Bitcoin Mining and Sustainable Energy

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Abstract

This paper studies 14 public bitcoin mining companies in North America that had negligible size in early 2021 and grew to control about 30 percent of worldwide minng by the end of 2024. About half of their operations occur in Texas, where sustainable energy providers offer curtailment subsidies to miners who shut down during peak demand, stabilizing loads on the grid. Our model shows that miners using sustainable energy will be more profitable than those using conventional sources, despite these shutdowns, as they receive low prices when energy is abundant (strong winds) and collect rebates for shutting down when energy is scarce (lack of wind). We test these predictions with data about miners' valuations and operations.

1 Introduction

In the spring of 2021, China's government unexpectedly banned proof-of-work cryptocurrency mining. Up to that point, China had hosted a majority of the global bitcoin network hashrate, and on short notice miners had to shut their Chinese operations and seek new venues. North America became a prime destination, and by the end of 2021 the United States had emerged as the largest site for proof-of-work data centers, with a large concentration in Texas.[1]

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[1]The news media has closely chronicled the migration of the crypto mining industry to the U.S. and in particular Texas. For example, see Dalvin Brown, "Bitcoin miners break new ground in Texas, a state hailed as the new cryptocurrency capital," The Washington Post, July 8, 2021.

Proof-of-work mining, as used in the bitcoin network, involves trial-and-error computations in which a miner appends a positive integer to a string that represents a "block" of unconfirmed bitcoin transactions. The augmented string becomes the input to a hash function, and the miner tests whether the output hashcode falls below a critical value set by the network. Most of the time the miner's guess will not yield a low enough hashcode, and the process is then repeated many more trillions of times until a miner somewhere in the world finds a valid solution and collects a reward that is currently set at 3.125 bitcoins, or about $280,000 at recent prices.[2] The network algorithmically adjusts the critical value so that on average ten minutes of trial-and-error "work" is expected to be necessary across the entire network until some miner wins the next block. No creativity or strategy is involved in the sequence of trial-and-error guessing; the process simply requires brute-force repetition of uninteresting work at the highest possible velocity. A successful bitcoin miner will have the capacity to guess random integers rapidly, akin to somebody skilled at approaching a lottery kiosk and buying many tickets very quickly.

Many U.S. bitcoin miners have elected to organize themselves as listed companies on the NASDAQ stock market, and by the end of 2024 more than a dozen publicly traded crypto mining companies, representing nearly 30% of the global hashrate, had floated their shares alongside those of more traditional miners of gold, copper, aluminum, and other minerals. Operating as public corporations represented a sharp break with the most common patterns of organization in the industry, which had previously been dominated by private partnerships and lone-wolf entrepreneurs.

Many of the mining companies in our sample locate in Texas, because that state has actively recruited proof-of-work miners to help stabilize demand for the power generated by companies that invest in renewable energy (Carter et. al, 2023). Texas has experienced rapid growth in renewable energy generation, especially wind power which now accounts for more than one-fourth of the statewide supply. However, providers often face a mismatch between supply and demand, which are affected in opposite directions by weather patterns. In particular, the windiest seasons of spring and fall have abundant supply of wind power but relatively little demand for energy, since mild temperatures tend to suppress demand for heating or air conditioning. The opposite conditions occur in the winter and summer,

[2]The system of mining incentives, which also involves customer user fees set continuously by auction, is detailed by Easley, O'Hara and Basu (2019) and Halaburda, Haeringer, Gans and Gandal (2022). Lehar and Parlour (2021) study the possibility of collusion among miners to induce bitcoin customers to pay higher user fees.

when the weather is generally less windy but demand for electricity will rise. Because bitcoin miners can absorb large quantities of energy but also shut down operations quickly,[3] they can provide a buffer beetween market supply and demand often referred to as "load balancing" or "grid stabilization," assuring renewable energy providers of a steady demand for their output. The presence of crypto miners willing to operate on this basis can encourage the construction of more wind power capacity, leading to greater generation of renewable energy across the entire grid (Cassauwers, 2021).

