onset, central banks, including the Federal Reserve, implemented aggressive quantitative easing (QE) measures, significantly expanding the money supply (M2) to support financial markets. This surge in liquidity fuelled investor appetite for riskier assets, likely playing a notable role in bitcoin's rapid ascent, which saw a near sixfold price increase from early 2020 to late 2021. However, this trend reversed sharply as inflationary pressures mounted. The Federal Reserve pivoted to quantitative tightening (QT) in 2022, contracting the money supply to curb rising prices. This abrupt shift to tighter liquidity conditions dampened demand for speculative assets, culminating in the broader 'crypto winter' of 2022. During this period, bitcoin's value declined sharply, exacerbated by market-specific challenges such as the failures of Terra Luna, Celsius, and FTX. These events clearly underscore how bitcoin's trajectory is shaped by the interplay of macroeconomic shifts, like the transition from QE to QT, and sector-specific events.

Interestingly, bitcoin rebounded substantially in 2023, and continued to rise in 2024, despite persistently elevated interest rates, suggesting that liquidity inflows continue to be a crucial driver of demand. This ongoing relationship between bitcoin and monetary conditions illustrates its unique position as a speculative, high-growth asset that thrives in times of ample liquidity but faces headwinds when monetary policy tightens.

Bitcoin: does its performance justify the 'digital gold' narrative?

As noted in previous sections of this report, a narrative has emerged, hailing bitcoin as digital gold, with proponents arguing that it functions as a modern, digital safe haven. Advocates of this view highlight bitcoin's decentralised, limited-supply structure, seeing it as a hedge against fiat currency debasement and inflation. However, the asset's relatively short history and significant volatility have led to mixed outcomes in its performance as a safe haven during times of economic turmoil. For instance, while bitcoin surged during liquidity expansions in the COVID pandemic, it sharply declined in response to 2022's geopolitical uncertainties – precisely at a time when traditional safe-haven assets such as gold saw more stable performance.

Gold, in contrast, has a long-established reputation as a safe haven, maintaining its value through centuries of market cycles and geopolitical disruptions. Its price typically rises during periods of economic stress and inflation, providing a buffer against fiat currency instability. This stability was evident during the Russia-Ukraine conflict, where gold exhibited relatively steady gains or held its value even as bitcoin suffered pronounced downturns.

This divergence fuels the ongoing debate over bitcoin's potential as a digital gold. While bitcoin's price gains in certain inflationary periods support the argument, its erratic response to broader economic shocks undermines its consistency as a safe haven. In many ways, bitcoin appears to occupy a hybrid role: it can act as a hedge against monetary expansion and currency debasement, but its high volatility and sensitivity to liquidity conditions suggest it has yet to rival gold as a stable sanctuary in times of broader market distress. For investors, this distinction underscores the likely complementary, rather than substitutive, roles that bitcoin and gold may play in diversified portfolios.

Final thoughts

Bitcoin's journey highlights its evolving role within global finance. While its limited supply and decentralised nature initially fuelled the 'digital gold' narrative, bitcoin's performance has demonstrated a considerable sensitivity to liquidity, monetary policy, and broader market sentiment. It has not consistently behaved as a safe haven during periods of geopolitical or economic uncertainty, and often exhibited notable positive correlation with other risk-on assets such as stocks. While bitcoin can offer diversification benefits within a portfolio, it should not be viewed as a direct substitute for gold or other traditional safe havens. It appears that bitcoin's current role is best understood as a unique, high-risk, high-reward asset whose long-term performance will likely depend on continued technological development, regulatory clarity, and broader adoption within the financial system.

II: Digital Mining Primer

Digital Mining epitomises the exchange of computational resources for crypto-native rewards. Despite controversies, this technology has continually advanced and solidified its role as the backbone that secures Bitcoin.

Satoshi Nakamoto's last-known forum post was made on 12 December 2010, and Nakamoto's last email was sent on 26 April 2011. Since then, despite increasing participation from institutional entities, development of the Bitcoin protocol has continued through a distributed, open-source process, primarily coordinated via the Bitcoin Core project. Bitcoin, as a purely digital, permissionless system (meaning anyone can participate without needing approval from a central authority), relies on its distributed ledger technology for transaction recording and validation. This is fundamental to its value proposition and sets it apart from legacy financial systems. To understand how this works in practice, this section describes the mechanics of the Bitcoin protocol, specifically focusing on the process of block creation and the crypto-economic incentive mechanism integral to achieving distributed consensus.

A Summary

Within the Bitcoin network, transactions are grouped into sequential blocks, forming an immutable chain – thus the term 'blockchain'. These blocks are validated and appended to the ledger by a distributed network of nodes – computers running the Bitcoin Core software, or other compatible implementations. This software is freely available for download and installation. Consequently, any individual with internet access and a suitable device can run a node, enabling participation in the creation, validation, and propagation of blocks. This open and permissionless design ensures the ledger's decentralisation, transparency, and global accessibility.

Insights

Different Types of Bitcoin Nodes

For this primer we focus on the Bitcoin network, as it is the network relevant to the majority of miners in our sample. The Bitcoin network consists of various types of nodes, each playing a crucial role in maintaining the integrity and functionality of the system:

Full nodes: Full nodes are the backbone of the Bitcoin network. They maintain a complete copy of the ledger, validate transactions and blocks against Bitcoin's consensus rules, and relay this information to other nodes. Full nodes ensure that all transactions comply with the protocol, and they reject any blocks or transactions that violate the rules. As of 2024, there are thousands of full nodes distributed globally, ensuring the network's decentralisation and resilience.

Mining pool servers: These are specialised servers run by mining pool operators that coordinate the collective hashing power of many individual mining hardware units (primarily ASICs), which are operated by pool participants ('miners'). Pool servers use specific protocols (like Stratum) to distribute work assignments and receive results. Critically, they incorporate full node functionality to interact with the Bitcoin network – validating transactions, building block templates, and broadcasting successfully mined blocks. They act as the central coordination point for most of the network's mining activity.

Mining nodes: A mining node enables participation in the creation of new blocks. It can operate independently on the network, similar to a setup used by a 'solo miner', or it can connect to a mining pool server to contribute hashing power to a collective effort. When operating independently, these nodes handle their own validation, block creation, and block propagation (requiring full node capabilities) and direct specialised hardware (ASICs) to perform the Proof-of-Work necessary to find a valid block hash.

Light nodes (SPV nodes): Light nodes, or simplified payment verification (SPV) nodes, do not store the entire blockchain. Instead, they rely on full nodes to verify transactions. SPV nodes are typically used in lightweight Bitcoin wallets, which require less storage and computational power.

While this overview focuses on Bitcoin-specific node types, for those who want to learn more about the broader landscape of actors and roles within distributed ledger technology (DLT) systems, we recommend consulting our prior research report, "Distributed Ledger Technology Systems: A Conceptual Framework".[52]

Why the reference to 'mining' in the context of creating new bitcoin?

The term 'mining' in the context of Bitcoin was first introduced by Satoshi Nakamoto in the original Bitcoin whitepaper published in 2008. Nakamoto used this term to draw a parallel between the process of creating new bitcoins and the extraction of precious metals like gold. In traditional mining, precious metals are extracted from the earth through labour-intensive work. Similarly, in Bitcoin mining, new bitcoins are generated as a reward for emerging as the first entity finding a valid solution to a cryptographic challenge, a process that requires significant computational effort.

The analogy served to make the concept of Bitcoin mining more accessible, particularly to those familiar with the idea of resource extraction and labour. By equating bitcoin creation with mining, Nakamoto underscored the effort and resources required to produce new bitcoins, thus highlighting their value. Moreover, 'mining' aptly illustrates the competitive nature of bitcoin creation. Like gold prospectors vying for precious metals, Bitcoin miners must expend considerable financial and physical resources in pursuit of rewards.

Despite its widespread use, the term 'mining' has been controversial. Critics argue that 'mining' implies the extraction of a physical resource, whereas bitcoin is created or 'minted' through computational processes.

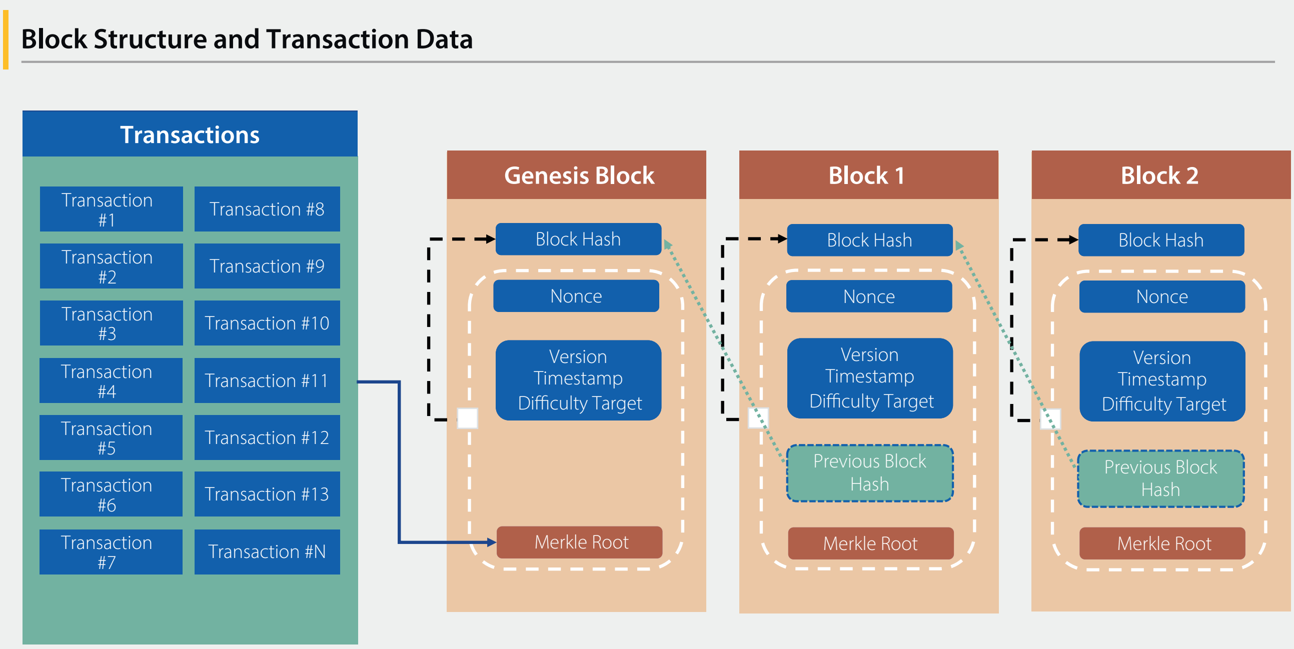
Some have suggested that 'minting' would be a more appropriate term, as it better reflects the creation of new currency rather than the extraction of materials from the earth. However, 'mining' has persisted in the lexicon, largely because of its effectiveness in conveying the concept to a broad audience.

The Process of Block Assembly

Transaction selection and validation

The process of block assembly in Bitcoin is central to its functionality as a secure, decentralised ledger. As illustrated in Figure 12, this begins with the selection of transactions from a node's memory pool (mempool), where unconfirmed transactions reside. Each transaction entering the mempool undergoes stringent validation against Bitcoin protocol rules, including verification of digital signatures, confirmation of sufficient sender balance, and a check to prevent double-spending. Only validated transactions proceed to the block assembly stage, where they are prioritised based on their associated fee rate (the fee paid relative to the transaction's weight or size). This fee-driven approach to transaction ordering, while not enforced by protocol, is widely adopted and standard in software implementations used to build block templates, as miners have an incentive to maximise their revenue.

Figure 12: Schematic representation of block assembly and blockchain structure. Source: Cambridge Centre for Alternative Finance



Block header construction, hashing, and immutability

While transaction selection is crucial, block assembly also involves constructing the block header, which contains critical metadata that links the block to the chain and ensures its immutability. The block header includes: the Merkle root, the previous block's hash (linking the blocks together), a timestamp, a difficulty target, and a nonce.

The Merkle root is a single hash value derived from all the transactions in the block through a process of repeatedly hashing pairs of transaction IDs (or intermediate hashes) until a single root hash remains. This structure, called a Merkle tree, allows for efficient verification of transaction inclusion.

Crucially, the block header also includes the hash of the previous block, creating a cryptographic chain where each block's integrity is inextricably linked to all preceding blocks. Because both the Merkle root and the previous block's hash are inputs to the hash function that generates
the current block's hash, any modification to even a single transaction within any prior block would invalidate all subsequent blocks. This cascading effect makes any alteration – and thus tampering – immediately detectable and would require re-mining all subsequent blocks, so that each block header again satisfies the difficulty target, which is considered a computationally prohibitive task in a network like Bitcoin. This combination of chained hashes and the avalanche effect is the foundation of the blockchain's immutability.

Insights

Understanding Cryptographic Hash Functions

A cryptographic hash function is an algorithm that takes an input (of arbitrary size) and produces a fixed-length output, often called a hash, hash value, or digest. Think of it like a digital fingerprint for data.

Here are the key properties:

Deterministic: The same input will always produce the same output hash.

One-way (pre-image resistance): It is computationally infeasible to determine the original input data given only the hash value. You can easily go from input to hash, but not the other way around.

Collision resistance: It is computationally infeasible to find two different inputs that produce the same hash value (a 'collision'). While collisions theoretically exist, finding such an occurrence is practically impossible in secure hash algorithms.

Avalanche effect: A small change in the input (even a single bit) leads to an entirely different output, which should appear completely random and unrelated to the original input.

Fixed-size output: The size of the output stays the same regardless of input size – whether it is a single letter or an entire novel.

To provide a practical example, imagine the SHA-256 hash function (the algorithm Bitcoin uses) is used to produce a hash value for the following input:

- Input: 'ccaf' → Output: *50896e7209436ff6eebc7e22b42ddbfcf7fa56c4f484684484ca12a2d816190b*
- Input: 'CCAF' → Output: *17c791bb0b94d53db4f09edbeb97b6d61c72c97201a3d94abe050f0a9f1b9a36*
- Input: 'CCAF!' → Output: *55672c6a6773b332709350cd51127fa787b3849394618163009b68269c6b712f*

Notice how changing the case from 'ccaf' to 'CCAF', or adding a single character ('!'), results in completely different and unpredictable hash values. This demonstrates the Avalanche effect and the sensitivity of the hash function to input changes.

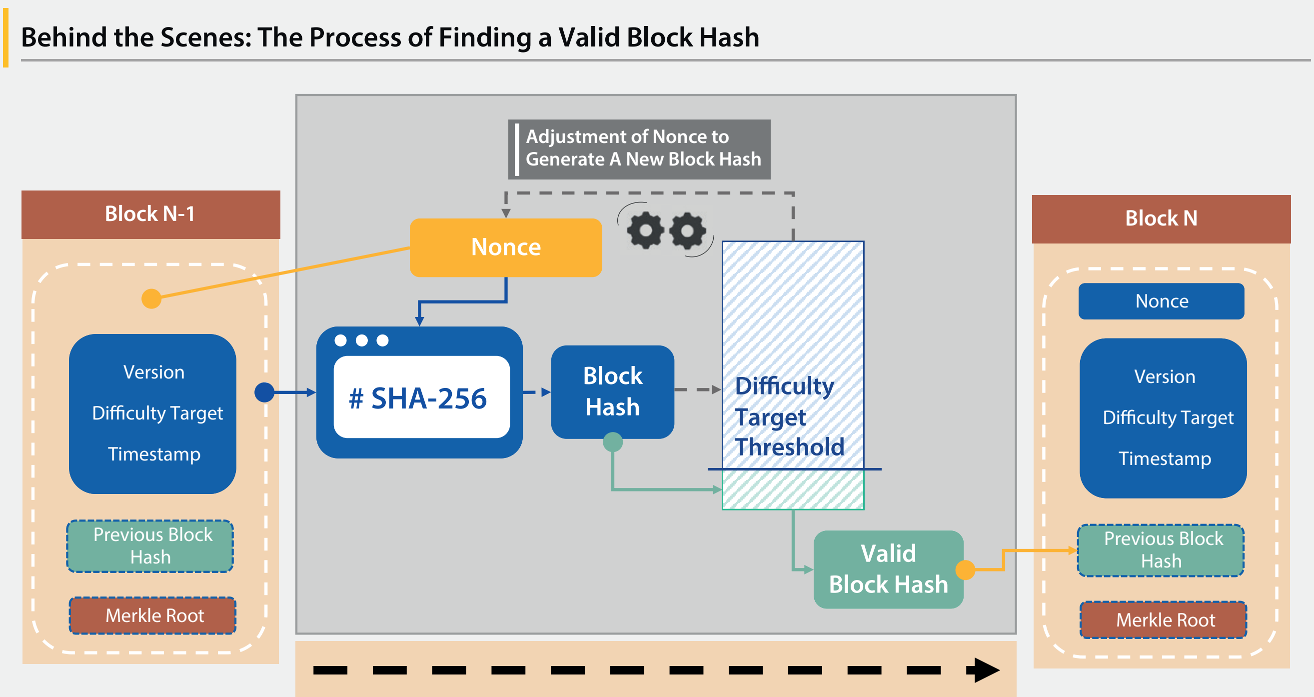
Proof-of-Work, A Key Mechanism Behind Bitcoin's Security

To secure decentralised networks like Bitcoin, PoW was introduced as a mechanism that makes misconduct computationally costly, thereby incentivising honest behaviour. In PoW systems, miners compete to solve a cryptographic challenge, which requires finding a nonce (i.e., an arbitrary number) that, when hashed with other block data, produces a hash value below a certain target threshold. This process is a brute-force trial-and-error approach, where miners repeatedly adjust the nonce and rehash the block header until they find a valid solution (see Figure13). To use an analogy, this process resembles a lottery where miners use processing power to generate vast numbers of 'tickets' (cryptographic hashes), racing to be the first to find any ticket that meets the network's specific winning criteria.

The scale of this computational effort is immense. At the time of writing, the implied computational power securing the Bitcoin network is close to 800 quintillion hashes per second – orders of magnitude greater than what the combined effort of the top 500 supercomputers worldwide likely can achieve (see Appendix C). Assuming the expected block time of 10 minutes, statistically, it would require about 480 sextillion trials to find a valid block hash. To put the number of trials into perspective, this is close to 70 times the approximated number of grains of sand in the Sahara Desert, or seven times the estimated number of stars in the observable universe.[53]

The difficulty of the challenge adjusts dynamically to ensure roughly predictable block times. Yet, it is important to note that the actual time it takes to mine a block varies and is unknown. A new block can be found in seconds, or it may take miners more than an hour to find a valid block hash. The dynamic adjustment of the difficulty threshold ensures that, on average, block times stay around 10 minutes, independent of any influx or withdrawal of computational power.

Figure 13: Simplified illustration of the mechanics behind Proof-of-Work, depicting the transition from one block (Block N-1) to the next (Block N). The diagram highlights the iterative process where a miner searches for a block hash that satisfies the difficulty target threshold by repeatedly adjusting the nonce. The resulting valid block hash serves as unforgeable proof of expended computational resources.
Source: Cambridge Centre for Alternative Finance



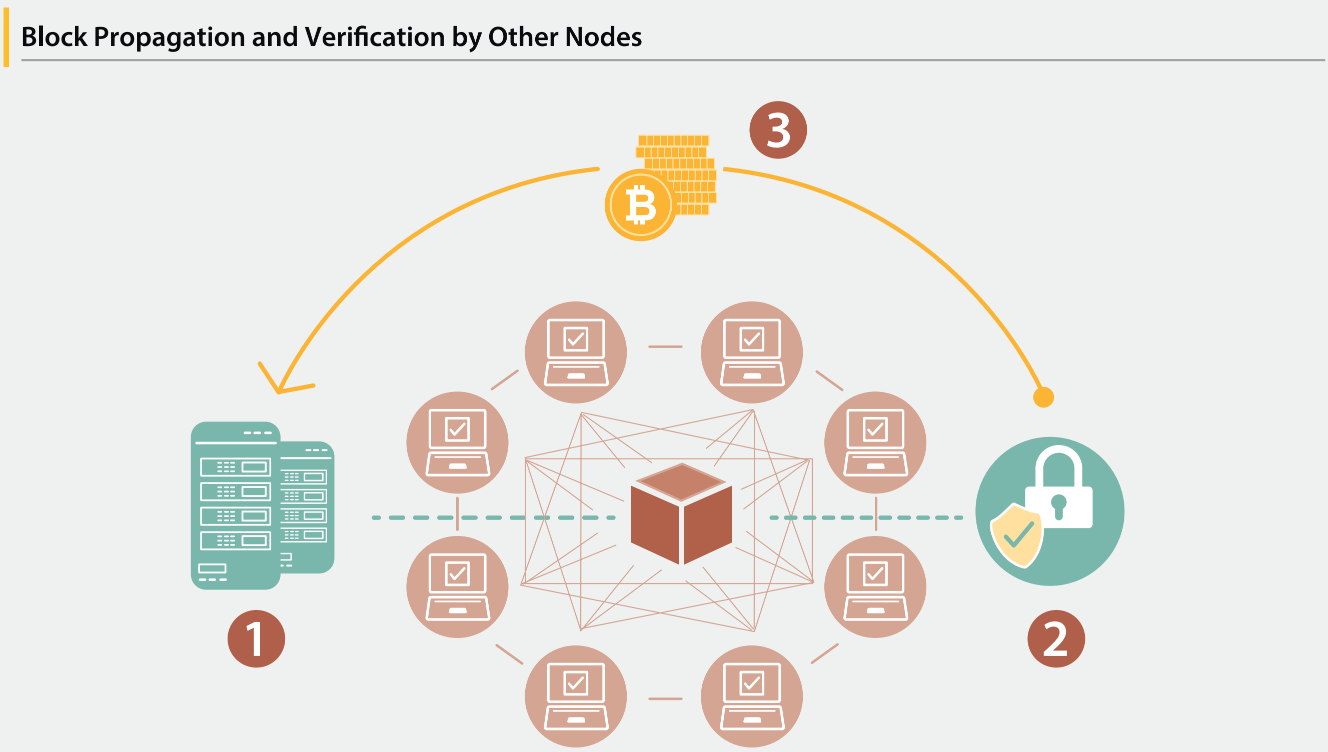
Block propagation and verification

Once a miner successfully mines a block, it is broadcast to the entire Bitcoin network (see Figure 14). Upon receiving a new block, nodes begin the verification process. This involves checking that the block adheres to all of Bitcoin's consensus rules. These rules include, but are not limited to: the block hash being below the target difficulty, ensuring all transactions within the block are valid, and confirming the block reward is correct. Notably, while generating a valid block hash is a resource-intense endeavour, the verification process is remarkably efficient as all inputs are known – including the nonce. Given the deterministic nature of the hashing algorithm, the same input must lead to the same output. This asymmetry – difficult to create, easy to verify – is a cornerstone of Bitcoin's security.

If a miner attempted to reward themselves with more than the allowed block reward, for example, 100 BTC instead of the correct amount (which reduces over time due to halving events), the block would be rejected by honest nodes. This is because the Bitcoin protocol specifies the exact amount that can be minted per block, which is currently 3.125 BTC (after the 2024 halving).

After verification, if the block is valid, it is appended to the node's copy of the ledger, and the network moves on to the next block. This decentralised verification process ensures that no single entity can control or alter the blockchain.

Figure 14: Block propagation and validation in a blockchain network, where a newly mined block is broadcast to other nodes, validated, and subsequently concatenated to each node's version of the ledger. Source: Cambridge Centre for Alternative Finance



Ensuring network security through a crypto-economic incentive mechanism

The primary purpose of mining in blockchain networks is to secure and maintain network integrity, achieved through a crypto-economic incentive model that discourages dishonest behaviour by aligning participant interests – namely, by encouraging miners to act honestly to maximise their profits and avoid losses. This incentive structure hinges on the balance between potential rewards and the significant costs of misbehaviour.

To participate in mining, miners make substantial upfront investments in specialised hardware and incur ongoing electricity costs. These capital and operational expenses create a powerful disincentive to act dishonestly, as cheating could result in lost rewards, representing an opportunity cost that outweighs any short-term gain.

To illustrate this, consider the following example: executing a 51% attack would require controlling a majority of the network's hashrate. Assuming the use of Bitmain Antminer S21 Pro, a modern purpose-built mining device, achieving sufficient computational power for such an attack would necessitate approximately 1.74 million units. Based on current market prices of $6,318 per unit,[54] this translates to a procurement cost of $11 billion. Additionally, it would incur a daily operating cost of $7.3 million, assuming an electricity rate of $50/MWh. It is important to note that this is a simplified illustration, and the true cost would undoubtedly be vastly higher. Procuring such a massive quantity of hardware would likely face significant supply chain constraints, potentially driving up prices and delaying deployment. Furthermore, operating this number of units would require substantial infrastructure, including access to 6.1 GW of power to meet the machines' energy demands, as well as extensive data centre infrastructure to house the equipment. Building or purchasing the required infrastructure would further incur considerable capital expenditure and time. While a thorough quantification of attack costs requires further research, Nuzzi et al. (2022;[55]) offer a more comprehensive assessment of attack vectors and their economic implications.

This example highlights the challenges associated with mounting an attack that serve as powerful deterrents to discourage dishonest behaviour. This reinforces the game-theoretic model underlying Bitcoin's security, where honest participation is incentivised. In this system, the Nash equilibrium – a state where no participant can improve their outcome by unilaterally changing their strategy – is achieved when all miners act honestly, following the rules of the protocol. If a miner attempts to deviate from these rules, such as by double-spending or creating invalid blocks, the network's consensus mechanism will reject these actions. This results in financial loss for the dishonest miner, as no rewards are received even if the block hash satisfies the difficulty criteria. This ensures that it is in the best interest of miners to act honestly, thereby maintaining network integrity. The result is a self-regulating system where economic incentives align with the network's security needs, making it resilient to attacks and manipulation.

Given the random nature of finding a valid solution to the cryptographic challenge, a return is not even certain for honest actors, as only the entity who first proposes the block reaps the reward. Over time, pool structures offering different payout mechanisms have emerged to address this uncertainty, which will be explored later in this section.

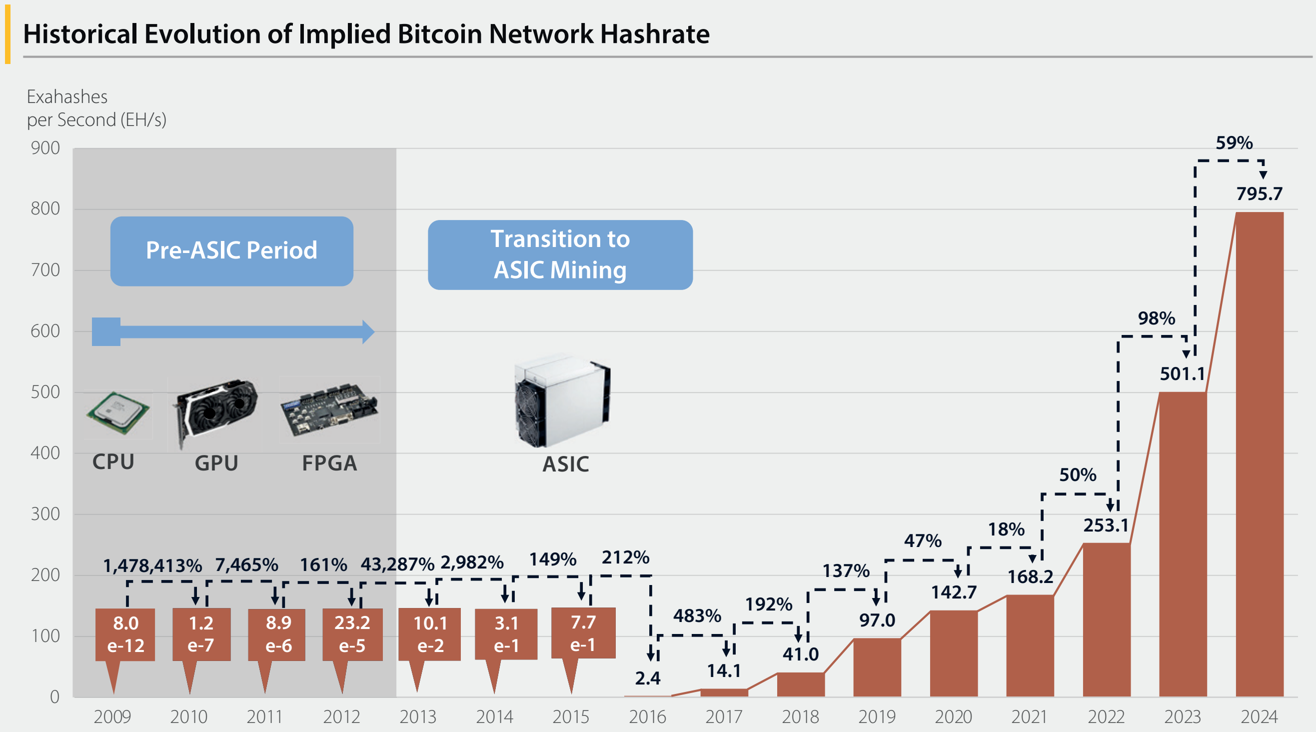
The Evolution of Network Hashrate

The computing power securing the Bitcoin network is commonly referred to as 'hashrate' and is usually expressed in the number of computations per unit of time. The magnitude of the computational power provided has vastly changed over time, as illustrated in Figure 15. A clear upward trajectory becomes apparent, with notable jumps corresponding to the introduction and widespread adoption of more advanced mining hardware. In the early years, the steep rise in implied network hashrate can largely be attributed to the low starting point of network activity, which initially consisted of only a few participants running Bitcoin on their personal computers. As interest in Bitcoin grew, the network effect spurred activity leading to a rapid growth in the user base. This coincided with the discovery of mining as a profitable activity, which quickly led to shrewd actors transitioning from CPU to GPU mining, then to FPGAs. The most transformative development, however, was the advent and rapid adoption of application-specific integrated circuit (ASIC) miners, ushering in the era of industrial-scale mining operations. This event catalysed a technological paradigm shift from the usage of conventional at-home devices such as GPUs, to purpose-built mining hardware deployed at industrial scale in specialised data centres, often referred to as 'mining farms'. This development fundamentally transformed the Bitcoin mining landscape. More information on the evolution of mining hardware will be provided in Part IV.

Following the initial surge caused by the transition to ASICs, hashrate growth generally stabilised, albeit with occasionally more pronounced fluctuations such as those seen in 2021 and 2023. This could occur for a variety of reasons, some more and some less obvious. In 2021, for instance, China's clampdown on mining spurred a significant drop in hashrate.[57] Conversely, 2023 witnessed a steep increase. The following year, 2024, has seen another notable YoY increase of nearly 295 EH/s, reaching 796 EH/s. An essential concept to consider in this context is the effect of rising hashrate on mining economics. As hashrate increases, so does the average rate at which blocks are solved, causing deviations from the protocol's target of a 10-minute block interval over each 2016-block adjustment period. To counteract this, the protocol adjusts mining difficulty roughly every two weeks (or 2016 blocks), ensuring that block times re-align with the 10-minute average despite the increased computational power. This difficulty adjustment mechanism is crucial for maintaining the stability and predictability of the Bitcoin network. Consequently, to maintain the same level of rewards, miners must continuously increase their own computational power in tandem with rising network hashrate.

This dynamic directly impacts the profitability of mining operations. From a user's perspective, a higher hashrate strengthens network security by making it more difficult for any attacker to reverse transactions or disrupt the network, but for miners, it can impose significant costs, as increased difficulty adversely affects their revenue.

Figure 15: The implied year-end Bitcoin network hashrate from 9 January 2009 to 31 December 2024, using a 7-day moving average and expressed in exahashes per second (EH/s)**.** Data source: Coin Metrics [56]



The relentless rise in hashrate, especially after the introduction of ASICs, has significantly reshaped the mining landscape. Although a higher hashrate bolsters network security by making it more resilient to attacks, it has introduced several challenges. The specialised technical expertise and substantial investment required to build and operate a competitive setup have raised entry barriers, deterring smaller participants who lack the resources or economies of scale necessary to mine effectively. This development has not been without controversy. Concerns have been raised about a trend towards centralisation, with some fearing that the industrialisation of mining inevitably leads to a concentration of mining power among a few large entities, thus standing in contrast to Bitcoin's decentralised ethos.

While the industrialisation of the landscape very likely led to dwindling numbers of at-home miners, a vibrant, geographically diverse landscape of professional mining firms has emerged. The risk of collusion among a group of larger actors also seems rather unlikely given the substantial capital commitments these actors had to take for hardware procurement and infrastructure development, which likely would become void after a successful attack on the network. Today, the topic of centralisation is more related to censorship concerns with a focus on mining pools, rather than individual miners.[58] This is because a few large mining pools control a significant portion of the network hashrate, creating the potential for censorship of transactions or blocks.

Mining Pools

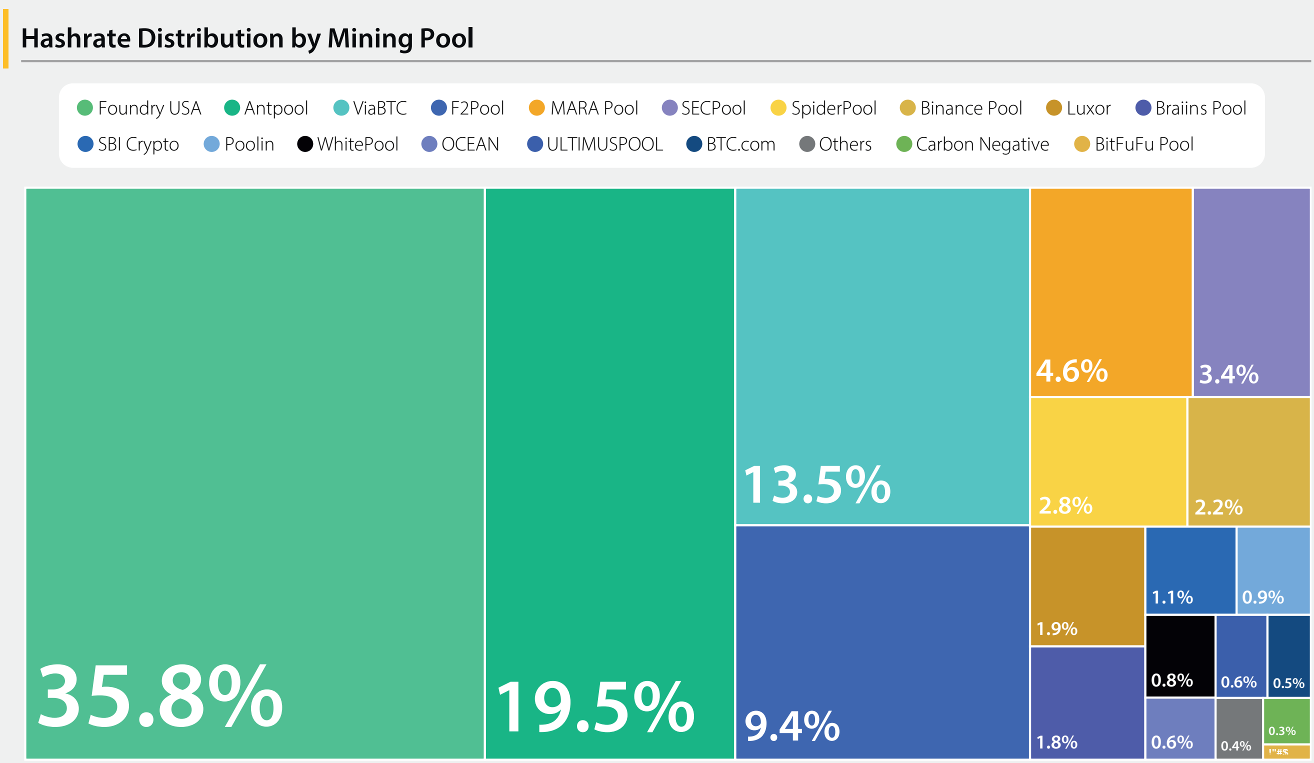
What are mining pools?

As the Bitcoin network has grown and mining has become increasingly competitive, individual miners have found it challenging to mine blocks and receive rewards consistently. This challenge arises from the sheer computational power required to solve the cryptographic challenge – in other words, the increasing difficulty of finding a valid block hash. To address this issue, miners formed so-called 'mining pools', which are groups of miners who combine their computational resources to increase their chances of finding a block and share the rewards. A mining pool is a collective of miners who combine their computational resources to increase their chances of successfully mining a block. By pooling their efforts, miners can receive more consistent payouts, as the likelihood of the pool solving a block is higher than that of any individual miner. When a block is successfully mined by the pool, the rewards are distributed among all participants based on their contributed computational power, known as 'shares'. Figure 16 provides an overview of the current mining pool landscape. It becomes apparent that there are a few dominant actors: Foundry (35.8%), Antpool (19.5%), ViaBTC (13.5%), and F2Pool (9.4%), who collectively control the large majority (>75%) of hashrate. This concentration can be attributed to several factors, including economies of scale, ease of use, and reliable infrastructure, which allows larger pools to offer more competitive payout structures and lower fees, attracting more miners.

Mining pools operate by coordinating the computational efforts of individual miners. Once a miner joins a pool, they connect their hardware to the pool's server, which provides a block template containing information such as recent transactions, the previous block hash, and target difficulty. The pool server assigns smaller, less difficult cryptographic challenges to each miner. These smaller tasks, referred to as 'shares', are partial solutions that involve finding nonces which meet a reduced difficulty target. This allows miners to demonstrate their computational contribution without the need to find a valid block hash. The pool server aggregates these efforts, coordinating and combining them to ultimately solve the full block, thereby distributing work efficiently among its participants. To ensure miners always work on the most profitable block, pool servers continuously monitor the network for new transactions and recently mined blocks, and accordingly, provide mining nodes with updated block templates.

When a miner successfully solves a share, it is submitted back to the pool server as proof of work, serving as evidence of the miner's contribution to the

Figure 16: Share of various mining pool operators on Bitcoin network hashrate (in %) based on a 6-month observation (as of 30 December 2024). Source: Mempool.space [59]



pool. This proof forms the basis for determining miner rewards. To that end, mining pools have adopted a variety of payout structures that enable their clients to select one that matches their desired risk-return profile. Some of the most common payout schemes are shown in Figure 17.

Risks stemming from the consolidation of mining power amongst a few pool operators

The concentration of hashrate in a few large mining pools has been an ongoing subject of controversy.[60] One of the key concerns raised is about the creation of block templates by pool operators. Essentially, these templates determine which transactions are included in the blocks being mined. As a result, the pool operators have significant control over the contents of the blocks, which introduces the potential for censorship – concerns that are not only theoretical but are supported by practical observations.[61] This centralisation of decision-making power within a few large pools means that a small number of entities could influence the selection of transactions, potentially excluding certain transactions or prioritising others based on criteria that may not align with the broader network's interests. This, on the surface, could be seen as detrimental to the decentralised ethos of Bitcoin and could undermine trust in the network.

Why centralisation may be less of an issue than expected

Despite these risks, the centralisation of mining power in pools may be less problematic than it appears at first glance. One reason is that miners retain ultimate control over their hardware. If a mining pool were to engage in misconduct, miners could quickly withdraw their hashrate from the pool. The ability to reallocate computational power nearly instantly acts as a deterrent against potential misconduct or undesirable behaviour by pool operators, a safeguard that has been demonstrated in practice.[62]

Additionally, mining pools are in constant competition with one another. This competition helps to prevent any single pool from gaining too much influence over the network. Despite some pools controlling a significant portion of the hashrate, the distributed and competitive environment makes it difficult for any single pool to exert disproportionate control without risking an exodus of miners. However, this safeguard may be subtly undermined by indications of proxy pool formations. These formations comprise ostensibly individual mining pools that, in practice, rely on block templates from another provider. Consequently, this dependency may inflate perceived decentralisation, as actual pool centralisation is likely greater than superficially apparent.[63]

Figure 17: Common payout structures of mining pools, along with the advantages and limitations of each structure.
Source: Cambridge Centre for Alternative Finance

Common Payout Structures Offered by Mining Pools

	Full Pay-Per-Share (FPPS)	Pay-Per-Last-N-Shares (PPLNS)	Pay-Per-Share (PPS)	Pay-Per-Share Plus (PPS+)	SOLO Mining
Description	Miners receive a fixed reward that includes both the block reward (subsidy) and transaction fees, based on their contribution to the pool's total hashrate.	The miner receives a share of the block subsidy and transaction fees that the pool successfully mines, proportional to the number of shares they contributed compared before a block was solved by the pool.	Miners are paid a standard fee for each valid share they submit, only from the block subsidy (not transaction fees).	A combination of PPS and PPLNS. Miners receive fixed payments for the block subsidy (PPS), and additional payments from transaction fees (PPLNS).	Miners work independently and receive the full block reward and transaction fees if they mine a block. There is no pooling of resources, but miners can benefit from the pool's infrastructure, including optimised block construction.
Advantages	Miners earn predictable income from both, block subsidy and transaction fees independent of a mining pool operator's performance.	Generally low mining pool fees. Dependence of miner payout on a mining pool operator's luck factor.	Lower mining pool fees compared to PPS+ and FPPS. More predictable income compared to PPLNS.	Combines the predictable income from block subsidy with transaction fees earned by the mining pool operator.	The miner keeps 100% of the block reward.
Limitations	Generally higher pool fees due to mining pool assuming entire risk of payout variability. No potential benefits from luck factor and pool-specific transaction fees.	Dependence of miner payout on a mining pool operator's luck factor.	Transaction fees not part of the payout.	Generally higher pool fees due to mining pool assuming risk of standard payout fee from block subsidy.	Substantial computational power required for reasonable chance to solve a block. Income highly dependent on one's own luck factor.

Innovation as another solution to combat the risks of centralisation

The current predominant communication protocol between miners and pool servers is Stratum V1, which was introduced in late 2012.[64] Before its introduction, mining pools operated using a more primitive protocol known as the getwork protocol. This approach required miners to frequently communicate with the pool server to receive work units, which involved significant data transfer and created inefficiencies. Stratum V1 revolutionised mining by streamlining the communication between miners and pool servers. It allowed miners to request only a minimal amount of data and generate new work independently, reducing the need for constant communication with the pool server. This not only increased efficiency but also significantly reduced latency, allowing miners to work more effectively and leading to higher network stability.

However, as mining continued to evolve and centralisation concerns grew, the limitations of Stratum V1 became more apparent. Major shortcomings of Stratum V1 included its lack of encryption, which made communication between miners and pool servers vulnerable to attacks, and its centralised job assignment model, which, as discussed previously, has led to concerns around potential censorship. These limitations paved the way for Stratum V2, which builds on the foundation of its predecessor while addressing some of its shortcomings. Stratum V2 offers enhanced decentralisation by allowing miners to create their own block templates, giving them more control over the mining process and reducing the risk of centralised power within pools. Additionally, it introduces end-to-end encryption, further securing the communication between miners and pool servers. Newer protocols also push decentralisation: DATUM, for example, increases miner autonomy by requiring block template construction on the miner's own full node, while proposals like Braidpool aim for fully decentralised pools without central operator control.

III: Survey Methodology

The CCAF conducted a targeted survey of digital mining firms to gather representative insights into the industry's operations, market sentiment, and environmental impact.

Survey Overview

Introduction

Between June and September 2024, the CCAF conducted an online survey targeting companies whose business models were fully or partially related to the minting of digital currencies. The purpose of the survey was to provide a representative and in-depth understanding of digital mining operations, market dynamics, and environmental considerations.

Participant recruitment and vetting

Participants were registered individually following a vetting process to ensure eligibility. This process combined advice from well-connected industry stakeholders, independent desk research, and verification of company details through public registers. Upon successful vetting, participants received a personalised link to a secure web-based questionnaire hosted on Qualtrics. These measures were taken to maintain data integrity and confidentiality.

Recruitment efforts included collaboration with key industry stakeholders such as the Bitcoin Mining Council, as well as outreach through messaging platforms like WhatsApp, Telegram, and social media. Prospective participants were either directly invited to register or directed to a registration form to submit the required information. A total of 97 companies registered for the survey and 49 completed it, yielding a response rate of 50.5%. The most common reason cited for non-completion was the survey's comprehensiveness, both in terms of time commitment and the granularity of the questions. Only complete responses were included in the analysis.

Survey design and structure

The survey consisted of 25 questions organised into three thematic segments. The first segment, Operations, included ten questions addressing organisational and technical aspects of digital mining. The second segment, Markets and Industry Sentiment, featured eight questions designed to assess market dynamics and participants' perceptions of the industry. The third segment, Environment, contained seven questions exploring the industry's environmental footprint. For a complete list of survey questions, please refer to Appendix D.

To ensure accessibility for a global audience, the survey was available in English and Chinese. The questionnaire utilised various formats to capture comprehensive data, including single and multiple-choice questions, open-ended responses, input fields for numerical data, slider-based questions for quantitative or qualitative assessments, and rating scales where participants evaluated topics on a scale of one to five. Questions were a mix of mandatory and optional, with some follow-ups dynamically tailored based on prior responses. This design allowed the survey to remain focused on the primary areas of interest while adapting to the specific contexts of individual respondents.

Respondent Profiles

Business structure and profile

Analysis of the survey responses yielded valuable insights into the structure and operational focus of the participating organisations. Of the respondents, 40.8% were publicly listed companies, while 59.2% were privately held (see Figure 18(a)). Notably, 98.5% of the total power capacity reported was dedicated to Bitcoin mining, with only 1.06% allocated to other cryptoassets and 0.46% to high-performance computing (HPC) (see Figure 18(b)). The overwhelming emphasis on Bitcoin mining is indicative of its central role in the industry, particularly following Ethereum's transition to PoS. This dominance informed the survey's focus on Bitcoin-related operations to enhance the relevance and quality of findings. Consequently, while acknowledging the broader digital mining landscape, the report will primarily concentrate on Bitcoin mining, with exceptions explicitly noted.

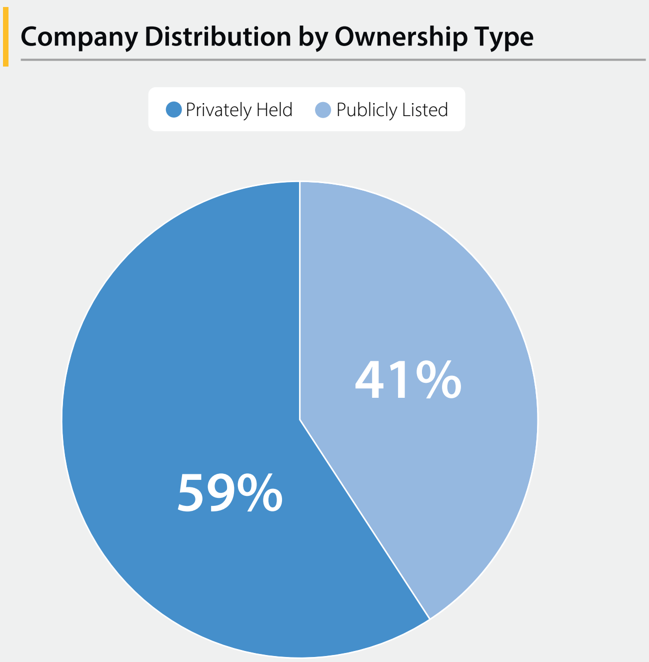
While HPC and other cryptoasset mining activities represented a small fraction of the reported power capacity, these segments possess distinct economic characteristics that are worth noting. HPC, for instance, boasts a substantially higher revenue potential per unit of electricity compared to Bitcoin mining. However, this advantage is offset by significantly greater capital expenditure (CAPEX) requirements, making a direct comparison less meaningful (further details are provided in Part IX). The divergent investment profiles of these activities illuminate the driving force behind the prevalence of Bitcoin mining: its comparatively lower barrier to entry, in terms of upfront capital, renders it a far more accessible option for a wider range of participants.

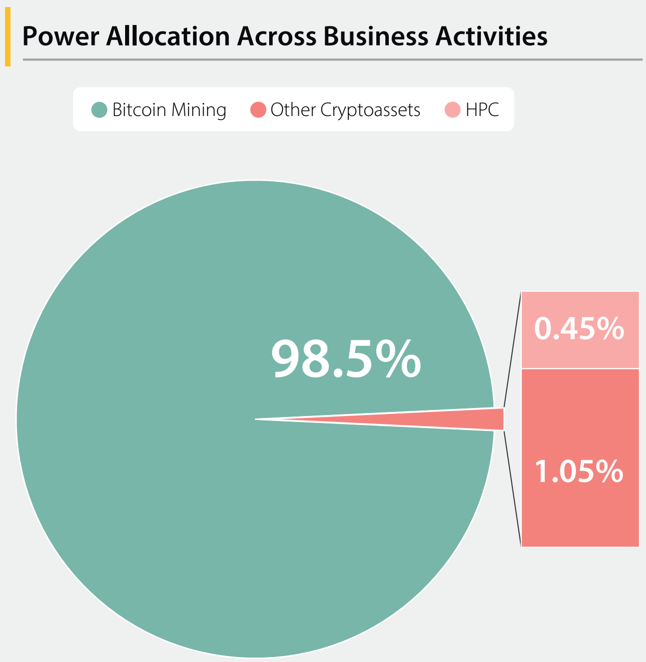
Data validation and integrity

To ensure the validity and reliability of the data, a robust validation process was implemented. When unusual values were identified, respondents were contacted for clarification. If a response was received, the data was updated accordingly. In cases where no response was received but the intent was clear, adjustments were made to reflect the intent – for example, where direct and/or all-in electricity rates were apparently provided in \$/kWh instead of \$/MWh. Where ambiguity persisted, the affected data was excluded from the analysis. These measures ensured the dataset maintained a high degree of accuracy and reliability.