We study the operations and market valuations of Texas-based mining companies compared to those in other parts of North America. We identify 14 publicly traded bitcoin mining companies whose main operations are in North America, and we collect data from monthly operating reports that most of them publish without interruption after listing their shares on the NASDAQ market. These reports document the monthly mining output and installed hashing power of each company, as well as details about inventories of cryptocurrency held, orders for new mining rigs, and forecasted expansion plans.

We use a model in Section 2 below to study the behavior of miners using sustainable energy compared to those using conventional sources of electric power. We identify conditions under which a sustainable miner may be more profitable despite shutdowns induced by erratic energy supply. The model generates several predictions that we test using data from the 14 publicly traded mining companies. As predicted by the model, we find that the Texas miners are less productive due to frequent shutdowns of their operations, but they benefit from very low electricity prices when the supply is high, and from rebates and subsidies paid in exchange for their (mandatory) participation in "curtailment" schemes that intermittently force them offline when the electricity supply is low. As shown in analysis below, we have weak evidence that Texas-based mining companies trade in the stock market at higher valuations than their competitors over the range of low to moderate bitcoin market prices. When bitcoin prices are high, however, the opportunity cost of not mining bitcoin during curtailment periods makes miners located elsewhere more valuable than those in Texas. We also find evidence of comovement between miners' stock prices and an index of stocks of clean energy providers.

Our paper complements an emerging literature, often published in operations research or engineering journals, that shows the potential of load balancing for stimulating the supply side of the renewables market. These papers include Shan and Sun (2019); Bruno, Weber

[3]An executive of one crypto miner told us that his company is required to power down its rigs on 15 seconds' notice from its utility provider under the terms of their contract.

and Yates (2022); and Niaz, Liu, and You (2022).

Our model shares thematic similarities with Bastian-Pinto et al. (2021), who examine the role of bitcoin mining as a hedge for renewable energy investments. Their real options framework explores how wind farm investors might switch between selling electricity and mining bitcoin based on price fluctuations. While their model provides valuable insights into investment incentives for renewable energy producers, it treats electricity prices as exogenous and does not explicitly model interactions between miners and utilities. In contrast, our model incorporates curtailment contracts and load-balancing agreements, recognizing that miners are not merely passive price takers but active collaborators with utilities in shaping electricity consumption patterns. While both models are static, our approach differs in its focus on firm-level profitability and financial market valuation, demonstrating that publicly traded miners employing flexible energy strategies are systematically valued at a premium. Additionally, whereas Bastian-Pinto et al. (2021) rely on simulated scenarios, our theoretical predictions are validated using real-world data from publicly traded mining firms, offering empirical evidence that adaptive energy usage enhances firm valuation. By bridging insights from energy markets and financial markets, our model provides a complementary yet distinct perspective on how bitcoin mining interacts with sustainable energy sources.

Li et al. (2024) find similar theoretical results of bitcoin mining's role in stabilizing renewable energy grids' profits, focusing on policy implications. Our study provides both theoretical and empirical validation of these results, showing that publicly traded mining firms adjust their electricity consumption in response to price fluctuations and curtailment incentives. Unlike Li et al. (2024), who assume regulator-driven pricing mechanisms, our model endogenizes firm-level decision-making and real-world contracting between miners and utilities. We demonstrate that miners using sustainable energy can achieve higher profitability despite intermittent shutdowns due to lower energy costs and compensation from curtailment contracts. Further, our empirical findings show that financial markets value these adaptive strategies, as reflected in higher market valuations for mining companies with flexible energy arrangements.

The claim that proof-of-work crypto miners could provide net benefits to the environment is sometimes met with skepticism, since the benefits of load balancing may be exceeded by environmental costs arising from miners whose energy sources rely on fossil fuels. Most of the miners in our sample claim to be engaging in "green," "sustainable," or "renewable" energy consumption, but researchers have been skeptical (Solomon 2022), and many of the

companies' claims often apply to plans for future electrical installations not yet operating. The electricity consumption of crypto mining has received considerable public scrutiny. The Congressional Research Service (2019) provides a detailed overview of the mining process along with a chronology of regulatory interventions by the U.S. and other countries due to the high levels of energy use. Some North American jurisdictions such as New York state and the province of British Columbia have passed or are considering restrictions on proof-of-work mining due to its impact on consumer utility prices (Benetton, Compiani, and Morse, 2021). Partly in response to the controversy over their high energy consumption, mining companies have sought out sources of sustainable or renewable energy. Along with its public relations benefit, using renewable energy may be attractive to miners because wind or hydropower are often generated in remote geographical areas where a mining company may be less likely to compete with nearby households for a share of the energy supply and will also avoid criticism for nuisance externalities such as the emission of continuous loud noise.

The remaining sections of the paper are organized as follows. Section 2 presents an overview of our model. Section 3 describes our dataset. Section 4 contains our analysis. Section 5 includes a discussion and conclusions.

2 Model Overview and Intuition

The core of the model looks at the behavior and profitability of bitcoin miners who use sustainable energy, which is characterized by its variable supply depending on factors like weather or season. Compared to conventional sources, sustainable energy can be more abundant (and cheaper) under certain conditions, but its supply may be less reliable. This creates interesting dynamics for miners who must decide when to mine, based on the cost of energy at any given time.

We classify miners into three groups: (1) *Individual miners (I)* who pay the highest retail price for electricity (p_I). (2) *Conventional-energy-powered mining facilities (C)* that pay a lower commercial rate ($p_C < p_I$). (3) *Sustainable-energy-powered mining facilities (S)* whose energy costs (p_S) fluctuate with the supply of renewable energy — cheaper in "good" *(G)* weather conditions, but potentially more expensive or unavailable in "bad" *(B)* conditions. That is $p_S(G) < p_S(B)$, where $p_S(G)$ and $p_S(B)$ denote the energy price in "good" and "bad" states, respectively.

All miners, including sustainable miners, operate only if mining is profitable. A miner's

profit depends on both the amount of energy used (which is tied to the miner's hashing power) and the cost of that energy. As the sustainable electricity price p_S increases in a bad state, the profit margin for a sustainable miner shrinks because the cost of energy rises.

The sustainable miner shuts down when the cost of sustainable energy $p_S(B)$ becomes too high, specifically when it exceeds the retail price p_I. Given the free entry of individual miners, mining at p_I brings zero expected profits. Thus mining at $p_S(B) > p_I$ would lead to losses. Shutting down at higher prices to prevent losses is temporary, as the miner can resume full operations when the energy state shifts back to "good" and prices drop again.

If the price $p_S(B)$ is lower than p_I but higher than in a "good" state, the sustainable miner does not shut down but reduces operations. The miner decreases hashing power to maximize profitability as energy costs rise, since mining at full capacity would no longer be efficient.

The reduction in mining is a response to the miner's need to balance energy costs with the probability of winning a block. In "good" states, when energy is cheap, the miner can afford to increase hashing power, raising the probability of winning and expected revenue. However, in "bad" states with higher $p_S(B)$, the marginal cost of increasing hashing power outweighs the benefit of a higher probability of winning.

As energy prices rise, each additional unit of hashing power yields diminishing returns. When energy is cheap, adding hashing power is cost-effective, even with small gains in the probability of winning. But when energy is expensive, the cost of using more power increases quickly, making it inefficient to mine at full capacity, as the energy costs would exceed the potential gains.

This is the basic intuition behind Proposition 1, where $h_S^*(G)$ and $h_S^*(B)$ denote sustainable miner's optimal electricity use in "good" and "bad" state, respectively. This result follows directly from the variable supply of sustainable electricity, resulting in variable electricity prices.

Proposition 1 *S who entered the market finds it optimal to shut down or decrease their mining operations in state B, i.e., $0 \leq h_S^*(B) < h_S^*(G)$.*

(All proofs in the appendix.)