Where applicable, weighting mechanisms were applied to adjust for regional or operational imbalances. All instances where weighting was used are explicitly stated in the relevant data sections. This transparency is essential to provide clarity on the data adjustments and enhance the reliability of the findings.

Figure 18: Distribution of companies by ownership type (in %); and (b) distribution of power between business activities (in %) as of 30 June 2024. The data shown in Figure 18(b) is weighted based on power capacity. Source: CCAF Survey. Sample size: (N=49)





Sample representation

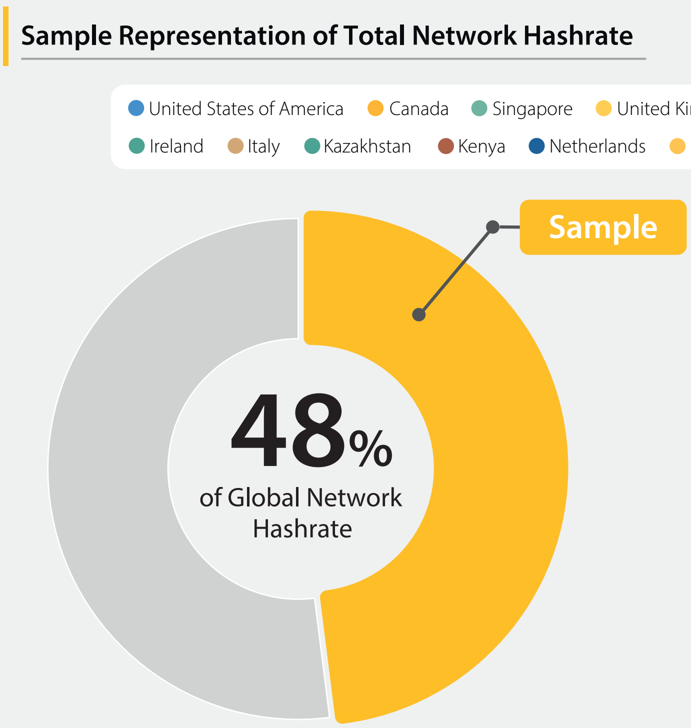
The survey's final sample represented a computational power of 268 EH/s, equivalent to 48% of the implied Bitcoin network' hashrate (as of 30 June 2024). This corresponded to a power capacity of 7.3 GW, comparable to the power consumption of the Czech Republic. Respondents' headquarters were located in 16 different countries (see Figure 19(b)), with operational activities spanning 23 countries (see Figure 20).

While the sample exceeded expectations in terms of computational power, the study acknowledges potential geographical biases. Mining activity in regions such as the United States may be overstated, while operations in regions such as Russia, Africa, and parts of the Asia-Pacific may be underrepresented. This is attributed to variations in survey participation across regions. In any future iterations, particular attention will be given to address these biases by reinforcing regional outreach efforts through seeking collaborations with local partners and offering the survey in additional languages.

Geographical Distribution of Mining Activity

While Figure 19(b) offers insights into the geographical distribution of respondents' headquarters, it is important to recognise that a company's headquarters location does not always align with the location of its operational activities – an important distinction when assessing the global footprint of the industry. Although the survey does provide valuable data on the geographical distribution of mining activity, it is important to acknowledge the inherent difficulties in accurately mapping this distribution. As discussed in the previous section, potential biases in survey participation can affect the representativeness of the findings. However, these challenges extend beyond the scope of this survey, as pinpointing the precise location of Bitcoin mining operations has long been a complex issue for researchers and industry participants alike. Over the years, various methodologies have been devised to explore this, each with its own strengths and limitations.

Figure 19: Survey coverage of total implied Bitcoin network hashrate; and (b) distribution of participant headquarters by country (as of 30 June 2024). Source: CCAF Survey. Sample size: (N=49)



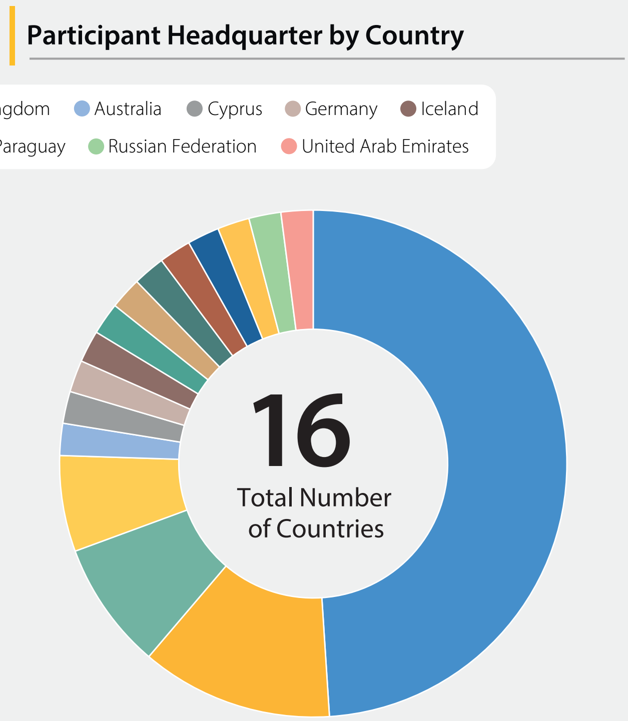
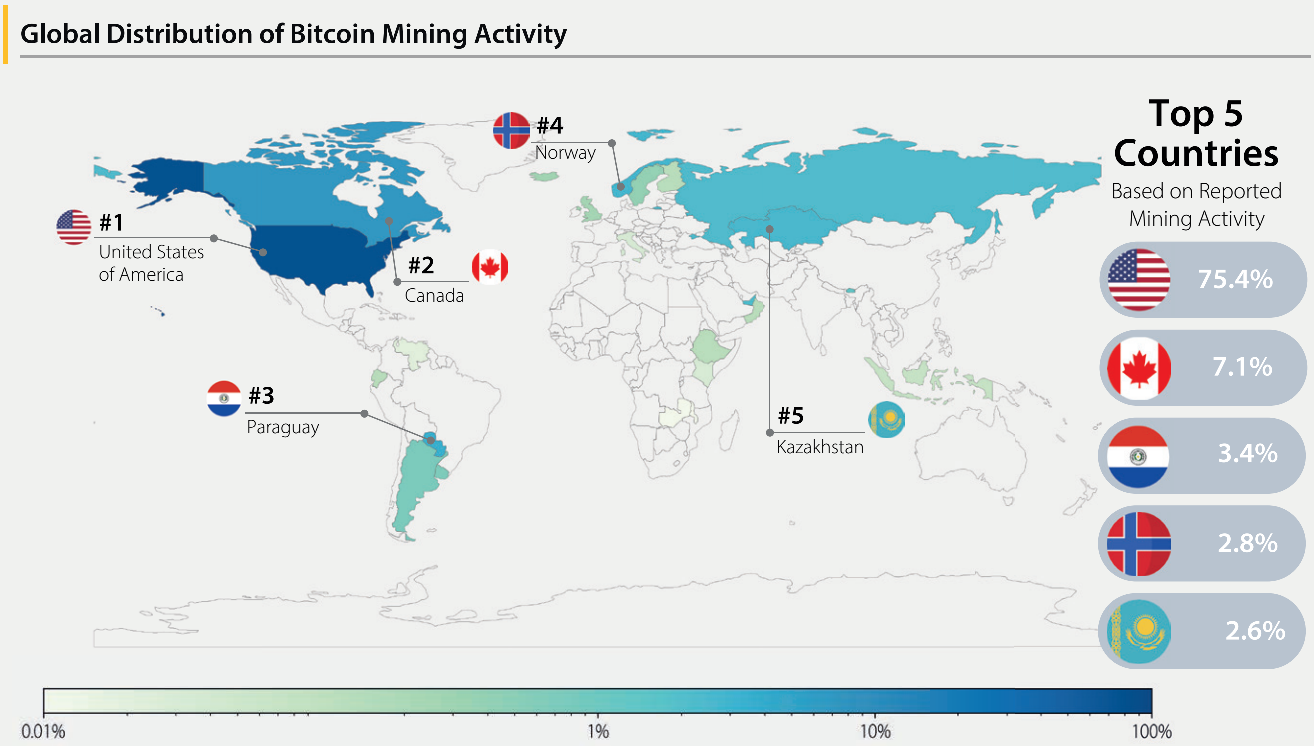


Figure 20: Global distribution of Bitcoin mining activity by country (in %) based on survey responses, highlighting the top five countries by reported activity (as of 30 June 2024). In addition to these, activity has also been identified in the following countries: Russian Federation (2.26%), United Arab Emirates (2.17%), Bhutan (1.35%), Argentina (0.72%), Uruguay (0.69%), Sweden (0.39%), Iceland (0.27%), United Kingdom (0.24%), Ecuador (0.12%), Oman (0.12%), Finland (0.12%), Ethiopia (0.12%), Indonesia (0.07%), Kenya (0.03%), Italy (0.03%), Venezuela (0.02%), Zambia (0.01%), and Malawi (0.00%). Responses are weighted by the reported power consumption of participants. Source: CCAF Survey. Sample size: (N=49)



The primary challenge lies in how Bitcoin's network operates. Mining nodes typically communicate directly with mining pool servers, which act as intermediaries. Consequently, only the mining pool itself can infer the origin of the hashrate based on its connected nodes, while the wider network can only identify the location of the pool servers. Since these servers may be geographically distant from the actual mining activity, the true geographical distribution of hashrate remains elusive.

Our research centre previously developed the CBECI Mining Map to address these challenges. This interactive digital tool traced the geographical distribution of mining activity by collaborating with mining pools. This approach provided a unique opportunity to track mining activity at the country level and, in some cases, even observe intra-country trends, such as historical seasonal migrations of mining activity within China.[65a]

While the CBECI Mining Map offers valuable historical insights, its data has become outdated, with the last available update dating back to January 2022.[65b] Regulatory changes, such as China's clampdown on digital mining [66] and similar but less severe actions in Kazakhstan [67], likely have notably altered the global mining landscape. As a result, the map now offers a historical perspective rather than a contemporary view.

This lack of up-to-date geographical data has significant implications, particularly when assessing Bitcoin's environmental impact. Methodologies that estimate CO_2 or greenhouse gas (GHG) emissions often adopt a location-based approach, tying emissions to the electricity mix of the regions where mining occurs. Relying on historical data can inadvertently distort these calculations. As mining operations relocate, the electricity mix associated with them may shift dramatically, altering the resulting environmental footprint. Using outdated data in location-based models risks producing estimates that no longer reflect the status quo, underscoring the importance of utilising contemporary data for reliable results. This topic will be explored in greater detail in Part VI.

A contemporary perspective on the geolocational distribution of mining activity

To address the prevalent issue of outdated data on the geographical spread of Bitcoin mining activity, which was previously obtained from mining pools, this survey of individual mining firms provides a fresh perspective, reflecting key trends in the industry. While the data offers valuable insights, it is important to acknowledge potential biases in the survey's participant composition. Miners in countries such as the United States showed a considerably higher level of engagement than other countries. Therefore, the specific country percentages warrant cautious interpretation. Yet, despite these limitations, the survey highlights several interesting directionally relevant developments in global mining activity that occurred since the publication of our last CBECI Mining Map update in 2022.[65b]

Figure 20 shows that, based on survey data, the United States firmly established itself as the largest global Bitcoin mining hub, accounting for 75.4% of respondents' mining activity. However, as mentioned previously, the precise figure should be viewed with care. While the U.S. clearly stands as the pre-eminent hub for Bitcoin mining, quantifying the exact level of activity remains challenging, with estimates varying greatly – other sources, for instance, suggest a considerable but much lower share of 36%.[68] In our survey, Canada ranks second with 7.1%, which generally underscores North America's central role in the digital mining ecosystem. South America has also seen increased activity, led by Paraguay (3.4%), marking a stark contrast to prior CBECI Mining Map data where the region played a much less significant role.

In the Middle East, the UAE stands out, accounting for 2.2% of activity, while in Europe, activity remains largely concentrated in the Nordics, led by Norway at 2.8%. Africa, while still a smaller player on the global stage, has some emerging activity, with Ethiopia (0.1%) showing signs of increasing prominence. It is plausible that some countries, for example Ethiopia, may already host significantly more mining activity than the survey results indicate.[69]

Similarly, while survey responses indicate that Russia accounts for only 2.3% of the global hashrate, there is evidence that mining activity in the country is significantly higher.[70] However, recent regulatory developments in Russia, including regional bans and a newly proposed taxation framework, are likely to weigh on future mining activity.[71] In the Asia-Pacific region, participation in the survey was limited, with the Kingdom of Bhutan emerging as a notable exception, accounting for 1.36% of the reported hashrate. No data on hashrate was collected from China, which until a few years ago was the global mining hotspot. Reports indicate that some mining activity still exists within China, albeit on a much smaller scale.[72] Yet, other reports contend that despite its reduced visibility, China may still host a meaningful share of global mining operations.[73]

Goals and Limitations

The survey aimed to achieve three primary goals: (i) to inform policymakers; (ii) provide benchmarks for industry stakeholders; and (iii) contribute to academic research. To support these objectives, the study sought to mitigate inherent biases by improving regional representation and accessibility. While the current survey was offered in English and Chinese, future iterations will expand language options to encourage broader participation.

By focusing specifically on Bitcoin mining, the survey streamlined its scope to minimise ambiguity and enhance data quality. While some limitations and biases remain, in most cases they are not expected to materially affect the overall findings, as operational expenses in Bitcoin mining are largely standardised globally, given the competitive nature of the sector. This standardisation enables meaningful comparisons and ensures that the insights derived from the survey are robust and reliable.

IV: Hardware and E-Waste

The evolution of digital mining hardware tells a remarkable story. This section explores its history, examines technological paradigm shifts, and considers its environmental impact.

In digital mining, the rapid development of new, more powerful and efficient hardware has spurred an arms race, among manufacturers and miners alike, where relentless innovation or the ability to deploy state-of-the-art devices dictates competitive survival. This section traces the remarkable evolution of this hardware, from the era of general-purpose CPUs to the highly specialised ASICs that now dominate, and reveals intricate insights into market shares of hardware manufacturers and firmware providers, as well as observes end-of-life strategies and the sector's contribution to e-waste.

The Evolution of Mining Hardware

A miner's hashrate and the energy efficiency of their operations are largely determined by the characteristics of the hardware they employ. Given that electricity costs constitute the vast majority of a mining firm's operating expenses (as shown in Part VII), there is a strong incentive for miners to regularly upgrade their mining fleet. The resulting turnover, or 'churn', of hardware naturally comes with environmental implications in the form of e-waste.

The early days, from CPUs to FPGAs

During the first years after Bitcoin was launched, mining was a rudimentary process. The network was small, and computational demands were modest, allowing early adopters to mine blocks using standard personal computers. This era, which began with the launch of Bitcoin in 2009, was characterised by the use of CPUs. CPUs, which are general-purpose processors designed to handle a wide range of tasks, were sufficient to meet the early computational demands of the Bitcoin network.

However, as bitcoin gained value and popularity, the network expanded and competition for block rewards intensified. The increasing difficulty of mining led to a demand for more powerful and efficient hardware, catalysing the first significant transformation in mining technology. By October 2010, miners had begun using GPUs, which were originally designed for rendering graphics in video games. GPUs are better suited to perform many operations in parallel, making them a more efficient tool for mining than CPUs. This efficiency gain made GPUs the preferred hardware, but the leap in performance was short-lived.

Insights

What are ASICs and why are they used in Bitcoin mining?

An Application-Specific Integrated Circuit (ASIC) is a specialised microchip designed to excel at one specific task with remarkable efficiency. In Bitcoin mining, that task is calculating SHA-256 hashes, a core component of the cryptographic algorithm that ensures the Bitcoin network's security and functionality. Given the competitive nature of mining and the financial rewards at stake, miners are driven to use the most powerful and efficient hardware available to maximise their chances of earning rewards while keeping costs low.

ASICs vastly outperform general-purpose processors like CPUs and GPUs when it comes to calculating these hashes. If a CPU is like a Swiss Army knife – versatile but not particularly exceptional at any one task – an ASIC is more like a precision-engineered surgical tool, designed to do one thing extraordinarily well. This laser-focused specialisation means ASICs consume far less energy per unit of computing power and pack significantly more computing power into a smaller space (i.e., high computational density) compared to CPUs, GPUs, or even FPGAs.

The arrival of ASIC miners revolutionised Bitcoin mining. It drove a tremendous increase in the network's hashrate, which in turn required constant adjustments to mining difficulty to maintain Bitcoin's predictable block issuance schedule. It also ushered in an era of industrial-scale mining operations, which now dominate the scene. Today, ASICs are the gold standard for Bitcoin mining, playing an indispensable role in securing the network.

In 2011, FPGAs emerged as the next step in the evolution of mining hardware. FPGAs offered significant advantages over GPUs due to their flexibility in hardware and software configuration. While more labour-intensive to set up and optimise, FPGAs were faster and more energy-efficient than even the most advanced GPUs, making them well-suited for the increasingly competitive world of Bitcoin mining. This marked a shift towards more specialised hardware, setting the stage for the next evolution in mining technology.

Modern-day mining, a shift to purpose-built devices

The relentless pursuit of greater performance and efficiency culminated in a third generational shift, namely the development of ASICs. ASICs are custom-designed chips built to perform a specific task rather than being suitable for general-purpose applications. The first generation of ASICs was announced in 2012, with the first commercial deliveries arriving in 2013. These devices quickly dominated the mining industry, rendering previous hardware obsolete due to their superior efficiency and computational power.

The most significant technological advancement in ASICs since their inception has been the progressive reduction in chip size. In semiconductor manufacturing, smaller chip sizes typically lead to greater efficiency, as smaller transistors require less electrical power to transmit data. The first ASICs were built using a 130 nm (nanometre) process, but by 2024, cutting-edge ASICs had shrunk to just 3 nm. This reduction has dramatically increased the efficiency and power of mining hardware, allowing miners to solve more hashes per unit of electricity consumed, as illustrated in Figure 21.

However, the pace of technological advancement in mining hardware has begun to slow. The rapid leaps in computational power and efficiency that characterised the early years of ASIC development have given way to more incremental improvements. This slowdown reflects the maturation of mining technology and the challenges of further scaling semiconductor technology, a trend often discussed in the context of Moore's Law. As chip feature sizes approach the practical limits of current fabrication techniques, further improvements become increasingly challenging and costly. Despite this trend, manufacturers have demonstrated renewed progress since 2023, achieving significant efficiency gains. If they meet their projected performance targets (see Figure 22), rapid technological advancement may continue into 2025.

The trajectory of technological innovation is a crucial factor influencing the competitive landscape of the ASIC market. Competition within this market remains fierce, with a few dominant players vying for market share. The following section provides an overview of the current market structure and examines the dynamics in ASIC manufacturing and firmware usage.

Figure 21: Historical evolution of ASIC (SHA-256) mining hardware efficiency and hashrate from 1 November 2013 to 31 December 2024. Data source: ASICMinerValue [74]

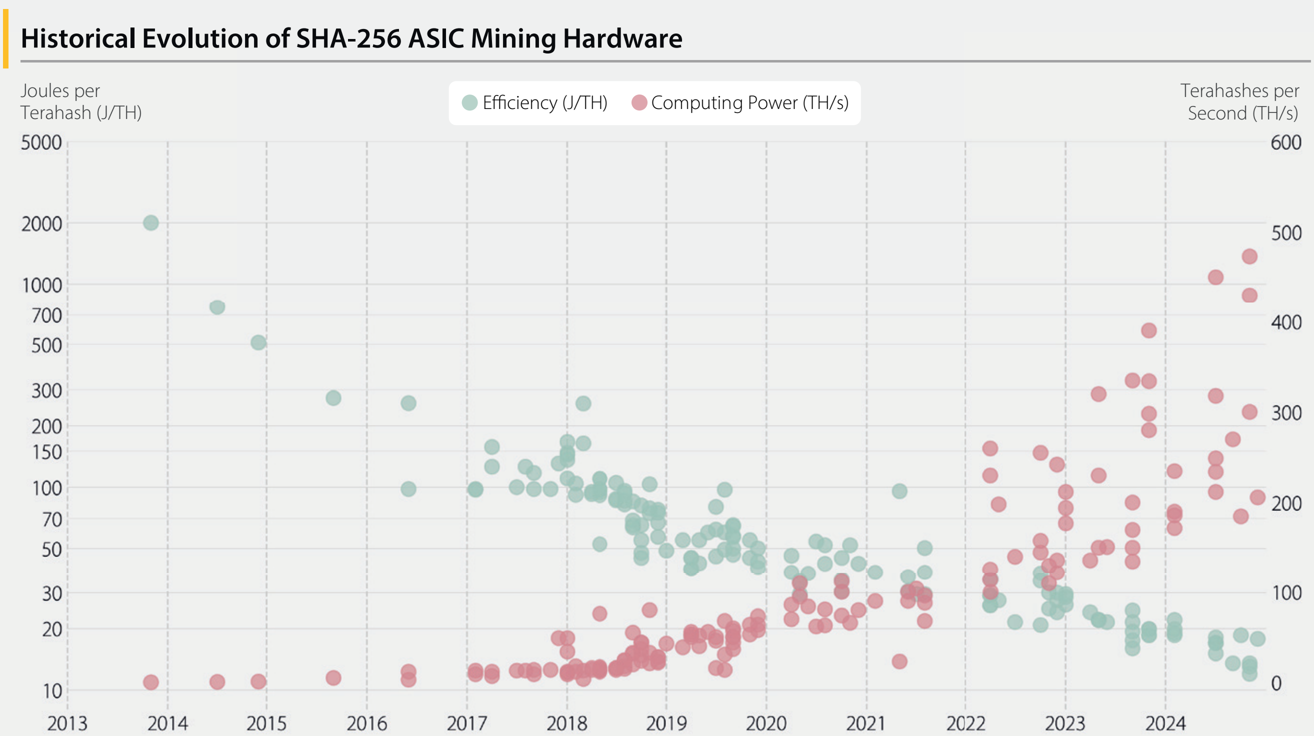
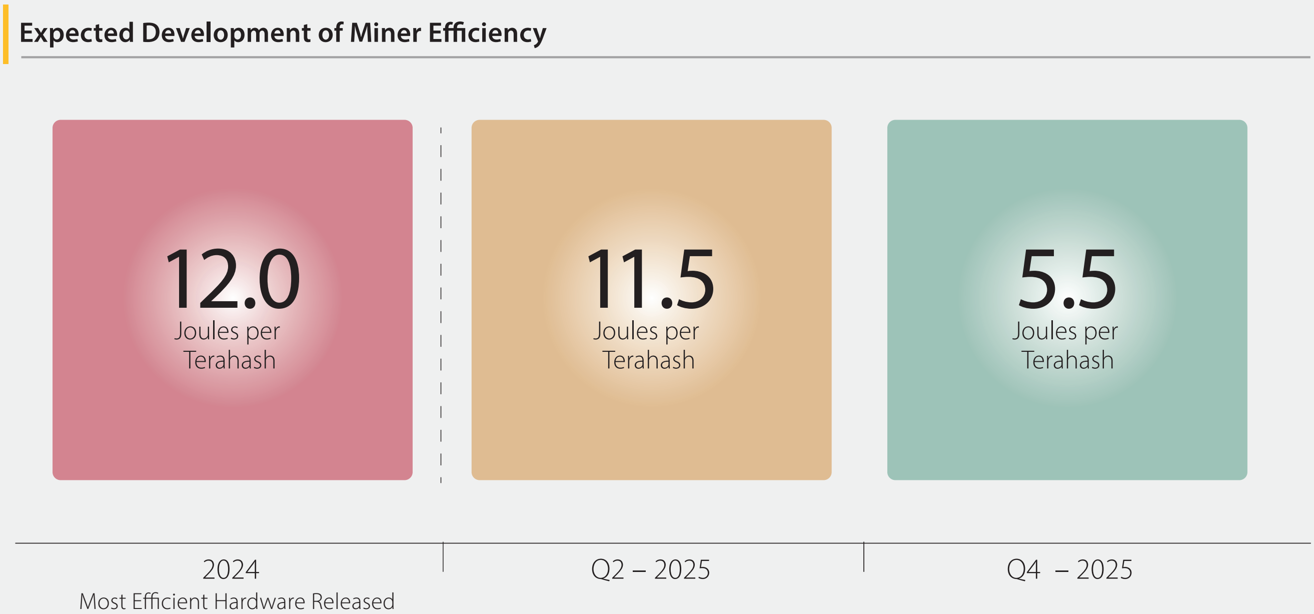


Figure 22: Expected average efficiencies (in J/TH) of anticipated next-generation ASIC (SHA-256) mining devices. Source: TheMinerMag [75]



ASIC Market Structure and Firmware Usage

Hardware market

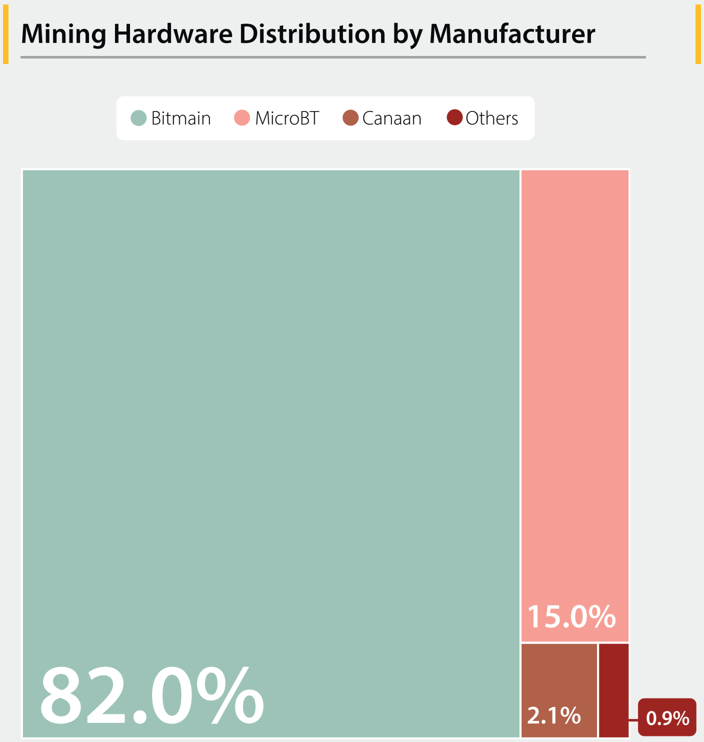
As illustrated in Figure 23(a), the market for ASIC mining devices demonstrates oligopolistic tendencies. Bitmain dominates the landscape, commanding an overwhelming 82.0% market share, followed by MicroBT (15.0%) and Canaan (2.1%). Collectively, these three manufacturers account for over 99% of the entire ASIC market. Other named manufacturers, including Bitfury, Auradine, ePIC, Bit Mining, Iceriver, iPollo, and Goldshell, make up the remaining fraction, illustrating the currently minimal foothold of smaller players.

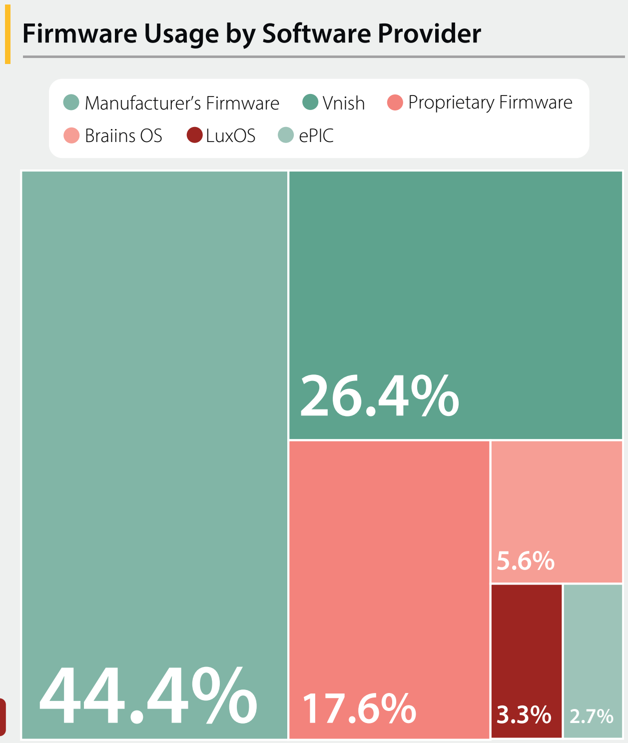
This concentrated market structure is unsurprising to those familiar with the industry. The dominance of a few key players has long been a topic of debate, [76] raising questions about market power and the potential for disruption. While new manufacturers continue to announce their intentions to enter the market, the barriers to entry remain formidable. Competing effectively with entrenched incumbents requires substantial capital investment, deep technical expertise, and critical access to semiconductor foundries. Despite these challenges, some new entrants, such as Bitdeer, Auradine, and Proto, are gaining traction with notable pre-orders and backing from established digital mining firms.[77] The future will tell whether the ASIC market is indeed ripe for disruption, or the concentration among a few manufacturers will remain.

Firmware providers

Turning to firmware, the landscape appears more fragmented (see Figure 23(b)). Stock firmware remains the most popular choice, used by 44.4% of miners. However, third-party firmware providers also play a significant role, with Vnish leading at 26.4%. Notably, there is a growing tendency among mining firms to develop custom firmware, tailored to their specific operational needs, which accounts for 17.6%. Other third-party providers such as Braiins OS (5.6%), LuxOS (3.3%), and ePIC (2.7%) constitute the remaining distribution.

Figure 23: Market share of ASIC (SHA-256) manufacturers (in %); and (b) the market share of firmware providers (in %), as of 30 June 2024. Responses of (a) and (b) are weighted by the reported hashrate of participants. Source: CCAF Survey. Sample sizes: Figure 23(a) (N = 46), Figure 23(b) (N = 31)





Insights

What is Firmware and Why is it Important?

Firmware is the specialised software that controls and optimises the operation of mining hardware, particularly ASICs. Think of it as the brain that directs the intricate workings of these powerful machines. It acts as an intermediary between the mining hardware and the mining pool, managing the complex calculations required to mine Bitcoin and ensuring the hardware runs efficiently. While seemingly less prominent than the hardware itself, firmware plays a critical role in determining the overall performance, stability, and profitability of mining operations.

Essentially, firmware dictates how effectively an ASIC utilises its computational power to calculate SHA-256 hashes, the core cryptographic function that underpins Bitcoin's security. Well-designed firmware can fine-tune various parameters, such as clock speeds and voltage, to maximise hashrate output while minimising power consumption. This optimisation directly impacts a miner's ability to compete for block rewards and maintain profitability in the highly competitive mining landscape.

The firmware landscape is diverse. While many miners rely on the manufacturer-provided firmware that comes pre-installed on their ASICs, alternative options exist. Vnish, for example, has gained popularity as a robust third-party firmware, known for its stability and ability to unlock a higher degree of customisation than many stock firmware. It enables miners to exert more granular control over their hardware's performance, often leading to increased hashrate and improved energy efficiency.

Beyond third-party options, some mining operators opt for custom-developed firmware, tailored specifically to their unique hardware configurations and operational needs. This approach allows for the highest degree of optimisation, enabling miners to fine-tune performance parameters with surgical precision, potentially achieving the maximum possible performance from their existing ASIC hardware. By optimising performance and reducing unnecessary stress on the components, custom firmware can also help to extend the lifespan of the ASICs. The benefits of custom firmware often include improved hashrate, increased energy efficiency, enhanced control over hardware settings, and the ability to implement unique features, such as dynamic frequency scaling and advanced error correction.

Ultimately, choosing the right firmware, whether it be manufacturer-provided, third-party, or custom-developed, is a critical decision for miners seeking to optimise their operations and maximise profitability.

Retirement of Mining Equipment and E-waste

Understanding inventory turnover

The retirement of mining hardware, defined as the process by which equipment is withdrawn from active use, provides critical insights into the dynamics of the Bitcoin network. Chief among these insights is the ability to estimate the hashrate expected to be removed from the network over time, which, in turn, impacts mining difficulty. Since hashrate and network difficulty are critical factors influencing mining profitability, understanding patterns of hardware retirement helps inform expectations regarding hashrate fluctuations.

Equally important is gaining clarity on the fate of retired hardware to understand whether these devices are responsibly recycled or contribute to the growing issue of e-waste. This involves determining whether the equipment is only temporarily out of commission or permanently withdrawn.

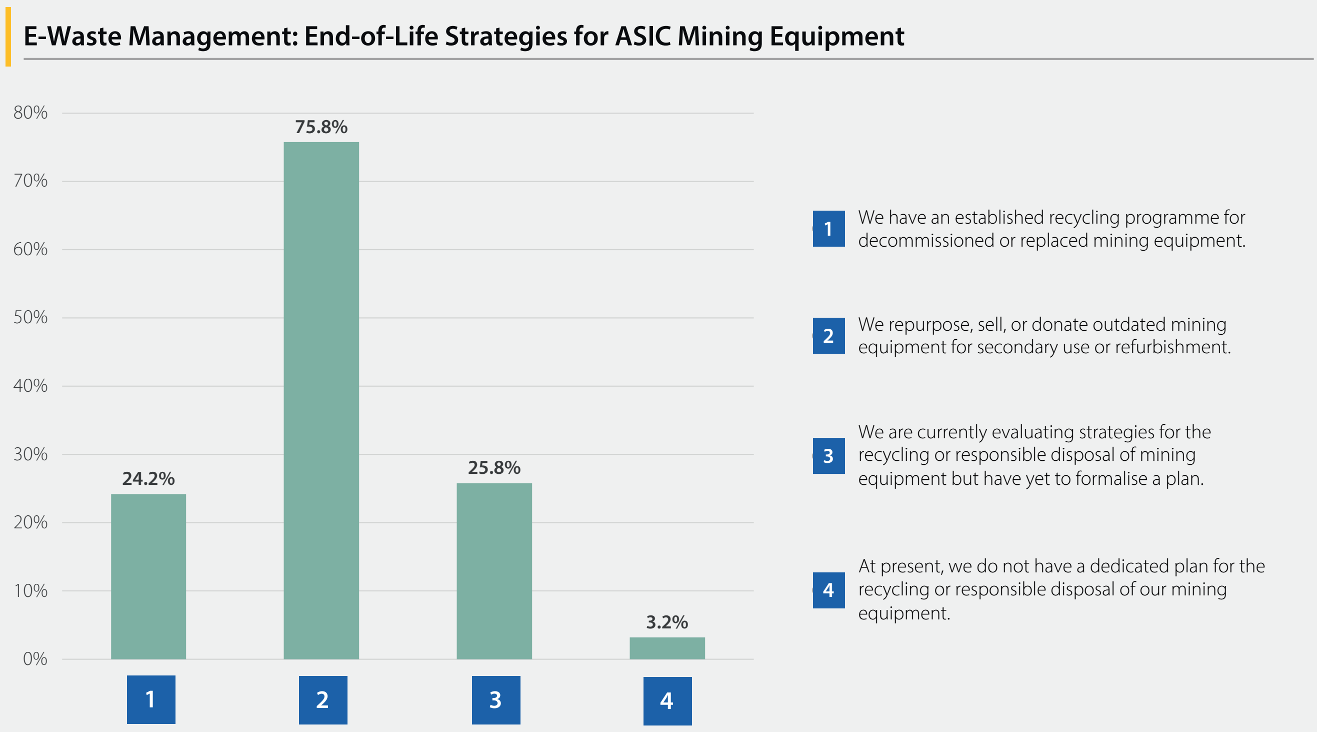
Reasons for hardware retirement

Mining equipment may be retired for a variety of reasons, such as replacing older devices with more efficient newer generations, addressing hardware malfunctions, or reallocating data centre space for other purposes. While the survey did not directly address the specific reasons behind each individual retirement decision, miners were asked questions aimed at understanding the ultimate fate of the hardware. This inquiry centred on two key questions: first, what happens to mining hardware after it is retired, whether it is reused, refurbished, or permanently disposed of; and second, how these outcomes contribute to our understanding of e-waste and the resulting implications on the industry's environmental footprint.

Survey results on hardware retirement

Figure 24 summarises survey responses on how miners manage their retired hardware. Participants were able to select multiple options, reflecting the variety of strategies they employ to handle phased-out equipment. The majority (75.8%) indicated that a significant portion of retired devices is not permanently withdrawn from use. Instead, these units are repurposed, sold, donated for secondary use, or refurbished, suggesting that a large proportion of hardware may only be temporarily out of commission.

Figure 24: Adoption rate of various e-waste management practices (in %) at the end of the ASIC mining equipment lifecycle (as of 30 June 2024). Source: CCAF Survey. Sample size: (N=31)



For devices that are permanently retired, the survey also sheds light on disposal and recycling practices. Around 25.8% of participants reported actively exploring recycling strategies, while an additional 24.2% stated they have established recycling programmes in place. These findings demonstrate a growing awareness within the industry of the environmental challenges associated with responsible hardware disposal in an effort to mitigate e-waste. Nevertheless, not all respondents indicated the same level of preparedness. A small percentage (3.2%) admitted to lacking any plan for responsible disposal or recycling of retired equipment.

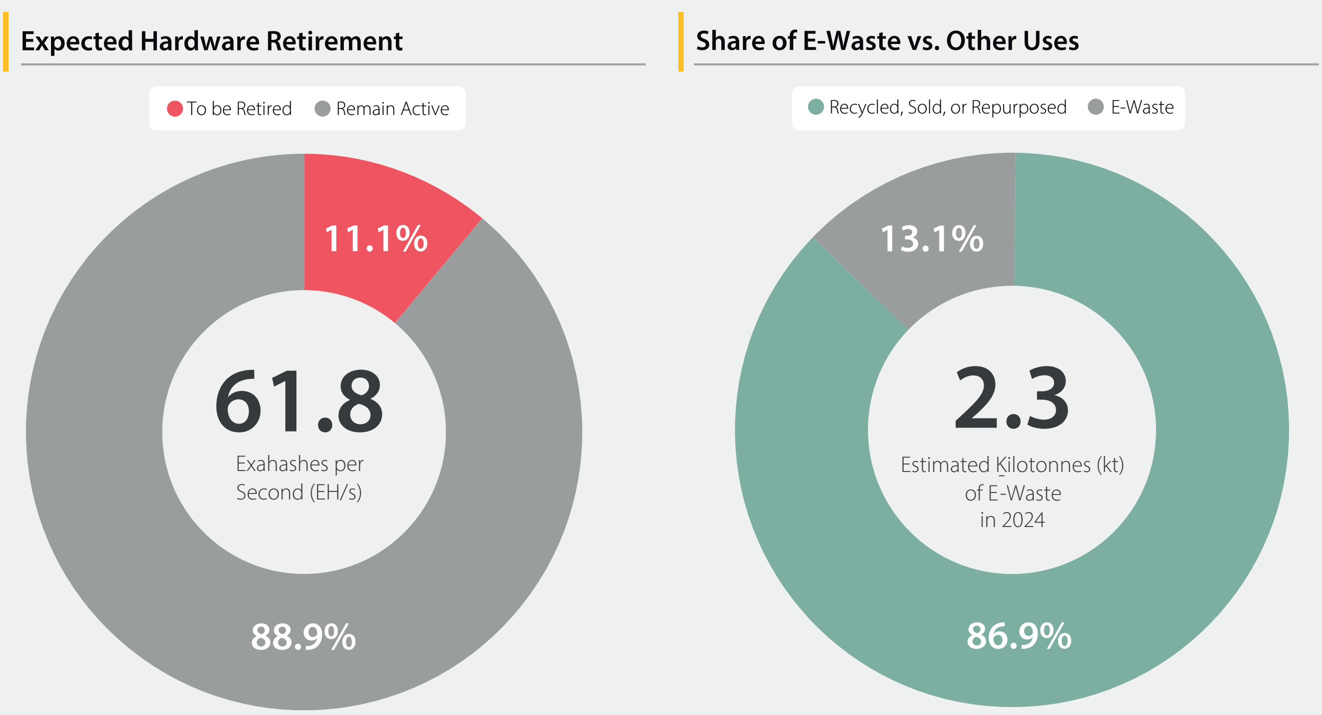
Practical implications of survey findings

To translate the survey findings into practical insights, miners were asked about expected hardware retirements. The responses indicated that approximately 11.1% of network hashrate (as of 30 June 2024), equivalent to 61.8 EH/s, was expected to be retired between 30 June and 31 December 2024 (see Figure 25(a)). However, not all of this retired hardware might have been permanently removed; a significant portion could have been only temporarily out of commission as devices may have been repurposed, refurbished, or redeployed.

Since e-waste remains a persistent concern in discussions surrounding the environmental footprint of digital mining, miners were queried about the extent to which their phased-out hardware would likely not be recycled or find secondary use. The responses suggest that 13.1% of the expected hardware retirements could be considered non-recycled e-waste. Translating this into estimated tonnage, based on survey data and a set of simplifying assumptions, results in approximately 2.3 kilotonnes of e-waste in 2024, as shown in Figure 25(b).

This finding is noteworthy insofar as it is significantly lower than e-waste estimates suggested in peer-reviewed literature.[79] On that note, it is essential to recognise that the estimate presented in Figure 25(b) is based on a markedly simplified methodology. The stark discrepancy stems from the assumed widespread adoption of recycling and secondary use practices within the industry, which may not be fully captured by other models. While the approach used in this report has its limitations, the findings do suggest that recycling and secondary use are not merely peripheral activities but crucial variables that should be considered in more advanced e-waste assessment models.

Figure 25: (a) Anticipated temporary and permanent retirement of mining hardware between 30 June 2024 and 31 December 2024, shown as percentage (%) of total operational hashrate (as of 30 June 2024) and equivalent hashrate in EH/s (extrapolated to total network hashrate); and (b) share of e-waste compared to other uses, presented as a percentage (%) and approximated e-waste in kilotonnes (kt) for 2024. The e-waste tonnage estimate is based on survey responses and underpinned by specific assumptions. The Bitmain Antminer S19 serves as a benchmark for hardware retirements, using manufacturer specifications for device net weight (14.35 kg) and hashrate (95 TH).[78] To calculate the e-waste estimate, these data points, combined with survey responses extrapolated across the network, are utilised to determine e-waste for H2 2024. For H1 2024, the calculation is based on the 7-day average implied Bitcoin network hashrate as of 31 December 2023, assuming hardware disposal plans during H1 2024 were similar to those in H2 2024. The e-waste estimate for the entire year of 2024 is then derived by summing the estimates for H1 2024 and H2 2024. Source: Analysis conducted by the authors, data obtained from CCAF Survey and Coin Metrics [54]. Responses of (a) and (b) are weighted by the reported hashrate of participants. Sample size: Figure 25(a) (N=47), Figure 25(b) (N=29)



V: Electricity Consumption

The computationally-intense nature of digital mining drives considerable electricity consumption. This section provides survey-based insights into electricity usage, contrasts these findings with theoretical estimates, and explores the evolution of consumption patterns over time.

Bitcoin's substantial electricity consumption remains a critical point of discussion and analysis. This section focuses on quantifying the network's electricity usage by examining findings on key operational variables such as the energy efficiency of mining hardware. The resulting survey-based consumption estimate is then contrasted with that of established theoretical models, such as CBECI, to offer a nuanced perspective on electricity consumption patterns, utilising different estimation techniques.

Digital Mining and Its Energy Needs, an Ongoing Controversy

The energy requirements of digital mining have long been a source of contention among stakeholders. As outlined in Part II, resource utilisation is fundamental to the crypto-economic incentive mechanism underpinning PoW, where it deters malicious behaviour through the costliness of computational work. Nonetheless, the energy consumption associated with PoW has been a frequent target of criticism, especially given the existence of alternative, more energy-efficient, consensus mechanisms, such as Proof-of-Stake (PoS). [80] For instance, unlike PoW, where participants ('miners') must demonstrate an unforgeable proof that computational resources have been spent, PoS requires participants to commit financial resources, or 'stake', to the network. In the case of Ethereum, validators are required to stake 32 ETH as collateral. This stake acts as a security deposit, incentivising honest behaviour. Validators who act negligently or maliciously, whether intentionally or not, risk losing a portion or all of their staked collateral through a process known as 'slashing'. This financial penalty mechanism is designed to ensure that validators act in the best interest of the network. While a broader discussion of this topic falls outside of this report, it is worth emphasising that consensus mechanisms are not uniform in their objectives or trade-offs. Simplistic, one-dimensional comparisons tend to overlook relevant aspects, such as the security and decentralisation properties each mechanism provides.

Central to the environmental discourse is the question of the magnitude of electricity consumption and the methodologies used to approximate it. Over time, various approaches have emerged, each with its own strengths and limitations.[81] A key element in most of these estimations is the assumed efficiency of employed hardware. By combining insights into hardware efficiency with on-chain data, such as implied network hashrate, electricity consumption estimates can be derived.

The decentralised and permissionless nature of most blockchain networks poses a significant challenge. With no central registry or mechanism to track participants, anyone can become a participant, leaving the exact composition of hardware in use largely unknown. Historically, theoretical assumption-based models have been the primary method for approximating the hardware miners employ. This report complements these models by directly querying mining firms about the efficiency of their operational fleets, offering a practitioner's perspective alongside theoretical estimations.

Efficiency of Mining Hardware

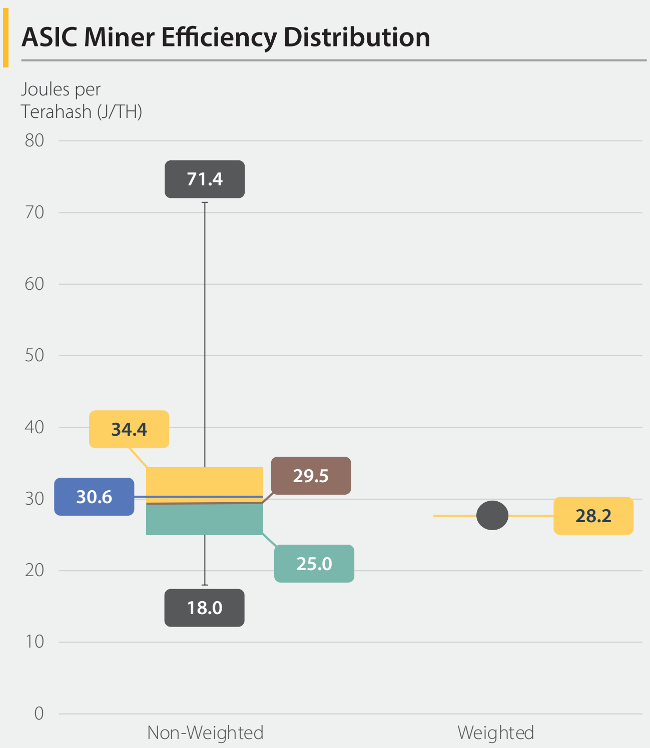
The findings are summarised in Figure 26(a), which illustrates hardware efficiencies derived from survey responses, expressed in joules per terahash (J/TH). This metric quantifies electricity consumption per unit of computational power, with lower values signifying more efficient devices.

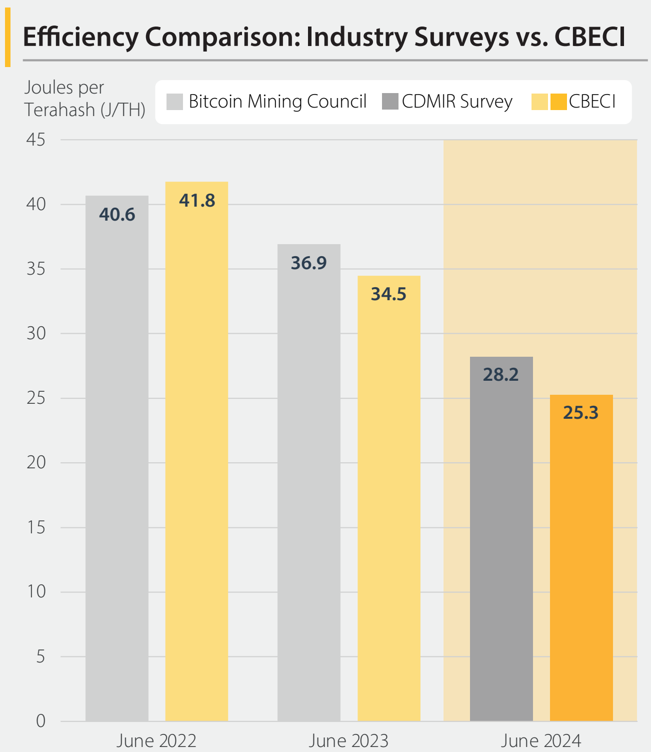
An analysis of non-weighted responses reveals an efficiency range between 18.0 J/TH and 71.4 J/TH, with half of the responses concentrated between 25.0 and 37 J/TH. The median efficiency, at 29.5 J/TH, is slightly lower than the average (30.6 J/TH), highlighting the influence of less-efficient outliers. A plausible explanation could be the operation of older devices in regions with exceptionally low electricity costs.[85]

Weighted efficiency, which accounts for the relative scale of operations (based on hashrate) of respondents, is approximated at 28.2 J/TH and serves as the benchmark for hardware efficiency in this report. This value is slightly lower than the median and average non-weighted efficiencies, suggesting that larger mining firms tend to utilise more efficient equipment compared to smaller firms.

Figure 26(b) juxtaposes theoretical efficiency estimates from our CBECI model with firm-level survey-derived figures over time. External comparisons, such as those with the Bitcoin Mining Council's survey findings, reveal close alignment between these approaches, with only minor deviations. Consistent with expectations, CBECI estimates generally indicate slightly less efficient hardware during periods of high mining profitability and vice versa. For the most recent period, the CBECI model estimates an efficiency of 25.3 J/TH, while survey data suggests a moderately less efficient figure of 28.2 J/TH, which reflects a 24% YoY increase in efficiency from the last survey data (June 2023). Importantly, the survey results give credence to the projected increase in hardware efficiency by our CBECI model (Survey: +31% versus CBECI: +39%) from June 2022 to June 2024, albeit slightly less pronounced.

Figure 26: (a) Distribution of ASIC (SHA-256) miner efficiency, comparing weighted (based on hashrate) and non-weighted figures in joules per terahash (J/TH); and (b) comparison of ASIC (SHA-256) efficiency estimates between industry surveys and the Cambridge Bitcoin Electricity Consumption Index (CBECI), as of 30 June 2024. Data sources: CCAF Survey, Cambridge Centre for Alternative Finance [82], Bitcoin Mining Council (2022-2023; [83-84]). Sample size: (N=45)





Insights

Methodologies for Estimating Electricity Consumption

Estimating the electricity consumption of blockchain networks, particularly those for PoW consensus-based mechanisms like Bitcoin, is paramount to understanding their environmental footprint. Over time, several methodologies have emerged to tackle this complex assessment, each with their own advantages and limitations.

Top-down approach: This widely adopted method provides a relatively straightforward estimation by multiplying the implied network hashrate by the assumed energy efficiency of a representative mining device. However, its accuracy hinges on an accurate selection of this 'representative' device, which can be difficult given the large variety of mining devices in use.

Economic approach: Based on the premise that miners are profit-driven, this approach estimates electricity consumption at the break-even point where mining revenue equals operational costs. While conceptually understandable, its results are highly sensitive to cryptoasset price volatility, fluctuating electricity costs across regions, and assumptions regarding miners' operational expenses.

Hybrid top-down approach: This method combines aspects of the top-down and economic approaches to refine consumption estimates. It computes the efficiency of a hypothetical mining device based on the characteristics of real mining hardware that meets or exceeds a defined profitability threshold. The derived efficiency, along with implied network hashrate, is then used to estimate overall electricity consumption. This approach offers a more nuanced view than the basic top-down method, but still relies on certain economic assumptions inherent in the profitability threshold.

Extrapolation based on direct measurement: This method involves directly measuring the energy use and computational output (hashrate) of a small, representative portion of the network and extrapolating these findings to the entire network. Its accuracy depends heavily on the representativeness of the sample and the scalability of the measurements.

Understanding the limitations of each method is crucial for interpreting estimations of blockchain electricity consumption. Ongoing research aims to refine existing methodologies or develop new ones. However, a key determinant in all cases will be access to more comprehensive, granular, and up-to-date data on mining operations and hardware efficiency. The dynamic and ever-evolving nature of the digital mining industry underscores the need for continuous refinement of these analytical approaches.

Growing efficiency and its impact on consumption

Figure 27 provides more granular insights into the development of hardware efficiency over time. This chart highlights the impact of advancements in technology in conjunction with a changing digital mining landscape, which together have led to much higher approximated efficiency levels. As the data reveals, efficiency at the beginning of the observed period (1 January 2021 to 31 December 2024) stood slightly above 60 J/TH, deteriorated towards 70 J/TH in early 2021, before gradually improving to 23.7 J/TH by the end of 2024. Note that efficiency is given as energy per unit of computing power (J/TH); thus, a lower value signifies higher efficiency, as less energy is needed for the same level of computing power. Turning to the implied network hashrate, we can observe a substantial increase, surging by 455% from 143 EH/s to 796 EH/s over the same period.

This dynamic is noteworthy because both variables directly influence electricity consumption. Essentially, as mining hardware becomes more efficient, it consumes less energy to perform the same amount of work. Conversely, as the network hashrate grows, it requires more energy to maintain that level of activity, assuming efficiency remains constant. Thus, improvements in efficiency help mitigate the energy demands of rising hashrate levels.

Figure 27: Relationship between ASIC (SHA-256) miner efficiency (in J/TH, right axis), based on the CBECI model, and implied Bitcoin network hashrate (using a 7-day moving average) in EH/s (left axis) from 1 January 2021 to 31 December 2024. Data sources: Cambridge Centre for Alternative Finance [82], Coin Metrics [56]

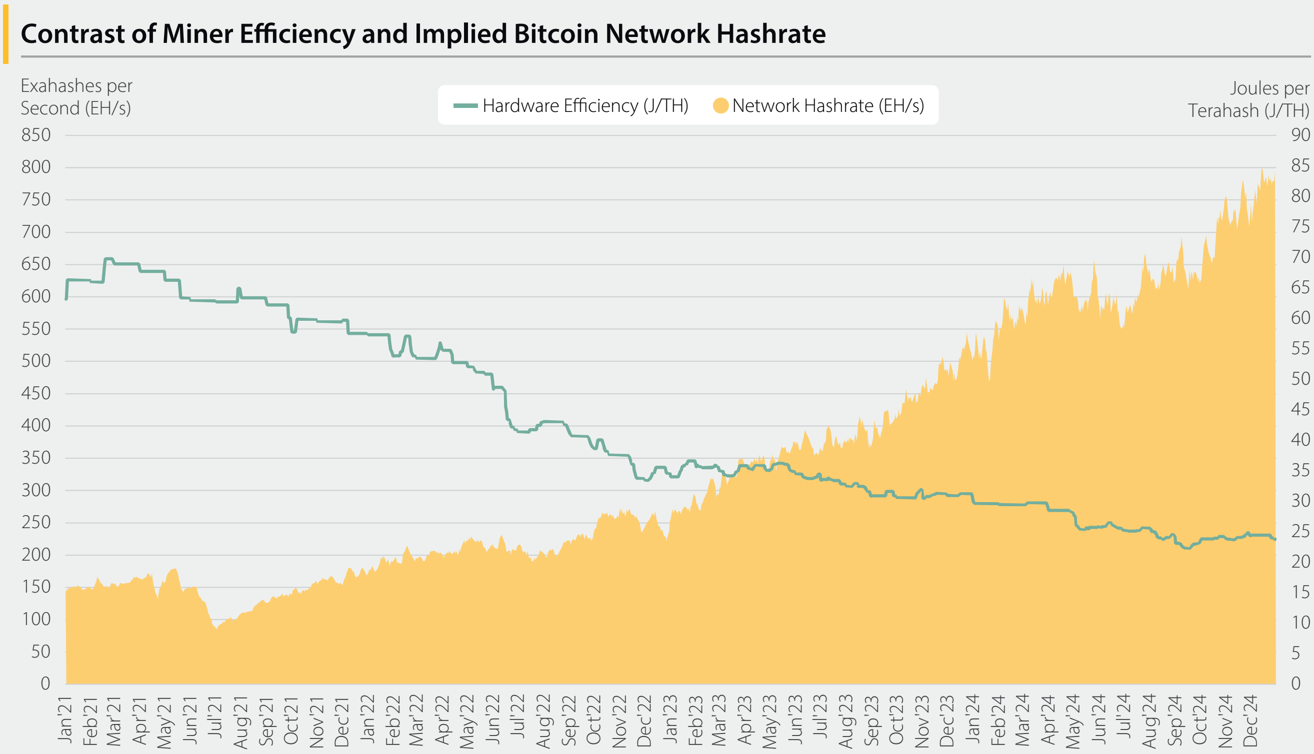


Figure 28 demonstrates this relationship more clearly. The combined effect of these trends shows that increases in computing power do not lead to electricity consumption necessarily moving in the same direction or to the same degree, although a positive relationship is still evident over time. The chart shows that while both implied network hashrate and electricity consumption have risen over time, their growth trajectories have diverged considerably. Over the observed period, the implied network hashrate rose by a substantial 455%, whilst annualised electricity consumption slightly more than doubled (+111%), reflecting the efficiency gains in mining hardware.

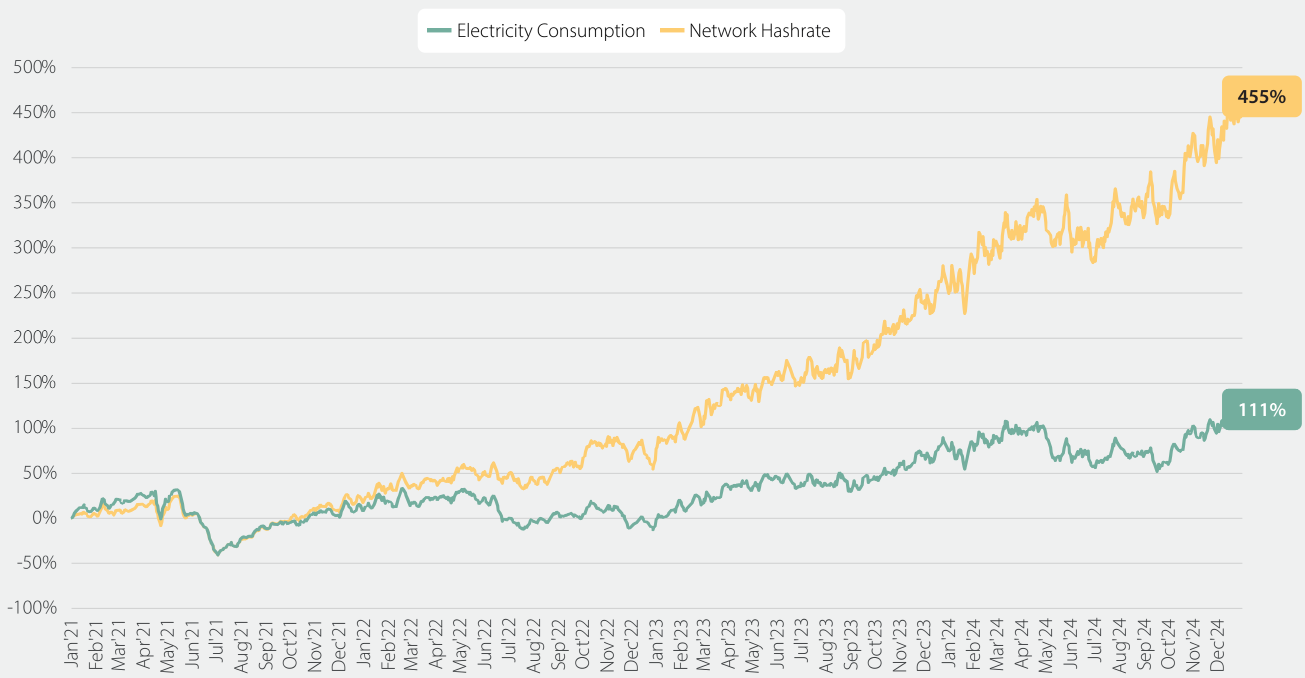
This observation can be effectively summarised in a simplified statement:

"Over the past five years, for each unit increase in electricity consumption, the Bitcoin network's hashrate (a key security indicator) increased by approximately 4 units."

Another reason why this observation is important is that it highlights the fallacy of relying on simplistic extrapolations to forecast future energy usage. While there is an apparent positive relationship between network hashrate and electricity consumption, the relationship is not directly proportional. Any estimations of future energy demand, especially when considering multi-year periods, should adequately reflect expected changes in hardware efficiencies.

Figure 28: Trend of implied Bitcoin network hashrate (using a 7-day moving average) and electricity consumption from 1 January 2021 to 31 December 2024 by cumulative percentage change in both metrics. Source: Analysis conducted by the authors, data obtained from Cambridge Centre for Alternative Finance [82], Coin Metrics [56]

Development of Implied Bitcoin Network Hashrate vs. Electricity Consumption



Electricity Consumption

Using the weighted hardware efficiency derived from survey responses, the annualised electricity consumption of the Bitcoin network is estimated at 138.2 TWh as of 30 June 2024 (see Figure 29), representing a 17% YoY increase. To place this figure in a global context, this consumption level equates to approximately 0.54% of the world's total annual electricity consumption.[86] The survey-based estimate also shows close alignment with the CBECI model (137.4 TWh) estimate.

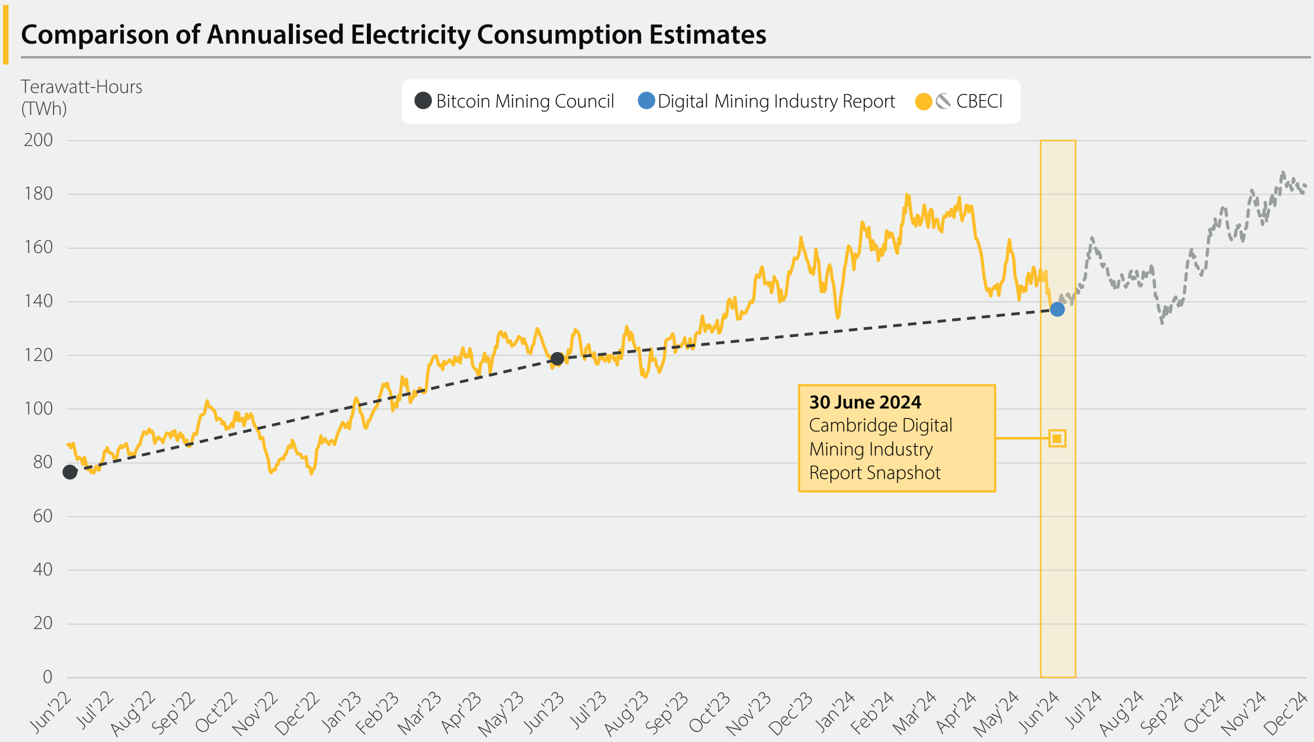
This consistency strengthens confidence in the findings, as it suggests that, despite the decentralised nature of mining, electricity consumption can be approximated with a reasonable margin of error, as different estimation methods come to an approximately similar conclusion.

Figure 29 further illustrates the progression of electricity consumption beyond June 2024. By the end of December 2024, hardware efficiency improved to 23.7 J/TH, yet electricity consumption rose to 183 TWh due to a substantial increase in network hashrate, from 558.7 EH/s (30 June 2024) to 795.7 EH/s (31 December 2024). Despite these increases, annual electricity consumption remained close to the pre-halving all-time peak of 180 TWh in March 2024.

Looking ahead

Projections based on publicly available ASIC chip development data (see Figure 22) indicate continued advancements in hardware efficiency, with the most efficient devices currently achieving 12 J/TH and forthcoming designs anticipated to reach sub-10 J/TH levels by 2025. The extent to which these improvements are realised will depend on miners' ability to upgrade existing fleets or expand operations, as well as the actual materialisation of the projected efficiency gains in chip design.

Figure 29: Comparison of annualised electricity consumption estimates, contrasting historical and current survey-based esti-mates with CBECI, measured in terawatt-hours (TWh). For the CCAF survey-based electricity consumption estimate (as of 30 June 2024), the weighted hardware efficiency in Figure 26(a) has been utilised. Similarly, the Bitcoin Mining Coun-cil estimates utilise the hardware efficiency reported in their respective surveys. In both cases, the survey-based esti-mates derive annualised consumption from hardware efficiency and implied Bitcoin network hashrate (using a 7-day moving average). The CBECI estimate has been extended to 31 December 2024 to illustrate how the model projects electricity consumption trends since the survey snapshot on 30 June 2024 Data sources: CCAF Survey, Cambridge Centre for Alternative Finance [82], Bitcoin Mining Council (2022-2023; [83-84]). Sample size: (N=45)



VI: Energy and Environment

Digital mining stands at the crossroads of innovation and environmental accountability, influencing energy demand, sourcing, and utilisation.

The environmental footprint of digital mining has long been a subject of debate, with critics highlighting its resource-intensive nature and proponents emphasising its role as the backbone of Bitcoin's security model. This section delves into the complexities of this issue, offering fresh data and multifaceted insights to enrich the discussion from diverse perspectives.

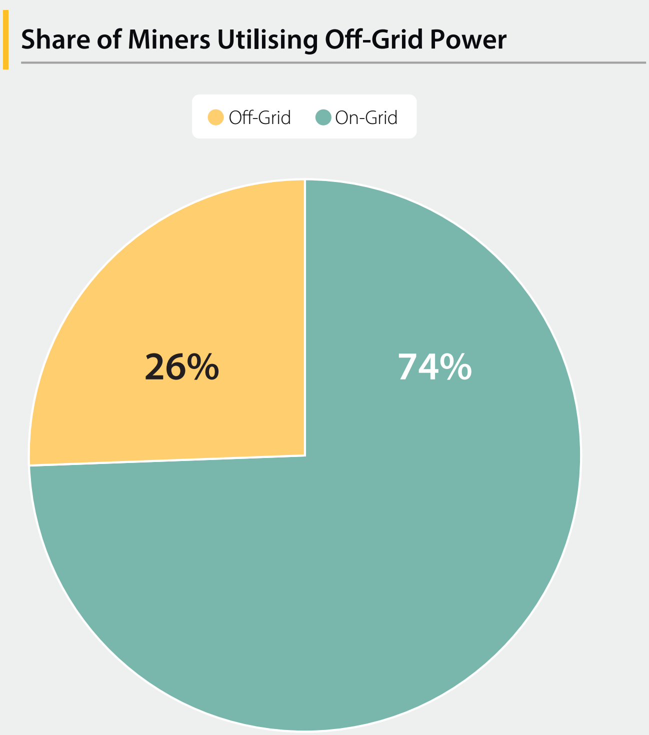
It begins by examining off-grid energy use and the electricity mix that powers mining operations, emphasising the critical importance of understanding these factors for accurate environmental impact assessments. Methodological differences are explored, with an example that will highlight how different assumptions can influence results. Beyond its immediate climate impact, emerging evidence suggests digital mining could play a transformative role in our energy system through innovative solutions such as the utilisation of stranded natural gas, demand-side response, and waste-heat recovery, among others. By combining empirical data, methodological critique, and forward-looking analysis, this section not only evaluates digital mining's environmental footprint but also its potential to support a more sustainable energy future.

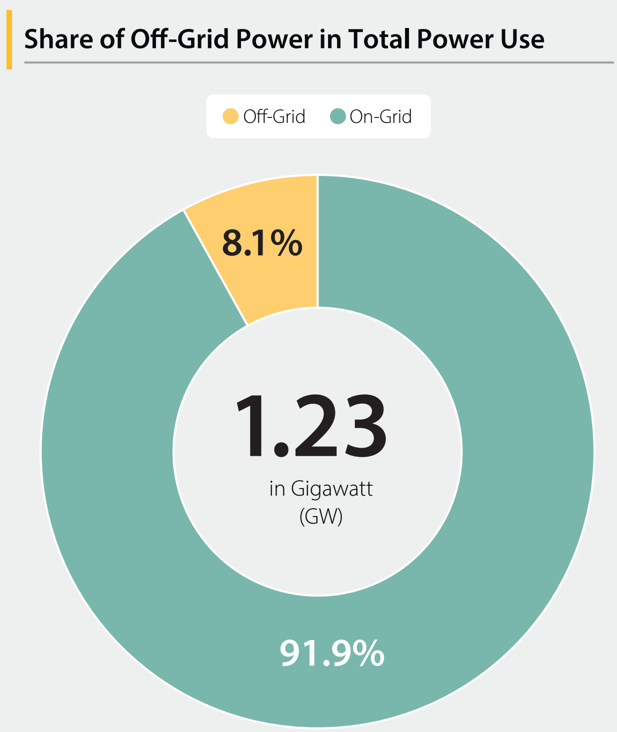
The Role of Off-Grid Power in Digital Mining

Off-grid energy refers to electricity produced independently of centralised power grids, relying on locally sourced energy such as solar, wind, or hydropower. This setup contrasts with grid-connected systems, which feed into or depend on national or regional electrical infrastructure. While the concept of off-grid energy is common across various industries, it has gained particular attention in digital mining due to its potential for cost savings and tackling the industry's environmental footprint.[87]

As illustrated in Figure 30(a), 26% of surveyed digital mining firms reported utilising off-grid energy sources, while the remaining 74% did not. In terms of total power consumption, however, off-grid energy accounts for only 8.1%, or 1.23 GW, with grid-connected power overwhelmingly dominating (see Figure 30(b)). These results suggest that, while off-grid resource access is a growing topic of discussion, the majority of miners continue to favour grid-connected power for most of their operations, likely tapping into off-grid resources during opportune times.

Figure 30: (a) Percentage of miners utilising off-grid power; and (b) share of off-grid power in total power use, expressed as a percentage (%) and in gigawatts (GW). The network-level estimate of off-grid power usage (in GW) was derived by extrapolating the sample data based on hashrate coverage. Responses for (b) are weighted by the reported power consumption of participants. Data as of 30 June 2024. Source: Analysis conducted by the authors, data obtained from CCAF Survey. Sample size: (N = 43)





Despite the relatively small share of off-grid power in total consumption, the observation that over one-fourth of firms are already accessing off-grid energy highlights the potential of this form of power procurement to become more prominent in the future. Public statements by mining firms further corroborate this trend, with many indicating that off-grid power will play an increasingly crucial role in their energy strategies.[88]

Industry stakeholders attribute this potential shift to the flexible, location-agnostic nature of digital mining, which uniquely positions miners to act as buyers of first and last resort. In practical terms, this flexibility allows miners to tap into otherwise stranded energy, absorb temporal oversupply of electricity from VREs, or utilise fossil fuel by-products such as flared natural gas.[89] This dynamic creates a symbiotic relationship between miners and energy producers, with the former benefiting from access to low-cost energy, while the latter finds new markets for otherwise stranded resources.[90]

Electricity Mix and Environmental Implications

The importance of electricity mix in digital mining

A thorough understanding of the electricity mix associated with digital mining is essential to assessing the industry's environmental footprint. Before delving into the survey findings, it is important to establish why this topic holds such significance.

The environmental impact of digital mining arises primarily from the indirect emissions associated with the electricity consumed by mining operations. While other factors, such as e-waste, contribute to the overall environmental footprint, their impact is relatively negligible. Literature estimates these factors to account for less than 1% of the total climate-related impact of digital mining,[91] a conclusion supported by our survey findings (see Figure 25(b)). As a result, the climate impact of mining activities depends almost entirely on the energy sources used for electricity generation. Consequently, a profound understanding of the industry's overall electricity mix and how this mix evolved over time is fundamental for any environmental impact assessment.

Methods to estimate the electricity mix

Various methodologies have been devised over time to estimate the electricity mix associated with digital mining. Location-based assessments are most commonly used and rely on IP-based data to approximate the geographical distribution.[92] These methods provide a broad overview but have been criticised for their imprecision.[93] To address this gap, industry bodies and community estimates have increasingly turned to survey-based approaches. [83] While these methods offer a higher degree of granularity, they are not without limitations, as they rely on (i) the ability to achieve a sufficiently large sample and (ii) are subject to respondent bias, among others.

The following assessment presents survey-based estimates, which are then subsequently compared and contrasted with our CBECI estimate, which relies on IP-based data, to stress the degree to which different methods can affect outcomes.

An industry-based estimate on Bitcoin's electricity mix

A key objective of directly surveying mining firms was to determine the energy sources utilised by mining firms. To achieve this, respondents were presented with a list of energy sources to select from. Additionally, they had the option to estimate their electricity mix using a location-based approach, by selecting the 'On-Grid' option. The electricity mix was then determined by utilising the information on the geographical distribution of survey respondents' operations. For those willing to provide more granular information, the survey allowed to specify precise locations, such as 'United States, Texas'.

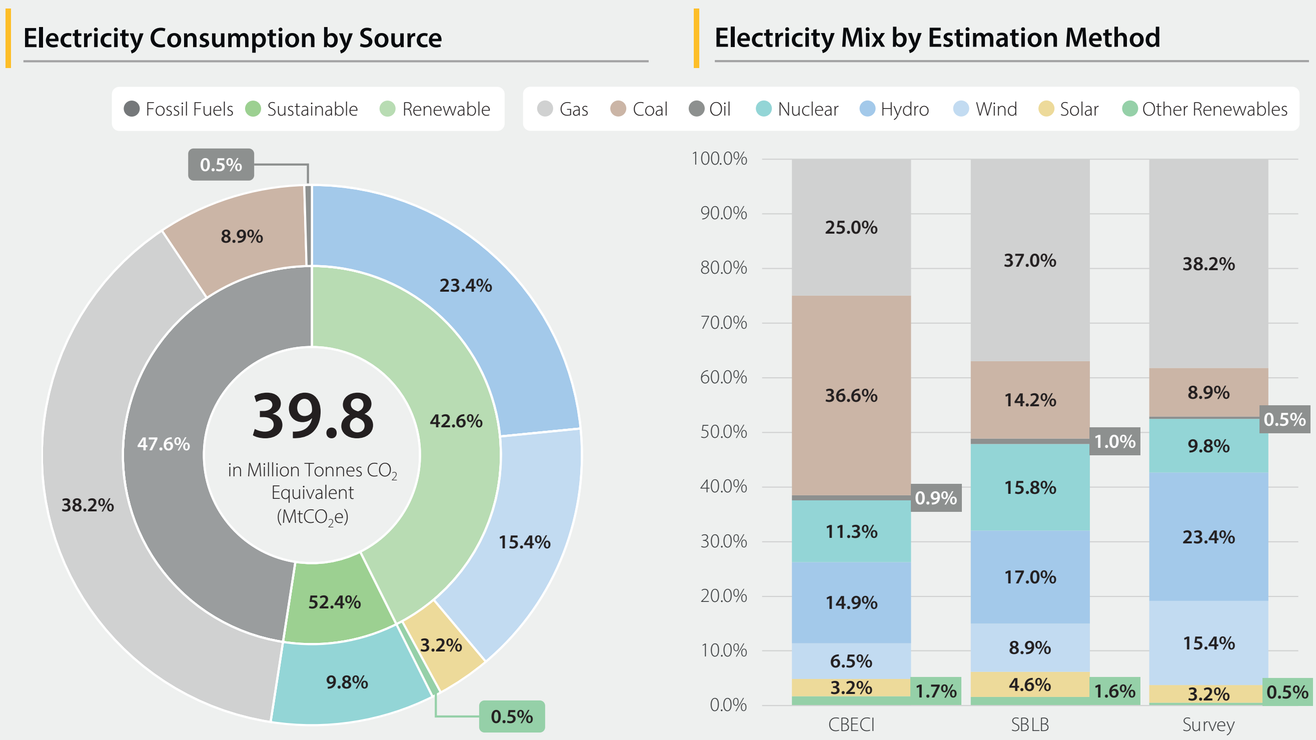
Turning to Figure 31(a), the survey responses reveal that the industry's electricity mix consists of 47.6% fossil fuels and 52.4% sustainable energy sources. Breaking down the sustainable energy sources further, renewables account for 42.6%, comprising 23.4% hydropower, 15.4% wind energy, 3.2% solar energy, and 0.5% other renewables. Additionally, nuclear energy constitutes 9.8% of the mix. Within fossil fuels, natural gas dominates, accounting for 38.2%, making it the largest single energy source, followed by coal at 8.9% and oil at 0.5%. Based on the determined electricity mix, GHG emissions associated with the electricity usage by Bitcoin mining operations are estimated at approximately 39.8 $MtCO_2e$.

Comparing outcomes: Location-based versus survey-based methods

To examine the impact of different electricity mix estimation methods, three approaches are compared. The first is the 'CBECI' estimate, which relies on IP-based data to approximate the geographical distribution of mining activity. The second method, derived from survey responses and based on the geographical distribution of mining operations (see Figure 20), is referred to in this report as 'SBLB'. Lastly, the electricity mix directly reported by miners in Figure 31(a) is referred to as 'Survey'.

As shown in Figure 31(b), notable differences arise depending on the method employed. CBECI estimates the share of sustainable energy sources at 37.6%, significantly lower than the Survey (52.4%) and SBLB (47.9%) estimates. A key insight from these observations is the critical role of contemporary data. This becomes evident when comparing the CBECI and SBLB results. Both approaches rely on a location-based methodology, which might initially suggest

Figure 31: (a) Electricity consumption by energy source (in %) and annualised GHG emissions (assuming an annualised electricity consumption of 138.2 TWh), in million tonnes CO_2 equivalent ($MtCO_2e$); and (b) estimated electricity mix (in %) based on three different methods: (i) CBECI representing our theoretical estimation model; (ii) SBLB (short for survey-based and location-based) a location-based estimate predicated upon the geographical distribution of mining activity shown in Figure 20, and (iii) Survey, the estimate derived from survey responses. Data as of 30 June 2024. Responses for (a) are weighted by the reported power consumption of participants. Sources: Analysis conducted by the authors, data obtained from CCAF Survey, Cambridge Centre for Alternative Finance [82]. Sample size: (N = 49)



similar outcomes. However, substantial differences emerge in both the share of sustainable sources and the composition of fossil fuels. The SBLB estimate aligns much more closely with the Survey results, with fossil fuels accounting for 52.1% in SBLB compared to 62.4% in CBECI. Within fossil fuels, the CBECI model attributes 36.6% to coal, making it the predominant energy source. In contrast, SBLB identifies natural gas as the predominant source (37.0%), closely matching the Survey estimate (38.2%). These discrepancies are largely data-driven, rooted in CBECI's reliance on the latest update of IP-based data (as of January 2022). Preliminary evidence from mining pool data and conversations with industry experts suggests that the geographical landscape has since fundamentally shifted, which is supported by findings presented earlier in this report (see Figure 20).

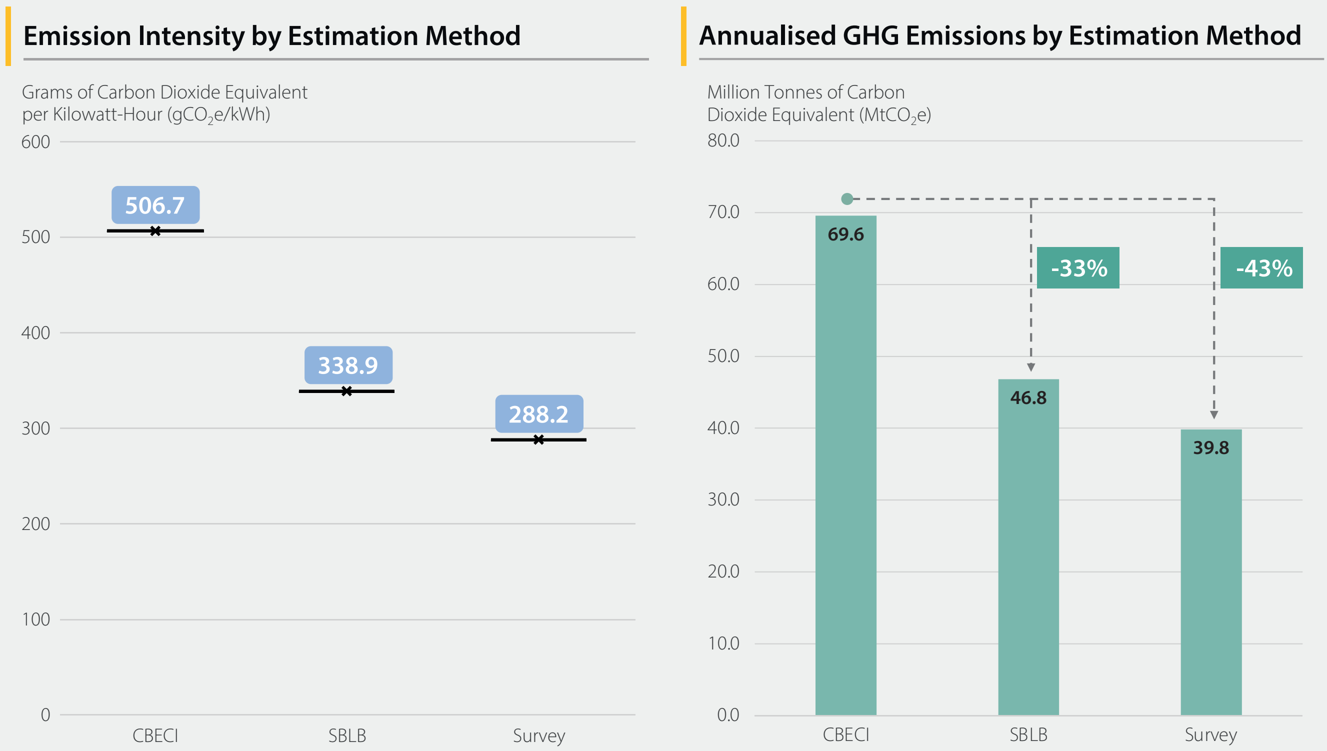
When comparing SBLB and Survey results, a difference exists but is much less pronounced. Both methods identify natural gas as the predominant energy source (37.0% in SBLB vs. 38.2% in Survey), but they diverge more substantially on renewable sources. Hydropower accounts for 17.0% (SBLB) compared to 23.4% (Survey), wind energy for 8.9% vs. 15.4%, nuclear energy for 15.8% vs. 9.8%, and coal-fired power for 14.2% vs. 8.9%. These findings suggest that while location-based and survey-based assessments yield relatively similar overall results in the share of sustainable sources (47.9% vs. 52.4%), they differ notably in the composition of those sources, with miners seemingly being particularly drawn to regions with an abundance of hydropower and wind energy.

Impact of different methods on GHG emission estimates

Having discussed the electricity mix, the focus now shifts to the impact of variations in the electricity mixes of these three examples on emissions calculations. The initial step in this process is the computation of emission intensity, which is derived from the primary energy sources within the mix. The intensities for each of the three estimates are shown in Figure 32(a). Unsurprisingly, the CBECI (506.7 gCO_2e/kWh) is significantly higher than both SBLB (338.9 gCO_2e/kWh) and the Survey-based estimate (288.2 gCO_2e/kWh).

These variations in emission intensity naturally carry over to GHG emissions estimates (see Figure 32(b)), with Survey (39.8 $MtCO_2e$) being approximately 42.8% and SBLB (46.8 $MtCO_2e$) roughly 32.8% lower than CBECI (69.6 $MtCO_2e$). These divergent outcomes highlight the importance of relying on granular, up-to-date data when conducting environmental

Figure 32: (a) Estimated emission intensities (in gCO_2e/kWh); and (b) annualised GHG emissions (in $MtCO_2e$) based on different estimation methods: (i) CBECI representing our theoretical estimation model; (ii) SBLB a location-based estimate predicated upon the geographical distribution of mining activity shown in Figure 20, and (iii) Survey, the estimate derived from survey responses. Data as of 30 June 2024. Data sources: CCAF Survey, Cambridge Centre for Alternative Finance [82], Coin Metrics [56]. Sample size: (N = 49)



impact assessments, as any starker deviations in the electricity mix can lead to fundamentally different results. To place the survey-based estimate in a broader context, the 39.8 $MtCO_2e$ figure represents approximately 0.08% of global annual GHG emissions. For comparison, this is similar to the annual emissions of Slovakia (39.8 $MtCO_2e$)[94] and roughly half the estimated environmental impact of the global tobacco industry (84 $MtCO_2e$).[95]

A broader perspective on the industry's environmental footprint

Although emissions estimates related to electricity consumption are crucial for determining the industry's climate footprint, several other factors warrant consideration. A growing body of literature explores potentially beneficial use cases of digital mining that could mitigate the industry's environmental footprint.[96] These potentially beneficial applications include, among others, incentivising the reduction of routine flaring, capturing waste heat for reuse, and acting as a demand-side response (DSR) resource for grid operators. Some of these use cases will be explored in this section, alongside a discussion on how these could be integrated into a comprehensive climate impact assessment. Furthermore, literature has emerged showcasing the potential of digital mining in incentivising the development of renewable energy infrastructure by opening up new revenue streams.[97-98] A broader consideration of the digital assets ecosystem also reveals further opportunities. For example, one of our previous collaborative research reports discussed the potential and actual use of the crypto-asset market for fundraising in support of solar power initiatives, or facilitating peer-to-peer (P2P) payment or energy trading of solar power.[99]

Digital Mining, A Potential Solution to Gas Flaring?

Stranded gas in energy systems

Natural gas plays a critical role in global electricity generation, providing a flexible and reliable energy source that complements intermittent renewables such as wind and solar. Its efficiency and relatively lower emissions compared to coal make it a cornerstone of many energy systems. However, a significant portion of natural gas is classified as stranded, meaning that it cannot be economically transported due to the absence of pipelines or the high costs of infrastructure development and lacks an on-site use case.[100]

Stranded gas, often a by-product of oil extraction (associated gas) or the anaerobic decomposition of organic material in landfills (producing landfill gas, or LFG), constitutes a major environmental challenge. Without viable utilisation or transport options, these gases are frequently flared or vented. Flaring burns excess gas, converting hydrocarbons like methane into CO_2, while venting releases methane and other gases directly into the atmosphere. Both practices contribute significantly to greenhouse gas emissions, with venting being particularly harmful due to methane's significant global warming potential, which is over 80 times higher than that of CO_2 over a 20-year period.[101]

Flaring is often regarded as a less harmful alternative to venting because it converts methane and other hydrocarbons into CO_2, which has a significantly lower GWP. However, real-world flaring efficiency frequently falls short of the commonly assumed 98% combustion rate. A study using airborne sampling has shown that the average methane destruction efficiency of flares in key U.S. basins is approximately 91.1%, with some flares operating as low as 60% efficiency.[102] These inefficiencies, combined with unlit flares, result in methane emissions that may notably exceed prior estimates.

The global implications are considerable. In 2022 alone, approximately 139 billion cubic metres of natural gas were flared worldwide, resulting in around 357 $MtCO_2e$ emissions.[103] These findings stress the importance of exploring alternative use cases for stranded gas to reduce routine flaring.

Associated gases often represent not only an environmental challenge but also a missed opportunity to harness this energy. The mitigation of routine flaring and venting is critical for achieving global climate goals, such as those outlined in the Paris Agreement, and initiatives like the World Bank's Zero Routine Flaring by 2030 emphasise the need for innovative solutions to address this problem.

Bitcoin mining as a solution

Digital mining, with its location-agnostic nature and flexible load profile, has been hailed by industry stakeholders as a compelling solution.[104] By installing modular generators at remote oil fields and landfills, miners can convert stranded gas into electricity to power their operations. Evidence also suggests that the combustion efficiency of the employed gas engines exceeds that of flare stacks, meaning they convert more of the highly potent methane into less harmful CO_2.[105]

Therefore, creating on-site demand for electricity, such as for digital mining operations, may not only offer a means of energy monetisation and associated cost advantages for both miners and energy producers but also could create a positive spillover effect on the environment by reducing the emissions of methane and other hydrocarbons, while simultaneously utilising otherwise wasted energy to power computation.[106]

Case Study

Crusoe Energy – Mitigating Natural Gas Flaring to Power Computation

Crusoe Energy, a vertically integrated AI infrastructure provider, innovatively addresses environmental and economic challenges of natural gas flaring in the oil and gas industry. Crusoe's Digital Flare Mitigation (DFM) technology utilises otherwise wasted gas to power modular data centres, converting a source of emissions into a computational resource. The company deploys specialised, mobile data centres directly to oil and gas well sites to capture gas that would otherwise be flared. This captured gas fuels on-site generators, producing electricity to power the data centres' operations.

The electricity generated primarily powers Crusoe's compute infrastructure, used for applications including Crusoe Cloud and Bitcoin mining. Crusoe offers HPC services through its cloud platform, providing scalable, cost-effective compute power for workloads like AI training and inference, machine learning, and scientific simulations. Whilst historically utilising some captured energy for digital mining, Crusoe is increasingly focused on cloud computing and AI.

Crusoe's approach offers several environmental and economic advantages. Flaring is a major source of methane, a potent greenhouse gas. By capturing and utilising this gas, Crusoe's DFM reduces the environmental impact of oil and gas production. Whereas flaring is usually assumed to reduce methane emissions by 91.1% to 98%,[102] Crusoe reports its DFM technology reduces methane emissions by up to 99.9%.[105] Importantly, using flared gas as a fuel transforms a wasted by-product into a valuable resource.

Crusoe Energy's DFM technology highlights the potential for innovation to simultaneously address environmental challenges and meet growing computational demand. This model integrates sustainability into energy-intensive sectors, servicing industries reliant on HPC computing. Specifically, repurposing stranded energy for server farms to support computationally intense workloads is particularly impactful given the expected increase in power demands for data centres (see Part IX).

Survey insights on stranded gas utilisation

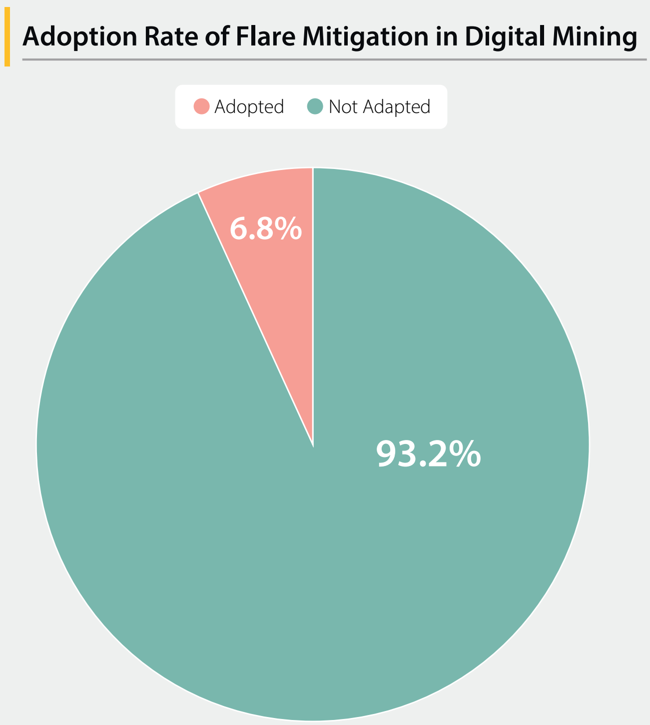
While the theoretical and practical benefits of stranded gas utilisation are well-documented,[107] understanding its current adoption within the digital mining industry requires an analysis of real-world data. To that end, survey findings offer insights into how theory is applied in practice. The data reveal that 6.8% of respondents currently use stranded natural gas, either fully or partially, for powering their operations (see Figure 33(a)). While this figure may appear modest, it reflects a nascent practice that has already gained traction within the industry. The use of stranded gas by even a small yet notable proportion of firms suggests that this approach could become more commonplace as economic and regulatory conditions continue to evolve.

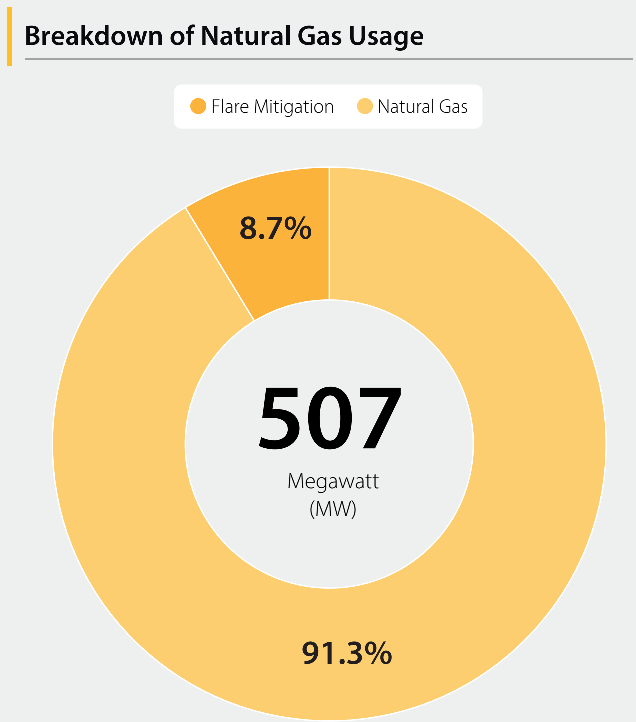
The data further show that stranded natural gas contributes 507 MW to the industry's power usage, representing approximately 3.3% of the total energy mix. Furthermore, this accounts for about 8.7% of the industry's total natural gas usage (see Figure 33(b)). While these proportions may appear modest, they demonstrate that stranded gas utilisation is an active component of the sector's energy mix, contributing to emissions mitigation efforts. It is worth noting, however, that no data were received on the use of landfill gas, even though known projects exist.[108] While those appear to be much smaller in scale, utilising LFG could represent another strong lever for reducing GHG emissions, with landfills accounting for about 10% of anthropogenic methane emissions globally.[109]

Complementary approaches and broader considerations

While digital mining offers a promising avenue for stranded gas utilisation, it is not the sole application for mitigating associated emissions and harnessing energy more effectively. Other use cases, ranging from HPC solutions to hydrogen production, among others, also present viable alternatives.[110] Moreover, it is equally important to recognise that these solutions should be viewed as transitional measures aimed at mitigating emissions in the short-term while the energy sector transitions towards a more sustainable future. Within this context, digital mining does seem to align with both economic and environmental objectives by incentivising the mitigation of routine flaring and venting, thus contributing to global climate goals like those outlined in the Zero Routine Flaring by 2030 initiative. However, the scalability of using digital mining for flare mitigation depends significantly on practical factors such as the availability and cost of modular generation technology and the required scale of initial investment. Equally important is the regulatory landscape; navigating complex approvals across different jurisdictions presents a hurdle, while supportive policies – particularly those incentivising methane capture and utilisation – can be pivotal in accelerating project adoption and scaling. [111]

Figure 33: (a) Share of digital miners using power from otherwise flared natural gas (in %); and (b) breakdown of the industry's natural gas usage (in %) and associated power (in MW) derived from otherwise-flared natural gas, as of 30 June 2024. Responses for (b) are weighted by the reported power consumption of participants. Source: CCAF Survey. Sample sizes: Figure 33(a) (N = 44), Figure 33(b) (N = 44)





Quantifying the environmental impact of flare mitigation

The survey data provide a foundation for a simplified thought experiment, offering a means to quantify the potential positive externalities of utilising otherwise stranded gas in digital mining. At the same time, this exercise underscores the stark variability of outcomes depending on the underlying assumptions, serving as a reminder to approach such projections with caution.