A direct consequence of lowering intensity of mining in "bad" state, as described by Proposition 1, is that a sustainable miner on average mines fewer blocks (and therefore

bitcoins) than their mining power would suggest. Nonetheless, the sustainable miner can still be more profitable than conventional miners due to the lower cost of energy in the "good" state. When energy is abundant and prices are low, the miner can operate at a higher hashing power and significantly higher profitability. Whether this increased profitability in the "good" state outweighs the reduced or absent activity in the "bad" state overall depends on the frequency of "good" states, denoted by α. Proposition 2 establishes this result formally and characterizes the relevant threshold for α.

Proposition 2 *S may be more profitable than C, even though it is mining fewer bitcoins than its mining power capacity, when*

$$\alpha > \bar{\alpha} = \begin{cases} \left(\frac{p_I - p_C}{p_I - p_S(G)}\right)^2 & \text{when } p_S(B) > p_I \\ \frac{(p_I - p_C)^2 - (p_I - p_S(B))^2}{(p_I - p_S(G))^2 - (p_I - p_S(B))^2} & \text{otherwise.} \end{cases}$$

In the "bad" state, energy is both scarce and expensive, and the utility faces the risk of grid overloads, infrastructure strain, or even blackouts. For the utility, these outcomes have high costs, represented by L, which include deployment of expensive auxiliary energy sources, infrastructure damage, loss of reputation, and potential penalties or customer losses due to service failures. Rather than raising prices excessively (which may be legally or ethically constrained), the utility offers curtailment payments to large consumers, like mining facilities, in exchange for reducing their electricity usage. These payments compensate the miners for shutting down during peak demand periods, providing them with an alternative revenue stream.

Curtailment schemes may take different forms. When the price in the "bad" state is still low enough that $p_S(B) < p_I$, the sustainable miner still mines, albeit at a lower level, at some positive expected profit $\pi_S(B) > 0$. If the utility's cost of overloading the grid is higher, $L > \pi_S(B)$, the utility may offer $\pi_S(B)$ on the spot for stopping mining when the state is "bad." Such a scheme is called *Spot Buyout*, and it leaves the miner indifferent, while it improves utility's payoff at the cost of $(1 - \alpha)\pi_S(B)$ on average.

Alternatively, a utility and a miner may enter into a long-term contract with a fixed price for electricity and additional provisions. As shown below, these long-term, fixed-price contracts turn out to be better for both the utility and the miner, which may explain why we observe them in the industry rather than Spot Buyout curtailment. In fact, utilities such as ERCOT offer broadly two types of such long-term contracts; we will call them here a

fixed-price contract with shut-down provision (FPwSD) and a *fixed-price contract with resale option* (FPwRO).

Under the *fixed-price contract with shut-down provision (FPwSD)*, the utility offers a lower rate in the "good" state, $p'_S < p_S(G)$, in return for the miner shutting down upon request in the "bad" state. A fixed lower rate will encourage the miner to use more energy and permit it to earn higher profits when the state is "good," and since good states are characterized by excess supply of energy, higher usage does not overwhelm the grid nor put pressure on the price for other users. As we show in Lemma 1, this fixed price contract is better than the Spot Buyout for both the utility and the miner.

Lemma 1 *For any market characterized by $p_S(G) < p_S(B)$ and $\alpha < 1$, there exists a Fixed Price contract with Shut-Down provision (FPwSD) with $p'_S < p_S(G)$ that is more beneficial than Spot Buyout for both the electricity utility and the sustainable miner.*

The intuition behind this lemma relies on the differential effects of the electricity price change on the expected revenue and cost of the mining facility. While the optimal usage of energy changes linearly with the price, a miner's profit function is convex. This is because while the probability of winning each block changes linearly with electricity usage and, therefore, with electricity price, the cost of this electricity — the product of price and usage — is changing concavely. Thus, when the price of electricity decreases, the miner's expected revenue increases linearly while cost decreases at an accelerated rate.

Thus, when the utility offers a lower fixed price $p'_S < p_S(G)$ such that it is indifferent between FPwSD and Spot Buyout, the miner is strictly better off at such a lower price. That leaves room for other, slightly higher prices for the fixed-price contract that would make both parties better off.