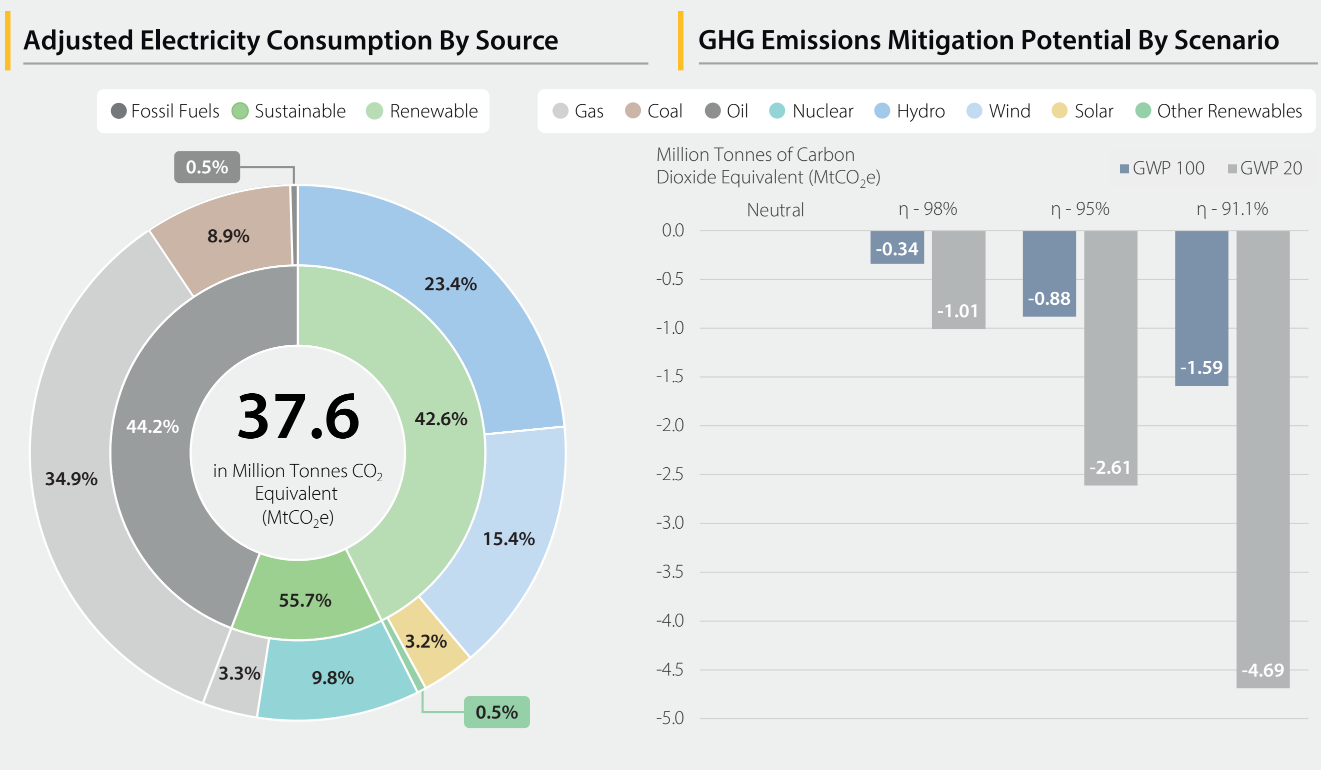
For instance, by reclassifying the 3.3% of power derived from flared gas as net neutral (relative to the counterfactual of flaring), the share of sustainable energy sources would increase from 52.4% to 55.7% (see Figure 34(a)). It is important to note here that this assumes flaring would otherwise remain unmitigated, a key aspect of additionality. Under this scenario, GHG emissions associated with digital mining would require a downward adjustment of -2.2 MtCO_2e, reducing the annualised emissions estimate from 39.8 MtCO_2e to 37.6 MtCO_2e.

Figure 34(b) expands on this by accounting for the higher combustion efficiencies of generators compared to flare stacks, illustrating a variety of scenarios using different GWP timeframes (20-year vs. 100-year).

At the 98% combustion efficiency typically used in flaring estimates,[102] reductions range from -0.34 MtCO_2e (100-year GWP) to -1.01 MtCO_2e (20-year GWP). However, these reductions become much more pronounced at lower assumed efficiency levels: at 95% efficiency, they range from -0.88 MtCO_2e (100-year GWP) to -2.61 MtCO_2e (20-year GWP), and at 91.1% efficiency, they reach up to -1.59 MtCO_2e and -4.69 MtCO_2e, respectively. This analysis unearths critical insight: the high sensitivity of the model to assumptions, with the approximated emissions reduction potential ranging from -0.34 MtCO_2e to -4.69 MtCO_2e, illustrating the wide spectrum of potential outcomes.

While these findings suggest that stranded gas utilisation holds potential for mitigating the industry's environmental footprint, the magnitude of this impact varies widely depending on the scenario considered. Annualised GHG emissions estimates exhibit a wide range from 39.8 MtCO_2e (without considering flare mitigation) to 37.6 MtCO_2e (under a net neutral scenario), or between 32.9 MtCO_2e and 37.3 MtCO_2e depending on assumed combustion efficiencies and the GWP timeframe. These stark variations highlight the importance of basing assessments on robust, real-world data, which necessitates site-specific assessments via on-site measurements or derived from satellite imagery.

Figure 34: (a) Electricity consumption by energy source (in %) and associated GHG emission estimates under a 'neutral' scenario, assuming no allocatable emissions from natural gas that would have otherwise been flared; and (b) the annualised GHG emission mitigation potential (in MtCO_2e) of utilising flare gas for power generation, computed using the following assumptions: power output of 507.2 MW (see Figure 33(b)), energy efficiency (44%),[112] gas heat content (39 MJ/m^3),[113] CH_4 density (0.717 kg/m^3), and CO_2 emission factor (2.75 kg/kg CH_4).[114] It is assumed that natural gas consists entirely of methane.[115] The analysis compares combustion efficiencies of flare stacks (91.1%, 95%, and 98%) to a gas engine combustion efficiency of 99.9%. Results are presented for both 20-year and 100-year GWPs. Data as of 30 June 2024. Source: Analysis conducted by the authors, data obtained from CCAF Survey



Beyond Baseload, Can Digital Mining Help Support Power Grids?

Growing importance of DSR in electric power systems

In recent years, DSR has evolved from a niche grid-balancing tool to a crucial component of the modern electric power system.[116] As power grids worldwide experience a surge in variable renewable energy (VRE) sources like wind and solar, managing the balance between supply and demand has become increasingly complex. Historically, grid operators typically relied on supply-side management for frequency control,[117] ramping up or down generation from traditional 'peaker' plants (power plants designed to quickly start and stop to meet short-term peaks in demand, such as gas turbines). However, the substantial growth in VREs has driven the industry towards a more active use of demand-side strategies and storage solutions to address the often substantial intraday variability in electricity supply.[118]

DSR allows consumers to reduce or shift their electricity usage during peak demand periods, thereby acting as a virtual power plant that can be called upon to stabilise the grid. Additionally, DSR not only enhances grid reliability but also can function as a tool to reduce carbon emissions in electric power systems by minimising reliance on spinning reserves and peaker plants,[119] which are often powered by fossil fuels.[120] As VREs continue to expand, the role of demand response in providing flexibility to the grid is expected to continue to grow.

Digital mining as a flexible load resource

Digital mining firms are emerging as strategic partners for grid operators, functioning as a highly flexible DSR resource. [121] Unlike data centres or industries like steel production, digital mining operations are capable of rapidly scaling their load up or down in response to real-time grid signals, incurring minimal operational costs, as the primary consequence is reduced Bitcoin mining output.[122-123] While rapid and frequent load changes would cause technical or economic issues for most industries, digital miners primarily forgo BTC rewards during curtailment periods. Many mining firms also utilise power purchase agreements (PPAs), contracts that primarily secure a long-term supply of electricity at a predetermined price. These agreements often include provisions that allow to sell pre-purchased power back to the grid during periods of high demand. This creates a compelling financial incentive for miners to curtail operations and provide power to the grid when it is most needed. This flexibility makes them particularly valuable in regions with isolated power grids, such as ERCOT in Texas, where limited interconnections with other grids make real-time load balancing more critical.

Case Study

Riot Platforms – Demand Side Response in Action

Riot Platforms, a prominent digital mining company operating primarily within the ERCOT grid, offers a compelling case study in the utilisation of digital mining as a demand-side response resource. Unlike traditional industrial loads, Riot's operations possess the ability to rapidly modulate power consumption with minimal operational disruption, primarily incurring opportunity costs related to forgone Bitcoin mining revenue.

Riot actively participates in ERCOT's demand response initiatives, notably through the Controllable Load Resource (CLR) programme. The CLR programme facilitates direct communication and control signals between ERCOT and Riot, enabling rapid load adjustments in response to grid conditions. Riot also strategically manages its load to minimise costs associated with ERCOT's Four Coincident Peak (4CP) programme, a transmission cost allocation mechanism based on the four highest monthly system-wide peak demand hours. Riot further employs PPAs that allow for the resale of electricity to the grid during periods of high wholesale prices. This creates a powerful economic incentive for curtailment when system demand, and thus market prices, exceed potential revenue from mining activity.

A notable example of Riot's contribution occurred during the August 2023 Texas heatwave. The company voluntarily curtailed consumption, providing over 84,000 MWh of energy back to the grid. This action not only contributed to system stability and mitigated potential price volatility for consumers but also generated nearly $1 million in revenue for Riot through the provision of ancillary services alongside about $24 million in power credits.[126]

Riot Platforms' operational model demonstrates the potential for large-scale, flexible loads to provide valuable grid ancillary services. Their ability to respond swiftly to market signals and grid operator requests, coupled with the financial incentives embedded in their energy agreements, positions them as a key contributor to grid resilience and demonstrates the evolving role of digital mining in modern energy systems, exemplifying a market-driven approach to grid stabilisation.

In some cases, the industry has already shown notable engagement in demand response initiatives, with digital miners constituting a significant portion of ERCOT's large-flexible load (LfL) resources.[124] When electricity prices spike or generation shortages arise, mining operators have demonstrated their ability to rapidly adjust their load and alleviate pressure on the system. Notably, these curtailments are often initiated pre-emptively, even before a formal conservation appeal, showcasing their potential as a real-time balancing tool.[125]

The current state of demand response in the digital mining industry

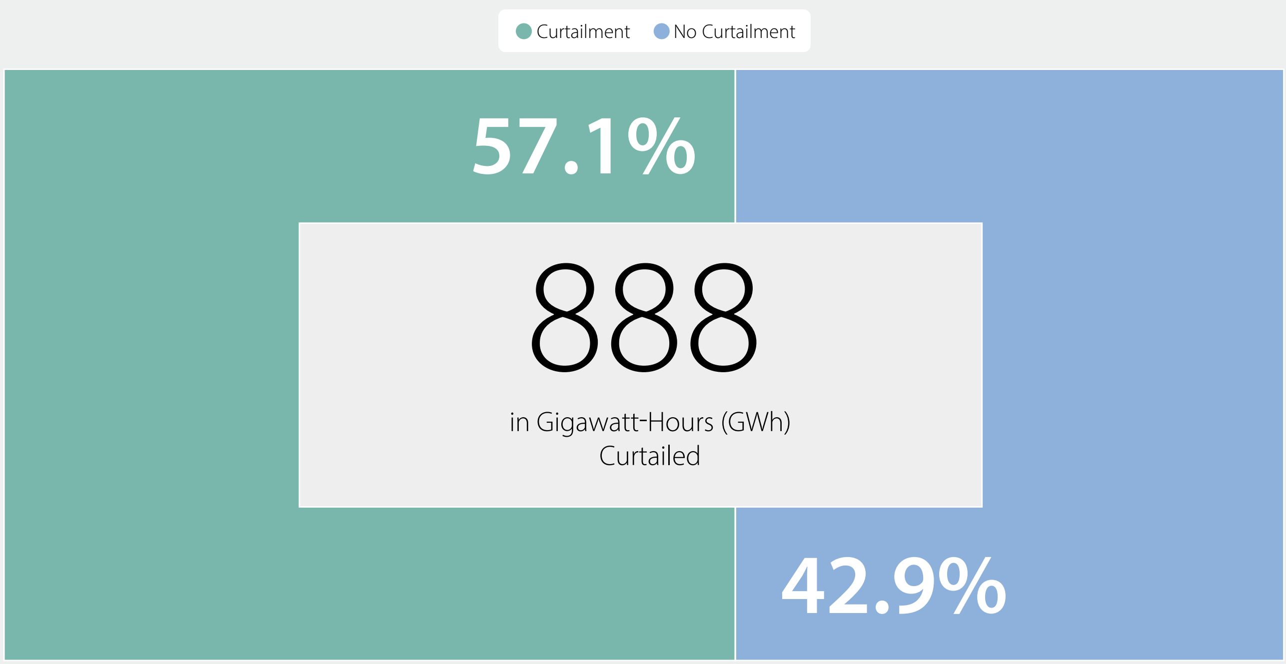
To develop a more comprehensive picture of how commonplace DSR has become in the industry, respondents were queried about their participation in load curtailment. Survey responses reveal that a significant portion of digital mining firms (57.1%) curtailed their computational load in 2023, contributing to a total of 888 GWh of curtailed load (see Figure 35). This demonstrates the supportive role the industry can assume in ancillary service markets, a finding echoed by grid operators.[127] Real-world observations further indicate that the behaviour of mining firms is not merely reactive to conservation appeals, but instead responses may be pre-emptive based on market conditions, indicative of a strategic approach where mining operations align their load with system prices.[125]

On the surface, the integration of digital mining into DSR mechanisms offers clear benefits for grid stability and economic efficiency, particularly in isolated grids like ERCOT. The flexibility of mining operations could further provide a scalable solution to the intermittent nature of renewable energy. Recent estimates by the EIA project a significant increase in wind and solar curtailment,[128] a trend corroborated by the observable increasing frequency of negative system prices, particularly in nodal zones with high VRE penetration.[129]

Given their flexibility, digital mining firms can fulfil multiple roles simultaneously, from functioning as a buyer of last resort that absorbs excess supply that would otherwise be curtailed, to providing a buffer against supply shortages and price volatility. These characteristics position the industry as a potentially integral component of grid management strategies, where miners act not just as consumers but as virtual power plants that can be dispatched based on real-time grid needs.[130]

Figure 35: Share of digital mining firms engaging in load curtailment (in %) and the resulting total curtailed load at network-level (in GWh) for 2023, estimated by extrapolating the survey data to the entire network based on hashrate coverage of the sample. Data as of 30 June 2024.
Source: CCAF Survey. Sample size: (N = 49)

Participation in Load Curtailment by Digital Mining Firms



Broader implications and challenges

While digital mining presents promising benefits as a flexible load resource, its broader applicability depends heavily on local grid conditions. In regions with highly interconnected grids and ample transmission capacity, many of the challenges faced by isolated systems like ERCOT may not apply. Furthermore, the increase in load from mining operations raises concerns about whether this added demand could inadvertently increase reliance on fossil fuels.[131]

Nonetheless, as renewable energy penetration increases globally, even interconnected grids may start to see or are already seeing value in incorporating flexible demand resources to stabilise their systems. While digital mining is by no means the only solution, the characteristics previously stated highlight it as a potential tool that could be utilised. Some policymakers [132] and grid operators [133] are already exploring strategies to integrate digital mining into ancillary service markets, recognising the industry's potential to transcend cryptoasset production and contribute actively to a more resilient and sustainable energy system.

Climate Mitigation Efforts and Challenges

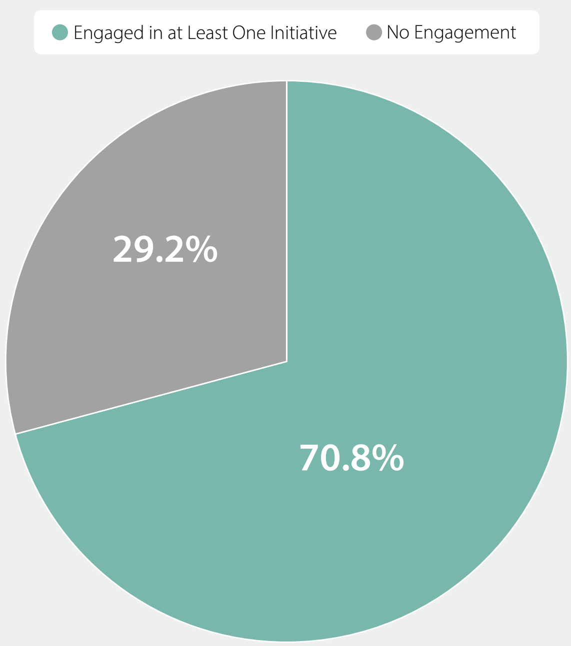
Industry engagement in sustainable activities

As concerns over the environmental impact of digital mining mount, many companies in the industry are actively implementing strategies to mitigate their environmental footprint. These efforts span measures such as improving energy efficiency, transitioning to lower-carbon energy sources, and optimising energy use. However, the extent of adoption varies significantly among firms, reflecting both the challenges and opportunities inherent in advancing toward more sustainable practices.

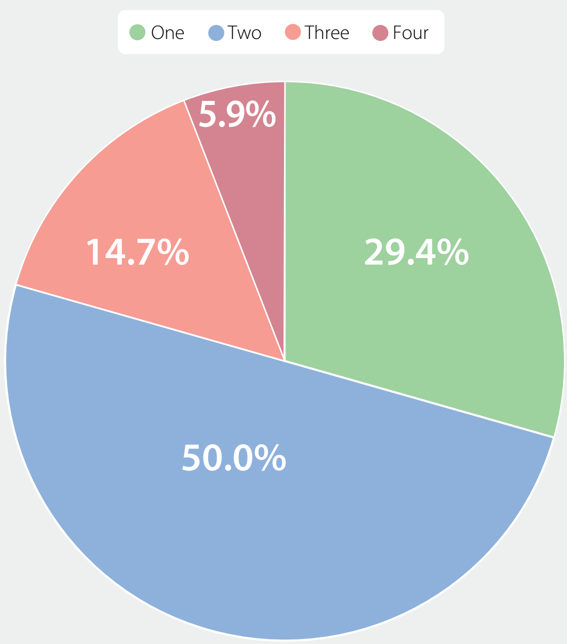
Figure 36(a) indicates that 70.8% of respondents are actively pursuing some form of climate mitigation strategy, while 29.2% are not engaged in such efforts. This widespread engagement reflects a high level of awareness within the industry about the need to address environmental concerns. Among firms reporting no action, potential reasons may include economic constraints, limited regulatory pressure, or a focus on short-term financial gains. Another possible explanation could be that operations of those firms are already carbon neutral or close to it. As depicted in Figure 20, a notable share of mining activity takes place in areas like Paraguay and Norway, where electricity grids are already heavily decarbonised due to the

Figure 36: Share of respondents engaging in at least one climate mitigation strategy; and (b) number of different climate mitigation strategies adopted by respondents (as of 30 June 2024). Source: CCAF Survey. Sample size: Figure 36(a) (N = 48), Figure 36(b) (N = 34)

Share of Respondents Engaging in Climate Mitigation Strategies



Number of Different Climate Mitigation Strategies Adopted by Respondents



availability of renewable energy sources. For firms in these locations, additional mitigation measures may be viewed as less urgent, particularly if they do not yield direct operational or financial benefits.

Figure 36(b) offers deeper insight into the level of engagement among firms in mitigation efforts. The data reveal that 29.4% of firms are engaged in a single measure, 50.0% adopt two measures, 14.7% implement three, and 5.9% pursue four strategies concurrently. This distribution highlights a trend where most companies prioritise a limited range of initiatives, likely selecting those that are both cost-effective and operationally advantageous.

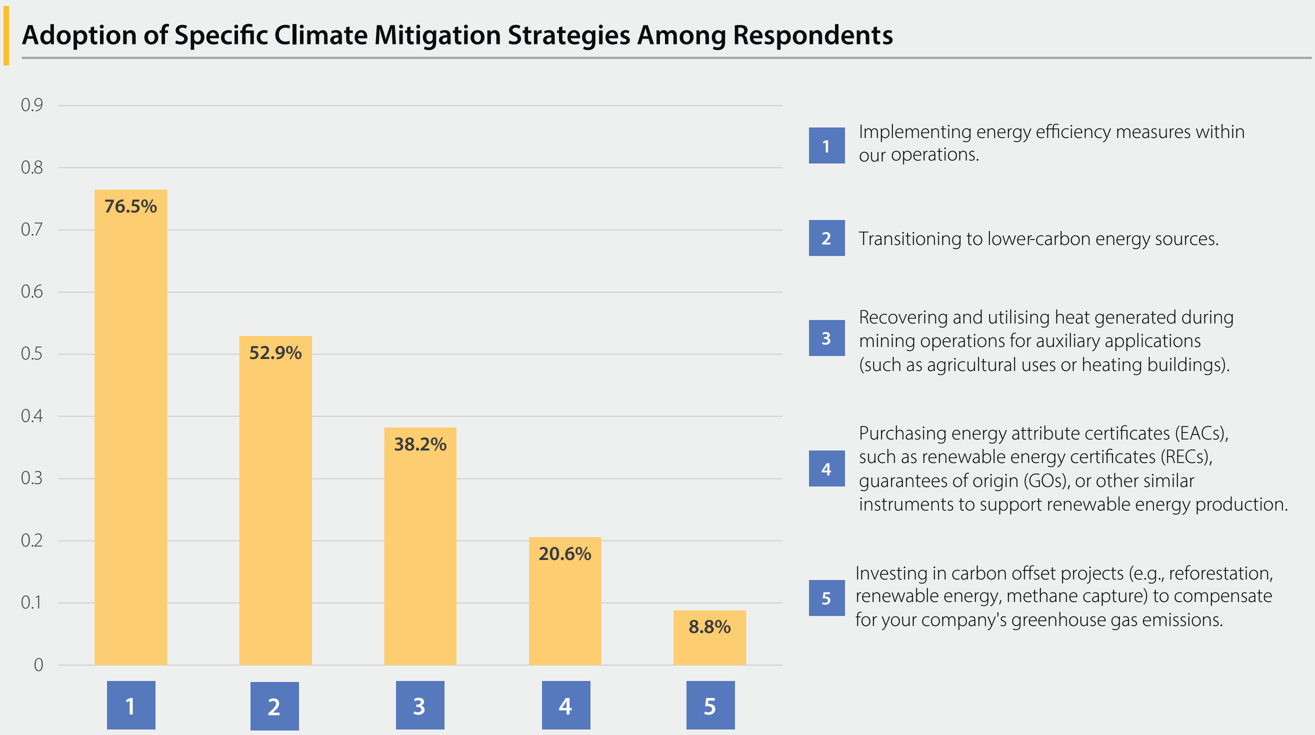
Identifying strategies of miners to mitigate their climate footprint

Observing now what specific measures respondents are engaging in, raising energy efficiency of operations crystallises as the primary means to improve environmental impact, with the vast majority of respondents (76.5%) planning to undertake such measures (see Figure 37). Such efforts include, among others, upgrading hardware, improving cooling systems, and adopting intelligent load management techniques. Unsurprisingly, improving power usage effectiveness, thereby reducing electricity consumption, also yields cost savings, rendering these an attractive first step towards more sustainable operations.

The second most commonly reported activity selected by more than half (52.9%) of respondents who engage in climate mitigation measures involves transitioning to greater reliance on renewable energy to power operations. This aligns with earlier findings from this report, which indicate that the industry already sources approximately 52.4% of its energy from sustainable sources. This substantial uptake underscores meaningful progress in reducing reliance on fossil fuels, particularly when compared to historical estimates.[68] Whilst renewable energy adoption lays the groundwork for greener operations, miners are also exploring complementary strategies to enhance sustainability. This is reflected in the notable uptake of utilising heat generated during the mining process for ancillary activities (38.2%). By redirecting this heat for applications such as district heating, greenhouse cultivation, or pool heating,[134] miners can transform a byproduct into a resource.

Considering that heating is a major source of global CO_2 emissions (4.1 $GtCO_2$), with over 60% met by fossil fuels,[135] effective utilisation of heat generated during computing processes can be a lever to offset energy demands elsewhere, harmonising the growing demand for computing services with its environmental footprint, and unlock new revenue streams for firms adopting such systems.

Figure 37: Adoption rate of specific climate mitigation strategies among surveyed respondents (as of 30 June 2024).
Source: CCAF Survey. Sample size: (N = 34)



Another interesting observation is that, despite the reported stark reliance on sustainable energy sources by mining firms, this is not matched by widespread usage of Energy Attribute Certificates (EACs), such as Renewable Energy Certificates (RECs). EACs are tradable, market-based instruments that represent the environmental attributes of renewable electricity generation. RECs, a specific type of EAC, certify that one megawatt-hour (MWh) of electricity was generated from a renewable energy source. Only 20.6% of surveyed firms engaging in climate mitigation measures reported purchasing these instruments. It is worth noting, however, that the phrasing of the survey question may not have fully accounted for the variety of methods by which these certificates can be obtained, with purchase being only one of those.

Nonetheless, this disparity suggests that while miners may predominantly rely on sustainable energy, they do not consistently adhere to standard market-based accounting practices, such as those recommended by the GHG Protocol or RE100.[136] Consequently, this lack of formal documentation may prevent some firms from credibly claiming their sustainable energy usage in ESG reporting.

Beyond accounting practices, engagement in voluntary carbon markets also appears limited. Only 8.8% of firms reported purchasing carbon offset credits from projects such as reforestation or renewable energy development, indicating a preference for direct operational improvements over compensatory measures. None of the surveyed firms indicated investments in advanced carbon removal technologies like direct air capture (DAC) or carbon capture and storage (CCS). This is not unexpected, given the comparatively much higher costs of such projects. For instance, the costs of DAC typically range from $134 to $344 per tonne of CO_2 removed.[137] In contrast, nature-based offset credits, such as reforestation projects, tend to be significantly less expensive, typically ranging between $5 and $9 per tonne CO_2.[138]

To put the report's findings on GHG emissions into perspective, consider a simplified example that approximates the financial cost to offset Bitcoin-related emissions based on engagement in the voluntary carbon market. As illustrated in Figure 38, there is an extremely wide range of expected costs, from $167 million to $13.7 billion, largely depending on the type of offset credits used. The cost of offsetting emissions via nature-based carbon credits (NbS) ranges from $167 to $358 million, while technology-based credits (with DAC used as a proxy) range from $4.5 to $13.7 billion. This represents between 0.01% and 0.74% of bitcoin's market value (as of 31 December 2024). The stark discrepancy highlights the substantial premium associated with credits that offer greater certainty of additionality and permanence compared to NbS, some of which have shown disappointing results in impact evaluations.[138]

Although this simplified example considers only a limited set of offsetting approaches, it still provides valuable insights into the potential financial commitments needed to achieve carbon neutrality for Bitcoin.

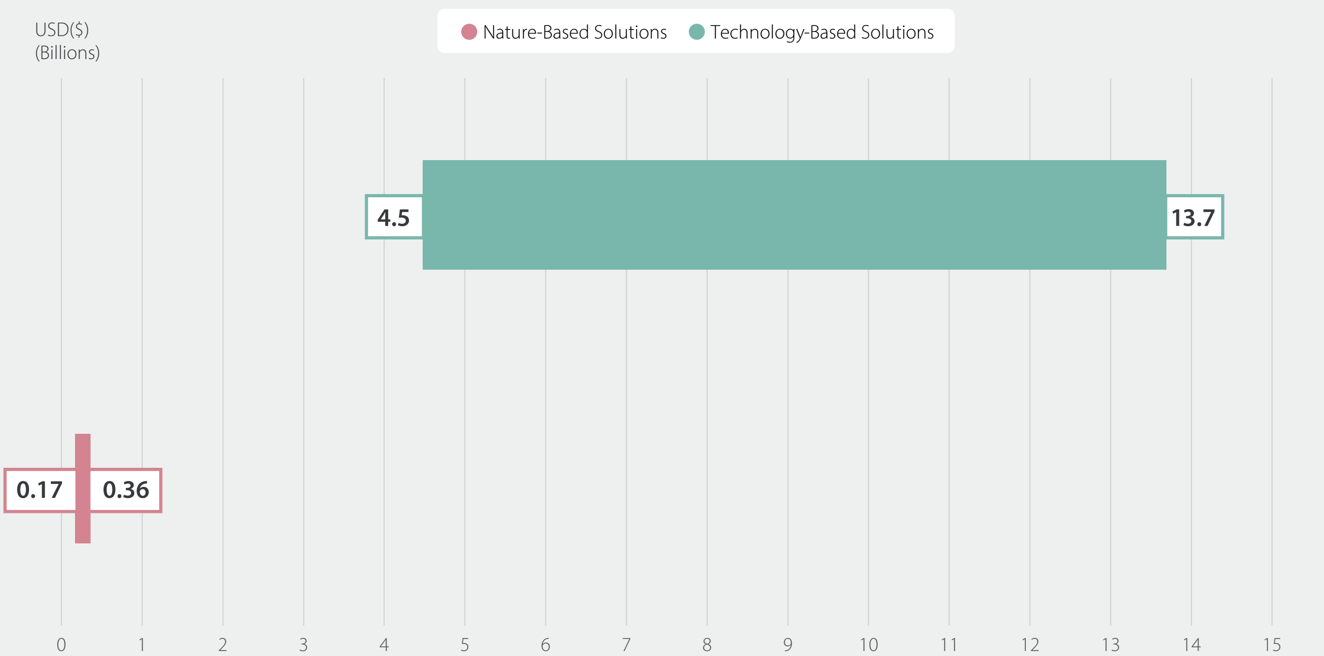
Navigating opportunities and challenges

The data reveals a mixed approach among mining firms in addressing their environmental impact. The relatively high adoption of energy efficiency measures and reliance on sustainable energy sources indicate that many companies are making meaningful progress in reducing their operational carbon footprints. The observation that over half of the industry's energy consumption already comes from sustainable sources is a promising sign, positioning digital mining ahead of other energy-intense sectors in its transition to lower-carbon energy solutions.[139-140] Looking ahead, the industry's focus on cost minimisation is also likely to drive further exploration of off-grid energy solutions to harness available energy more efficiently, whether through colocation in regions currently experiencing elevated levels of curtailment, or finding synergies with other industries such as the O&G sector, offering a pathway to more cost-effective and potentially sustainable operations.

However, the widespread lack of adherence to recognised carbon accounting standards remains a significant challenge, contributing to persistent criticism about the credibility of the industry's sustainability claims. This underscores the need for mining firms to complement their progress in renewable energy adoption with robust carbon accounting practices. Aligning these efforts with established frameworks could help validate their achievements and address the scepticism surrounding their environmental commitments.

Figure 38: Compares the estimated costs of offsetting Bitcoin-related emissions using carbon credits from nature-based solutions (NbS) and technology-based solutions (using DAC as a proxy). NbS costs are estimated at $5 to $9 per tonne CO_2, while the costs of technology-based solutions are estimated to range between $134 to $344 per tonne CO_2. The analysis further assumes a GHG emissions range between 32.9 to 39.8 $MtCO_2e$, with lower emissions corresponding to lower cost scenarios and higher emissions to higher cost scenarios to derive the lower- and upper-bound offset cost estimates. Source: Analysis conducted by the authors, data obtained from CCAF Survey, IEA (2020; [137]), and Swinfield, T., Shrikanth, S., Bull, J.W. et al. (2024; [138])

The Hypothetical Cost of Offsetting Bitcoin-related Emissions Using Carbon Credits



VII: Mining Economics

Digital mining is a dynamic and competitive endeavour. This section offers an overview of key metrics essential for evaluating operational profitability.

The revenue of mining firms is largely determined by external factors such as bitcoin price, block subsidy, and transaction fees. Therefore, a mining firm's competitiveness hinges on meticulous management of operational costs. This section outlines the underlying economics of Bitcoin mining, first examining essential revenue drivers before introducing the cost components that shape a firm's bottom line. Subsequently, key industry metrics such as hashprice, hashcost, and hash margin are presented to illustrate how the interplay of revenue and cost dynamics shapes the competitive landscape.

Miner Revenue: Block Reward and Transaction Fees

Bitcoin miners derive revenue from two primary sources: the block subsidy and transaction fees, which together constitute the block reward. The block subsidy is the predetermined number of newly minted bitcoins awarded to the miner who successfully adds a new block to the blockchain. In contrast, transaction fees are collected from users who pay to have their transactions included in a block (for a more detailed explanation of digital mining, please refer to Part II).

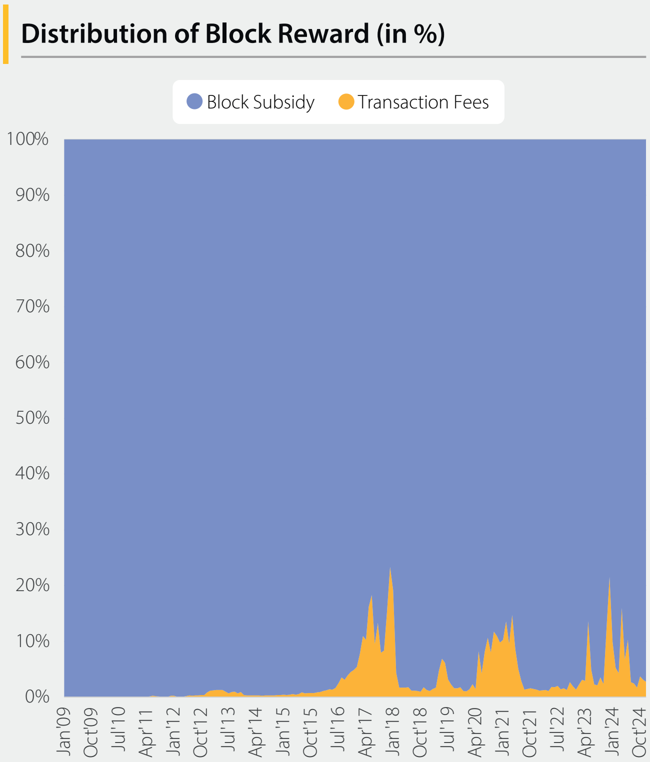
Figure 39 illustrates how the composition of this block reward has evolved over time. As shown in Figure 39(a), transaction fees have historically represented a relatively small portion of the overall reward. This is readily apparent in the chart, where transaction fees remain relatively small compared to the block subsidy for most of the period shown. However, since 2017, periods of heightened network activity have led to occasional spikes in transaction fees. Despite these spikes, transaction fees in 2024 still only accounted for approximately 6% of total mining rewards.

The gradual protocol-mandated reduction in new token issuance emphasises the growing importance of transaction fees for the long-term economic viability of mining. As the block subsidy continues to decline, miners will increasingly rely on transaction fees to cover their operational costs and maintain profitability. Figure 39(b) provides further context by illustrating the combined monthly value of block subsidies and transaction fees in BTC, showcasing the overall trend in miner revenue in native units.

Figure 40(a) highlights the stark volatility of transaction fees, which tends to be amplified during major events that increase network congestion, since users compete for timely inclusion of their transactions. A prime example is the April 2024 halving event. Despite the block subsidy being halved to 3.125 BTC, ViaBTC, the mining pool that mined the halving block (block height 840,000), earned a remarkable 74.051 BTC. This substantial reward was primarily driven by a surge in transaction fees, which reached 37.626 BTC, and an additional 33.3 BTC from the sale of an 'epic sat' – a collector's item part of every halving block, which was auctioned off separately.[142]

Despite miner revenue gradually declining in BTC terms, Figure 40(b) reveals that revenue measured in USD has actually increased over time. The seemingly paradoxical trend can be attributed to BTC price appreciation. This observation underscores the complex interplay between bitcoin price, hashrate, and network activity – all of which influence miner revenue in USD.

Figure 39: (a) Share of transaction fees and block subsidy on total Bitcoin block reward; and (b) total monthly transaction fees and block subsidy in BTC, from 9 January 2009 to 31 December 2024. Data source: Coin Metrics [46,141]



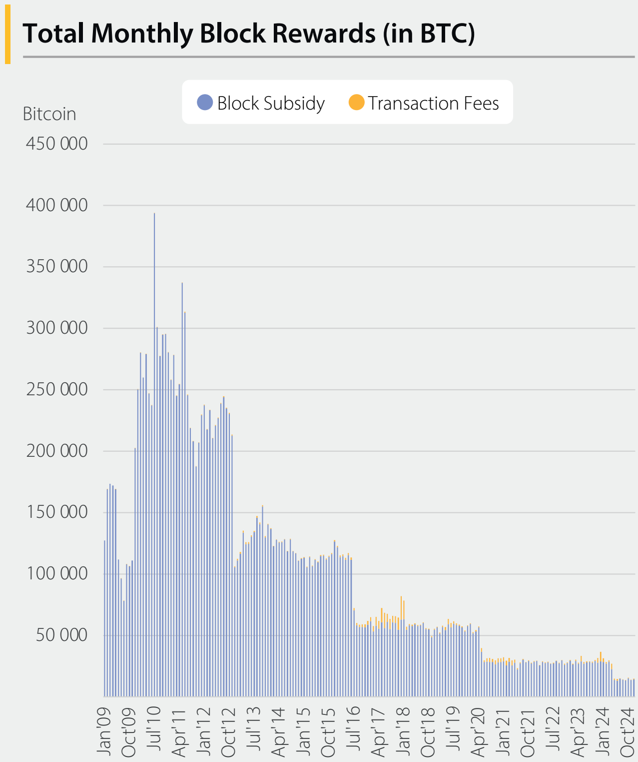
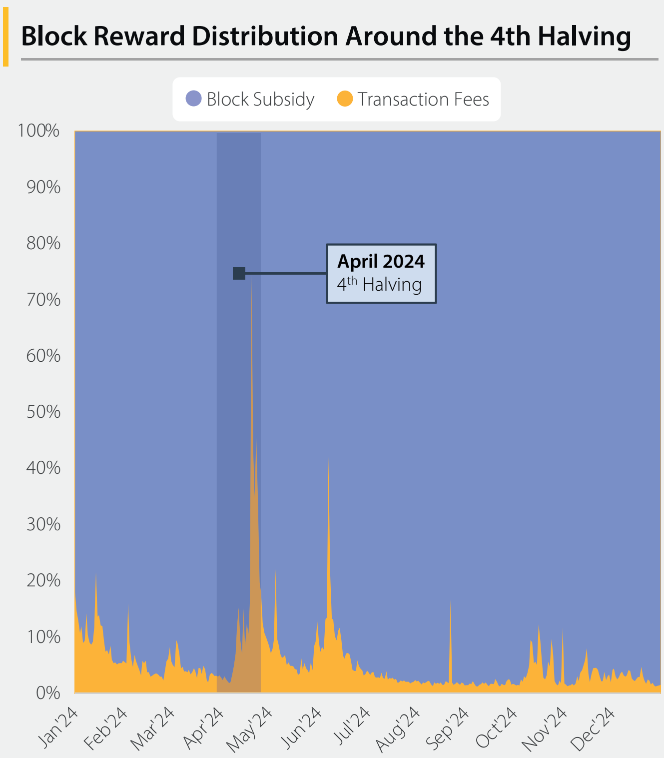
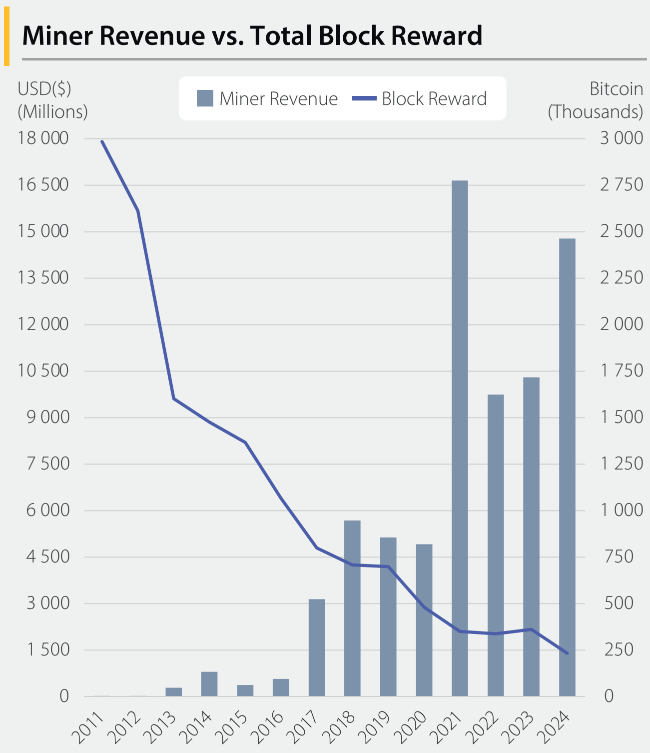


Figure 40: (a) Distribution of block reward by block subsidy and transaction fees (in %) around the 4th halving event, from 1 January 2024 to 31 December 2024; and (b) yearly miner revenue (in USD, left axis) alongside the total block reward (in BTC, right axis), from 1 January 2011 to 31 December 2024. Data source: Coin Metrics [46,141,143]





Evolving revenue streams and block space utilisation

This development sheds light on another important topic: namely, blockspace utilisation and its influence on the network's dynamic fee market. Figure 41(a) shows that initially, a significant portion of block capacity remained unused. However, as adoption increases and new categories of Bitcoin messages (such as those relating to Ordinals, Runes, and BRC20) emerged, blockspace utilisation has risen significantly. For simplicity, these categories are referred to as 'Ordinals transactions', 'Runes transactions', and 'BRC-20 transactions'. It is important to note that these are not technically new transaction types, but rather standard Bitcoin transactions carrying specially formatted data interpreted by their respective protocols. These new transaction categories have amplified the demand for blockspace, leading to a more diverse block space utilisation and competitive fees. As blocks consistently reach close to full capacity, users must bid higher transaction fees to secure timely inclusion, particularly during periods of elevated demand. This competitive fee market dynamic becomes increasingly important as block subsidies diminish and miners grow more dependent on transaction fees.

Figure 41(b) provides a closer examination of transaction fee volatility after the introduction of new token standards and protocols (such as BRC-20 inscriptions and Runes) to Bitcoin, focusing on daily-level observations. Surges in transaction fees appear to be temporary and particularly clustered around or soon after the launches of BRC-20 in April 2023 and Runes in April 2024. For example, the launch of the Runes protocol, which enables the creation of fungible tokens on Bitcoin, in April 2024 saw fees (in native units) skyrocketing to 1,260 BTC on a single day. These spikes offer deeper insights into the substantial impact temporary network congestion can have on fee dynamics.

Figure 42 provides a comprehensive overview of the evolving transaction and transaction fee landscape in Bitcoin. Figure 42(a) breaks down transaction fees by transaction type, highlighting the relative contribution of each type to the overall fee revenue on a monthly basis. Notably, regular transactions dominate fee revenue, accounting for approximately 79% of total fee revenue (December 2024). However, newer transaction types like inscriptions and Runes have started to gain traction, with Runes assuming the majority of all non-regular transaction type fees in the months following the launch of the protocol, with the exception of December. Figure 42(b) complements this analysis by showing the total number of transactions for each type on a monthly basis. This chart mirrors the picture in Figure 42(a), showcasing the surge in volume of Runes transactions. Interestingly, in November and December 2024, Runes transactions declined notably, on an absolute and relative basis – compared to other non-regular types.

Figure 41: (a) Utilisation (in %) of block space on a monthly basis from December 2009 to December 2024; and (b) the total transaction fees (in BTC) of various transaction types on a daily basis from 17 February 2023 to 31 December 2024. Source: CCAF Blockchain Analytics by @alexneu_btc on Dune dashboard [38] and @data_always [144]

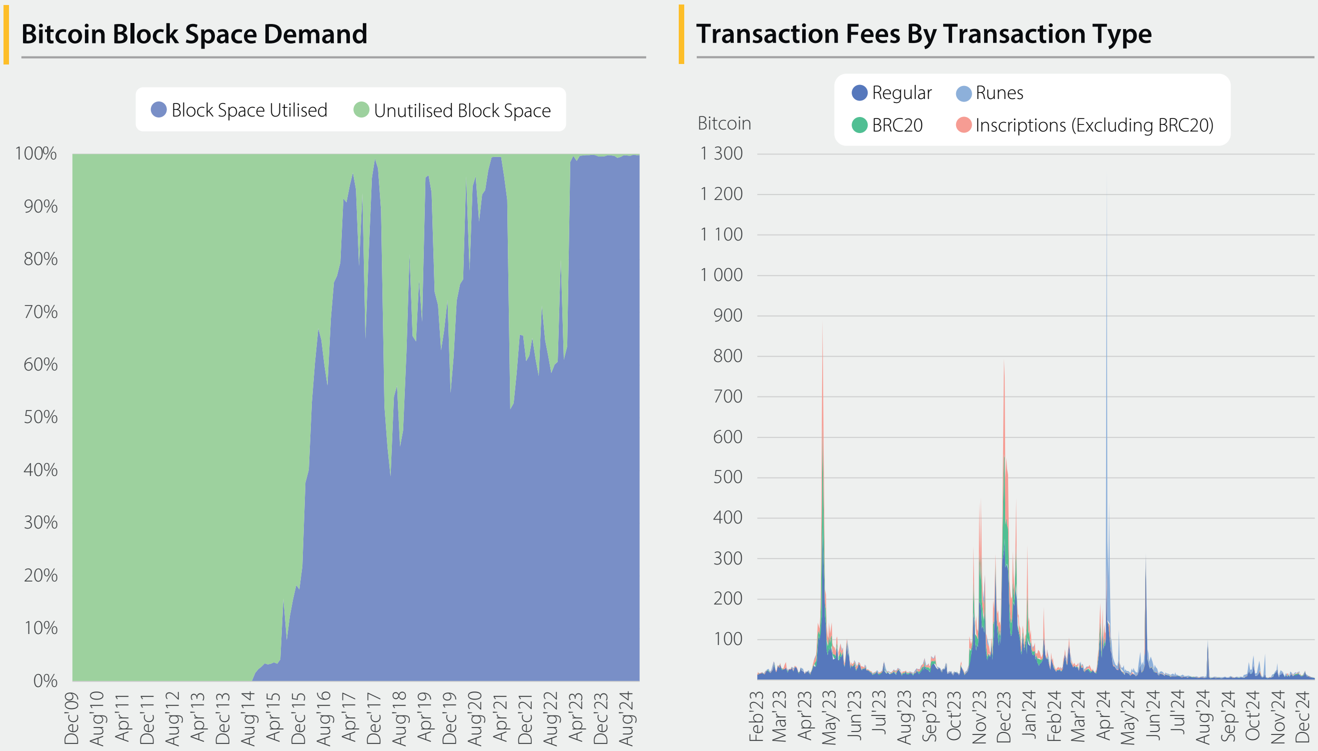
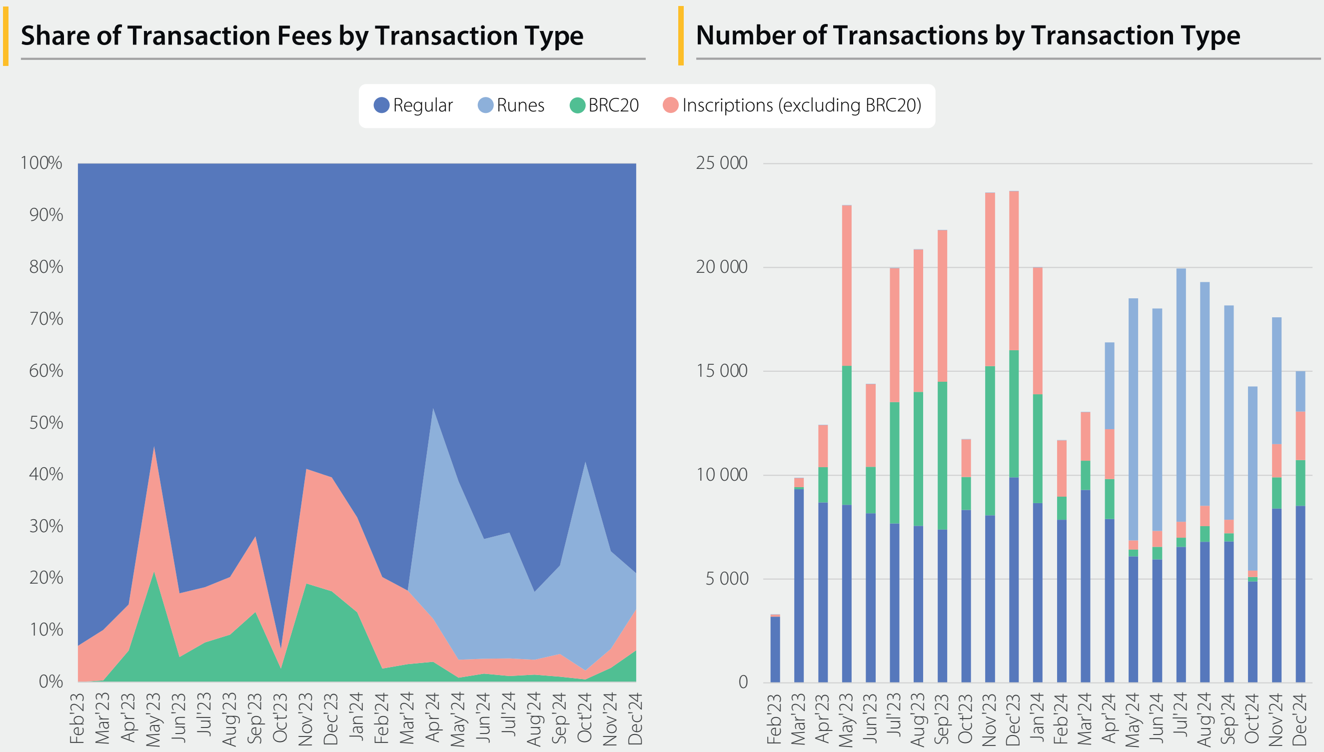
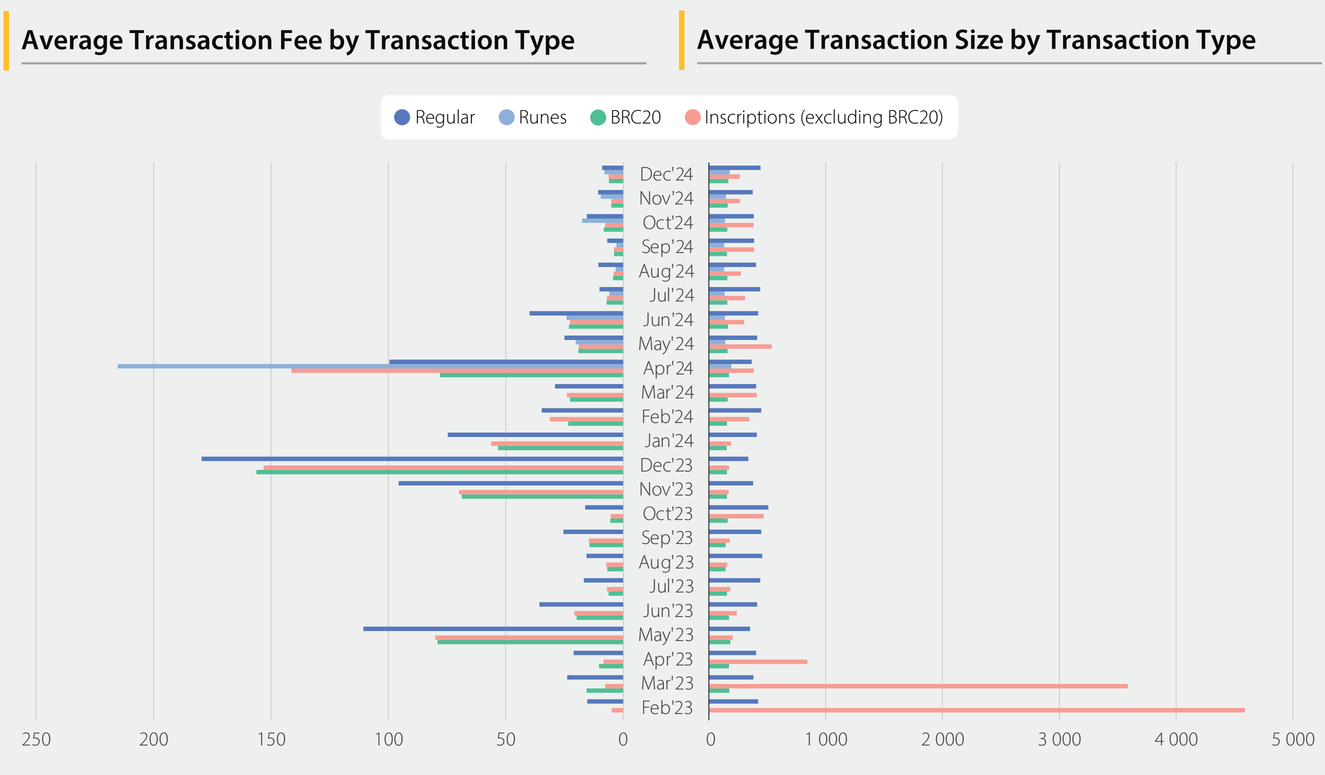


Figure 42: (a) Distribution (in %) of transaction fees per transaction type; and (b) aggregated number of transactions by transaction type, both on a monthly basis, from 17 February 2023 to 31 December 2024. Source: CCAF Blockchain Analytics by @alexneu_btc on Dune dashboard [38]



To gain a granular understanding of fee dynamics, we can examine the average transaction fees paid per transaction type. Figure 43(a) reveals that regular transactions typically command the highest fees. However, a notable exception occurred in April 2024, where the average transaction fee for Runes transactions was more than double that of regular transactions. This anomaly explains the observation from Figures 42(a) and (b): Runes transactions accounted for 41% of total transaction fees in April 2024, despite constituting only 15% of total transactions during that period. A similar, albeit less pronounced, disparity emerged in February 2023, with inscriptions representing 7% of transaction fees but only 3% of transactions. In the latter case, the discrepancy can be attributed to transaction size. As illustrated in Figure 43(b), the average size of transactions containing Ordinals inscriptions in February and March 2023 was substantially larger than that of regular transactions, driven by the inscription of image data. [145]

Figure 43: (a) Average transaction fee by transaction type, in satoshis (sats) per virtual byte (vB); and (b) average transaction size in vB, from 17 February 2023 to 31 December 2024. Source: CCAF Blockchain Analytics by @alexneu_btc on Dune dashboard [38]



The Cost Structure of Digital Mining Firms

Given the resource-intensive nature of digital mining, a firm's cost structure emerges as a key determinant of its operational success. Digital mining is unique in that the product – bitcoin – has the same price regardless of the firm's mining process: firms do not compete on output price as bitcoin is a perfectly homogeneous good, with its price entirely dictated by the market. Instead, competition revolves entirely around cost management, rendering a firm's ability to minimise expenses central to its ability to thrive in the industry.

Observations on cost structures

To better understand a firm's cost structure, miners were surveyed about their electricity rates, particularly the rates for direct electricity usage. The term 'direct' denotes the raw utility costs or operating expenses related to in-house electricity generation. As shown in Figure 44(a), the median direct electricity rate reported by miners is $45 per megawatt-hour (MWh). The data reveals considerable variation across the sample, with rates ranging from $20/MWh to $65/MWh. Notably, half of the responses cluster within a narrower band of $38.5 to $55/MWh, indicating that electricity rates can vary widely amongst firms.

Beyond utility bills, miners shoulder a range of other operational expenses, encompassing selling, general, and administrative expenses (SG&A), and the cost of goods sold (COGS). SG&A includes costs associated with sales, marketing, executive compensation, office rent, and other indirect overheads. COGS, conversely, represents direct costs attributable to the production of goods or services. Aggregating these expenses with direct electricity rates yields an 'all-in' electricity rate, a more comprehensive cost metric. While the range of all-in rates mirrors that of direct rates ($25/MWh to $70/MWh), the distribution is tighter, with half of the observations concentrated between $50.8 and $65/MWh.

Figure 44(b) reveals that direct electricity costs constitute the lion's share (81.1%) of total operating expenditures (excluding non-cash expenses), while SG&A and COGS represent the remaining 18.9%, or $10.5/MWh. This breakdown, derived from median values for direct and all-in electricity rates, emphasises the substantial weight of electricity costs in the overall cost structure. The survey findings align with previous CCAF research conducted in 2020,[3] which also identified direct electricity costs as the predominant expense.

Consequently, certain firms appear to possess a distinct competitive advantage in securing cost-effective energy access. However, this advantage may be intertwined with difficult-to-quantify risks, particularly when operating in regions characterised by extremely low-cost electricity but also social, geopolitical, or regulatory instability.

Estimating bitcoin production costs

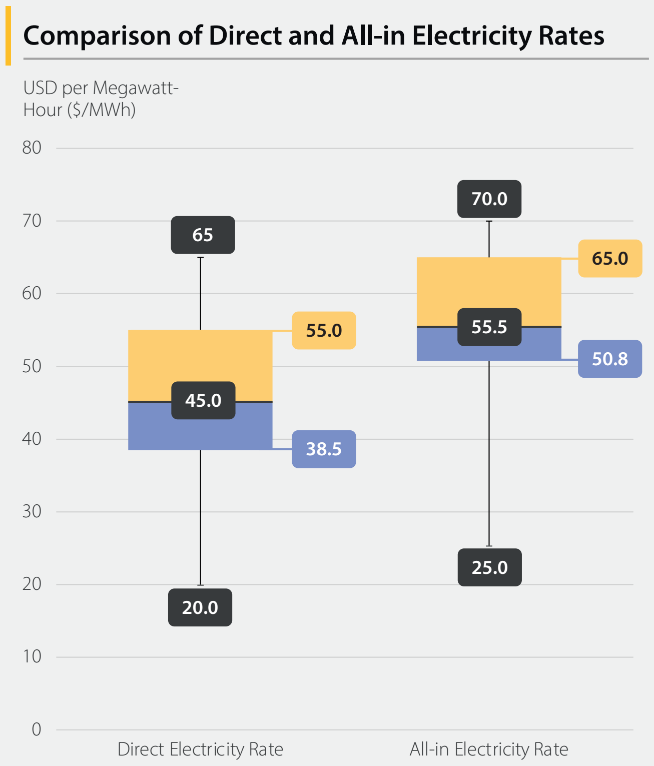
The data collected enables a simple approximation of the electricity and total costs required to mint one bitcoin. By holding the previously established hardware efficiency constant, Figure 45(a) illustrates the range of implied electricity costs for producing a single bitcoin, which spans from $17,417 to $56,606, with a median of $39,189. This finding lends credence to our theoretical CBECI bitcoin production cost estimate of $39,009 (as of 30 June 2024), which is also based on a direct cost approach. Focusing on all-in production costs, Figure 45(b) reveals an extended range of $21,771 to $60,960, with a median of $48,333.

As of the survey snapshot on 30 June 2024, bitcoin was trading at $62,763. Based on this price, illustrative profit margins can be derived under two scenarios. Considering only direct electricity costs, the margin stands at 37.6%. However, when incorporating the all-in electricity rate, which encompasses additional operational expenses such as SG&A and COGS, the margin diminishes to 23.0%. It is important to note that these calculations are predicated on the weighted miner efficiency (see Figure 26(a)) and the respective direct and all-in electricity rates (see Figure 44(a)) and are intended solely as illustrative examples, rather than a comprehensive assessment.

Key takeaways

The analysis underscores the critical role of electricity costs in shaping the economics of digital mining. Miners who can secure cheaper energy sources enjoy significant cost advantages, but they also face inherent risks tied to external factors such as geopolitical and regulatory uncertainties. Understanding these dynamics is crucial to develop a nuanced perspective on the competitive landscape and challenges mining firms must navigate.

Figure 44: (a) Box plots comparing direct and all-in electricity rates, in USD per megawatt-hour ($/MWh); and (b) a breakdown of corporate expenses into electricity and other expenses, showing the percentage share of each, as of 30 June 2024. The difference between the median all-in electricity rate and the median direct electricity rate is also shown, representing other expenses, in USD per megawatt-hour ($/MWh). Source: CCAF Survey. Sample sizes: Figure 44(a) (N = 35), Figure 44(b) (N = 32)



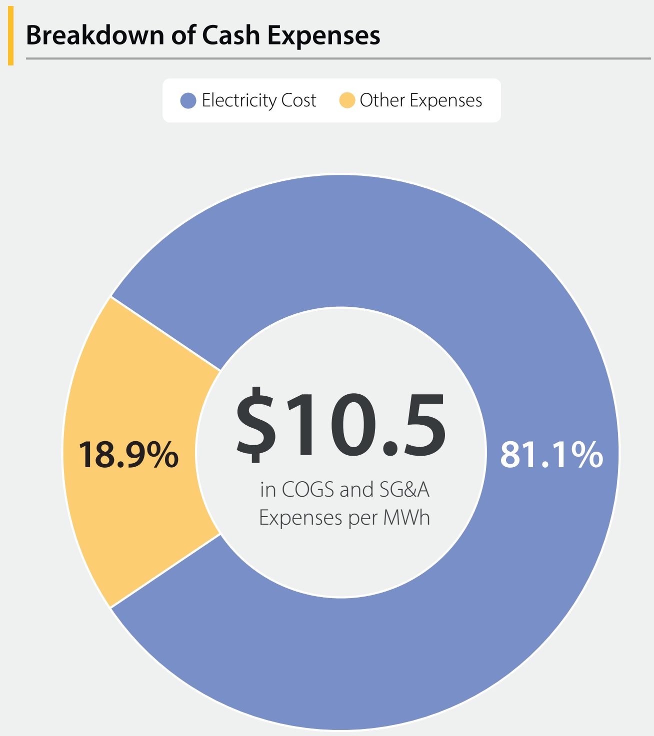
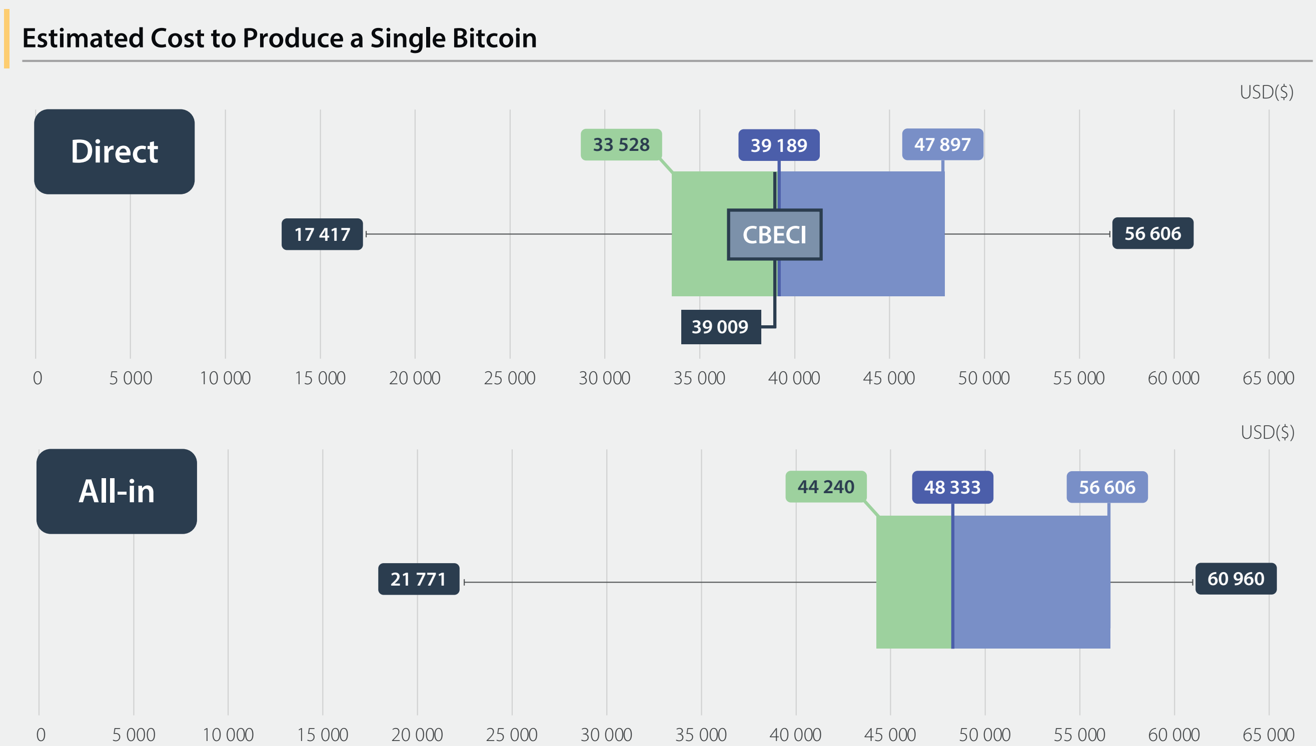


Figure 45: (a) Direct electricity cost; and (b) all-in cost of minting one BTC (in USD), as of 30 June 2024. The estimates have been computed using: (i) the hashprice in BTC, (ii) the weighted ASIC (SHA-256) miner efficiency shown in Figure 26(a), and (iii) the determined direct and all-in electricity rates (see Figure 44(a)). Source: Analysis conducted by the authors, data obtained from CCAF Survey, Coin Metrics [146]



Key Revenue Metrics

Hashprice is a critical concept for understanding the evolution of miner revenue over time. It is the revenue, measured in U.S. dollars or native units, per unit of computational power per day. As the network hashrate increases – driven either by new miners joining the network or existing ones upgrading to more powerful hardware – the computational power required to solve the cryptographic challenge also rises. Consequently, revenue per unit of computing power, denominated in native tokens, diminishes. A rise in the bitcoin price can act as a counterbalancing force to this trend; ergo, hashprice in USD and native unit terms do not move in tandem. Overall, monitoring hashprice enables miners to swiftly evaluate the profitability of their operations and serves as a valuable metric for investment decisions.

Figure 46(a) showcases the historical trend of hashprice (in BTC) from 2020 to 2024. The chart highlights the rapid decline in BTC earnings per unit of computing power. While a rise in bitcoin price or transaction fees could theoretically offset the decline in BTC rewards, Figure 46(b) shows that this did not adequately compensate for increases in difficulty and declines in block subsidy. This demonstrates that miners must continually seek ways to raise the efficiency of their operations or reduce costs to maintain profitability.

Figure 46: (a) Daily hashprice in BTC per petahash per day (BTC/PH/day); and (b) the daily hashprice in U.S. dollars (in USD/PH/day), from 1 January 2020 to 31 December 2024. Data source: Coin Metrics [146-147]

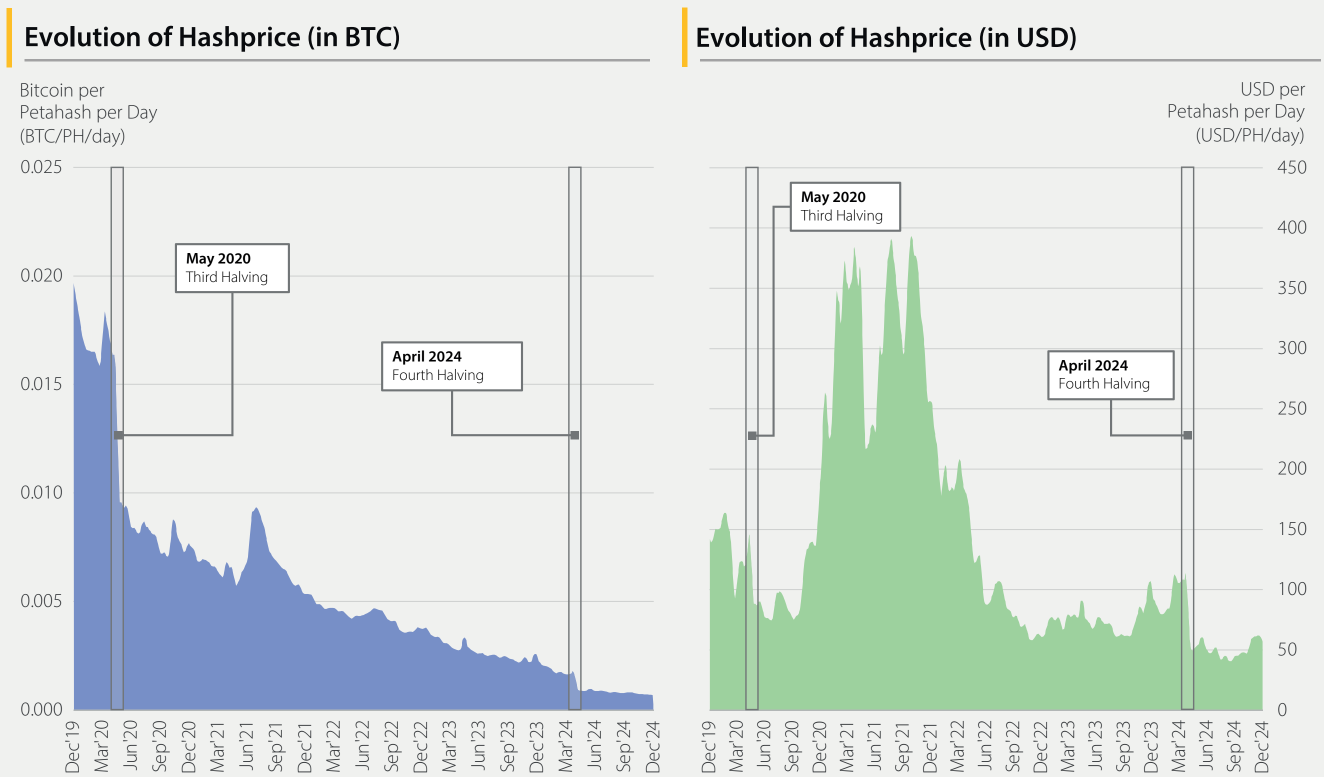
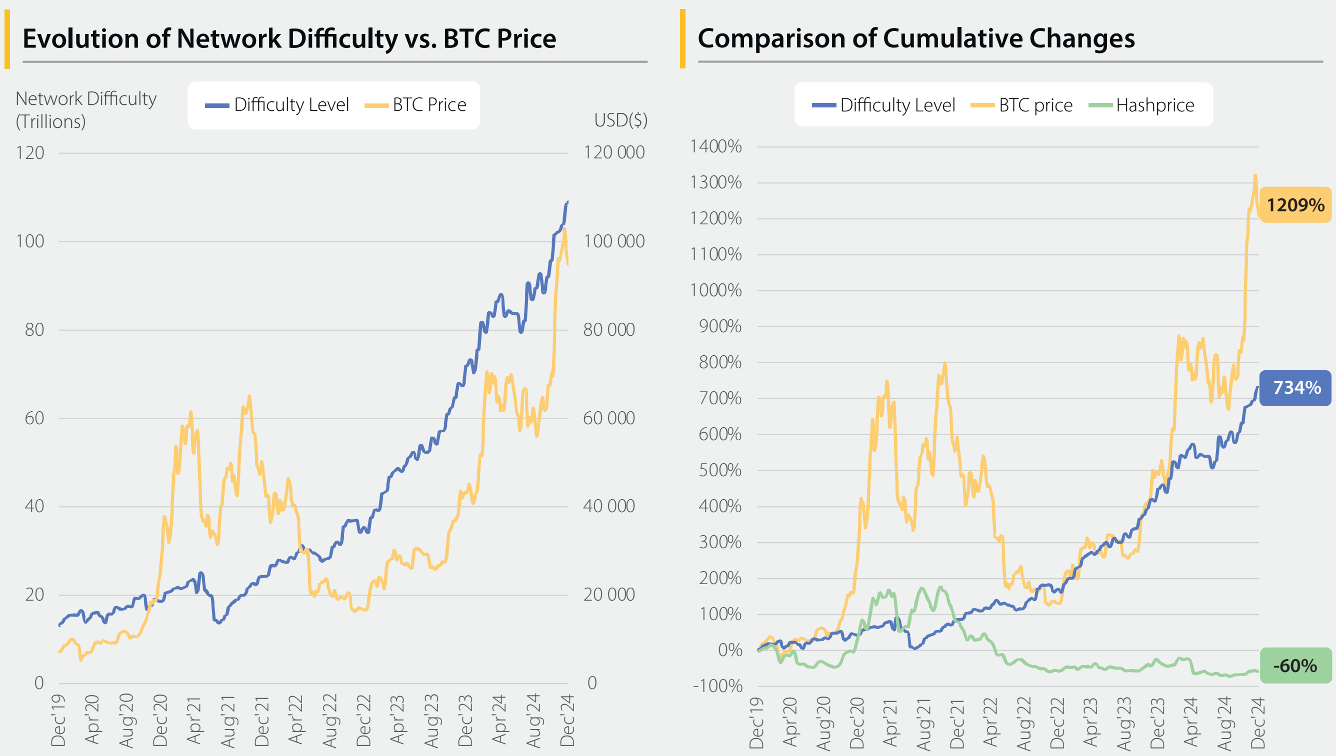


Figure 47(a) and (b) illustrate these dynamics and provide a detailed view of the interplay between bitcoin price, network difficulty, and hashprice. Figure 47(a) reveals a substantial rise in both network difficulty and the price of bitcoin over the observed period. However, the correlation between these metrics is far from consistent, with network difficulty exhibiting a steadier and less volatile upward trajectory. Crucially, network difficulty often increased even during periods of bitcoin price declines, demonstrating that even precipitous drops in bitcoin's value do not always deter mining activity. Conversely, sharp increases in bitcoin's price also do not automatically lead to an immediate equally sharp upward reaction in mining activity. This can be explained by the physical constraints associated with the activity itself, such as hardware procurement and deployment – all of which take time to operationalise. This dynamic can exert significant pressure on mining firm profitability when bitcoin price stagnates or declines while network difficulty continues to climb.

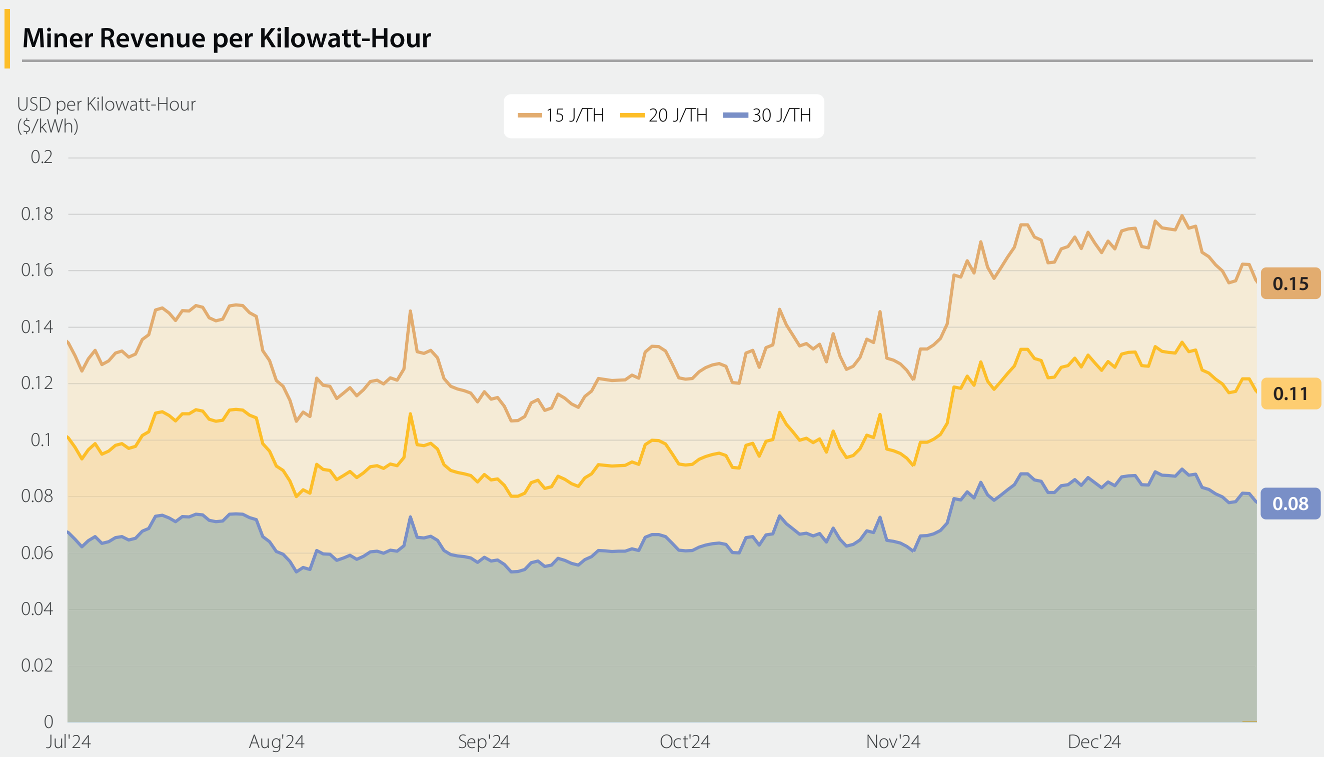
Figure 47(b) shows the cumulative development of bitcoin price, network difficulty, and hashprice. During the period under review, bitcoin price (+1209%) consistently remained either close to or above network difficulty (+734%). Yet, despite the considerably larger increase in bitcoin price, hashprice experienced a significant decline (-60%). This drop can be attributed to two halving events during the period (May 2020 and April 2024), which reduced the block subsidy from 12.5 bitcoin to 3.125 bitcoin – a 75% reduction. Given the relatively minor contribution of transaction fees to overall miner revenue, even the substantial rise in bitcoin price proved insufficient to offset the combined revenue reduction driven by higher network difficulty and the diminished block subsidy.

Figure 47: (a) Evolution of network difficulty (left axis) and BTC price (in USD, right axis); and (b) the cumulative percentage change in network difficulty, BTC price (in USD) and hashprice (in USD/PH/day), from 1 January 2020 to 31 December 2024. Source: Analysis conducted by the authors, data obtained from Coin Metrics [45,147-148]



This trend is expected to continue and underlines the increased competition in the mining sector, encapsulating the challenge miners face in sustaining profitability. Another more recent metric that has gained traction is expressing miner revenue in terms of U.S. dollars per kilowatt-hour.[148] Given the strong association of digital mining with energy, and electricity being a core driving cost factor, examining revenue from this lens is also intuitive, as it allows for a straightforward comparison of revenue and cost. As shown in Figure 48, previous-generation devices (30 J/TH) currently generate about $0.08/kWh, whereas newer models achieve roughly between $0.11 – $0.15/kWh.

Figure 48: ASIC (SHA-256) miner revenue per kilowatt-hour (USD/kWh) for varying hardware efficiency levels from 1 July 2024 to 31 December 2024. Source: Analysis conducted by the authors, data obtained from Coin Metrics [147]



Key Cost Metrics

In contrast to hashprice, hashcost represents the cost per unit of computational power, typically measured in U.S. dollars. While primarily encompassing electricity expenses, hashcost can also be calculated on an all-in basis, factoring in additional operational costs such as hardware depreciation and maintenance.

Hashcost is a convenient metric for miners as it can be readily used alongside hashprice to determine the profitability or break-even point of their operations. It can be computed for entire operations or applied granularly to specific mining units. Essentially, if hashcost exceeds hashprice, miners are operating at a loss. Thus, monitoring both metrics allows miners to make informed decisions about scaling operations, upgrading equipment, or even temporarily or permanently shutting down unprofitable segments.

Figure 49(a) provides a simplified illustration of how hashcost can be applied in a practical setting. To provide context, the most efficient mining device currently available (as of 31 December 2024) achieves an efficiency of 12 J/TH.[150] The matrix showcases the operational cost per petahash (PH/s) per day and the cost of minting one bitcoin at different hardware efficiency levels and electricity rates.

Building on this, Figure 49(b) presents the relationship of bitcoin prices and our CBECI bitcoin production cost estimates over time, revealing closer insights into the profitability of mining. The chart depicts a prolonged period of depressed margins from summer 2022 to around spring 2023, and more recently, a compression following the fourth halving event in April 2024. However, closer to the end of 2024, the spread significantly widened and the difference between BTC price and production cost marked a new all-time high in absolute terms. The hash margin, introduced next, provides further insights into profitability.

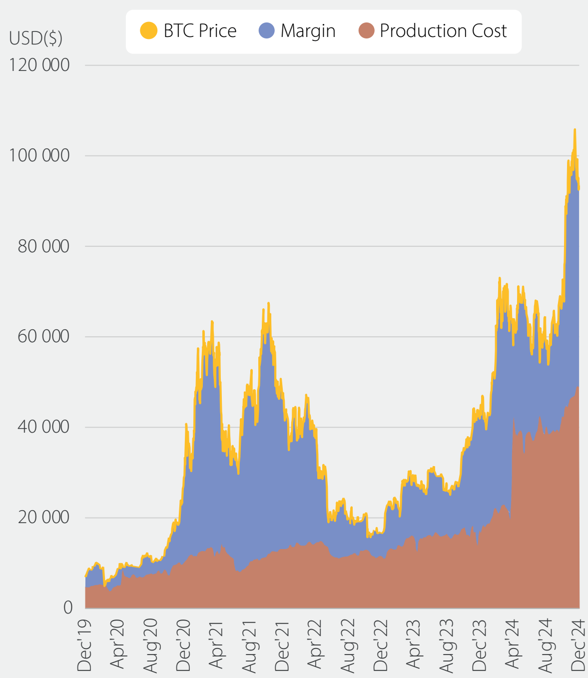
Figure 49: (a) Breakdown of hashcost (in USD/PH/day) and minting cost per bitcoin (in USD/BTC) for various combinations of ASIC (SHA-256) miner efficiency (in J/TH) and electricity rate (in USD/MWh) as of 31 December 2024; and (b) the BTC price, estimated BTC minting cost, and profit margin (in USD) from 1 January 2020 to 31 December 2024. Source: Analysis conducted by the authors, data obtained from Cambridge Centre for Alternative Finance [82], Coin Metrics [146]

Hashcost and Production Cost of One BTC

Miner Efficiency in Joules per Terahash (J/TH)

Electricity Rates in USD per Megawatt-Hour ($/MWh)	15 J/TH	20 J/TH	25 J/TH	30 J/TH	35 J/TH	40 J/TH	45 J/TH
$20 /MWh	$7	$10	$12	$14	$17	$19	$22
	$12 382	$16 510	$20 637	$24 765	$28 892	$33 020	$37 147
$40 /MWh	$14	$19	$24	$29	$34	$38	$43
	$24 765	$33 020	$41 275	$49 529	$57 784	$66 039	$74 294
$60 /MWh	$22	$29	$36	$43	$50	$58	$65
	$37 147	$49 529	$61 912	$74 294	$86 677	$99 059	$111 441
$80 /MWh	$29	$38	$48	$58	$67	$77	$86
	$49 529	$66 039	$82 549	$99 059	$115 569	$132 079	$148 588
$100 /MWh	$36	$48	$60	$72	$84	$96	$108
	$61 912	$82 549	$103 186	$123 824	$144 461	$165 098	$185 736

Historical BTC Price, Production Cost, and Margin



Hash Margin, A Measure of Profitability

To gain an intuitive understanding of mining profitability, the hash margin metric can function as a key indicator. This metric is a quick and useful reference point that provides surface-level insights about what configurations of electricity rates and hardware efficiency are economically viable at a given hashprice. Hash margin can be expressed in absolute terms as follows:

$$\text{Hash Margin} = \text{Hashprice} - \text{Hashcost}$$

which represents the difference between the hashprice and hashcost. Alternatively, it can be expressed in percentage terms using the following formula:

$$\text{Hash Margin (\%)} = \frac{(\text{Hashprice} - \text{Hashcost})}{\text{Hashprice}} \times 100$$

representing the proportion of hashprice that constitutes profit. Therefore, this metric offers a direct, quick, and intuitive measure of mining profitability.

The matrix displayed in Figure 50(a) features these margins (both on an absolute and percentage basis) for various electricity rates and miner efficiencies, holding hashprice constant. The table vividly demonstrates the gravity of the impact both electricity costs and miner efficiency can have on profitability. It also allows for the identification of break-even points, indicating specific combinations of electricity rates and miner efficiencies where profit turns to loss. For instance, at an electricity rate of $80/MWh, miners with an efficiency of 25 J/TH are slightly above break-even, while those with 30 J/TH are already experiencing a loss. Conversely, at a lower electricity cost of $40/MWh, miners with an efficiency as low as 45 J/TH still remain profitable, which underscores the impact of electricity costs on mining viability.

Figure 50(b) provides a practical example of applying this metric over time, using an efficiency level of 30 J/TH, which was considered top-of-the-line in 2020. The chart graphically depicts the stark fluctuations in profitability across market cycles, reaching a peak of 91% during the most favourable conditions and falling below 10% in less advantageous times. Notably,

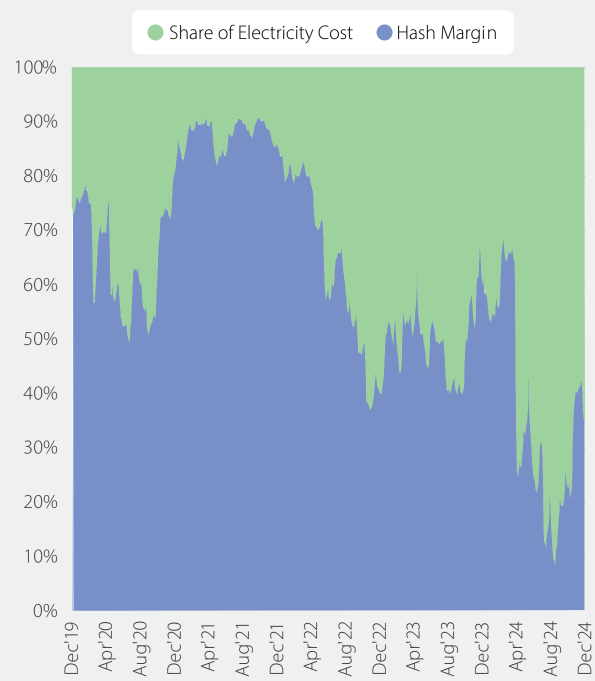
Figure 50: (a) Calculated hash margins, in absolute (USD/PH/day) and percentage (%) terms, for various combinations of ASIC (SHA-256) miner efficiency (in J/TH) and electricity rate (in USD/MWh) as of 31 December 2024, assuming a hashprice of $54.3/PH/day; and (b) a practical example of the hash margin metric applied over time from 1 January 2020 to 31 December 2024, assuming an efficiency of 30 J/TH and an electricity rate of $50/MWh. Sources: Analysis conducted by the authors, data obtained from Coin Metrics [147]

Hash Margins (USD and %)

Miner Efficiency in Joules per Terahash (J/TH)

Electricity Rates in USD per Megawatt Hour ($/MWh)	15 J/TH	20 J/TH	25 J/TH	30 J/TH	35 J/TH	40 J/TH	45 J/TH
$20 /MWh	$47	$45	$42	$40	$37	$35	$33
	87%	82%	78%	73%	69%	65%	60%
$40 /MWh	$40	$35	$30	$25	$21	$16	$11
	73%	65%	56%	47%	38%	29%	20%
$60 /MWh	$33	$25	$18	$11	$4	-$3	-$11
	60%	47%	34%	20%	7%	-6%	-19%
$80 /MWh	$25	$16	$6	-$3	-$13	-$23	-$32
	47%	29%	12%	-6%	-24%	-41%	-59%
$100 /MWh	$18	$6	-$6	-$18	-$30	-$42	-$54
	34%	12%	-11%	-33%	-55%	-77%	-99%

Application of Hash Margin in Practice



throughout the five-year period that included two halving events, the hash margin remained above the break-even point, even rebounding to 35% by the end of 2024.

This hypothetical example suggests that the operational lifespan of these purpose-built devices may extend beyond five years, barring technical faults. Even with an assumed electricity rate of $50/MWh, profitability was maintained throughout the observed period. Furthermore, when applying a reduced rate of $40/MWh, it becomes evident that such units, despite their age, would still hold a competitive advantage over current next-generation devices operated at electricity rates of $80/MWh or higher. This observation supports the survey findings displayed in Figure 24, which show that the vast majority of initially phased-out devices may find secondary use elsewhere.

VIII: Miner Sentiment

Innovation, adaptability, and foresight are paramount for navigating the dynamic and competitive world of digital mining. This section highlights key concerns of mining firms, their strategies for mitigating risks, and perceived growth barriers.

Navigating the dynamic landscape of digital mining demands more than operational prowess; it requires strategic foresight and adaptability. Building on the operational insights previously examined, this section analyses prevailing miner sentiment and strategic thinking – exploring their primary concerns (ranging from energy costs to regulatory uncertainty), favoured risk mitigation strategies like diversification and hedging, and perceived barriers to growth, such as deployment limitations. Furthermore, we analyse their forward-looking expectations for network hashrate and bitcoin price and benchmark their forecasts with actual results to see how accurately miners' forecasts match realised market conditions.

What Keeps Miners Awake at Night?

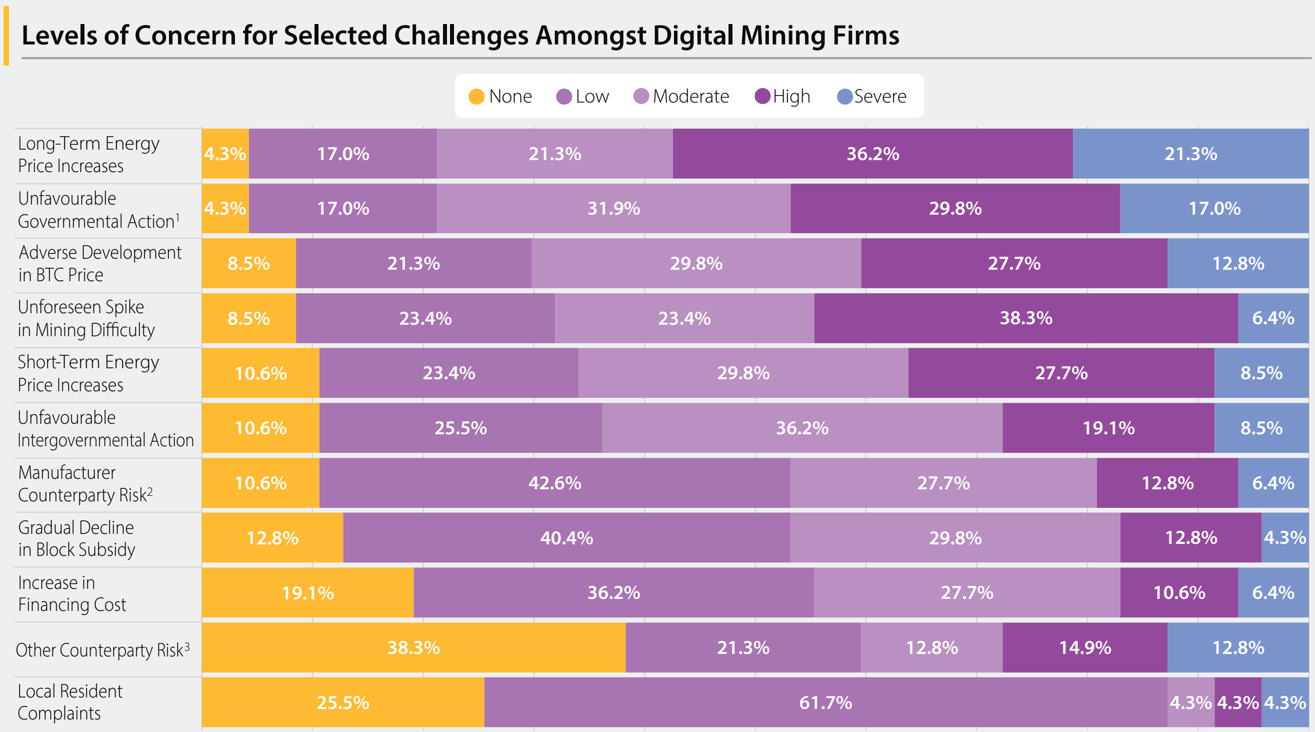
To understand miners' most pressing concerns, a series of potential challenges were presented for ranking based on their level of importance or severity. The results, depicted in Figure 51, offer insights into how the mining community perceives each event and the distribution of the selected ranking.

Perhaps unsurprisingly, long-term electricity prices emerged as the major concern, with 57.5% of respondents identifying this as at least a high concern and 21.3% classifying it as severe. This result reflects the fundamental role energy costs play in miners' strategic considerations. Interestingly, short-term price spikes are perceived as significantly less worrying. This is understandable, given miners' ability to temporarily reduce their computational load during periods of heightened prices. While this strategy can mitigate short-term price spikes, it is not a sustainable solution, as curtailing operations halts mining activity and eliminates access to network rewards.

Adverse governmental actions at the country or state level are also a prominent concern amongst miners, with nearly half of respondents viewing such actions as at least a high concern. This reflects ongoing regulatory uncertainties, including potential restrictions, unfavourable taxation policies, or outright bans. In contrast, miners exhibited a more relaxed attitude toward the possibility of coordinated global action, likely due to the logistical and political challenges of achieving such unified measures across jurisdictions with likely divergent interests.

Other major concerns identified include unexpected bitcoin price developments and mining difficulty adjustments, both of which have a direct and immediate impact on miners' profitability. The order of ranking is somewhat comprehensible, as mining difficulty is closely tied to hardware deployment and available rack space and typically moves in a

Figure 51: Digital miner sentiment on a variety of key industry challenges. Notes: [1] pertains to actions at local or federal level, [2] comprises non-delivery or delayed delivery, the delivery of faulty units and related risks, [3] reliance on third-party hosting services, as of 30 June 2024. Source: CCAF Survey. Sample size: (N = 47)



unidirectional manner, rendering its trajectory more predictable. In contrast, bitcoin price movements are influenced by a broader set of factors, such as historical trends, macroeconomic expectations, and speculative sentiment, making them inherently more volatile and challenging to forecast.

Interestingly, counterparty risk, whether related to manufacturers or other stakeholders, appeared to be of minimal concern to most respondents. This general lack of concern, however, masks a stark contrast in perception regarding the use of third-party providers for miner hosting. While nearly 40% of respondents viewed it as of no concern, 12.8% ranked it as severe. This discrepancy likely arises because many respondents may not utilise such services and therefore have limited exposure to associated risks. For those miners who do rely on third-party hosting, counterparty risk becomes a significant concern, with the level of concern likely correlated to the degree of dependence on these providers and the diversification of their third-party relationships.

The gradual shift in mining economics, specifically the transition from a major reliance on block subsidies to a model that increasingly depends on transaction fees, does not yet seem to cause much worry. This suggests that miners are either confident in their ability to adapt or do not view the transition as imminent, given that Bitcoin has only just entered its fourth halving cycle.

Finally, miners expressed the least concern about the impact of citizen actions on their operations. While citizen opposition to mining facilities has become more prominent in recent years, often citing noise pollution as a key grievance, [151] miners seem confident in their ability to address such concerns. For example, miners have turned to solutions such as immersion or liquid cooling technologies, which significantly reduce noise levels compared to traditional air cooling. Proactively deploying these technologies in facilities located near residential areas helps mitigate noise pollution and thereby minimise any potentially adverse impact on residents' quality of life, thus reducing the likelihood of complaints.[152]

These findings highlight that while some concerns, such as energy costs or adverse governmental action, are widely shared across the industry, others, like counterparty risks or citizen opposition, appear to be idiosyncratic.

Navigating Uncertainty, How do Miners Manage Their Risk?

Having analysed the key concerns of miners, the next step is to examine how miners perceive the usefulness of various mitigation measures to address these and other challenges. As shown in Figure 52, power hedging strategies stand out as one of the most widely valued approaches. This aligns with the previously discussed significance of access to reasonably priced power on miners' profit margins.

As highlighted in Figure 51, long-term electricity prices are a major concern for the industry, with nearly 60% of respondents identifying them as at least a high concern. Correspondingly, nearly 60% of respondents view power hedging or energy trading as a crucial lever for mitigating the risks associated with power price variability. These findings underscore that energy costs are central to miners' strategic considerations, and that tools which enable them to stabilise this critical input are highly valued.

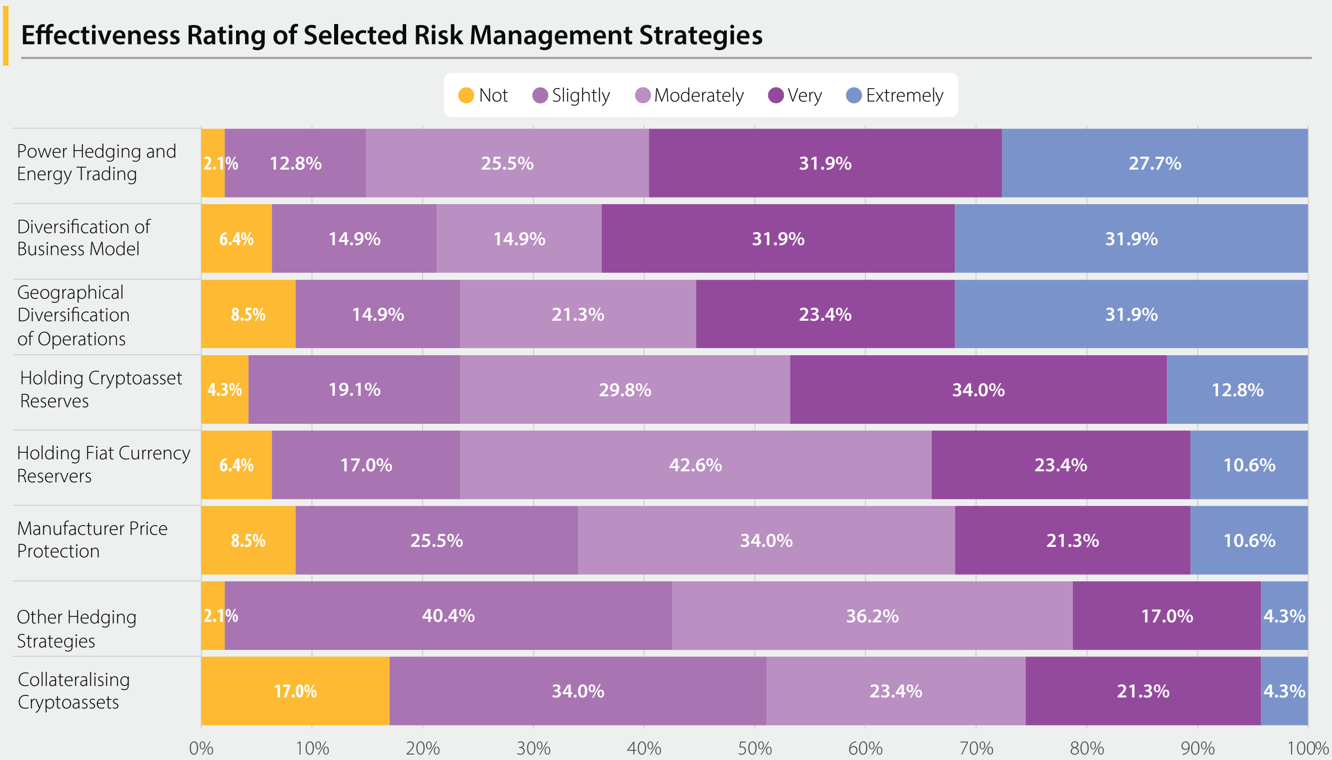
Another risk mitigation measure, ranking nearly on par with power hedging strategies, is the diversification of business models, with 63.8% of respondents deeming it at least very effective. As the Bitcoin network progresses through successive halving cycles, diversifying operations into adjacent fields, such as AI, appears prudent.