Another type of a long-term fixed-price contract is the *fixed-price contract with resale option (FPwRO)*. Under this contract, the miner has access to a predetermined amount of electricity at a fixed price independent of the state, $\tilde{p}_S$. The miner can however sell this electricity back to the grid at market prices, which may be an attractive option in the "bad" state when the market price is high.

The sustainable miner is willing to pay a higher fixed price under the FPwRO contract compared to the FPwSD, as halting mining in the "bad" state allows for additional revenue through energy resale. As a result, the utility's profits in the "good" state increase

under FPwRO compared to FPwSD. However, the utility faces a tradeoff, as its profits decrease in the "bad" state due to some of the high-priced energy sales being captured by the miner through resale. Consequently, neither contract consistently dominates the other; the choice depends on environmental conditions. Specifically, the utility prefers FPwSD over FPwRO when both the price and the probability of the "bad" state occurring are relatively high. Nonetheless, either fixed-price curtailment contract (FPwSD or FPwRO) is more cost-effective for the utility in inducing mining shutdowns during the "bad" state than the Spot Buyout. Therefore, when the utility faces sufficiently high costs from grid overloads, these long-term curtailment contracts are the most effective solution. Moreover, these contracts also increase the profitability of the sustainable miner.

This is the basic intuition behind Proposition 3:

Proposition 3 *If the sustainable electricity utility faces cost $L > \pi_B$ for overwhelming the grid in state B, the utility benefits from offering curtailment schemes (such as FPwSD or FPwRO) to induce mining shut downs. At the same time, such curtailment payments increase profitability of the mining facility.*

2.1 Predictions of the model

The main conclusions of the model are that the high variance of supply of sustainable energy leads to following results:

- Miners using sustainable energy sources find it optimal to periodically shut down (or decrease) their mining operations, which results in mining fewer coins than their mining power would suggest (Proposition 1).
- Miners using sustainable energy sources may be more profitable despite their periodic shut-downs (Proposition 2).
- Sustainable energy utilities may find it profitable to set up curtailment schemes, inducing periodical shut-downs. These curtailment schemes further increase profitability of the mining facilities (Proposition 3).

In the following sections, we show that these results are consistent with empirical evidence.

2.2 ERCOT Demand Response Programs

ERCOT, the operator of Texas's electricity grid, establishes the framework for several *demand response programs* available to large industrial customers, including mining facilities. These programs are designed to ensure grid stability by incentivizing large electricity consumers to reduce power usage during periods of high demand or limited supply.[4] While ERCOT sets the guidelines for these programs, individual utilities contract directly with miners, offering agreements based on ERCOT's rules. To make participation financially attractive, these programs often offer electricity rates below typical retail prices. Two prominent types of demand response programs within the ERCOT framework are the *Responsive Reserve Service* (RRS) and the *Voluntary Load Response* (VLR).

RRS compensates miners for their availability to reduce load during critical periods, helping to prevent blackouts.[5] Even if miners are not frequently called upon to curtail operations, they are paid for their availability, often with discounted energy rates. This structure is analogous to the FPwSD contract in our model, where miners are compensated for being ready to reduce usage.

VLR provides flexible load reduction during periods of high electricity prices. Participants in VLR can choose when to curtail usage and are compensated based on the amount of load curtailed and prevailing market prices, typically calculated by multiplying the curtailed energy by the market price during the curtailment period.[6] This structure is effectively equivalent to selling electricity back to the grid and aligns with our model's FPwRO contract, where miners profit by reselling their unused energy during periods of high demand.

In summary, ERCOT's demand response programs, such as RRS and VLR, closely resemble the long-term contracts described in our model. While spot payments are theoretically possible, they are not commonly utilized.