While only a few miners had announced concrete plans to diversify into AI in the past, this trend has recently shifted. Numerous publicly listed mining firms have now publicised plans to expand into the space,[153-156] with some already having taken concrete steps by building the necessary infrastructure and recruiting key personnel.

Ensuring geographical diversification of operations is another prominent risk mitigation strategy, rated as at least very effective by 55.3% of respondents, including 31.9% who ranked it as extremely effective. The materialisation of force majeure risks, such as China's clampdown on digital mining in 2021, can have devastating impacts on firms operating in affected regions. This development, for instance, triggered a cascade of issues that made timely redeployment both costly and tedious, if miners were even able to recover their hardware.[157] A similar situation arose for some miners that hosted equipment in Russia after a major hosting provider was designated a sanctioned entity by OFAC. [158] Consequently, it is unsurprising that many miners view geographical diversification as a critical tool for managing risk.

Interestingly, more miners viewed holding cryptoasset reserves as a more effective means of mitigating risks compared to holding fiat reserves. At first glance, one might expect the opposite, as fiat reserves offer stability in volatile markets. However, the financial health and

Figure 52: Common risk management strategies employed by digital mining firms and their rated effectiveness, as of 30 June 2024.
Source: CCAF Survey. Sample size: (N = 47)



business prospects of mining firms are closely tied to the value of the underlying cryptoasset, with the price appreciation of bitcoin also boosting the value of mining equipment and infrastructure. These responses suggest that miners prefer to maintain a bullish stance on positive developments in crypto markets by holding liquid reserves in cryptoassets, with some firms even leveraging debt to further increase their exposure.[159] The correlation of bitcoin prices with the broader cryptoasset market is discussed in Appendix A.

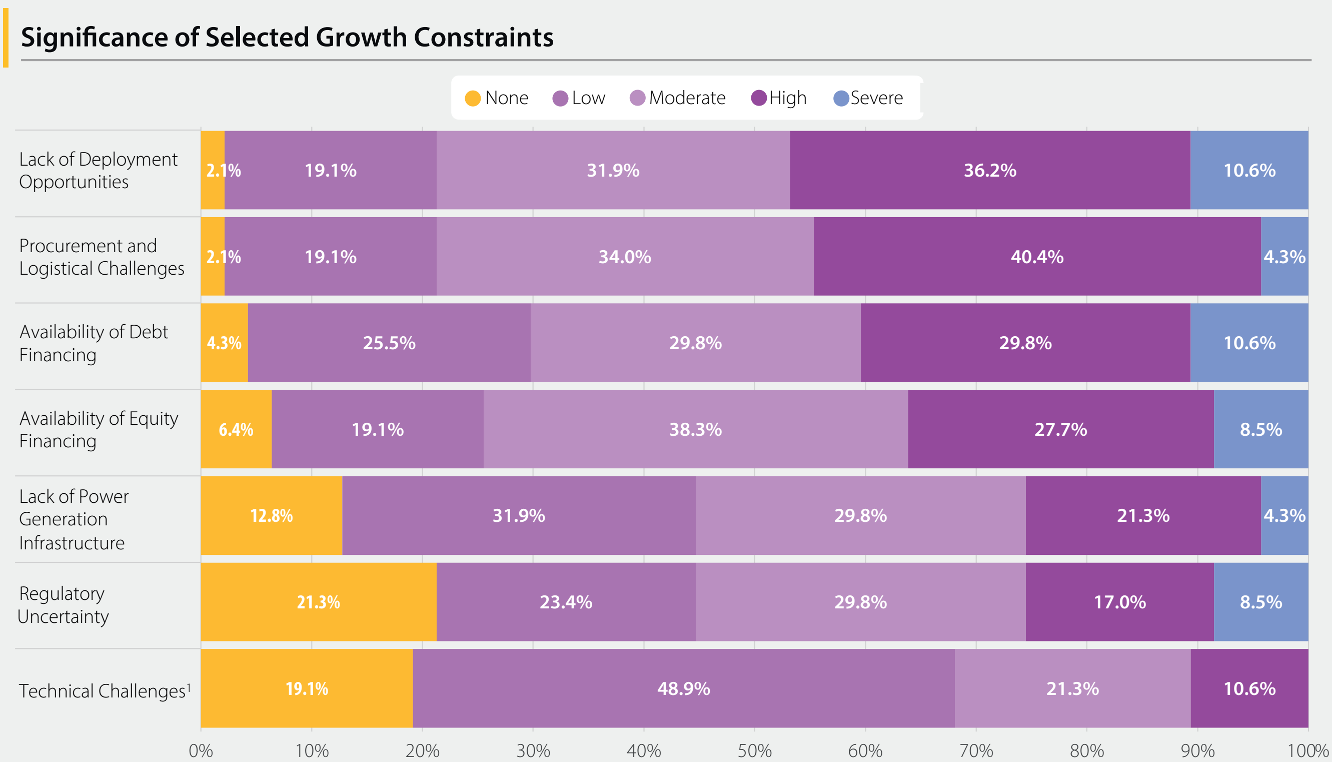
Manufacturer price protections did not rank high in perceived effectiveness, despite the historically pronounced volatility of ASIC prices.[160] Nevertheless, almost 70% of respondents still rated this strategy as at least moderately effective, suggesting that miners recognise the importance of mitigating price volatility in hardware procurement. Other strategies, such as hedging production risk through derivatives to lock in bitcoin prices, or securing against upward movements in mining difficulty, ranked lower in perceived effectiveness. However, with 57.5% and 49% of respondents respectively rating them as at least moderately effective, these strategies evidently remain relevant for some miners.

Scaling Hurdles, What are the Key Expansion Barriers?

Finally, we turn to the key constraints miners identified as barriers to their growth (see Figure 53). Survey responses reveal that a lack of deployment capacity – the availability of suitable infrastructure to host mining hardware – is perceived as a critical limiting factor, with 46.8% of respondents ranking it as at least a high constraint. This challenge becomes particularly acute when external factors, such as governmental actions, lead to a contraction in existing deployment opportunities.

Although the disruptions caused by China's clampdown on digital mining have largely subsided, miners seem to continue to face challenges securing adequate deployment capacity. Insufficient space at existing facilities and limited opportunities for expansion remain key barriers to growth. This dynamic may also reflect manufacturers' efforts to develop hardware designs aligned with traditional data centre form factors, such as 3U, to leverage synergies with existing HPC infrastructure and optimise computational power density.[161]

Figure 53: Perceived significance of various growth constraints faced by digital mining firms, as of 30 June 2024.
Note: [1] such as access to power distribution infrastructure. Source: CCAF Survey. Sample size: (N = 47)



Another notable constraint to miners' growth ambitions is related to hardware procurement and delivery delays for ASIC devices. While this issue is somewhat related to manufacturer counterparty risk, the two are perceived rather differently in terms of their impact. Non-availability of ASICs and delayed deliveries are seen as major barriers to growth, with 44.7% of respondents ranking them as at least a high constraint. In contrast, manufacturer counterparty risk itself does not appear to be a notable concern. This divergence suggests that while miners may trust manufacturers as reliable partners, they still face challenges in procuring or accessing the hardware necessary to realise their growth ambitions.

Access to debt and equity financing appears to be viewed as at least a moderate constraint by most respondents (70.2% and 74.5%, respectively). This perception likely varies significantly depending on the size and structure of the mining firm. Larger, publicly listed firms may face fewer challenges in this area, as evidenced by recent reports of successful debt and equity raises.[162]

Survey responses reveal an important distinction between constraints related to hosting and power infrastructure. While insufficient hosting capacity or a lack of new hosting infrastructure development were identified as major barriers to growth, power infrastructure appears to be less of a concern. About 44.7% of respondents viewed power availability and related distribution infrastructure (68%) as at most a low constraint. Public statements from mining firms further corroborate this, highlighting substantial potential to expand operational capacity based on existing power contracts.[163] In contrast, the bottleneck seems to lie in the availability of brownfield sites, i.e., operational facilities with existing hosting capacity capable of immediately energising additional equipment. This disparity in responses becomes more apparent when considering the required capital expenditures and the time-intensive nature of expanding data centre capacity,[164] underscoring the challenges miners face in scaling their operations despite sufficient power infrastructure.

Beyond power infrastructure, regulatory uncertainty is also not perceived as a major barrier to growth, with 44.7% of respondents viewing it as a low constraint at most. While earlier findings indicated that adverse governmental actions remain a key concern for miners, regulatory uncertainty does not seem to play a significant role in limiting their growth ambitions. This could indicate that miners are confident in their ability to continue expanding despite potential regulatory headwinds.

Case Study

From Shoebox to Server Rack: Hut 8 Driving Standardisation in Mining Hardware Form Factors

Hut 8 Corp., a U.S.-based public energy infrastructure platform with Bitcoin mining operations, is at the forefront of a shift in Bitcoin mining hardware design. In partnership with Bitmain, Hut 8 has introduced the U3S21EXPH, a next-generation ASIC miner with a U form factor. This marks a shift away from the traditional 'shoebox' designs, which are often non-standardised and optimised for specific cooling methods or space constraints.

The U form factor aligns with the standardised designs prevalent in HPC data centres, facilitating easier deployment, maintenance, and retrofitting. Designed to be 'rack-ready', the U3S21EXPH mirrors servers in traditional data centres and utilises direct-to-chip liquid (DTC) cooling. DTC cooling circulates a dielectric liquid coolant directly over the surface of the mining chips via cold plates to efficiently absorb and dissipate heat, improving performance and reducing energy consumption.

A key advantage of the U3S21EXPH is its significantly higher computational density compared to previous generations of miners. Hut 8 has developed a custom design for its data centre infrastructure, enabling it to house these miners at densities of up to ~180 kW per rack. This translates to a substantial increase in hashrate per unit of space, maximising the utilisation of existing infrastructure.

Hut 8's strategic adoption of HPC-compatible form factors unlocks new synergies between Bitcoin mining and HPC, potentially setting a precedent for the industry. By embracing these standardised designs, mining firms may be able to optimise operational efficiency and cooling costs. This strategic move could help firms to capitalise on the growing convergence of digital mining and HPC.

Forecasting the Future, How Well did Miners Predict the Markets?

Hashrate predictions

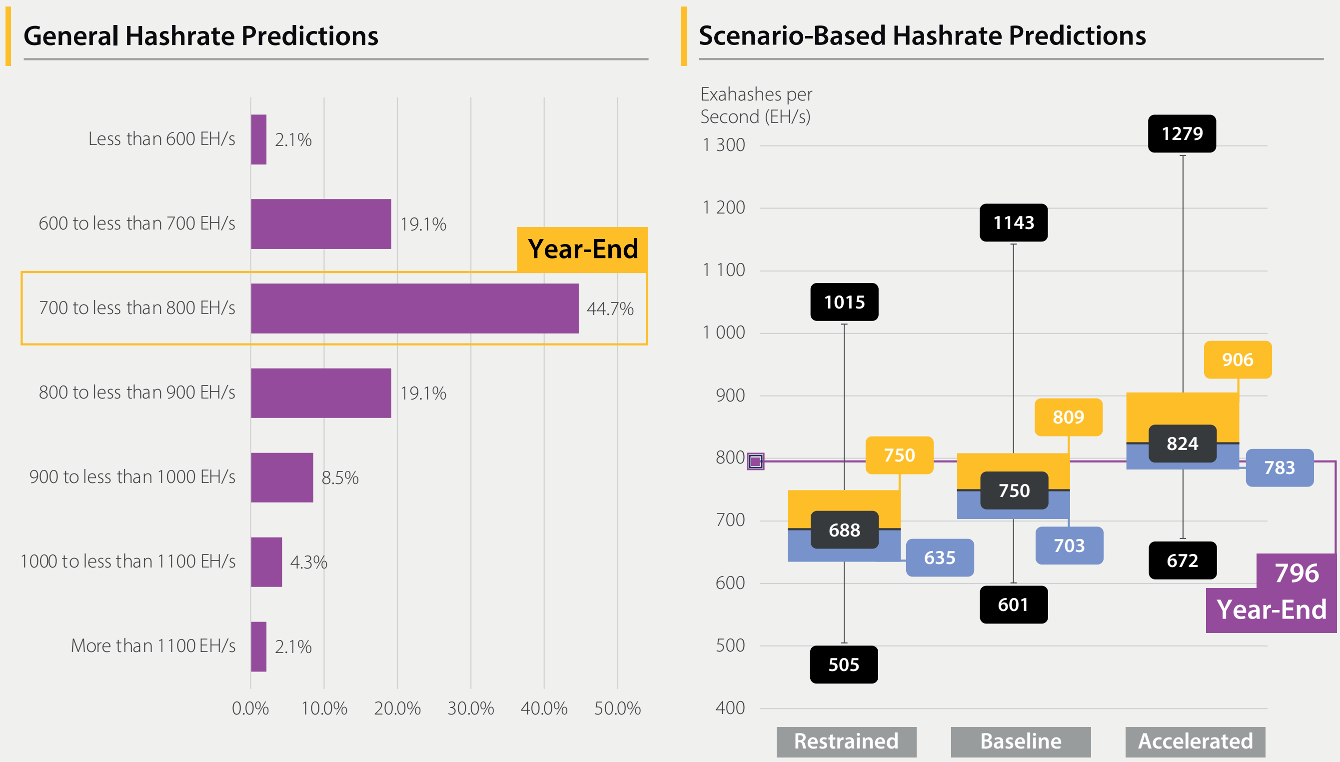
In analysing Bitcoin miners' expectations for hashrate growth by the end of 2024, a clear consensus emerged around moderate increases in network computational power. With the actual hashrate at year-end reaching 796 EH/s, miners demonstrated strong predictive capabilities, with projections closely aligning with actual developments.

Figure 54(a) summarises the survey results, illustrating miners' hashrate expectations across predefined ranges. A significant share of respondents (44.7%) accurately anticipated the hashrate would fall between 700 and 800 EH/s. Another 19.1% of respondents expected slightly lower levels within the 600–700 EH/s range, while an equal proportion anticipated higher levels in the 800 to 900 EH/s range, further reinforcing the general consensus around moderate growth. A more cautious stance was observed among 14.9% of miners, who projected the hashrate to reach 900 EH/s or go beyond, while only a small minority (2.1%) anticipated stagnation below 600 EH/s.

Figure 54(b) provides additional granularity by capturing miners' expectations across restrained, baseline, and accelerated scenarios. The restrained scenario, reflecting the most optimistic (from a miner's perspective) estimates, saw projections ranging from 505 EH/s to 1015 EH/s, with a median estimate of 688 EH/s. The baseline scenario, representing miners' assessment of the most likely outcome, spanned from 601 EH/s to 1143 EH/s, with a median of 750 EH/s. Interestingly, the accelerated scenario, which encompassed the most conservative projections, yielded a median estimate of 824 EH/s, closer to the realised value of 796 EH/s. This suggests that while the baseline scenario captured the overall trend, the accelerated scenario more accurately reflected the year-end outcome. The projections for this scenario ranged from 672 EH/s to 1279 EH/s, highlighting the wide range of possibilities miners envisioned under this high-growth scenario.

Taken together, Figure 54(a) and (b) provide a comprehensive view of miners' expectations that can be compared with actual outcomes. Overall, the results suggest that miners appear to be fairly adept in predicting hashrate trajectories and thus are well informed about market trends and network-wide equipment deployments.

Figure 54: (a) Distribution (in %) of year-end 2024 implied Bitcoin network hashrate projections (in EH/s) across predefined ranges; and (b) projected year-end 2024 estimates (in EH/s) under three growth scenarios (Restrained, Baseline, Accelerated), where Restrained represents an optimistic (from the perspective of digital mining firms) scenario, Baseline the expectations, and Accelerated a conservative scenario. Hashrate projections (as of 30 June 2024) are contrasted with year-end result (as of 31 December 2024). Data sources: CCAF Survey, Coin Metrics [56].
Sample sizes: Figure 54(a) (N = 47), Figure 54(b) (N = 35)



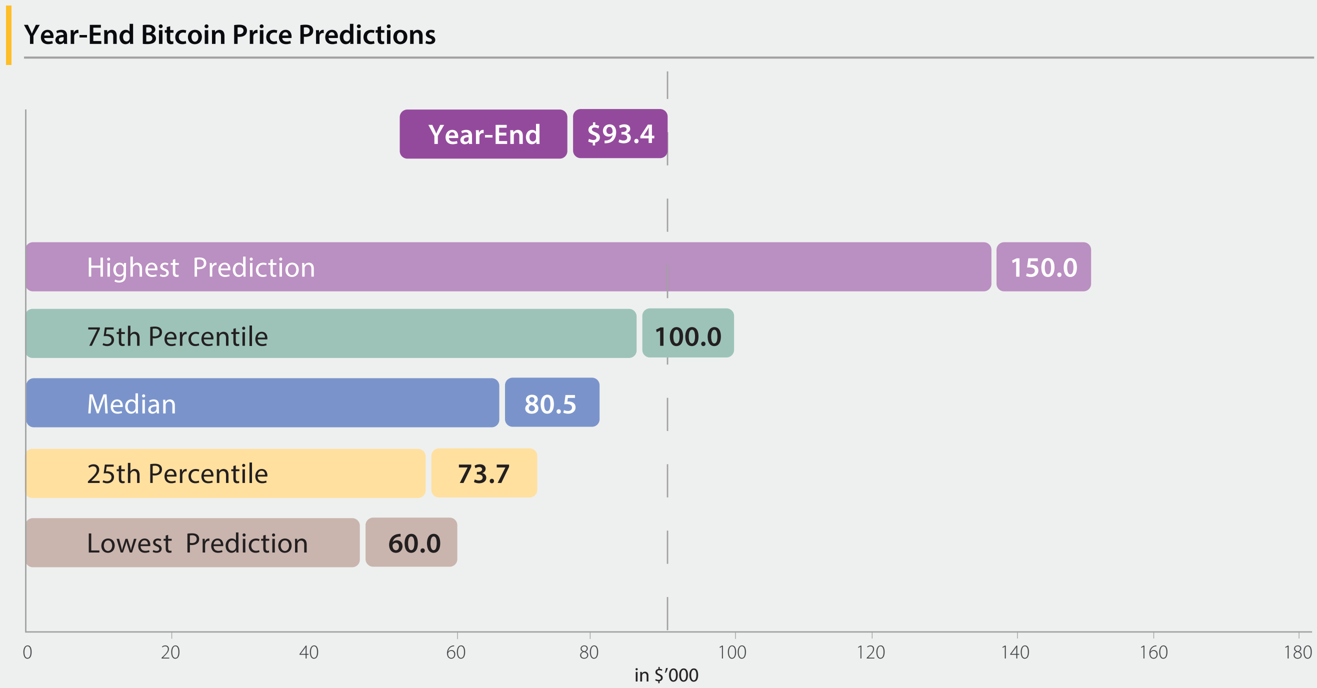
Bitcoin price predictions

Miners' predictions for bitcoin's year-end price in 2024 revealed a wide range of expectations (see Figure 55), from $60,000 to $150,000, with a median forecast of $80,500. This indicated a generally optimistic outlook, with most anticipating substantial gains from the mid-year price of $62,763 recorded on 30 June 2024. The realised year-end price of $93,390 fell at the higher end of miners' expectations, reinforcing the prevailing sentiment of confidence within the mining community.

Several key events throughout 2024 likely shaped this positive sentiment. In January, the SEC's approval of spot Bitcoin ETFs in the U.S. provided a significant institutional tailwind, increasing demand and liquidity. This development coincided with Bitcoin entering its fourth halving cycle in April 2024, which has, historically, been shown to be a catalyst for price appreciation driven by the reduction in newly minted token supply. Later in the year, the U.S. election fuelled further market optimism,[165] with the new administration's perceived pro-crypto stance fostering renewed confidence within the industry. The confluence of these events seemed to have culminated in a strong year for bitcoin, with the cryptoasset more than doubling its price, rising from $44,049 to $93,390.

The year-end outcome, exceeding the majority of miners' expectations, underscores the community's overall ability to identify longer-term catalysts for price growth despite prevailing uncertainties. While some miners adopted a more cautious outlook, others accurately anticipated a significant price appreciation, reflecting a diversity of perspectives shaped by varying assumptions about market dynamics, regulatory developments, and macroeconomic factors. This variability underscores the inherent complexity of forecasting in a volatile and rapidly evolving industry, where even well-informed predictions must contend with a high degree of uncertainty and dynamic market forces.

Figure 55: Five-number summary of respondent predictions (as of 30 June 2024) for the year-end BTC price in 2024 and the actual year-end BTC price (both in USD) as of 31 December 2024. Data sources: CCAF Survey, Coin Metrics [45]. Sample size: (N = 46)



IX: Trends

The future of this dynamic industry will be a confluence of challenges and opportunities, where technological innovation converges with the need to secure resilience through diversification or mastery in specialisation.

The Future of Mining, Quo Vadis?

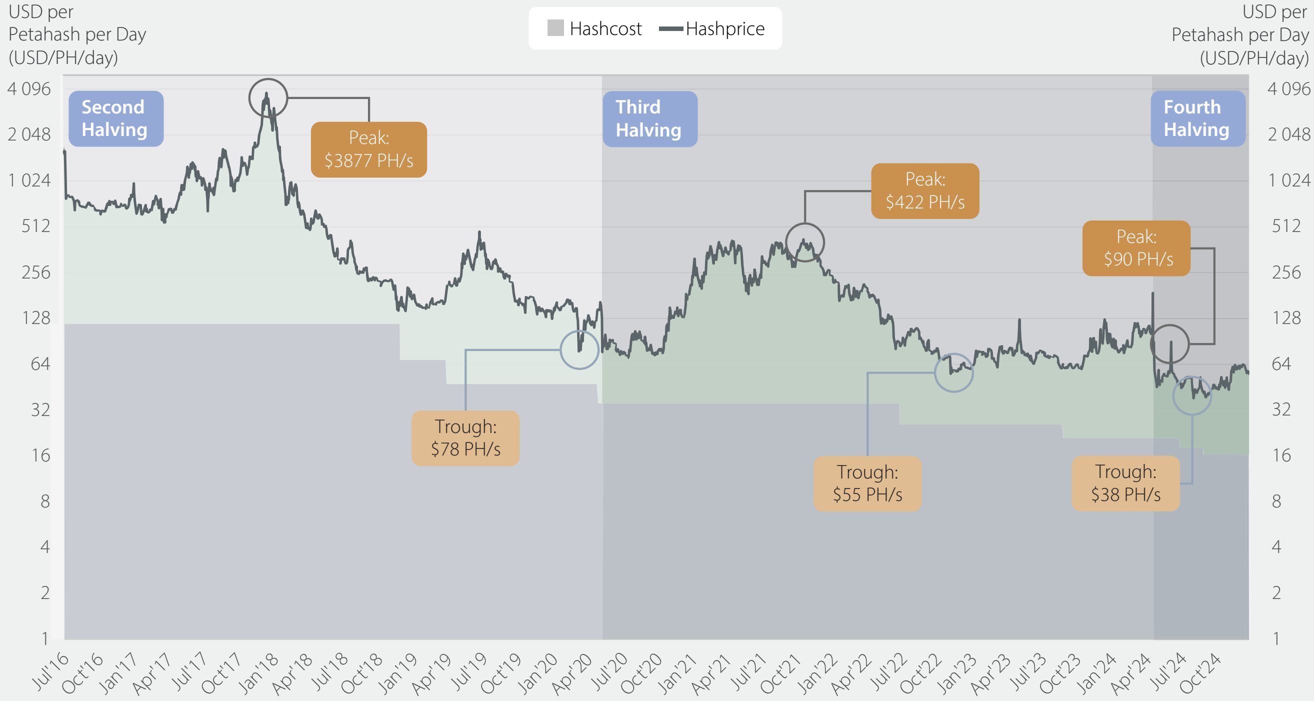
In this section, we examine how the digital mining landscape is expected to evolve in the future and elucidate some potential strategic imperatives that could help mining firms navigate an increasingly competitive environment. A focal point in this discussion is the looming threat to Bitcoin's security budget, driven primarily by the gradually diminishing block subsidy upon which miners have historically relied. As the decline in subsidy (in native units) continues, and the network progressively transitions to a transaction fee-based model, this threat is becoming more acute with each successive epoch.

The initial analysis centres around understanding revenue patterns in the industry, tracing the evolution of miners' compensation over time, while simultaneously exploring how technological innovation has influenced operational costs – two keystone elements that underpin the profitability of digital mining. By linking these dynamics, the analysis unravels fluctuations in revenue, shedding light on the competitive and volatile environment miners are likely to face in the future.

Figure 56 vividly illustrates the stark contrast between peaks and troughs in hashprice across epochs. During the second epoch, hashprice soared to a peak of $3,877 before plunging to a trough of $78 per PH/day, representing a dramatic 98% decline. In the third epoch, this pattern persisted, with hashprice falling from a high of $422 to a low of $55 per PH/day (an 87% decline). Similarly, in the current epoch, hashprice has already exhibited considerable volatility, dropping from $90 per PH/day at its peak to $38 at its lowest point – marking a 58% decline – before rebounding to $54 by the end of 2024. Beyond underscoring the pronounced disparity between peaks and troughs, these figures reveal a gradual downward trend in hashprice, shaped by upward difficulty adjustments and halving events that, collectively, have not been fully counterbalanced by increases in bitcoin's price. However, volatility remains an intrinsic characteristic of hashprice, with historical data revealing that significant, albeit temporary, spikes have followed previous halving events. If these historical patterns hold, miners may anticipate a similar short-term elevation in hashprice during this epoch.

Figure 56: Historical trends in hashprice and hashcost (in USD/PH/day) and their evolution across epochs from 8 July 2016 to 31 December 2024. Hashcost is based on $50/MWh and the most efficient hardware available at any point. The following devices have been selected (in chronological order): Bitmain Antminer S9, S15, S17 Pro, S19 Pro, S19 XP, S21, S21 Pro, S21 XP. Source: Analysis conducted by the authors, data obtained from Coin Metrics [147], ASICMInerValue [74]

Historical Trends in Hashprice and Hashcost Across Epochs



Yet, there is also a silver lining: while hashprice has gradually declined, hashcost, too, followed a downward trajectory, driven by steady gains in hardware efficiency. As technological advancements continue to drive innovation in mining devices (see Figure 21), miners have become increasingly resilient to lower troughs in hashprice, with hashcost falling from $128 at the beginning of the second epoch to $16 at the beginning of the fourth epoch – a reduction of 87.5% over approximately eight years. With even more efficient devices expected to emerge during the fourth epoch, this trend will likely persist, albeit at a decelerating pace as the industry approaches the physical and economic boundaries of Moore's Law.

Building on the insights into hashprice and hashcost, the analysis now turns to a critical measure of operational profitability: the ratio of gross profit to COGS, commonly referred to as the 'markup ratio'. A markup ratio of 0 means miners are operating at breakeven, while a markup ratio of, for example, 35 means that for every $1 of COGS, the miner generates $35 in gross profit. The previous discussion focused on the interplay between compensation and expenditures, while Figure 57 provides a more nuanced perspective by charting the evolution of markup ratios across epochs. These ratios are dynamically adjusted for two hypothetical hardware adoption scenarios to determine hashcost:

- **Scenario 1: Immediate upgrade:** Miners always upgrade immediately to the most efficient hardware as soon as the device becomes available. This is the lowest hashcost scenario.

- **Scenario 2: Epoch upgrade:** Miners upgrade to the most efficient device available at the start of each epoch, and do not upgrade otherwise. This is the highest hashcost scenario.

The chart reveals notable deviations in markup ratios between the two scenarios, particularly during periods of rapid hardware innovation – most prominently between Q4 2018 and Q2 2020, as well as following the introduction of the Bitmain Antminer S21 series. Despite these fluctuations, seemingly, miners generally operated equipment at breakeven or better in both scenarios, except during a brief downturn in March 2020 under Scenario 2, when the ratio turned slightly negative.

To explore broader trends, the table below summarises the dataset's key findings, revealing two noteworthy insights. Firstly, across nearly all epochs and scenarios, indicators exhibit a clear downward trend, implying smaller margins for profitability. Secondly, the volatility of the markup ratio – on both an absolute and normalised basis – has steadily decreased over time, driven by decreases in the volatility of bitcoin price and network difficulty.

Shifting focus to the first point, medians and averages highlight the growing importance of electricity costs in determining miners' competitiveness. As margins tighten, the ability to manage operating expenses will likely play an even more pivotal role in sustaining profitability. Interestingly, minimum markup ratios exhibit the opposite trend, indicating that while overall markup ratios have declined, the capacity to remain above break-even during adverse conditions has improved.

This juxtaposition reveals a paradox: while the general decline in markups points to more challenging times ahead, the reduction in volatility and higher minimum values suggest that miners are better equipped to weather periods of financial strain. Advances in hardware efficiency appear to be a key driver of this increased resilience, enabling miners to better navigate through troughs in the market cycle.

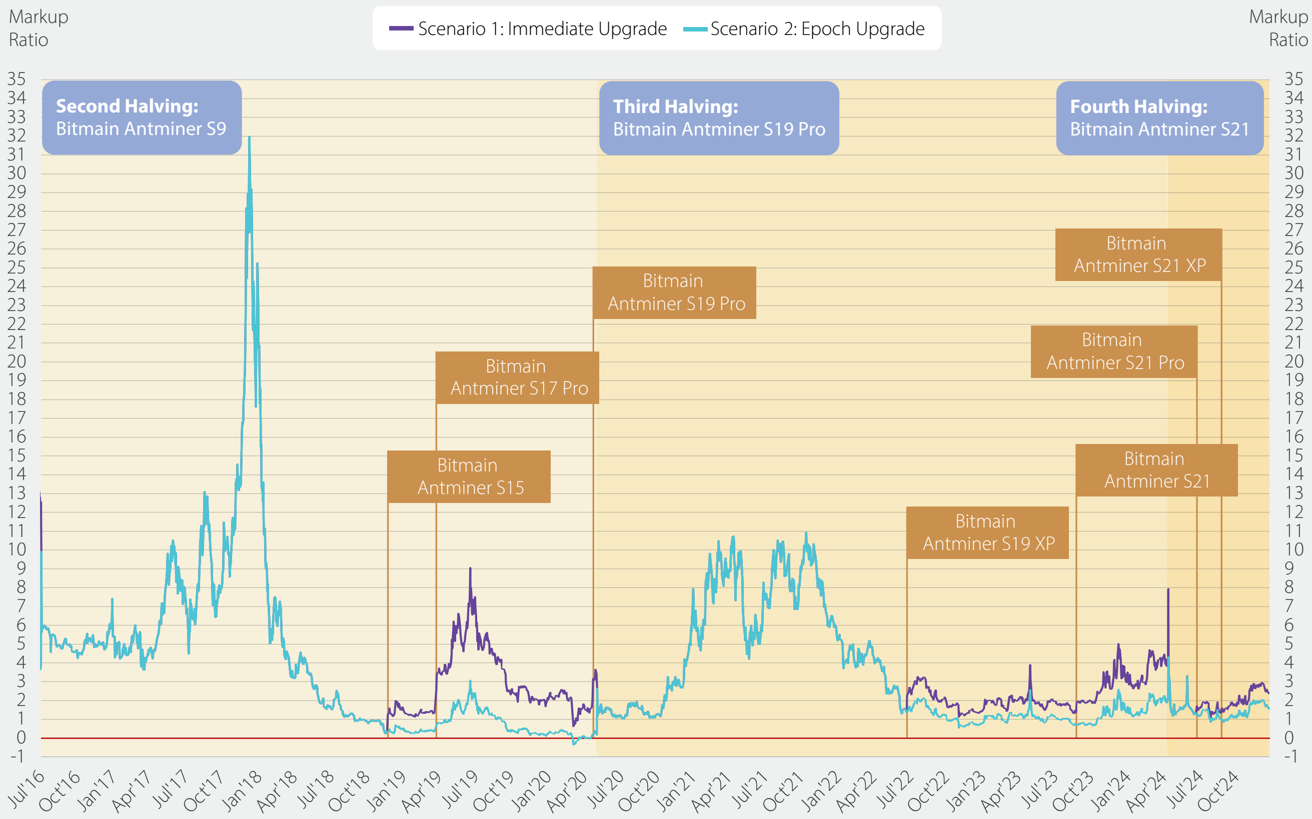
As the fourth epoch unfolds, it remains uncertain whether these trends will persist or whether entirely new dynamics will emerge. Moreover, this analysis does not account for whether potentially lower CAPEX requirements for hardware may have offset declining gross profit margins, thereby allowing mining firms to maintain stable ROIs.

However, maintaining stable profitability is likely to become increasingly challenging, as the effects of a dwindling block subsidy and growing network difficulty must be offset by either higher transaction fees or an increase in BTC price – the latter offering only a temporary remedy as the block subsidy eventually converges to zero. The analysis above has demonstrated that hashprice has steadily declined over time, and even when technological advancements are factored in, those have historically failed to fully compensate for hashprice declines, leading to compressed margins. Additionally, the question remains as to how much further mining technology can drive down costs, given that next-generation devices already utilise cutting-edge 3nm chips.

As the reliance on a volatile fee market inevitably grows and profitability pressures intensify, mining firms can proactively explore ways to diversify their revenue streams, optimise operational efficiency, and increase their resilience across cycles to remain competitive. The following introduces a curation of actionable items that could help mining firms navigate future uncertainty and transform upcoming challenges into strategic advantages.

Figure 57: (a) Development of markup ratios over time under two distinct hardware adoption scenarios; and (b) summary statistics of markup ratios for each epoch from 08 July 2016 to 31 December 2024. In Scenario 1, miners upgraded hardware seven times, while Scenario 2 involved two upgrades, with both scenarios starting from the Bitmain Antminer S9. Hardware upgrades are indicated in chart. In both scenarios, and consistently across all epochs, COGS was assumed to amount to $50/MWh. The number of observations for each epoch are as follows: epoch 2 (N=1402), epoch 3 (N=1441), and epoch 4 (N=255). Source: Analysis conducted by the authors, data obtained from Coin Metrics [147], ASICMInerValue [74]

Markup Ratio Trends Across Epochs and Impact of Hardware Upgrade Cycles



	Epoch	Minimum	25th Percentile	Median	Average	75th Percentile	Maximum	σ
Scenario 1 Immediate Upgrade	2	0.22	1.98	4.38	4.99	5.85	31.97	4.50 *90% CV*
	3	1.00	1.82	2.77	3.86	5.18	10.92	2.68 *69% CV*
	4	1.12	1.50	1.71	1.87	2.02	3.28	0.50 *27% CV*
Scenario 2 Epoch Upgrade	2	-0.34	0.56	2.47	4.15	5.53	31.97	4.90 *118% CV*
	3	0.56	1.17	1.73	3.36	5.18	10.92	2.96 *88% CV*
	4	0.83	1.16	1.35	1.43	1.67	3.28	0.38 *27% CV*

Diversification of Business Model to AI & HPC Services

As Bitcoin mining faces mounting challenges from declining block subsidies and intensifying competition, diversifying into HPC infrastructure for AI workloads offers a critical path forward. By retrofitting existing assets or building new facilities, miners can leverage their expertise in managing power-intensive operations to meet the surging demand for AI training and inference. This strategic pivot not only enables miners to repurpose their infrastructure for broader technological applications but also introduces stable, predictable revenue streams that counterbalance the inherent volatility of digital mining. The details and implications of this transformation will be explored in greater detail in the next segment 'The Convergence of Digital Mining and AI'.

More Effective Harnessing of Energy Resources

The economics of Bitcoin mining are heavily influenced by energy costs, which remain one of the most critical factors for maintaining profitability (as discussed in Part VII: Mining Economics). Innovative energy sourcing strategies are therefore essential. One notable approach involves harnessing flared or vented natural gas from O&G sites or biogas from landfills. By converting these by-products of oil extraction and organic waste into electricity, miners can access low-cost, previously 'wasted' energy resources while simultaneously reducing their carbon footprint (as highlighted in Part VI: Energy, and Environment). This method aligns with the growing emphasis on sustainable operations, quite literally transforming waste into a valuable asset.

Equally transformative is the integration of waste-heat recovery systems. Mining operations generate a significant amount of heat as part of their operations that can be repurposed for commercial, residential, or agricultural use. By capturing this thermal energy, miners not only cut down on their operational costs but also create a dual-purpose utility that enhances overall efficiency.

Leveraging VRE oversupply is another innovative strategy gaining traction. Miners can collocate to underutilised renewable energy infrastructure, such as solar or wind farms, to take advantage of periods when energy production exceeds local demand. This allows them to, for instance, access electricity at significantly reduced costs by strategically increasing mining activity during off-peak hours and scaling down when power is less abundant. Employing less CAPEX-intense devices can help compensate for reduced uptime to maintain attractive ROIs. Furthermore, deeper integration with grid operators enables miners to participate in DSR initiatives, adjusting their energy consumption to balance supply and demand and earning compensation for providing these ancillary services. This adaptability not only optimises energy usage and stabilises power grids, but also strengthens the bottom line of mining firms, reinforcing their role in improving efficiency within the energy system.

Case Study

MARA – Harnessing Waste Heat for Sustainable Community Heating

MARA, a digital asset technology company, has launched a pilot project in Finland's Satakunta region to convert waste heat from one of its data centres into an energy source for local residents, helping to address environmental concerns while exploring new revenue opportunities.
At the heart of this pilot is a 2 MW data centre that is connected to the region's district heating network serving around 11,000 residents. By capturing excess heat generated from computing processes, MARA reduces reliance on other energy carriers for heating, likely cutting carbon emissions. This integration of data centre technology and local infrastructure offers an innovative alternative to conventional heating methods.

Key benefits

- **Effective usage of energy:** Redirecting waste heat to community heating demonstrates responsible energy usage and underscores a broader commitment to sustainability.
- **Diversified revenue stream:** By selling captured heat, MARA benefits from an uncorrelated source of revenue, showing how digital mining can yield financial returns beyond network rewards or transaction fees.
- **Community integration:** Providing a reliable and sustainable heat supply likely strengthens rapport with local stakeholders and highlights the potential for similar projects in other regions.

Challenges and considerations

While promising, such undertakings face several challenges. For instance, the overall environmental footprint heavily depends on whether the data centre relies on sustainable energy or fossil fuels. Economic viability is also a key factor, with the feasibility of such projects hinging on electricity prices and ongoing operational costs of both the data centre and the heat recovery system. Scalability is another limiting factor. While the Satakunta region seems to offer favourable conditions, such as an existing district heating network and demand for heating due to its climate, replicating this model elsewhere will require careful consideration of local circumstances.

Despite these challenges, MARA's Finland pilot exemplifies a broader shift in the digital mining industry, where 'waste' energy is increasingly being repurposed. Harnessing the heat generated during the mining process for ancillary activities may prove to be a lever for mining firms to manage their carbon footprint while creating additional value for local residents and their shareholders.

Hedging Strategies for Risk Management

As Bitcoin miners navigate the volatility of both cryptoasset prices and energy costs, hedging strategies have become indispensable for managing financial risk. One tool is the hedging of hashprice, where miners can use financial derivatives to lock in future revenue based on their computational power. By selling derivatives with hashprice as the underlying,[166] miners can secure a set revenue for their future BTC production, effectively pre-selling their hashing power, thereby protecting themselves from adverse movements in bitcoin price and difficulty adjustments that could jeopardise their bottom line. This approach ensures a predictable income stream, shielding miners from market fluctuations that might otherwise undermine profitability. While derivative-based strategies are not the most popular, Figure 52 shows that more than one-fifth of survey respondents consider them at least very effective.

However, the risk management tool deemed most effective by miners is actively hedging against energy cost volatility by securing fixed-rate contracts with power providers. More than half of survey respondents view this strategy as highly effective. Fixed-rate contracts mitigate exposure to the unpredictable nature of energy prices, ensuring that spikes in electricity costs do not erode profit margins. Some firms may also operate an energy trading desk to work with financial derivatives to hedge these risks. Utilising these tools can make a significant difference in a miner's ability to sustain operations during bearish market cycles or periods of reduced transaction fee revenue. These measures, employed in tandem with revenue hedging, allow miners to maintain a steady cash flow regardless of short-term market conditions.

Innovative Revenue Generation Strategies Beyond Transaction Fees

With the diminishing block subsidy and volatile fee landscape, Bitcoin miners are increasingly exploring innovative revenue opportunities beyond traditional transaction fees. Layer-2 technologies, like the Lightning Network (refer to Appendix B), offer miners a chance to participate in facilitating faster, off-chain transactions. Whilst these networks might reduce on-chain transaction volume, they open new revenue channels within the Bitcoin ecosystem for participants acting as liquidity providers or transaction facilitators, indirectly benefiting miners through increased Bitcoin utility and potential increases in on-chain activity related to Layer-2 networks.

Furthermore, innovations like digital asset inscriptions, tokenised assets, and smart contract functionalities via Taproot are gaining momentum. These developments increase demand for block space, particularly for complex transactions that often carry higher fees. Miners strategically prioritising these high-fee transactions, including non-standard transactions with unique functionalities or larger OP_RETURN data, can significantly enhance revenue. This includes opportunities arising from novel script types and data embedded within transactions. Moreover, mechanisms like Replace-by-Fee (RBF) allow senders to increase fees on unconfirmed transactions, further benefiting miners. As these applications mature, they are likely to contribute a larger, more consistent portion of miner earnings compared to volatile traditional fees. This diversification into new revenue streams positions miners to thrive in a changing Bitcoin ecosystem.

Strategic Expansion Beyond Traditional Mining Activities

To create more resilient and diversified businesses, many miners are broadening their scope beyond Bitcoin, recognising the diversification of the business model as one of the most important measures to reduce risk (see Figure 52). While exploring synergies with AI/HPC have already been pointed out earlier, there are a variety of other avenues that can be utilised.

One such avenue involves engagement in staking on PoS-based blockchain networks like Ethereum. By participating in validation processes, mining firms can generate additional and more predictable yield compared to digital mining, diversifying income streams and aligning themselves with the growth of other blockchain ecosystems, effectively reducing the sole reliance on Bitcoin and positioning them to benefit from broader blockchain adoption.

Beyond staking, miners are strategically investing within the wider Bitcoin and Web3 ecosystem to further diversify their revenue. This includes direct investments in mining hardware manufacturers, securing vital equipment supply chains and potentially influencing future technological advancements in mining hardware itself. Moreover, operating their own mining pools provides greater flexibility and supplementary income. Strategic partnerships with other digital asset companies, such as custody providers, trading platforms, and Web3 development studios, can also create new business opportunities and further diversify portfolios. These combined efforts integrate miners more deeply into the digital asset ecosystem and can reduce their dependence on digital mining revenue.

Case Study

Bit Digital's Diversification into Ethereum Staking

Bit Digital, a platform for digital assets and AI infrastructure, has expanded its cryptoasset-related activities beyond Bitcoin mining by diversifying into Ethereum staking.

Bit Digital is pursuing its Ethereum staking operations through a joint venture with Mega Matrix Corp. (MTMT). This collaboration leverages MTMT's expertise in staking technology to enable Bit Digital to participate securely and efficiently in Ethereum's PoS network. The joint venture, named Mega Digital, focuses on both native staking (directly validating on the Ethereum network) and liquid staking. Liquid staking involves using protocols that provide representative tokens for staked ETH. These tokens allow for more flexible staking strategies and potentially higher returns – at the price of counterparty risk.

As of 31 December 2024, Bit Digital reported holdings of approximately 27,623 ETH, of which 21,568 ETH were staked in native staking protocols. Over the course of the year, their staking business yielded rewards totalling 566.4 ETH.

By incorporating Ethereum staking into their business model, Bit Digital establishes an additional source of somewhat predictable cryptoasset rewards, complementing the bitcoin generated from their mining operations. This strategic move also gives the company a foothold in the expanding Ethereum ecosystem.

Final thoughts

The future of Bitcoin mining depends on the industry's ability to innovate and adapt to a rapidly evolving economic and technological landscape. As block subsidies decline and competition intensifies, miners must diversify their operations and embrace new opportunities to remain competitive. Realising synergies with HPC for AI workloads offers a transformative path forward, as will be explored in the following section.

Equally critical is the optimisation of energy resources. Strategies such as leveraging flared natural gas, integrating waste-heat recovery systems, and harnessing oversupply from renewable energy sources can reduce costs, improve efficiency, and align with growing sustainability imperatives. Diversification into new revenue streams – from staking on PoS-based blockchains to broader ventures within the digital assets ecosystem – can further strengthen miners' resilience by diversifying their revenue streams. Adopting a broader perspective may enable mining firms to safeguard their competitiveness across cycles while simultaneously contributing to the growth and innovation of the digital assets ecosystem.

The Convergence of Digital Mining and AI

The digital mining industry is undergoing a significant transformation as companies seek to diversify their operations in response to evolving market dynamics. Traditionally focused on Bitcoin and other cryptoasset mining, some traditional mining firms are repurposing some of their infrastructure or building new infrastructure to support AI and HPC workloads. This shift is not just about adapting to the anticipated increasingly more volatile revenue streams from digital mining, as alluded before; it is also a strategic move to tap into the rapidly growing demand for AI compute. By leveraging their expertise in managing large-scale computing infrastructure, and the capacity to grow based on existing power contracts, mining firms could be well suited to position themselves at the intersection of two transformative sectors – cryptoassets and AI.

The computational intensity of AI and its consequences

The dramatic surge in computational power necessary for training the latest generation of AI models is a testament to the significant strides that have been achieved over the last few years in raising AI capabilities. Profound advancements in machine learning and the increasing integration of AI across various domains, have fundamentally shifted the computational landscape.

The computational demands for training models that could process and understand large volumes of data – from text in multiple languages to high-resolution images – have skyrocketed, as shown in Figure 58. There has been a consistent 6-7x increase per year in the training intensity of leading-edge AI models from 2010 to 2024. This surge is not merely a reflection of more powerful hardware but also mirrors the increasing complexity and capability of the AI models themselves.

In particular, the language and vision domains have been at the forefront of this surge in computational demands. Language models, such as those used in translating languages and generating human-like text, have grown increasingly large. The training of models like OpenAI's GPT series exemplifies this trend, where each new iteration demands significantly more computational power than its predecessor. Similarly, in computer vision, the models have expanded in capacity and sophistication to perform tasks ranging from facial recognition to autonomous driving – all requiring extensive computational input.