3 Data Description

To test the implications of our model, we collect data on all publicly traded bitcoin mining companies with North American operations that are listed on the NASDAQ market during

[4]https://www.ercot.com/services/programs/load

[5]https://www.ercot.com/services/programs/load/laar

[6]https://www.ercot.com/services/programs/load/vlrp, https://www.ercot.com/news/release/2022-12-06-ercot-creates-voluntary

a sample period that begins in May 2021 and continues to the end of December 2024. We include only those companies that achieve market capitalizations of at least $100 million at some point during the sample period, 14 firms in all, and we ignore a number of penny stocks that also have listed their shares. The roster of companies appears in Table 1. One firm, Riot Platforms,[7] has been public for more than seven years, but the majority of the companies represent recent additions to the public markets, with most having become listed on the NASDAQ during a wave of special purpose acquisition company (SPAC) transactions that occurred in the technology industry in 2021. Table 1 shows that the NASDAQ-listed crypto miners are legally registered in a diverse set of common law jurisdictions, including the U.S., United Kingdom, Canada, Australia, and the Cayman Islands, and their NASDAQ listings require all of them to make standard financial and governance disclosures to the U.S. Securities and Exchange Commission (SEC). Four of the companies have minor operations outside North America, and one firm (Bitfarms) represents a relocation of hardware that had previously been installed in China. The most popular location for mining is Texas (seven companies), followed by New York (five companies), North Dakota (three), and Quebec (three). According to media reports, all of the U.S. mining companies except MARA Holdings belong to one or more mining pools, which are mutual organizations in which operators reduce risk by sharing resources and rewards (Cong, He, and Li, 2021; Makarov and Schoar, 2021).

Figure 1 shows the evolution of the market capitalization of the equity of the publicly traded bitcoin miners using daily data since April 30, 2021. The figure indicates sharp swings in value within the industry, reflecting volatility significantly greater than the risk of bitcoin itself. At the inception of the sample at the end of April 2021, three companies were public, and together they had a market cap of about $7.0 billion. Companies are added to the chart at the different times that they list their shares, and a local maximum for the industry's market cap occurred in mid-November 2021, when 10 companies were public with an aggregate market cap of about $23 billion. As the market price of bitcoin declined precipitously after November 2021 due to the FTX scandal and other events in the "crypto winter," the value of mining stocks plummeted at an even faster rate than the underlying cryptocurrency. After a series of debt defaults and restructurings, including one company's

[7]Riot Platforms was known as Riot Blockchain until changing its name at the start of 2023. The company had been called Bioptix and was mainly focused on veterinary pharmaceuticals until taking the Riot Blockchain name in October 2017 and entering the bitcoin mining business during a run-up in the crypto markets.

Company	Listed	Registered	Current North America sites	Other sites
Riot Platforms Inc.	2017	USA	Texas	
CleanSpark Inc.	2020	USA	Georgia, New York, Mississippi, Tennessee	
Bit Digital Inc.	2020	Caymans	New York, Texas, Kentucky	Canada, Iceland
MARA Holdings Inc.	2021	USA	Texas, North Dakota, Nebraska, Utah, Kentucky, Ohio	UAE, Paraguay, Finland
Hut 8 Corp.	2021	Canada	Alberta, New York, Texas	
BitFarms Ltd.	2021	Canada	Quebec, Pennsylvania, Washington	Argentina, Paraguay
HIVE Digital Technologies Inc.	2021	Canada	Quebec, New Brunswick	
Cipher Mining Technologies Inc.	2021	USA	Texas	
Greenidge Generation Holdings Inc.	2021	USA	New York, South Carolina, Mississippi, North Dakota	
Argo Blockchain PLC	2021	UK	Quebec, Texas	
IREN Ltd. (Iris Energy)	2021	Australia	British Columbia, Texas	
TeraWulf Inc.	2021	USA	New York	
Core Scientific Inc.	2022	USA	Texas, North Dakota, North Carolina, Kentucky, Georgia	
Bitdeer Technologies Group	2023	Caymans	Texas, Tennessee, Washington	Norway, Bhutan

Table 1: **Publicly traded bitcoin mining companies.** The table lists 14 publicly traded bitcoin mining companies with the years of their NASDAQ stock market listings, countries of corporate registration, and principal geographic locations of their mining operations that were active at the end of 2024.

bankruptcy, the value of 13 publicly traded mining companies bottomed out at an aggregate $1.8 billion just prior to year-end 2022. A dramatic rebound then began in the industry, in parallel to the rise of bitcoin's market price, and with the cryptocurrency trading around $93,000 by year-end 2024, the 14 listed mining companies peaked at an aggregate value of $36.7 billion in mid-December 2024 before ending the year at $27.6 billion. Note that the chart does not reflect the value of the entire U.S. mining industry, since it only includes public companies and ignores both privately held miners and a number of public penny stocks.

We value the mining businesses of the 14 companies in our sample at the end of each month using the Merton-KMV model, which is widely used in Finance to estimate the values of companies that have risky debt vulnerable to default (see Bharath and Shumway, 2008). We follow the KMV approach used in Sundaram and Yermack (2007), assuming that each company has a default point equal to the book value of current liabilities plus one-half the book value of long-term liabilities. We obtain balance sheet data from companies' quarterly financial statements. For the two month-end points in between the start and end of each fiscal quarter, we interpolate balance sheet values by assuming, for instance, that debt grows at an even rate during each quarter. We observe the company's market value of equity at the end of each month and treat equity as a call option on the assets of the firm with a maturity

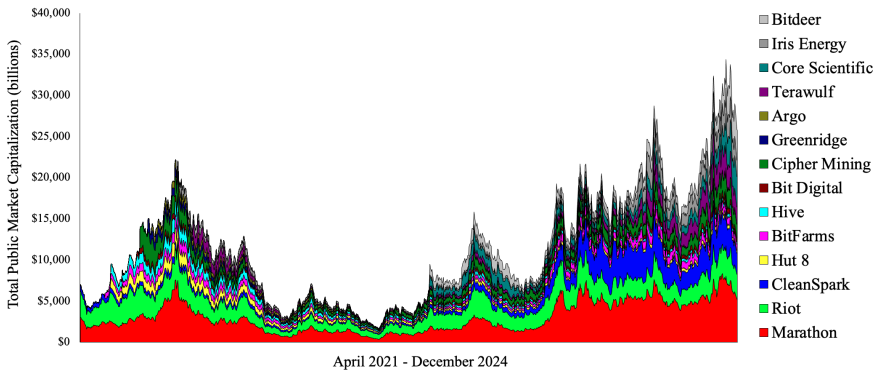


Figure 1: **Equity market capitalizations of bitcoin mining companies.** The figure shows the equity market capitalizations of 14 publicly traded bitcoin mining companies between April 30, 2021 and December 31, 2024. Each company is tracked from the date of its initial listing on the NASDAQ market; three companies were publicly traded prior to the start of the sample period.

of one year. We use the one-year Treasury rate and each firm's equity volatility as inputs to a Black-Scholes equation that allows us to solve for the market value of the company's underlying assets. The market value of debt then equals the estimated asset value minus the market value of equity. The value of the mining business equals the market values of equity plus debt, minus the value of cash and bitcoin held on the balance sheet.

Because most companies have very high equity volatility in the neighborhood of 1.00 annually, default is a significant risk for nearly all of them, and one company (Core Scientific) did reorganize under Chapter 11 bankruptcy during our sample period while others engaged in liability restructurings. At the end of 2024 the estimated market values of debt for the 14 companies in our sample ranged from a low of 51 cents per dollar of face value for Core Scientific to a high of $1.06 for IREN Ltd. (formerly Iris Energy), with a mean and median of 61 and 64 cents, respectively. As an example of how we apply the KMV method, consider the most valuable company in our sample, MARA (formerly Marathon) Holdings, which had an equity value of $5.1 billion at the end of 2024. While the company had $2.7 billion in liabilities, our KMV method estimates this debt's fair market value at $1.5 billion, or 55 cents per dollar of face value, mainly due to MARA's extremely high equity volatility of 1.12. Subtracting out the company's $0.4 billion in cash and $4.2 billion of bitcoin held at the end of 2024 implies a market value for its underlying mining business of $2.0 billion.