The consequences of this rapid increase in computational power are multifaceted. From a technological perspective, it has spurred developments in high-performance computing systems. Manufacturers and researchers have pushed the envelope in processing capabilities, leading to innovations in GPU architectures and parallel computing frameworks. However, these advancements also bring challenges, particularly in terms of energy consumption (see Figure 59) and by extension the environmental impact associated with it, with data centre electricity consumption expected to exceed 1000 TWh by 2030 up from an estimated 411 TWh in 2023, reflecting a CAGR of about 14.5% per year, vastly outpacing overall expected increases in global electricity demand (about 2% CAGR; baseline scenario), for the same period.[169]

Figure 58: Estimated training computations (in PetaFlop, 10^{15} FLOPS) for the training of different AI systems from 2 July 1950 to 24 December 2024. Accuracy is within a factor of 2, or 5 for undisclosed models. Source: Epoch (2024; [167]) with major processing by Our World in Data [168]

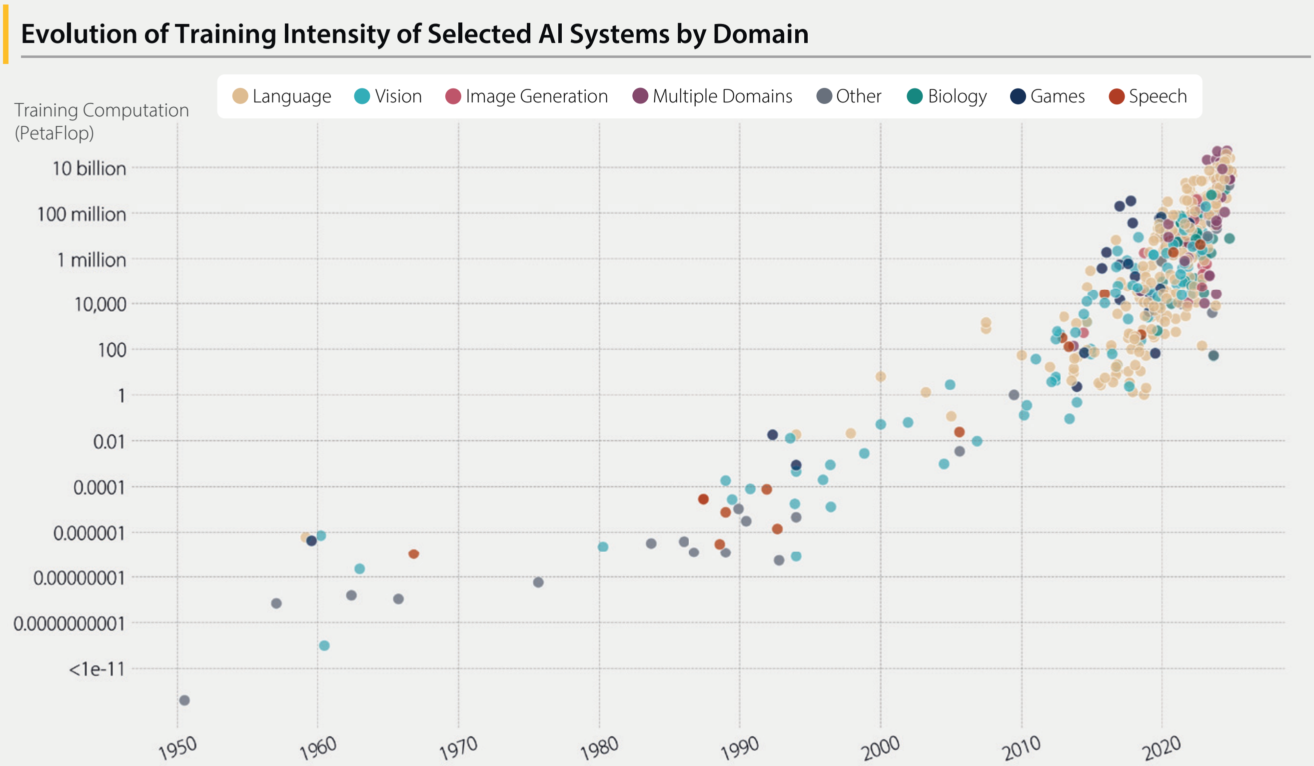
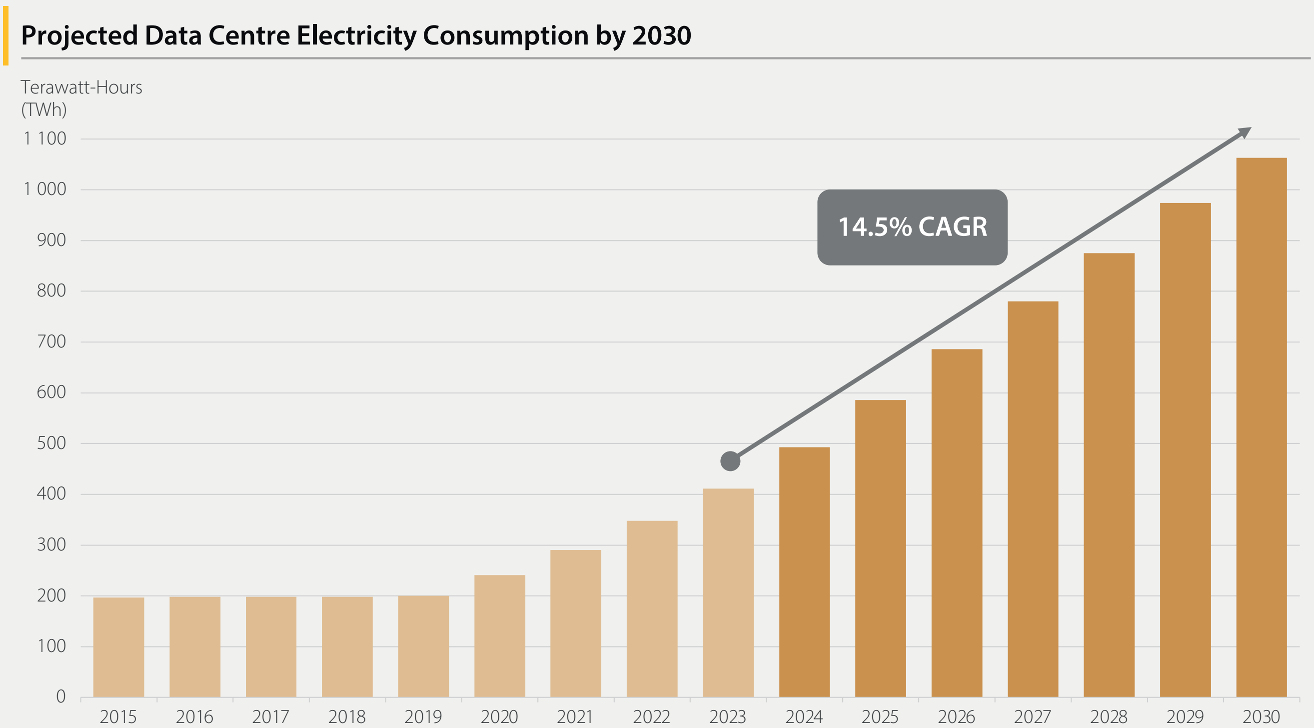


Figure 59: Estimated historical and future data centre electricity consumption from 2015 to 2030. Source: Goldman Sachs (2024; [170])



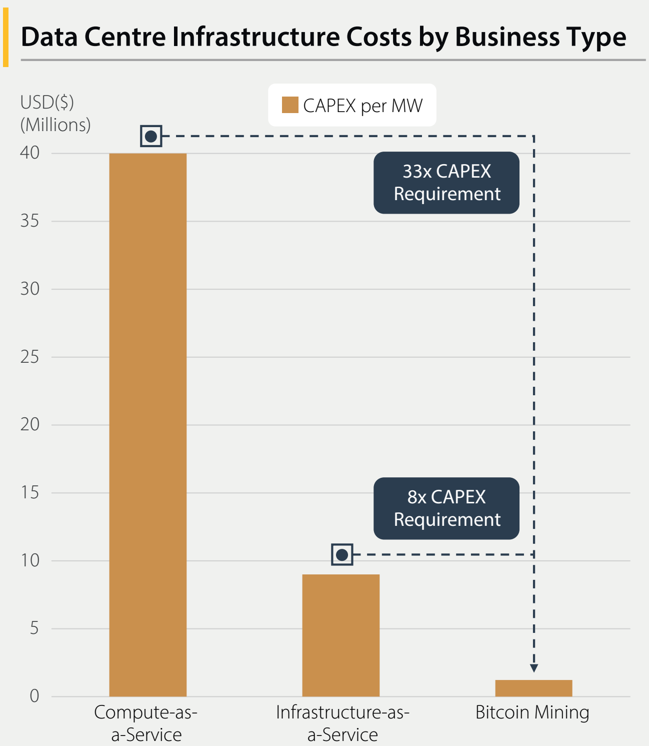
The power struggle: Bitcoin miners rise to the challenge

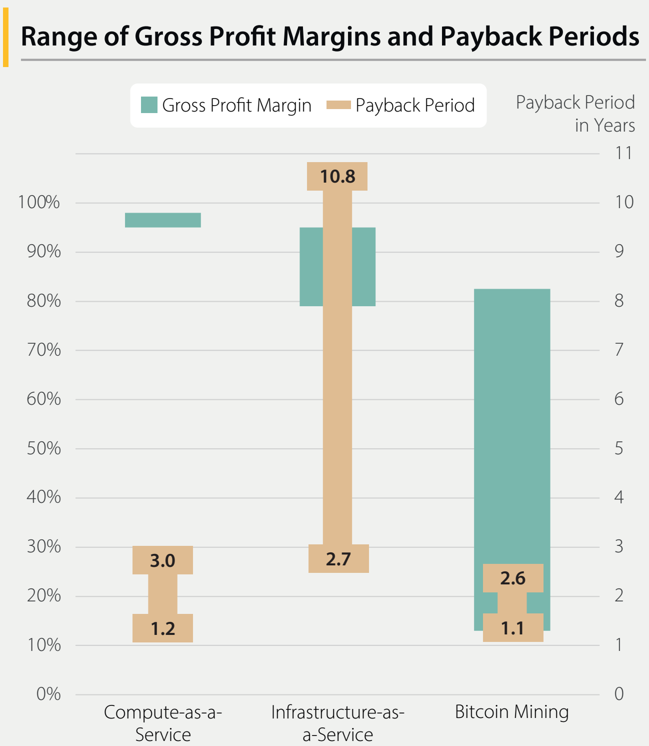
The skyrocketing increase in computational demand and the associated need for power creates an 'arms race' where access to significant resources becomes a critical differentiator for AI firms. Bitcoin miners, with their expertise in managing large-scale data centres and established power contracts, are uniquely positioned to capitalise on this trend. Their infrastructure can often be adapted for AI workloads far faster than building new facilities, allowing them to efficiently cater to the burgeoning AI industry. With global power demand for data centres expected to increase by 116% from 2024 to 2030, miners can repurpose existing infrastructure and position themselves as key players in this rapidly growing market.

At first glance, this strategic shift offers a compelling value proposition. It allows miners to diversify revenue streams and mitigate risks associated with cryptoasset market volatility. AI infrastructure typically generates more stable and potentially lucrative cashflows compared to traditional mining due to longer-term contracts and less volatile pricing structures. However, it is important to distinguish between different AI/HPC strategies mining firms can pursue. These include the build-out of infrastructure to host third-party hardware (Infrastructure-as-a-Service – IaaS), or directly offering computing services (Compute-as-a-Service – CaaS). Estimates from J.P. Morgan Research suggest CAPEX for these models ranges from $9 to $40 million per MW, a 8-33x difference compared to Bitcoin mining's $1.2 million per MW (see Figure 60(a)).

Despite these higher upfront costs, the revenue potential for AI workloads is significantly greater. CaaS workloads can generate revenues of $1,600 to $4,000 per MWh, while colocation services (IaaS) bring in $120 to $400 per MWh – both considerably higher than the $80 to $151 per MWh currently achievable with Bitcoin mining (see notes in Figure 60(b)). Additionally, gross profit margins reveal the financial characteristics of these business models. CaaS and IaaS exhibit relatively high and stable gross profit margins, ranging from 95% to 98% and 79% to 95%, respectively. In contrast, Bitcoin mining shows substantial variability, with gross profit margins ranging from 13% to 83%, depending on market conditions, equipment efficiency, and electricity costs.

Figure 60: (a) Expected capital expenditure per megawatt (MW) (in USD) by business type, namely compute-as-a-service (CaaS), infrastructure-as-a-service (IaaS) and Bitcoin mining; and (b) range of gross profit margins (in %, left axis) and payback periods (in years, right axis) by business type. The underlying assumptions per business type are as follows: revenue per MWh $1,600-$4,000 (CaaS), $120-$400 (IaaS), and $80.2 to $150.8 for Bitcoin mining. The numbers from the latter have been derived using a hashprice of $0.0543 per TH/day (as of 31 December 2024) scaled to 1MW using (i) the weighted hardware efficiency shown in Figure 26(a) of 28.22 J/TH, and (ii) the efficiency of a newer hardware model (Bitmain Antminer S21 Pro) of 15J/TH; power cost per MWh $70-$80 (CaaS), $20-$25 (IaaS), and $25-$70 for Bitcoin mining, which reflects the minimum and maximum hosting rate illustrated in Figure 44(a). Payback periods (in years) have been derived from gross profit (revenue – COGS) per MWh and CAPEX per MWh. The CAPEX requirement per MW for CaaS ($40m), IaaS ($9m) have been taken from J.P. Morgan Research. The CAPEX requirements for Bitcoin mining are based on own analysis and range between $0.24-$1.2 million per MW, accounting for the difference in ASIC market prices between more and less efficient devices.
Source: Analysis conducted by the authors, data obtained from CCAF Survey, Smith and Pearce (2024; [171]), Coin Metrics [147], and Luxor [172]





This variability in profitability highlights both a challenge and an advantage of Bitcoin mining. On one hand, mining returns are highly sensitive to external factors, such as bitcoin price and network difficulty. Conversely, the relatively low CAPEX requirement of Bitcoin mining allows operators to achieve notably shorter payback periods compared to AI/HPC infrastructure. This makes Bitcoin mining attractive for those prioritising rapid capital recovery and high returns under favourable conditions.

While Bitcoin mining can be a highly profitable venture, offering substantial returns and shorter payback periods under optimal conditions, transitioning into AI infrastructure provides an opportunity to diversify cashflows and reduce exposure to crypto market volatility. By blending the upside potential of Bitcoin mining with AI's stable and growing demand for computational power, miners may be able to build more resilient business models, balancing immediate profitability with long-term stability and business diversification.

Case Study

Core Scientific's Expansion into AI/HPC

Core Scientific, a leader in digital infrastructure for high-performance computing and digital mining, has strategically expanded beyond its traditional cryptoasset mining operations by providing state-of-the-art HPC infrastructure to AI hyperscaler CoreWeave. The agreement between these two firms demonstrates how having access to power and an experienced data centre team has positioned Core Scientific to capture opportunities in the rapidly growing AI market.

Under the agreement, Core Scientific will deliver approximately 500 MW of digital infrastructure to host CoreWeave's AI and HPC workloads, powered by NVIDIA GPUs. This move has enabled Core Scientific to expand its services from solely supporting cryptoasset mining to facilitating advanced AI computations, such as model training and real-time data inference.

Key outcomes of this expansion include:

- **Substantial revenue generation:** The expansion is projected to generate $8.7 billion in revenue over 12 years, highlighting the financial viability of AI-focused services.
- **Risk mitigation:** By diversifying into AI, Core Scientific reduces its reliance on the often highly volatile revenues from cryptoasset mining, creating more stable and predictable cash flows.
- **Efficient infrastructure repurposing:** The company capitalises on its existing data centres and power agreements, demonstrating how its mining facilities can be adapted to support HPC infrastructure.

Core Scientific's strategic expansion exemplifies how digital miners can leverage existing infrastructure and expertise to diversify into new, high-growth markets.

AI strategies of mining firms differ

The transition to AI is not without its challenges. The industry is experiencing a clear divergence in strategy as companies navigate this transformation. Firms like Core Scientific, Hut 8, Applied Digital, Iris Energy, and Bit Digital, among others, are actively integrating AI into their business models, likely as part of a long-term strategic move to leverage AI's potential to deliver predictable uncorrelated revenue streams.

Conversely, other firms are taking a more conservative approach, prioritising the optimisation of their current Bitcoin mining operations,[173] reflecting a preference for an established business model with lower upfront costs and a simpler operational structure. Unlike AI, which demands a client-centric approach with various applications and custom solutions, Bitcoin mining remains singular in focus, centred around a predictable block subsidy and transaction processing.

In addition, not all miners are equally positioned to capitalise on the AI opportunity, as retrofitting Bitcoin mining facilities into AI/HPC data centres presents significant technical and operational challenges. AI data centres require advanced networking with high-speed, low-latency GPU communication, sophisticated cooling systems such as direct-to-chip liquid cooling for power-dense servers, and stringent redundancy standards to ensure uninterrupted operations. Additionally, the infrastructure must be adapted to accommodate rack-mounted servers, which differ substantially from the shoebox design of Bitcoin ASICs. These demands for substantial capital investment, specialised expertise, and approvals for critical resources such as power, land, and zoning make the transition infeasible for many miners.[174]

The future of digital mining, specialisation versus diversification

The future of digital mining will be shaped by firms that effectively balance innovation and risk management, following a dual approach. While AI/HPC compute currently accounts for only 0.46% of the total power allocation of mining firms (see Figure 18), some already view AI/HPC infrastructure and computing services as core to their future strategy.

As AI and HPC become increasingly central to a range of industries – from finance and healthcare to automation and beyond – digital miners that adapt to this evolving landscape will be well-positioned to drive new innovations, including the development of decentralised AI systems powered by blockchain technology.[175]

For firms remaining focused on traditional mining, the future could still hold strategic opportunities. In times of surging bitcoin and altcoin prices, these companies could leverage their expertise to maximise gains in a vibrant market. Furthermore, if AI technology becomes more cost-effective, these more cautious firms could integrate AI in their business model with greater confidence and readiness. Yet, their long-term sustainability could be challenged by firms that are able to operate in a variety of different environments, being more resilient to the likely increasingly volatile nature of cash flows as the network incentive structure gradually shifts towards a transaction fee-based model.

Ultimately, the digital mining sector's evolution will depend on each firm's willingness to adapt to these transformative forces. Companies embracing AI could reshape the competitive landscape, creating a more diversified ecosystem that is resilient to both technological disruption and market volatility. Those maintaining their focus on digital mining might face a critical juncture, needing to balance the risks of missed innovation against the potentially greater rewards of specialising in their core competencies.

X: Final Thoughts

Digital mining has undergone a remarkable evolution over the last years. In this study, we offer cutting-edge insights into the industry's intricate mechanics and its broader impact.

The digital mining ecosystem has evolved rapidly, transitioning from hobbyist-driven communities tinkering with desktop PCs to billion-dollar industrial operations wielding state-of-the-art, purpose-built hardware. Despite this impressive growth, a lack of transparent, empirical data has often left policymakers, researchers, and the wider public grappling with outdated assumptions or anecdotal information.

This report seeks to bridge that gap. By collecting first-hand insights directly from mining firms, we offer a contemporary snapshot of key operational metrics, energy consumption patterns, industry sentiment, and environmental impacts. Our findings provide evidence that is both timely and granular, revealing:

- **Geographical shifts:** The United States solidified its position as the dominant global mining hub by a significant margin, with Canada ranking second. Notably, our findings reveal substantial growth in South America and the Middle East – trends that have so far not been captured in IP-based estimates. Furthermore, mining activity persists across northern and eastern Europe and parts of Asia.

- **Hardware lifecycles:** Indications from a significant share of miners that they either re-sell, recycle, or repurpose equipment suggest that assumptions about the scale of e-waste generated may be markedly smaller than often portrayed, and thus warrant further review.

- **Hardware markets:** The Bitcoin ASIC market is highly oligopolistic and dominated by a single manufacturer holding the vast majority of market share; the top three manufacturers collectively account for effectively the entire market. The firmware market presents a somewhat more diverse picture, with stock firmware being the most prevalent choice.

- **Hardware efficiency and power use:** The findings indicate that sub-30 J/TH device efficiency is common, and estimated electricity consumption aligns closely with our CBECI estimate – a concordance that instils confidence in the current CBECI modelling approach. This is important because given the very nature of reports, there is an inevitable time lag between data gathering and publication, rendering the availability of a reliable up-to-date estimate vital.

- **Environmental considerations:** Our analysis reveals significant divergences in GHG emissions estimates, with the recency of the underlying data emerging as a critical determinant of these variations. Moreover, various concepts regarding the technology's potential to function as an energy consumer of first and last resort were explored, highlighting how the industry may become increasingly integrated into energy systems.

- **Miner sentiment:** Long-term energy prices and local or federal adverse government intervention rank among miners' top concerns. Power hedging and diversification – ranging from geographical to business-related, have emerged as a means of choice for risk mitigation, while lack of deployment opportunities and logistical challenges were seen as primary factors impeding growth.

- **Industry trends:** Technical innovation alone may not suffice to offset diminishing block subsidies. Miners are likely to increasingly explore avenues like the build-out of HPC infrastructure to service AI workloads to stay competitive. Leveraging strategic synergies with related business fields exemplifies how digital mining firms could diversify their business model to increase their resilience across market cycles.

Yet, this study is only a starting point. While we have made strides to gather representative data, certain biases remain, and areas such as methane mitigation, particularly in the context of landfills, and waste-heat recovery, among others, require further enquiry. Furthermore, a comprehensive understanding of digital mining's impact requires examining not only its environmental footprint but also its broader societal and economic effects. For instance, recent evidence suggests that digital mining may drive notable local economic growth. Estimates, accounting for multiplier effects, indicate that the industry supports over 31,000 jobs in the United States alone.[176] Regular data collection and updates could prove critical in ensuring that policymakers and practitioners have reliable, contemporary datasets.

In closing, digital mining's future appears poised between technological innovation and environmental accountability. Our hope is that these findings spur evidence-based debates, guiding both the industry and regulators toward balanced policy measures that recognise the industry's transformative potential alongside its significant resource usage. By building on robust data and rigorous analysis, stakeholders can better navigate the challenges and opportunities inherent in this emerging frontier.

Glossary

51% Attack

An attack vector relevant to PoW consensus-based blockchains where a single entity or colluding group gains control over more than 50% of the network's total computational power ('hashrate'). This majority control can potentially enable the attacker to censor transactions, prevent confirmations, and reverse their own recent transactions (double-spending), thereby undermining the network's integrity.

Altcoin

A term broadly used to refer to any cryptoasset other than bitcoin. Altcoins often aim to offer different features, functionalities, or economic models compared to Bitcoin, ranging from platforms enabling smart contracts to currencies focused on privacy or specific use cases.

ASIC – Application-Specific Integrated Circuit

An application-specific integrated circuit is a specialised chip designed to perform a specific task with exceptional efficiency. Unlike general-purpose processors, ASICs are tailored to the precise needs of a particular application, such as cryptoasset mining. This customisation allows ASICs to achieve superior performance and energy efficiency compared to standard processors.

AUM – Assets Under Management

Assets under management represents the total market value of all financial assets that an investment management firm or financial institution manages on behalf of its clients. It serves as a key performance indicator for the size and scale of investment funds and managers.

Block Reward

The total compensation awarded to the successful miner or validator for adding a new valid block to a blockchain like Bitcoin or Ethereum. It usually comprises two elements: the 'block subsidy' (newly minted coins) and 'transaction fees' paid by users to incentivise the inclusion of their transaction into the block. However, depending on the incentive structure of each blockchain network, what in the end constitutes a block reward available to the block proposer may be more intricate and less straightforward.

Block Subsidy

The predetermined quantity of newly created cryptoasset units awarded according to protocol rules to the validator or miner who successfully adds a new block to the blockchain. Depending on the issuance policy of the specific blockchain network, this subsidy tends to diminish over time according to a fixed schedule (e.g., via halving events). In Bitcoin, for instance, it currently equates to 3.125 BTC per block and constitutes the primary economic incentive for mining.

Blockchain

A Blockchain is fundamentally a distributed and immutable digital ledger where transactions or data are grouped into chronological blocks. To form the chain aspect, each new block is cryptographically linked to the preceding one using a hash pointer. It is this specific chained structure, replicated and maintained across a network of computers, that provides the technology's key benefits: ensuring data integrity, enabling transparency, and offering strong resistance to tampering, all without reliance on a central intermediary.

CBECI – Cambridge Bitcoin Electricity Consumption Index

The Cambridge Bitcoin Electricity Consumption Index, developed by the Cambridge Centre for Alternative Finance, serves as a comprehensive digital resource for assessing Bitcoin's environmental impact. Its underlying model estimates electricity consumption and associated greenhouse gas emissions using a hybrid top-down approach for estimating electricity usage, combined with a location-based emissions analysis leveraging IP-based data. Beyond delivering these core findings, the CBECI situates its results within a broader context by comparing them to the environmental footprints of traditional industries, activities, and countries, providing a well-rounded perspective on Bitcoin's climate footprint.

CCS – Carbon Capture and Storage

Carbon capture and storage is an advanced technology process to capture carbon dioxide (CO_2) emissions from extractive industries, industrial processes and power generation, aiming to mitigate the effects of global climate change. The captured CO_2 is compressed for transportation, typically through pipelines, and securely stored in deep geological formations, such as depleted oil and gas reservoirs or saline aquifers. CCS plays a critical role in reducing greenhouse gas emissions, particularly in hard-to-abate industries such as cement, steel, and chemical production, where alternatives for decarbonisation are limited. Despite its potential, the widespread adoption of CCS faces significant challenges, including high implementation costs, the need for extensive supporting infrastructure, and considerations such as public acceptance and regulatory frameworks.

COGS – Cost of Goods Sold

Cost of goods sold refers to the direct costs associated with producing the goods that a company has sold during a specific period. This includes the cost of raw materials, direct labour involved in production, and manufacturing overheads directly attributable to the production process. COGS is an important figure in financial reporting, appearing on the income statement as a deduction from revenue to calculate a company's gross profit. Understanding COGS is essential for evaluating a company's profitability and production efficiency, offering valuable insights into cost management and pricing strategies.

Consensus Mechanism

The set of rules, protocols, and incentives that allow distributed nodes on a blockchain network to agree on the single, consistent state of the ledger, particularly the validity and order of transactions. Its purpose is to ensure data integrity and prevent double-spending in a decentralised environment without a central authority. These mechanisms typically combine a Sybil resistance method (like PoW or PoS) with rules for block proposal and chain selection. For simplicity and reflecting common usage, while not strictly technically accurate, the core Sybil resistance methods (PoW, PoS, etc.) are often themselves referred to as consensus mechanisms, a convention also used at times within this report.

Cryptoasset

A digital asset that utilises cryptographic techniques to secure its transactions and ownership, typically recorded on a distributed ledger (like a blockchain). It serves as a broad umbrella term encompassing various types of digital value or rights, including cryptocurrencies, utility tokens, security tokens, governance tokens, and digital collectibles ('NFTs').

Cryptocurrency

A term often used specifically for the native token (or 'coin') of a particular blockchain protocol, such as bitcoin (BTC) or Ether (ETH). As a type of cryptoasset, these native tokens are fundamental to the network, typically used for paying transaction fees ('gas') or participating in consensus mechanisms. This distinguishes them from non-native tokens, which are created on top of the blockchain (e.g., using standards like ERC-20 on Ethereum) to represent other assets or utilities.

D&A – Depreciation and Amortisation

Depreciation and amortisation are accounting methods used to allocate the cost of assets over their useful life. Depreciation applies to tangible assets like machinery or buildings, while amortisation applies to intangible assets like software or patents. D&A is a non-cash expense that reflects the gradual decline in the value of an asset over time and is important for accurately representing a company's financial performance.

dApps – Decentralised Applications

Decentralised applications are software applications that run on a blockchain or peer-to-peer (P2P) network of computers instead of a single computer. This means they are not controlled by a single authority and offer increased security and transparency. dApps are often used for financial transactions, gaming, and social media, but their potential uses are vast and still emerging.

DeFi – Decentralised Finance

Decentralised finance is an emerging financial ecosystem built on Ethereum and similar blockchains, enabling the creation of open, transparent, and accessible financial applications and services. Powered by smart contracts, DeFi supports a diverse range of financial instruments, including decentralised exchanges (DEXs), loans, stablecoins, and yield farming protocols. These instruments are built and managed on blockchain networks and do not rely on intermediaries, resulting in faster and more accessible services compared to traditional financial services. DeFi platforms provide various financial services, such as lending, borrowing, trading, and insurance, to anyone with an internet connection and without requiring personal information.

DSR – Demand Side Response

Demand side response programmes incentivise residential, commercial, and industrial consumers to adjust their electricity consumption during peak periods, contributing to grid stability and balancing supply and demand. This can involve shifting energy-intensive activities to off-peak hours, using energy storage systems, or temporarily reducing consumption altogether. DSR enhances the stability of the electricity system, supports the integration of renewable energy by addressing supply variability, reduces reliance on fossil fuel-based generation, and offers financial benefits to participants through reduced tariffs or direct incentives.

EAC – Energy Attribute Certificate

Energy attribute certificates are tradable, digital certificates that represent the environmental attributes, such as emissions reductions, of one megawatt-hour (MWh) of electricity generated from renewable sources, including solar, wind, hydropower, and biomass. EACs provide a transparent mechanism to track and verify the renewable origin of electricity, enabling consumers and businesses to support green energy generation indirectly, even if they cannot directly procure it from renewable sources. By creating economic incentives for renewable energy producers, EACs play a critical role in accelerating renewable energy development and helping stakeholders meet corporate sustainability goals or regulatory requirements.

GHG – Greenhouse Gases

Greenhouse gases (GHGs) are gases in the Earth's atmosphere that absorb and re-emit infrared radiation, trapping heat and intensifying the greenhouse effect – a major driver of climate change. The primary GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases, the latter being synthetic gases with a high global warming potential.

GWP – Global Warming Potential

Global warming potential measures the heat-trapping capability of a greenhouse gas in the atmosphere over a specific time period, relative to carbon dioxide (CO_2). This metric accounts for both the gas's radiative efficiency and its atmospheric lifetime. GWP is used to compare the climate impact of different greenhouse gases, with higher values indicating a greater warming effect. It is typically calculated over time horizons of 20 or 100 years.

For example, methane has a GWP of 29.8 over 100 years ('GWP100'), meaning it traps nearly 30 times more heat than CO_2 over that period. However, over a 20-year time frame ('GWP20'), methane's GWP increases significantly to approximately 82.5, reflecting its high radiative efficiency and short atmospheric lifetime.[101] This underscores methane's significant short-term contribution to global warming and the critical role of its reduction in limiting temperature increases to internationally agreed targets.

Halving

A programmed event in Bitcoin's protocol (and some other cryptoassets) that occurs approximately every four years (or 210,000 blocks), where the block subsidy awarded to miners for adding a new block is reduced by half. This mechanism controls the issuance rate of new bitcoins, ensuring scarcity and a predictable decline in monetary inflation over time.

Hash Function

An algorithm that converts an input of arbitrary size into a fixed-size string of characters (the 'hash'). Secure hash functions are designed to be deterministic, one-way (pre-image resistant), collision-resistant, and exhibit an avalanche effect. Used extensively in blockchains for data integrity, linking blocks, and PoW, where the difficulty of finding a hash value meeting specific criteria forms the basis of the cryptographic challenge miners must solve.

Hashrate

Hashrate measures the total computational power committed by miners to securing a PoW consensus-based blockchain networks. It quantifies the aggregate speed at which all participants perform hash calculations – essentially, how many attempts are made per second (measured in hashes per second, H/s) across the network to solve the cryptographic challenge required to mine a new block. Because this block discovery process is inherently probabilistic (akin to a lottery), the total network hashrate cannot be measured directly; instead, it is estimated by observing the average time between block discoveries relative to the network difficulty level over a specified period. Since finding a valid hash that satisfied the difficulty target is computationally intensive, a higher total network hashrate signifies greater competition and, consequently, enhances the network's security by rendering potential 51% attacks prohibitively expensive. Due to the immense computational scale involved, particularly on networks like Bitcoin, hashrate is commonly expressed using large metric prefixes such as terahash (TH/s: 10^{12} H/s), petahash (PH/s: 10^{15} H/s), or exahash (EH/s: 10^{18} H/s).

HPC – High-Performance Computing

High-performance computing refers to the use of supercomputers, computing clusters, and distributed systems to tackle challenges that require substantial computational power, far beyond the capabilities of standard computing systems. HPC systems are employed across diverse fields, including scientific research, weather forecasting, financial modelling, and artificial intelligence, where they enable large-scale simulations, real-time data analysis, and advanced problem-solving. These systems leverage parallel processing techniques, utilising multi-core processors, GPUs, and distributed memory architectures, alongside specialised software, to perform simultaneous calculations and significantly reduce processing times.

ICO – Initial Coin Offering

An initial coin offering is a blockchain-based fundraising method primarily used by startups in the blockchain space to raise capital for new projects. In an ICO, companies issue newly created crypto tokens or coins to investors in exchange for fiat currency or other cryptoassets. These tokens may serve as utility tokens, granting access to a product or service, or as security tokens, representing an investment in the project. While ICOs provide critical early-stage funding opportunities, they are also associated with substantial risks, including market volatility, regulatory uncertainty, and exposure to fraudulent schemes due to their limited oversight.

LFG – Landfill Gas

Landfill gas is a mixture of gases, primarily methane (CH_4) and carbon dioxide (CO_2), generated through the anaerobic decomposition of organic waste in landfills. It also contains trace amounts of nitrogen, oxygen, and volatile organic compounds (VOCs). Captured LFG can be utilised as a renewable energy source for electricity generation, direct heating, or conversion into renewable natural gas (RNG), reducing greenhouse gas emissions and serving as a sustainable alternative to fossil fuels. However, if not properly managed, LFG can escape into the atmosphere, with methane significantly contributing to climate change due to its high global warming potential. Furthermore, trace compounds in LFG, such as hydrogen sulphide and VOCs, can pose health risks to nearby communities.

Mempool – Memory Pool

A node's local holding area for valid, unconfirmed transactions waiting to be included in a block by block proposers. Transactions typically propagate across the network's mempools, from which they are selected (often prioritised by fee rate) to build candidate blocks.

MiCA – Markets in Crypto-Assets Regulation

The Markets in Crypto-Assets Regulation is a landmark piece of European Union legislation that provides a comprehensive regulatory framework for crypto-assets not already governed by existing financial regulations, such as the Markets in Financial Instruments Directive (MiFID). MiCA aims to protect investors, safeguard market integrity, preserve financial stability, and foster innovation in the rapidly evolving crypto market. It establishes detailed requirements for issuers of crypto-assets, including mandatory whitepaper disclosures, and for providers of crypto-asset services, such as custody, trading, and exchange operations, addressing transparency, authorisation, and supervisory oversight.

Mining Pool

A cooperative group of cryptoasset miners who combine ('pool') their computational resources (hashrate) to increase the collective probability of finding a block and earning rewards compared to mining solo. Rewards are typically shared amongst members based on their contributed work ('shares'), using various payout schemes to calculate individual earnings.

Network Difficulty

In cryptoasset mining (e.g., Bitcoin), difficulty is a parameter in PoW consensus-based blockchain networks that measures how 'difficult' it is to find a valid block hash below the current target value. This difficulty value is usually expressed as a relative measure, indicating how much harder mining currently is compared to when the network launched (defined as difficulty 1). To illustrate the scale, Bitcoin's difficulty, which started at 1, currently requires around 110 trillion times more computational effort per block. The 'difficulty adjustment' is an automated process embedded in the protocol that modifies this difficulty level at regular intervals (e.g., every 2016 blocks in Bitcoin) to maintain a consistent average block creation time (e.g., 10 minutes) despite changes in total network hashrate.

NFT – Non-Fungible Token

Non-fungible tokens are unique digital assets that represent ownership of a specific item or piece of content, whether digital (e.g., art, music, or collectibles) or physical (e.g., real estate or tickets). Unlike cryptoassets that are fungible and interchangeable, NFTs are distinguished by unique metadata and token standards, such as ERC-721 or ERC-1155. NFTs are typically stored on a blockchain, where they provide verifiable proof of ownership and authenticity. The metadata ensures their uniqueness, while the associated content is often stored off-chain. NFTs have gained significant traction in digital art and gaming, enabling innovative forms of ownership and monetisation, and are increasingly being adopted in virtual real estate, intellectual property, and ticketing systems.

Node

A Node is a computer connected to a blockchain network that stores, validates, and/or relays information (like transactions and blocks) according to the protocol rules. Different nodes perform varied functions. 'Full nodes', for instance, contribute fully to network security and decentralisation by downloading, validating, and relaying all transactions and blocks, ensuring adherence to consensus rules across the entire blockchain history. 'Mining nodes', primarily relevant in Proof-of-Work systems, participate in creating new blocks, often using specialised hardware (like ASICs for Bitcoin) and typically requiring connection to a full node. In contrast, 'Light nodes' (or SPV nodes) prioritise lower resource requirements by downloading only block headers and relying on full nodes for transaction verification, a common approach used in many wallets.

Nonce

A term often derived from 'Number used once', representing a value used in cryptographic processes, typically to ensure uniqueness or prevent replays. In the specific context of Bitcoin mining, the nonce is a crucial 32-bit field within the block header. Miners iteratively change this field and along with other header data repeatedly hash the combination in a quest to find a hash value that satisfies the network's current difficulty target. With modern high-performance mining hardware (ASICs), the ~4.3 billion possibilities offered by the 32-bit header nonce are exhausted rapidly. Therefore, to gain a larger search space, miners also modify data within the block's unique coinbase transaction – commonly referred to as the 'extra nonce' – to increase the maximum set of possible hash variations given the input data.

Ordinals, Runes, BRC-20, and Inscriptions

Protocols and standards developed primarily since the activation of Taproot on Bitcoin, enabling the creation of unique digital artefacts ('inscriptions', akin to NFTs) and fungible tokens ('BRC-20', 'Runes') by embedding data within standard Bitcoin transactions, utilising spaces like the witness field (for Ordinals/BRC-20) or OP_RETURN data carriers (primarily for Runes). These protocols have driven new use cases for Bitcoin and have already shown to alter demand dynamics for blockspace and influence transaction fees, at least temporarily during periods of high activity.

PoS – Proof-of-Stake

A type of blockchain consensus mechanism where participants ('validators') are chosen to propose and attest to new blocks, with selection often influenced by the amount of the network's native currency they lock up ('stake') as collateral. Honest behaviour is incentivised by staking rewards, while dishonest behaviour is penalised by loss of stake ('slashing'). PoS is considered significantly more energy-efficient than PoW, as it substitutes the computationally-intensive cryptographic challenge with a system based on economic collateral.. However, critics sometimes argue that PoS systems may lead to network control centralising around entities with large native token holdings – a model sometimes contrasted with PoW's system, where control and influence over the network's direction emerge from the interaction between multiple stakeholder groups with distinct roles and incentives, rather than being primarily determined by staked capital.

PoW – Proof-of-Work

A type of blockchain consensus mechanism, pioneered by Bitcoin, where participants ('miners') expend significant computational resources ('hashrate') competing to be the first to solve a cryptographic challenge (finding a valid hash by manipulating a nonce against the network difficulty target). The successful miner provides the proof, proposes the next block, and typically receives rewards. This intensive computational work serves as an unforgeable proof of effort, deterring malicious behaviour such as Sybil attacks (where an attacker creates numerous fake identities) by making meaningful participation prohibitively expensive – effectively attaching 'a cost to a vote'.

PUE – Power Usage Effectiveness

Power Usage Effectiveness is a metric used to evaluate the energy efficiency of a data centre. It is calculated by dividing the total energy consumed by the data centre, including energy for cooling, lighting, and other overhead systems, by the energy used solely for IT equipment. A lower PUE indicates greater energy efficiency, with an ideal score of 1.0 meaning all energy is dedicated to IT equipment – though this is rarely achievable due to unavoidable overhead energy needs. PUE helps data centre operators identify inefficiencies and implement improvements, such as optimising cooling systems and using energy-efficient hardware, to reduce costs and minimise environmental impact.

Public-Key Cryptography

A core pillar of cryptoasset ownership is public-key ('asymmetric') cryptography, with the private key at its centre. A private key is a secret piece of data granting the authority to sign transactions and spend funds; keeping this key confidential is paramount for security, as anyone with knowledge of the private has the ability to initiate transactions. From the private key, a corresponding public key is mathematically derived using a one-way function, meaning the private key cannot be determined from the public key. This public key, which does not reveal the private key and can thus be shared publicly, is used by the network to verify the owner's digital signature. Typically, a shorter, more user-friendly address is generated from the public key to act as a public destination for receiving payments, enhancing privacy by not directly exposing the public key. The entire process ensures security through a one-way flow: Private Key → Public Key → Address.

REC – Renewable Energy Certificate

Renewable energy certificates (RECs) are tradable instruments that represent the environmental attributes of one megawatt-hour (MWh) of electricity generated from renewable sources, such as wind, solar, or hydropower. RECs provide verifiable proof that electricity has been generated from renewable energy, allowing consumers and organisations to support green energy, meet sustainability targets, and demonstrate compliance with renewable energy commitments. Separate from the physical electricity, RECs are traded on markets, enabling the environmental benefits of renewable energy to be decoupled from the actual energy and monetised independently. Similar to Energy Attribute Certificates (EACs), RECs play a critical role in fostering renewable energy adoption and enhancing transparency in green energy markets.

SG&A – Selling, General, and Administrative Expenses

Selling, general, and administrative expenses refer to non-production costs incurred in running a business, as reported on the income statement. These expenses include salaries for administrative staff, marketing and advertising costs, rent, utilities, professional fees, office supplies, travel expenses, and depreciation of office equipment. SG&A represents a significant component of a company's operating expenses and is carefully analysed by management to identify cost-saving opportunities, monitor operational efficiency, and maintain profitability.

Soft- and Hard Fork

A Fork represents a divergence in a blockchain's protocol rules or transaction history, often occurring during software upgrades, and can be categorised as 'soft' or 'hard'. A 'soft fork' is a backward-compatible protocol change where new rules are introduced, typically by making existing rules stricter. While blocks created by upgraded nodes remain valid to non-upgraded nodes (ensuring backward compatibility), blocks produced by non-upgraded nodes might violate the new stricter rules and consequently be rejected by upgraded nodes. Successful adoption relies on sufficient network consensus enforcing the new rules, and soft forks do not inherently force a chain split.
In contrast, a hard fork is a non-backward-compatible change requiring participants to upgrade their software to follow the new rules, as new blocks are invalid under the old rules and vice versa. If significant support remains for both the old and new rules, a permanent chain split occurs, resulting in two distinct blockchains sharing history up to the fork point.

Sybil Attack

A type of attack on a peer-to-peer (P2P) network where a single or group adversary/ies creates a large number of pseudonymous identities (called Sybils) to gain disproportionately large influence over the system. In the context of blockchain networks, this could potentially allow manipulation of consensus, censorship of transactions, or other disruptions if not mitigated. Consensus mechanisms like PoW or PoS are fundamentally designed to provide Sybil resistance by making participation rights (like proposing blocks) costly to obtain – typically requiring significant computational resources (PoW) or economic stake (PoS) – thus preventing the inexpensive creation of fake identities that could allow an attacker to easily outnumber honest nodes and compromise network integrity in systems where influence is based on identity count.

Transaction Fees

Fees paid by users when sending blockchain transactions to incentivise block proposers (miners or validators) to include their transaction in a block, often securing faster confirmation from the mempool. While typically voluntary from a strict protocol standpoint, fees become economically necessary during network congestion. They are usually priced per unit of resource usage (e.g., data size like sats/vB in Bitcoin, or computation like gas in Ethereum), and their levels fluctuate based on network congestion (i.e., the demand for limited blockspace). Transaction fees form an important, and often increasingly significant, part of block proposer revenue, especially in cases where block subsidy diminishes over time.

VRE – Variable Renewable Energy

Variable renewable energy refers to renewable energy sources, such as solar and wind power, whose output fluctuates due to the intermittent nature of the underlying energy resource. The generation from VRE sources depends on weather conditions, resulting in variability across timescales ranging from minutes to seasons. This variability poses challenges for grid integration, requiring strategies such as energy storage, demand-side management, grid interconnections, flexible generation, and advanced forecasting techniques to ensure a stable and reliable electricity supply.

Appendix

A: Bitcoin and the Wider Cryptoasset Market from a Financial Perspective

As miners predominantly engage in Bitcoin mining, and are therefore rewarded bitcoin, this report did not materially consider the broader cryptoasset market.

Appendix A focuses primarily on bitcoin's performance, as it is the dominant cryptoasset rewarded to miners. A key component of miners' profitability is managing the price volatility of bitcoin. Miners typically have several options for managing their bitcoin rewards:

1. They have the choice to hold their revenue in BTC
2. Convert mined BTC into cash-like assets (such as fiat currency or stablecoins)
3. Use their BTC rewards as collateral to borrow cash-like assets
4. Convert their BTC into a low-risk asset (trading liquidity for a small but positive interest rate)
5. Convert their BTC into a different risky asset (e.g., another cryptoasset, stocks, or derivatives)

The following segments therefore primarily examine the financial performance of bitcoin, while also providing context by touching on the broader cryptoasset market.

Bitcoin Returns and Trends

Building upon the price analysis in Part I, this section delves deeper into bitcoin's performance metrics, including its historical returns and commonly used risk-adjusted performance measures, before drawing parallels with the broader cryptoasset market. These metrics offer a comprehensive view of bitcoin's evolving market behaviour, shedding light not only on historical returns but also on the associated risks. Furthermore, we will identify emerging patterns in bitcoin's performance, particularly as it transitions from a nascent, speculative asset to one with increasing institutional adoption and liquidity.

Analysis of historical monthly returns and the positive-to-negative ratio of months and years

Figure 61 shows monthly bitcoin returns alongside the positive-to-negative ratio. This ratio summarises the number of positive versus negative returns in a given month (column) or year (row). Analysing this ratio over time highlights periods of strong performance, as well as months and years marked by declines. While this approach only differentiates between positive and negative returns, disregarding their magnitude, it provides a useful initial perspective on the consistency of gains.

The years 2017 and 2023 stand out as particularly strong, each with a positive-to-negative ratio of 3.00. This indicates that in these years, positive monthly returns occurred three times as frequently as negative returns (i.e., nine out of twelve months exhibited positive returns). For example, 2017 saw exceptional gains in May (66.39%), August (65.60%), October (48.31%), and November (55.51%), reflecting widespread market optimism. 2023 marked bitcoin's recovery from the 2022 bear market, with substantial gains in January (39.98%) and October (28.39%). Conversely, 2018 and 2022 exhibited significantly lower positive-to-negative ratios of 0.33 and 0.50, respectively, reflecting the steep market corrections following the preceding bull runs.

In 2024, bitcoin exhibited notable gains in the first and final quarters of the year. The year began strongly, with returns of 44.15% in February and 16.02% in March. Similarly, the final quarter saw gains of 11.23% in October and 37.09% in November. The second and third quarters, however, presented a mixed performance, contrasting with the strong start and end to the year.

Identifying emerging patterns in monthly returns

Examining monthly performance across the years reveals interesting patterns. February and October have historically been strong performers, with a positive-to-negative ratio of 3.33, indicating that in these months, positive returns significantly outweighed negative ones from 2012 to 2024. More recently, October 2021 (40.32%) and February 2024 (44.15%) exhibited the highest and second-highest returns for those respective months during this period.

Conversely, August and September have historically been weaker months for bitcoin, each showing a positive-to-negative ratio of 0.63. This historical underperformance suggests a more cautious approach during these months, potentially indicating profit-taking or seasonal market corrections. However, while August and September have historically underperformed, neither of the two months ever exhibited the largest negative return within any year. Furthermore, September has historically exhibited the lowest volatility over the observed period.

Figure 61: Monthly returns (in %), positive-to-negative ratios (by month and year) and annual Sharpe ratios (using 3-month U.S. T-bills as the risk-free asset) from 1 January 2012 to 31 December 2024. Data sources: Coin Metrics [45] and Damodaran [177]

Monthly Returns, Return Patterns, and Risk-Adjusted Performance of Bitcoin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Positive Negative Ratio	Sharpe Ratio
2024	0.9%	44.2%	16.0%	-14.9%	11.1%	-6.8%	3.1%	-8.9%	7.3%	11.2%	37.1%	-3.2%	2.00	1.41
2023	40.0%	0.1%	23.2%	3.0%	-7.3%	12.0%	-4.1%	-11.2%	3.9%	28.4%	8.9%	11.9%	3.00	2.05
2022	-17.0%	12.3%	5.5%	-17.2%	-15.6%	-39.3%	20.8%	-14.3%	-2.9%	5.4%	-16.2%	-3.8%	0.50	-1.63
2021	14.2%	36.8%	29.6%	-1.8%	-35.4%	-6.0%	19.2%	13.0%	-7.3%	40.3%	-7.1%	-18.8%	1.00	0.59
2020	30.6%	-8.3%	-25.0%	34.5%	9.0%	-3.1%	24.0%	3.0%	-7.8%	28.2%	42.4%	47.6%	2.00	1.78
2019	-7.5%	11.2%	7.9%	28.6%	62.5%	26.7%	-7.2%	-4.5%	-13.8%	10.5%	-17.5%	-5.1%	1.00	0.92
2018	-27.8%	2.6%	-32.8%	33.3%	-19.0%	-14.8%	21.2%	-9.1%	-6.0%	-4.5%	-37.0%	-7.2%	0.33	-1.61
2017	0.0%	22.7%	-9.0%	27.8%	66.4%	6.7%	16.7%	65.6%	-8.6%	48.3%	55.5%	39.3%	3.00	2.87
2016	-14.7%	19.5%	-5.0%	8.2%	18.0%	27.0%	-7.3%	-8.4%	6.4%	14.8%	6.2%	30.6%	2.00	1.62
2015	-32.2%	17.3%	-4.0%	-3.4%	-2.9%	15.0%	7.9%	-18.9%	2.6%	32.7%	20.1%	13.9%	1.40	0.41
2014	10.1%	-31.4%	-17.4%	-1.4%	39.9%	1.8%	-8.9%	-17.8%	-18.7%	-13.4%	12.3%	-15.3%	0.50	-1.13
2013	51.4%	62.7%	181.3%	48.2%	-8.1%	-30.0%	9.5%	31.0%	-1.8%	61.2%	450.6%	-34.8%	2.00	2.68
2012	17.5%	-12.0%	0.3%	1.1%	4.8%	28.9%	39.5%	8.4%	22.7%	-10.1%	12.9%	7.6%	5.00	1.32
Positive Negative Ratio	1.17	3.33	1.17	1.60	1.17	1.17	2.25	0.63	0.63	3.33	2.25	0.86		

Analysing bitcoin's risk-adjusted performance

While the previous section focused solely on returns, a comprehensive understanding of performance requires a risk-adjusted perspective. The Sharpe Ratio summarises bitcoin's excess return per unit of risk, relative to a risk-free asset, where risk is measured by the standard deviation of bitcoin's returns. Generally, a Sharpe Ratio below 1 suggests that the asset's returns do not adequately compensate for its risk. Bitcoin has exhibited a wide range of Sharpe Ratios (from -1.63 to 2.87). 2013 and 2017 stand out with exceptionally high Sharpe Ratios of 2.68 and 2.87, respectively, indicating that investors were well-compensated for the risks they assumed. This was notably influenced by outlier returns in March (+181.3%) and November (+450.6%) of 2013. More recently, 2023 exhibited a notable Sharpe Ratio of 2.05, driven by strong gains in January (39.98%), March (23.20%), and October (28.39%), with volatility remaining at much lower levels, relative to 2013 or 2017.

Finding trends in consecutive return periods

When analysing financial returns, one important aspect is understanding how often trends persist – that is, whether a positive (or negative) return is likely to be followed by further positive (or negative) returns. This helps in assessing whether financial markets or assets exhibit momentum or tend to revert quickly. To quantify this, we examine the probability of consecutive return streaks. Specifically, we measure the likelihood that, given an initial positive or negative return, the next one, two, three, or more months will also exhibit the same sign.

To determine these probabilities, we employ conditional probability analysis, which calculates the chance of an event occurring given that a preceding event has already occurred. In this context, we estimate:

$$P_{+}(\text{streak of length } k \mid \text{first return is positive}) = \frac{\text{Number of times a streak of } k \text{ consecutive positive months occurred}}{\text{Total number of positive months that could have started a streak}}$$

$$P_{-}(\text{streak of length } k \mid \text{first return is negative}) = \frac{\text{Number of times a streak of } k \text{ consecutive positive months occurred}}{\text{Total number of positive months that could have started a streak}}$$

This means we count the number of times a streak of k consecutive positive or negative months occurs after the first return in the streak, and divide it by the total instances where a return series had the potential to develop. For the purposes of this analysis, each series begins with the first observation, which is also considered the potential starting point of a streak.

This approach is akin to a Markov chain, but instead of assuming fixed transition probabilities, we empirically derive these probabilities from historical data.

The analysis shown in Figure 62(a) and (b) reveals distinct patterns in the occurrence of consecutive positive and negative return streaks. As shown in Figure 62(a), in total, 90 periods (58%) exhibited positive returns, while 66 periods (42%) were negative. Turning to the conditional probability of these returns developing into longer streaks, Figure 62(b) depicts how the likelihood of a streak continuing changes with increasing streak length. The figure visually demonstrates that, overall, positive streaks consistently have a higher probability than negative streaks. The probability that a positive return extends to at least two consecutive months is 58.9%, whereas for negative returns, this probability is lower at 44.0%. This suggests that if we see a positive return in a given month, there is a greater than 50% chance that the following month will also be positive, indicating a degree of short-term momentum.

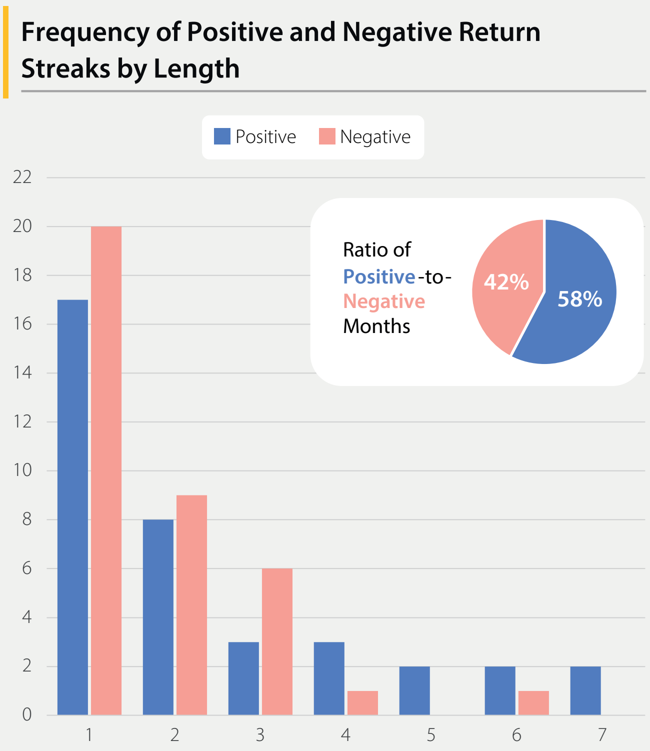
As expected, these probabilities decline as the streak length increases. The likelihood of observing at least three consecutive positive months is 36.7%, while for negative returns, this probability drops to 18.2%. Similarly, for streaks lasting at least four months, the probability further decreases to 23.3% for positive returns and 6.1% for negative returns, suggesting that positive trends tend to persist longer than negative trends. This indicates that negative trends are less likely to persist than positive ones, suggesting that periods of decline may be shorter-lived or more prone to reversal. Investors should be aware of this asymmetry when developing trading or investment strategies as it suggests that while market downturns can occur, they may be relatively short-lived compared to periods of positive growth. The longest positive streak observed in the dataset lasted seven months and occurred twice: once in 2012, from March to September, and again in the recent period from September 2023 to March 2024. In contrast, the longest negative streak persisted for six months, spanning from August 2018 to January 2019.

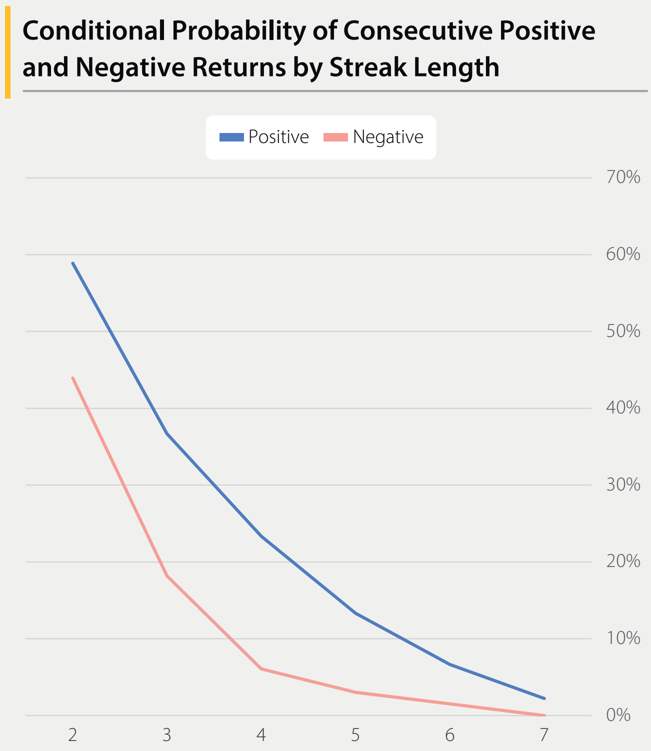
Analysing post-decline behaviour

Focusing on the period from 2017 to 2024, we can observe instances where sharp negative returns in bitcoin's monthly performance were followed by a strong recovery. A clear example is June 2022 (-39.26%), which was followed by a rebound in July 2022 (20.81%), illustrating the market's capacity to recover from extreme losses. Similarly, March 2020 (-25.05%), during the onset of the COVID-19 pandemic, was followed by a significant recovery in April 2020 (34.51%) as markets stabilised after an initial shock.

However, not all sharp negative returns lead to quick recoveries. In 2018, monthly returns exhibited multiple

Figure 62: (a) Frequency of positive and negative return streaks of various lengths (from one to seven periods) observed between 1 January 2012 and 31 December 2024, including the overall ratio of positive-to-negative months; and (b) conditional probability of observing a series of consecutive positive or negative returns extending to a specified number of periods (in %). Source: Analysis conducted by the authors, data obtained from Coin Metrics [45]





sharp declines during the first half of the year (January, March, May, June), with recoveries in April and July, but those recoveries were immediately followed by consecutive negative returns, reflecting a period of prolonged market stress, propelled by the burst of the ICO bubble. More recently, the sharp drop in August 2023 (-11.17%) was followed by a modest uptick of only 3.94% in September, followed again by a modest positive return in October. Similarly, the substantial decline in January 2022 (-17.03%) was followed by a recovery in February (12.26%), yet this recovery was not sustained, with negative returns in the following months of April and May, and another sharp drop in June. These contrasting outcomes highlight that whilst bitcoin can often bounce back after significant negative returns, certain periods of market distress can lead to extended downturns.

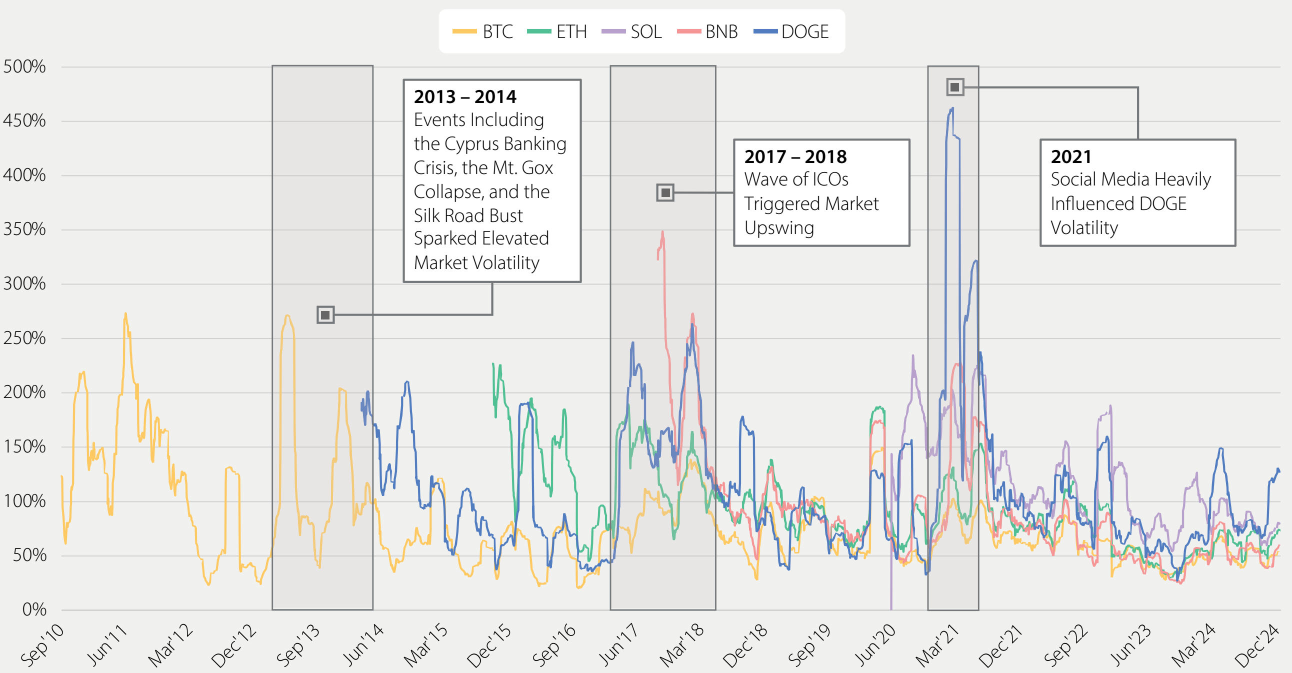
Risk-return dynamics show a shaky trend towards stability

Analysing volatility in conjunction with returns provides investors with a more complete understanding of the trade-offs between risk and reward and offers insight into the asset's evolving market behaviour. While volatility and price swings have historically defined bitcoin's price movement, the asset is increasingly showing signs of stabilisation (see Figure 63), driven by factors such as growing institutional adoption and broader market participation. This signals bitcoin's transition from a highly speculative to a more mature asset class, offering investors both growth potential and an increasingly stable risk profile. Furthermore, analysis of historical data reveals recurring patterns in bitcoin's monthly performance. Notably, since 2012, nine out of twelve months recorded positive returns more frequently than negative returns. February (3.33), July (2.25), October (3.33), and November (2.25) have historically shown the highest positive-to-negative ratios, while August (0.63), September (0.63), and December (0.86) have tended to underperform.

Beyond the investment narrative, Bitcoin's underlying technology, blockchain, has catalysed innovation across numerous sectors, giving rise to a diverse cryptoasset market that extends far beyond bitcoin itself. The cryptoasset market continues to evolve, with blockchain networks such as Ethereum, Solana, and others playing a vital role. Many of these platforms have positioned themselves as hubs for innovative decentralised financial applications and a wide variety of other products, spearheading the advancement of the ecosystem by offering traditional financial services in a public, decentralised manner.

Figure 63: Annualised volatility of leading cryptoassets from 16 September 2010 to 31 December 2024, based on daily log returns over a 60-day rolling window. Source: Analysis conducted by the authors, data obtained from Coin Metrics [178]

Volatility Comparison of Leading Cryptoassets



A Broader Market Perspective

Since bitcoin emerged as a tradable asset around 2010, when its market value was just a few million dollars, not only has the asset's value risen exponentially, but an entire ecosystem of cryptoassets has emerged, exhibiting remarkable growth. The ecosystem expanded from a combined market value of mere $18 billion in early 2017 to over $3.7 trillion by December 2024 (see Figure 64), an ascent reflecting not just the increasing adoption of cryptoassets, but also the evolving role of these assets within the global financial ecosystem. As reviewed in Part I, this evolution unfolded through a series of landmark events. A significant leap in value occurred in 2017, fuelled by a surge of retail investor interest, the rise of Initial Coin Offerings (ICOs), and increased media coverage, with the total market value of the ecosystem soaring to nearly $800 billion, rivalling that of major corporations at the time. However, the subsequent burst of the ICO market precipitated a significant contraction in cryptoasset prices.

By 2020, a shift towards institutional interest began to reshape the landscape. Companies such as MicroStrategy and Tesla allocated portions of their balance sheets to bitcoin, lending legitimacy to the asset. The economic disruptions and uncertainties caused by the COVID-19 pandemic in 2020 marked another period of rapid growth in the value of cryptoassets, propelled by a confluence of factors. These factors included corporate endorsements, El Salvador's adoption of bitcoin as legal tender, and the burgeoning popularity of decentralised finance (DeFi) and non-fungible tokens (NFTs). Alongside these crypto-specific developments, global macroeconomic shifts, such as the prevailing low interest rates resulting from expansionary monetary policies, also played a role. At its zenith in 2021, bitcoin's market value exceeded $1 trillion, with the entire ecosystem reaching a combined market value of over $3 trillion, surpassing that of tech giants like Apple and Microsoft.

However, those gains were short-lived and underscored the inherent volatility of cryptoassets. In 2022, systemic issues, including the collapse of the Terra Luna ecosystem and the high-profile failure of FTX, triggered a sharp downturn, eroding the combined market value to nearly $800 billion, which served as a stark reminder of the inherent risks in this nascent asset class.

Correlation patterns of bitcoin and other major cryptoassets

Correlations between cryptoassets reveal the degree to which individual coins behave as distinct assets. As shown in Figure 65, the cryptoasset market has historically demonstrated strong interconnectedness, particularly during intense market swings, asset prices often move in sync due to shared investor sentiment, liquidity flows, and broad macroeconomic forces.

Figure 64: Daily market value (in USD) of a portfolio of leading cryptoassets from 18 July 2010 to 31 December 2024. Major stablecoins include: USDT, USDC, and BUSD. Sources: Analysis conducted by the authors, data obtained from Coin Metrics [23], TokenInsights [24]

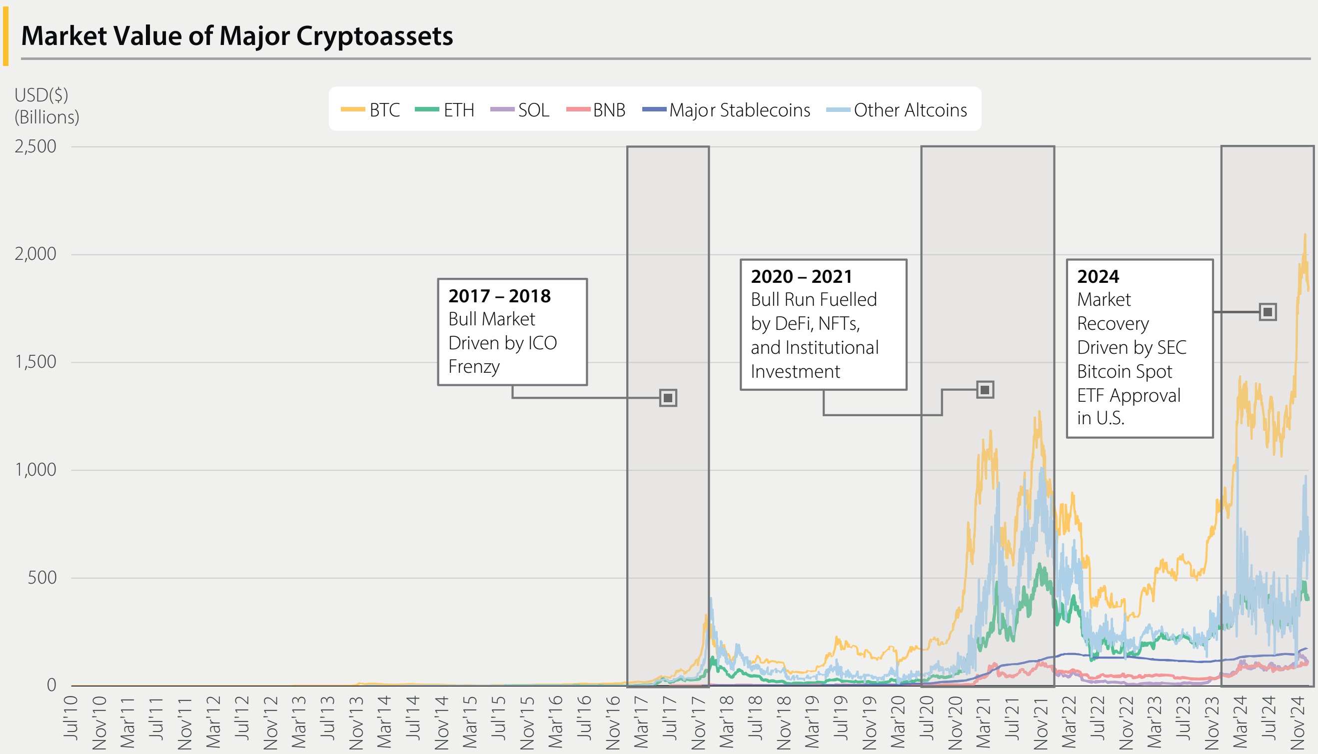


Figure 65: Annual Pearson correlation matrices for leading cryptoassets: Bitcoin (BTC), Ethereum (ETH), Cardano (ADA), Avalanche (AVAX), BNB Chain (BNB), Dogecoin (DOGE), Polkadot (DOT), Chainlink (LINK), Solana (SOL), and Tron (TRX) for the years 2021 to 2024, calculated using daily log returns. Source: Analysis conducted by the authors, data obtained from Coin Metrics [45]

Correlation Amongst Leading Cryptoassets

2021

	BTC	ADA	AVAX	BNB	DOGE	DOT	ETH	LINK	SOL	TRX
BTC	1.00									
ADA	0.59	1.00								
AVAX	0.47	0.60	1.00							
BNB	0.62	0.52	0.51	1.00						
DOGE	0.38	0.30	0.25	0.21	1.00					
DOT	0.69	0.64	0.54	0.58	0.31	1.00				
ETH	0.77	0.63	0.50	0.63	0.34	0.74	1.00			
LINK	0.69	0.66	0.52	0.62	0.36	0.73	0.79	1.00		
SOL	0.40	0.38	0.43	0.49	0.19	0.44	0.51	0.47	1.00	
TRX	0.66	0.58	0.45	0.59	0.33	0.67	0.68	0.68	0.41	1.00

2022

	BTC	ADA	AVAX	BNB	DOGE	DOT	ETH	LINK	SOL	TRX
BTC	1.00									
ADA	0.79	1.00								
AVAX	0.81	0.81	1.00							
BNB	0.83	0.79	0.84	1.00						
DOGE	0.69	0.68	0.67	0.70	1.00					
DOT	0.79	0.84	0.85	0.83	0.68	1.00				
ETH	0.90	0.80	0.85	0.84	0.71	0.83	1.00			
LINK	0.76	0.80	0.80	0.76	0.63	0.83	0.79	1.00		
SOL	0.79	0.79	0.86	0.81	0.67	0.81	0.82	0.76	1.00	
TRX	0.63	0.62	0.58	0.63	0.53	0.62	0.61	0.53	0.59	1.00

2023

	BTC	ADA	AVAX	BNB	DOGE	DOT	ETH	LINK	SOL	TRX
BTC	1.00									
ADA	0.66	1.00								
AVAX	0.58	0.64	1.00							
BNB	0.62	0.59	0.50	1.00						
DOGE	0.62	0.65	0.62	0.53	1.00					
DOT	0.69	0.76	0.72	0.60	0.67	1.00				
ETH	0.83	0.68	0.55	0.64	0.63	0.69	1.00			
LINK	0.61	0.64	0.59	0.54	0.60	0.70	0.66	1.00		
SOL	0.62	0.63	0.64	0.49	0.51	0.70	0.62	0.56	1.00	
TRX	0.59	0.55	0.52	0.48	0.53	0.58	0.60	0.52	0.54	1.00

2024

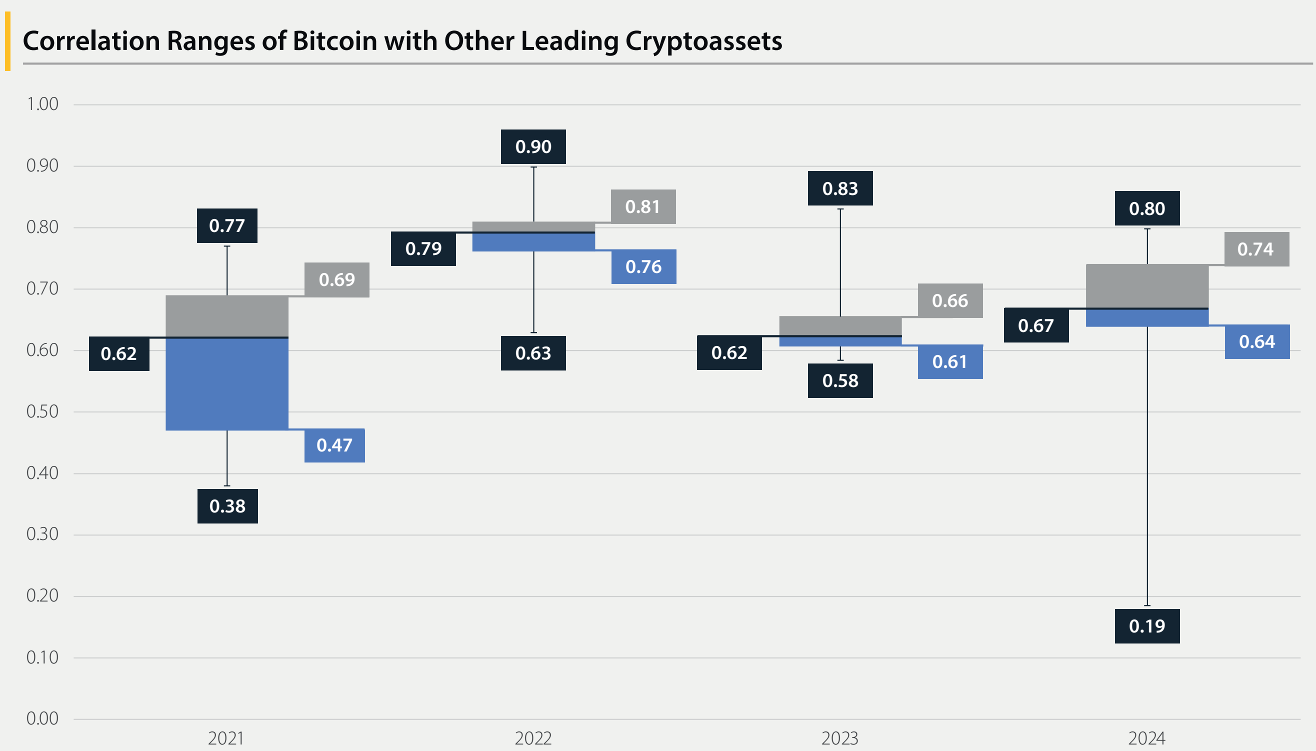
	BTC	ADA	AVAX	BNB	DOGE	DOT	ETH	LINK	SOL	TRX
BTC	1.00									
ADA	0.67	1.00								
AVAX	0.70	0.75	1.00							
BNB	0.64	0.54	0.54	1.00						
DOGE	0.77	0.67	0.63	0.52	1.00					
DOT	0.64	0.82	0.75	0.55	0.66	1.00				
ETH	0.80	0.68	0.70	0.63	0.70	0.67	1.00			
LINK	0.59	0.70	0.74	0.48	0.52	0.72	0.66	1.00		
SOL	0.74	0.65	0.75	0.60	0.63	0.65	0.69	0.60	1.00	
TRX	0.19	0.27	0.21	0.37	0.16	0.24	0.18	0.22	0.22	1.00

Examining bitcoin's correlation specifically with other cryptoassets reveals that the potential for diversification benefits can vary across different market conditions. Investors seeking diversification benefits may find them more readily achievable during bull markets, when correlations between cryptoassets tend to be lower. In contrast, bear markets often witness a rise in correlations, with assets moving more synchronously, thus limiting diversification opportunities. This reflects how bull market optimism and enthusiasm can diversify capital flows across individual assets based on project-specific sentiment, whilst the fear and uncertainty that permeate bear markets tend to impact the ecosystem universally, moderating the influence of individual price drivers.

A more granular analysis of the correlation between bitcoin and other cryptoassets in recent years (see Figure 66) further illuminates this dynamic. In 2021, the meme coin DOGE stood out as an outlier, exhibiting a noticeably lower correlation with bitcoin (0.38) compared to the median correlation of bitcoin with other cryptoassets (0.62). DOGE's performance, fuelled primarily by social media hype and retail investor interest,[179] diverged from broader market trends, highlighting how idiosyncratic factors can influence correlation. In contrast, the 'crypto winter' of 2022, precipitated by the collapses of the Terra Luna ecosystem and FTX, demonstrated the powerful force of systemic risk. Widespread sell-offs led to a marked increase in correlations across the board. The correlation range narrowed considerably to between 0.63 and 0.90, with the interquartile range clustering between 0.76 and 0.81. This highlights the vulnerability of the cryptoasset market to cascading failures. In 2023, correlations decreased notably, with the median dropping from 0.79 in 2022 to 0.62 in 2023. Despite this decrease, the range remained relatively consistent, albeit with a very high degree of clustering; three-quarters of correlations fell between 0.58 and 0.66. Last year presented a mixed picture, with a slightly higher median correlation (0.67) but also including a notable outlier: TRX, which exhibited a very weak positive correlation (0.19).

In conclusion, while transient periods of lower correlation between bitcoin and other cryptoassets may occur, the data suggests that the cryptoasset market remains largely characterised by significant interconnectedness and susceptibility to systemic shocks. Consistent diversification benefits, therefore, appear challenging to achieve, particularly during periods of market stress.

Figure 66: Box plots illustrating the distribution of Pearson correlation coefficients, calculated using daily log returns, between bitcoin and the following cryptoassets: Ethereum (ETH), Cardano (ADA), Avalanche (AVAX), BNB Chain (BNB), Dogecoin (DOGE), Polkadot (DOT), Chainlink (LINK), Solana (SOL), and Tron (TRX) for the years 2021 to 2024. Source: Analysis conducted by the authors, data obtained from Coin Metrics [45]



B: The Evolution of Bitcoin

Upgrades to Bitcoin are formalised through Bitcoin Improvement Proposals (BIPs), a process that enables the community to suggest, debate, and implement changes to the protocol. This decentralised approach to development ensures that no single entity controls Bitcoin, reflecting the core values of transparency, security, and decentralisation that underpin the entire ecosystem.

Over the years, Bitcoin has undergone significant changes, driven by the need to address scalability, security, and functionality challenges while preserving its decentralised nature. This development path has been fraught with philosophical and technical debates, innovations, and controversies that ultimately shaped Bitcoin as we know it today.

The block size debate: global payment system or store of value?

One of the most contentious periods in Bitcoin's history occurred between 2015 and 2017, centred around the issue of block size. The block size, initially set at 1MB by Bitcoin's creator, Satoshi Nakamoto, became a focal point of debate as the network grew and transaction volumes increased.[180] The 1MB limit, intended to prevent spam attacks and maintain decentralisation, began to constrain the network's capacity, leading to slow transaction processing times and higher fees.

The debate over block size was not just a technical discussion but an ideological clash that reflected differing visions for Bitcoin's future. On one side were those who saw Bitcoin primarily as 'digital gold' – a store of value rather than a medium of exchange. This group, which included many Bitcoin Core developers, argued that maintaining a smaller block size was essential to preserving decentralisation and security. They feared that increasing the block size would lead to centralisation, as only those with significant resources would be able to run full nodes, thus undermining the democratic nature of the Bitcoin network.

On the other side were those who envisioned Bitcoin as a global payment system, capable of handling large volumes of transactions efficiently. This group, which included many miners and businesses, advocated for a larger block size to increase transaction throughput. They argued that without scalability improvements, Bitcoin would be unable to compete with other payment systems, severely limiting its adoption. The debate intensified in 2015 with the introduction of BIP-101 by Bitcoin developer Gavin Andresen, which proposed increasing the block size limit to 8MB. Proponents of this proposal believed it would alleviate network congestion and make Bitcoin more accessible to everyday users. However, the opposition was fierce, with critics warning that the proposed changes would compromise Bitcoin's decentralised nature. Specifically, opponents argued that larger blocks would require more resources to process, potentially leading to fewer individuals being able to run full nodes, thus centralising validation power in the hands of larger entities.

Another significant scaling proposal, Segregated Witness (SegWit), was brought forward. Defined in BIP 141, SegWit was a soft fork upgrade that primarily aimed to solve transaction malleability, a bug that complicated the development of off-chain solutions. SegWit also increased effective block capacity; its 'block weight' accounting gave a discount to signature data ('witness'), allowing blocks equivalent to roughly 2MB up to a theoretical 4MB. Emerging from prolonged discussions, this change became central to fierce activation debates around mid-2017, notably involving the New York Agreement. During this period, SegWit itself was seen by some as a compromise, offering a modest increase in throughput without requiring a hard fork. However, for those who believed a larger block size increase was essential for Bitcoin to scale, SegWit was seen as insufficient.

This ideological divide ultimately led to a series of forks, the most significant being the creation of Bitcoin Cash in August 2017. Bitcoin Cash effectively split from the Bitcoin mainnet, initially implementing a 8MB block size, which was later raised to 32MB. This hard fork was a turning point in Bitcoin's history, highlighting the deep divisions within the community over how to scale the network. While Bitcoin Cash pursued a path focused on larger block sizes to achieve significantly scaled transaction throughput, Bitcoin took a different approach, with a focus on further optimising on-chain efficiency and developing off-chain scaling solutions.

Lightning Network

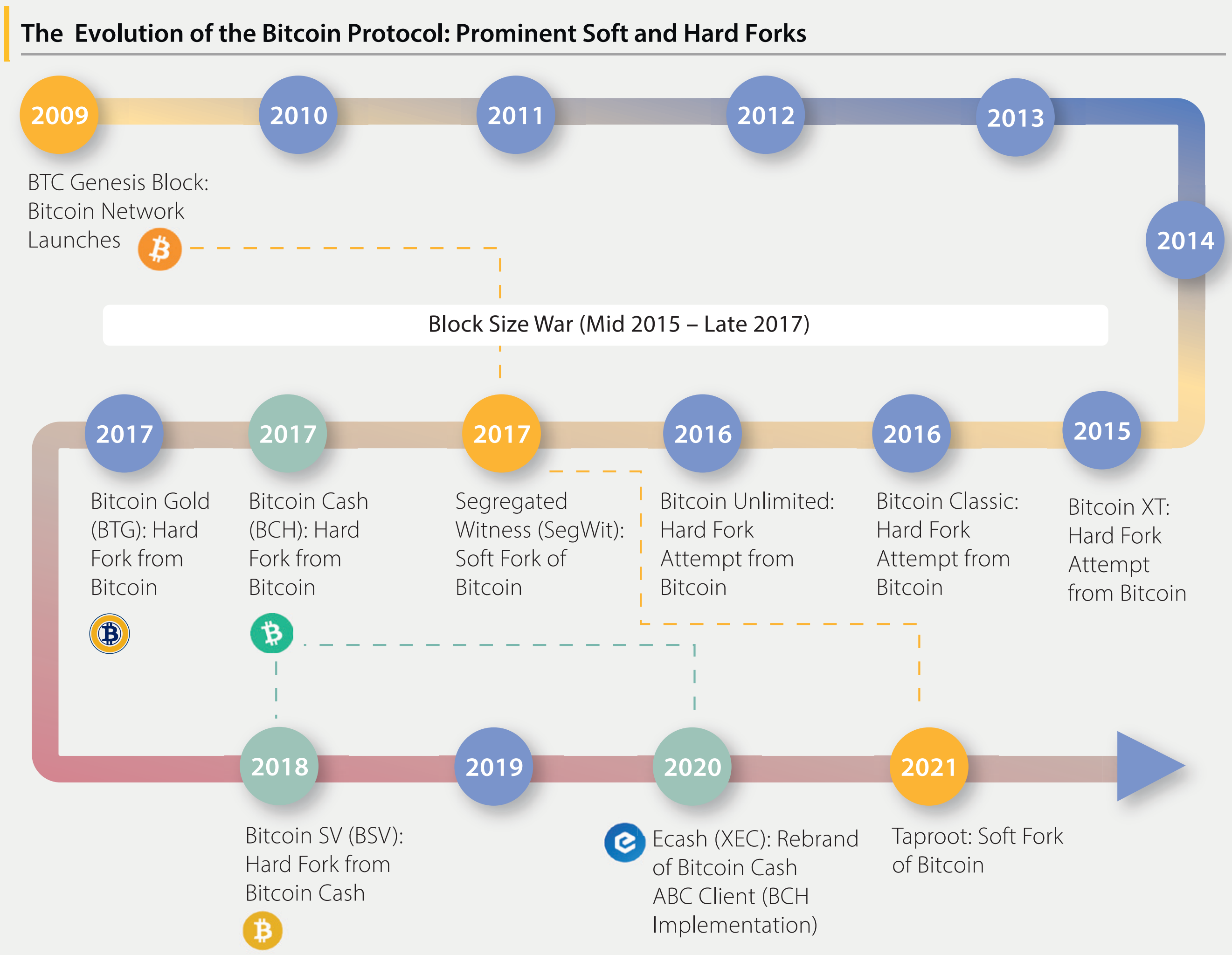
Building on the foundation laid by SegWit, the Lightning Network was proposed in 2015 by Joseph Poon and Thaddeus Dryja as a 'layer 2' scaling solution, operating atop the Bitcoin blockchain. The Lightning Network enables users to create a network of off-chain, peer-to-peer payment channels. Within these channels, participants can transact nearly instantaneously and at significantly reduced fees, as these transactions are not individually recorded on the Bitcoin blockchain. These channels are established by committing a funding transaction to the main blockchain, which locks up bitcoin to be used within the channel. Only the opening and closing transactions of these channels are ultimately settled and recorded on the Bitcoin blockchain. This mechanism reduces the load on the main chain, allowing for a much higher volume of payments within the Bitcoin ecosystem. Consequently, the Lightning Network significantly enhances Bitcoin's ability to scale, making micropayments feasible and positioning it as a more practical solution for everyday transactions – all while leveraging the security and decentralisation of the underlying Bitcoin network.

Taproot and the expansion of Bitcoin's functionality

Following the heated debates and forks, Bitcoin continued to evolve, with a focus on enhancing privacy, scalability, and functionality. One of the most significant upgrades in recent years was Taproot (BIPs 340-342), a series of updates activated in November 2021. At its core, Taproot implemented Schnorr signatures, a more efficient and privacy-enhancing cryptographic signature scheme compared to Bitcoin's original ECDSA. Taproot also introduced Merkleized Abstract Syntax Trees (MAST), which allow for complex spending conditions to be represented in a more compact and private manner. Only the relevant spending condition is revealed on the blockchain when a transaction is spent, enhancing both privacy and efficiency.

These improvements, taken together, optimised Bitcoin's use of block space. Complex transaction conditions, such as multi-signature setups or those with various spending paths, could now appear as simple transactions on the blockchain. This increased

Figure 67: Timeline of major Bitcoin protocol soft and hard forks. Source: Cambridge Centre for Alternative Finance



data efficiency and reduced transaction costs for users employing more advanced setups. By making complex transactions indistinguishable from simple ones, Taproot significantly enhanced privacy by concealing the underlying logic of transactions.

While Bitcoin does not support complex smart contracts like Ethereum, Taproot laid the groundwork for more flexible and complex transaction conditions through Tapscript, an updated scripting language designed to work with Schnorr signatures and MAST. Tapscript enables more sophisticated conditional spending, although it is still limited compared to the broader concept of smart contracts on other blockchains. The Taproot upgrade was widely supported within the Bitcoin community and faced little controversy, [181] marking a period of relative consensus compared to the earlier block size debates.

Building on the foundation laid by Taproot, new proposals continue to explore further enhancements to Bitcoin's functionality. One such proposal is BIP-118, also known as SIGHASH_ANYPREVOUT, which aims to improve the flexibility and efficiency of payment channels and other off-chain protocols. Another area of ongoing research and development is focused on exploring the potential of new opcodes to enable more complex and flexible operations on Bitcoin. These efforts underscore the ongoing commitment to innovation within the Bitcoin community, building on the foundations laid by previous upgrades such as SegWit and Taproot.

C: The Improbability of a Supercomputer 51% Attack on Bitcoin

A frequently posed question concerns the potential threat of supercomputers to the Bitcoin network, specifically in the context of a 51% attack. This thought experiment addresses this question by attempting a comparison between the computational power of the world's most powerful supercomputers and the implied hashrate of the Bitcoin network. While both supercomputers and purpose-built ASICs for Bitcoin mining represent powerful computing devices, they excel at fundamentally different tasks.

Supercomputer performance is typically measured in FLOP/s (floating-point operations per second), reflecting their strength in complex calculations with real numbers. Bitcoin mining, conversely, relies on SHA-256 hashing, a cryptographic process dominated by bitwise operations (logical AND, OR, XOR, shifts, etc). Due to the distinct nature of these operations (floating-point versus primarily bitwise operations), there is no direct conversion between FLOP/s and SHA-256 hashes per second (H/s). Consequently, to enable a rough approximation requires stark simplification and a series of assumptions that could materially impact the results. Therefore, any comparison between the two must be considered with caution, acknowledging that this is not a trivial apples-to-apples comparison. Nevertheless, a variety of data points can be used to approach such a comparison.

The total supercomputer (SHA-256) hashrate, $H_{sc,total}$, can be calculated as follows:

$$H_{sc,total} = N \times \frac{\textit{Supercomputer Core (FLOP/s)} \times \textit{Benchmark CPU (H/s)}}{\textit{Benchmark CPU (FLOP/s)}}$$

where,

N = the total number of cores across the world's top 500 supercomputers.

Supercomputer Core (FLOP/s) = the average performance per supercomputer core in FLOP/s.

Benchmark CPU (H/s) = the SHA-256 hashrate (in H/s) achieved by the reference CPU.

Benchmark CPU (FLOP/s) = the reference CPU's performance in FLOP/s.

Recognising that the definition of a 'core' varies significantly across different technical architectures, we calculate a weighted average across the 500 most powerful supercomputers (as of November 2024), by summing the theoretical peak performance of all 500 systems and, separately, summing the total number of cores across all 500 systems. Dividing the total theoretical peak performance by the total number of cores, N = 128,985,060, yields an average supercomputer core performance of 137 GFLOP/s. [182]

For our benchmark CPU we use the Intel Core i7-990x CPU. Based on Taylor (2017),[183] this CPU achieves a benchmark SHA-256 hashrate of 33 MH/s (33 million H/s). A benchmarking test (Geekbench 4) indicates that the same CPU achieves approximately 123 GFLOP/s (123 billion FLOP/s),[184] a figure roughly comparable to our defined supercomputer core. These figures allow us to establish a conversion factor between the benchmark machine, approximately 3,727 FLOP/s per H/s.

Applying the formula above yields a total hashrate of roughly 4.7 PH/s for the combined 500 most powerful supercomputers. This represents approximately 0.0006% of the implied Bitcoin network hashrate (as of 31 December 2024). In other words, it would take the world's 500 most powerful supercomputers more than three years to find a valid block hash for a single Bitcoin block at current difficulty level.

The methodology presented relies on several layers of approximation. The core count averaging, and, most importantly, the fundamental difference between floating-point and bitwise operations all contribute to a significant margin of error. Moreover, it is crucial to note that the calculation relies on a CPU-centric conversion factor. Supercomputers, however, typically incorporate a heterogeneous mix of processing units, including not only CPUs but also significantly more powerful accelerators like GPUs. These accelerators possess architectures highly amenable to parallel processing, rendering them considerably more efficient at SHA-256 hashing than traditional CPUs. Despite these limitations, the magnitude of the difference between the estimated supercomputer hashrate and the implied Bitcoin network hashrate is so profound that the core conclusion remains valid: even the combined computational might of the world's most powerful supercomputers, if hypothetically used to mine Bitcoin, would represent an insignificant fraction of the network's total hashrate. This renders a 51% attack using such resources profoundly improbable from a purely computational perspective. For further details on the underlying reasons for this disparity, and why this constitutes an apples-to-oranges comparison, please refer to Part II.

D: Survey Questionnaire

Theme	Survey Questions
Business and Operational Structure	Please indicate whether your company is privately held or publicly traded? Please specify the distribution of your firm's energy consumption among Bitcoin mining, other cryptocurrency mining, and HPC (High-Performance Computing) services. Leave any options that do not apply blank. Ensure that the total adds up to 100%. Please indicate the total power consumption of your operational mining fleet as of the end of June 2024, expressed in megawatt (MW). Please provide the total operational hashrate of your mining fleet as of the end of June 2024, expressed in petahashes per second (PH/s) Please indicate the country where your firm's headquarters is located. Please specify the geographical distribution of your company's mining activities worldwide. For each country, indicate the percentage of your total power consumption that takes place in that location. Ensure the cumulative total across all countries equals 100%. **Note:** This question relates only to your total cryptocurrency mining-related power consumption.
Hardware and E-Waste	Please specify the brand composition of your mining fleet. Leave any options that do not apply blank. Ensure that the total adds up to 100% Optional: Please specify the firmware used for your mining fleet. Leave any options that do not apply blank. Ensure that the total adds up to 100%. What percentage of your total operational hashrate (as of the end of June 2024) do you anticipate will be phased out or replaced by the end of 2024? Note: To select a value of 0, please click on the slider, move it to the right, and then drag it back to the 0 position. Optional: Regarding the mining hardware that constitutes the phased-out hashrate you specified in Question A5(a), what proportion of this hardware do you anticipate will not be recycled, sold, donated, or repurposed in any manner. **Note:** To select a value of 0, please click on the slider, move it to the right, and then drag it back to the 0 position. Optional: Considering the environmental implications associated with mining hardware as e-waste, how does your organisation plan to manage the recycling or responsible disposal of such equipment that is phased out or replaced? (Select all that apply)

D: Survey Questionnaire cont.

Theme	Survey Questions
Operations, Energy, and Environment	Optional: Kindly provide information on your company's electricity rates, hosting rates, and curtailment credits. While we encourage you to answer at least one of the first two items below, you may choose to respond to all if applicable to your operations. All rates should be averaged across all regions and facilities and provided in US dollars per Megawatt-hour ($/MWh).[1] Optional: To what extent do your operations rely on off-grid[2] electricity supply? Please use the sliding scale below to indicate the percentage of your total electricity consumption that is sourced off-grid. **Note:** To select a value of 0, please click on the slider, move it to the right, and then drag it back to the 0 position. Please indicate the percentage share of each primary energy source in your company's power generation mix. The total should add up to 100%. Leave any options that do not apply blank. **Note:** Should all fields be left blank or the sum not equal 100%, the remaining allocation will be automatically attributed to 'Grid mix' by default. Grid mix refers to the combination of different energy sources used to generate electricity supplied to the power grid, including fossil fuels, renewables, nuclear power, and other sources. This applies to you when you source electricity from the grid, and no contractual instruments such as PPAs or EACs exist that would allow you to associate a specific mix to your consumption. Here [185] you can find additional information to assist you in deciding whether to select specific energy sources or the grid mix option. Optional: Has your usage of natural gas or biogas directly contributed to mitigating routine flaring or venting at the source (e.g., oil fields, landfills)? **Note:** When answering this question, please consider the concept of additionality[186] in this context. This means that your natural gas or biogas usage should reflect reductions in flaring or venting that go beyond what is required by existing regulations or what would have occurred in the absence of your efforts. In other words, the reductions should be a direct result of your actions and not due to compliance with existing legal requirements. Follow-up: Since you selected either "Yes, all of our natural gas or biogas usage directly reduced the amount of gas that would have otherwise been routinely flared or vented." or "Yes, part of our natural gas or biogas usage directly reduced the amount of gas that would have otherwise been routinely flared or vented." in the previous question, please indicate the approximate percentage of your total gas usage that would have otherwise been routinely flared or vented. For clarification, here is an example.[3] In the last calendar year, if applicable, has your organisation engaged in electrical energy curtailment as part of your demand response strategy? Follow-up: Kindly state the total hours of curtailment in megawatt-hours (MWh). Does your company engage in any of the following climate mitigation strategies? (Select all that apply)

[1] Additional information: Direct electricity rate includes the costs of either or both purchased electricity and self-generated electricity, covering all relevant direct costs. This encompasses the rates for purchased electricity and, for self-generated electricity, the associated fuel costs. All-in rate includes Cost of Goods Sold and Selling, General, and Administrative Expenses. Does not include curtailment credits.

[2] Additional information: Off-grid refers to using electricity through systems that operate independently of, and are not directly connected to, the main power grid.

[3] Additional information: Consider a scenario in which gas is part of your company's electricity mix, procured through three distinct PPAs. The first PPA involves a conventional energy supplier, the second an oil exploration company where colocation mitigates routine flaring, and the third a landfill operator where colocation reduces gas venting.

D: Survey Questionnaire cont.

Theme	Survey Questions
Industry Sentiment	Based on your insights into the cryptocurrency mining industry, please rate the general level of concern associated with the following operational issues from 1 (No Concern) to 5 (Severe Concern). Based on your understanding and insights into the cryptocurrency mining industry, please rate the general effectiveness of the following risk mitigation strategies from 1 (Not Effective) to 5 (Extremely Effective). Drawing upon your expertise and experience in the cryptocurrency mining sector, please evaluate the extent to which each of the following factors poses a constraint on the growth of mining operations. Rate each factor on a scale from 1 (No Constraint) to 5 (Severe Constraint). What is your expectation for total Bitcoin network hashrate by the end of 2024? Optional: What are your exact projections (in EH/s), if you have any, for the total Bitcoin network hashrate by the end of 2024? Please provide estimates for conservative, baseline, and optimistic scenarios. What is your prediction for the price of bitcoin (BTC) at the end of 2024? Please specify your answer in US dollars (USD).

Suppose your total gas consumption is distributed as follows: 60% is attributed to the PPA with the oil explorer (thereby reducing routine flaring), 5% is associated with the PPA with the landfill (thereby reducing gas venting), and the remaining 35% comes from the conventional energy supplier. In this context, you would report 60% of your gas usage under the category Flared and 5% under Vented, resulting in a combined total of 65% of your gas usage that directly mitigates routine flaring and venting.

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