Table 2 provides information about the financial structure and crypto-related assets of the 14 public mining companies, including the total reported hashrates of their mining hardware

Company	Hashrate eh / sec.	Equity MV millions	Debt MV millions	BTC held	BTC mined 2024	Avg. mining success
Riot Platforms Inc.	10.7	$3,311	$500	17,772	4,828	0.70
CleanSpark Inc.	39.1	2,945	451	9,952	7,024	0.95
Bit Digital Inc. *	1.8	539	58	742	950	0.97
MARA Holdings Inc.	53.2	5,113	1,474	44,893	9,451	0.77
Hut 8 Corp. *	5.5	1,147	263	9,203	1,768	0.76
BitFarms Ltd. *	12.8	956	66	147	5,168	0.94
HIVE Digital Technologies Inc.	6.0	338	39	2,805	1,772	0.96
Cipher Mining Technologies Inc.	13.5	1,651	174	1,344	2,698	0.83
Greenidge Generation Holdings Inc. *	0.8	17	75		.	0.90
Argo Blockchain PLC *	2.7	77	32	2	754	0.69
IREN Ltd. (Iris Energy)	31.0	1,936	602	0	3,986	0.93
TeraWulf Inc.	9.7	2,166	315	5	2,745	0.82
Core Scientific Inc.	19.1	3,932	1,236	0	6,594	0.88
Bitdeer Technologies Group	5.3	3,623	727	594	2,519	0.90

Table 2: **Mining data for publicly traded bitcoin mining companies.** The table provides statistics about 14 publicly traded bitcoin mining companies as sourced from companies' monthly operating reports to the public. Each company's hashrate and bitcoin holdings, and equity and debt values are reported as of December 31, 2024, at which point these companies collectively accounted for 29.6% of the worldwide bitcoin mining hashrate. For each company, mining success equals the actual bitcoins mined divided by the expected amount, based upon the company's hashrate relative to the overall network hashrate. Mining success reported in the table is the average based upon all available monthly mining reports released by each company. Debt market value is estimated based on the KMV method. For five companies marked by an asterisk (*), debt and equity values are reported as of September 30, 2024, pending the disclosure of year-end balance sheet information.

and their holdings of bitcoins, which were either mined by the companies or, in some cases, purchased on the open market to augment their inventories. All data are reported as of December 31, 2024. Not all companies disclose their bitcoin inventories, and in these cases we use the carrying value of digital assets on those companies' balance sheets to estimate the approximate quantity held.

Figure 2 shows the growth of the companies' operating footprint, measured in exahashes per second (Eh/s), a statistic widely used to quantify the number of trial-and-error calculations performed by miners while competing for rewards on the bitcoin network. At the beginning of the sample period the North American mining companies had a negligible presence in the worldwide industry, but capacity grew quickly after the unexpected shutdown of mining in China. The 14 public companies in the sample accounted for 235.2 Eh/s by the end of 2024, close to 30 percent of the global hashing power that approached 800 Eh/s, an all-time high for the network.[8] Notably the companies continued to invest in additional

[8]The overall hashrate for the bitcoin network cannot be observed direcctly and is usually inferred by the solution times achieved by the network for individual bitcoin blocks. The statistic therefore represents worldwide hashing power operating at a moment in time. In contrast, companies generally report their

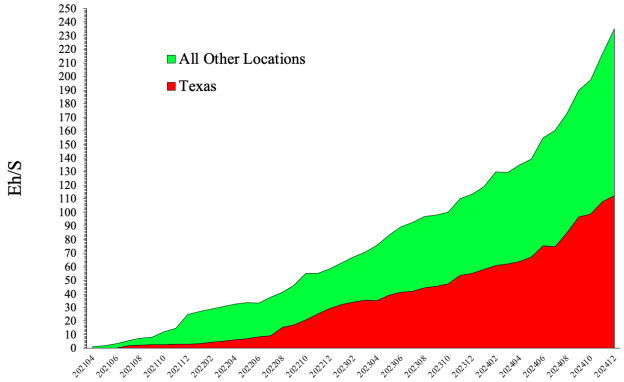


Figure 2: **Location of companies' mining facilities.** The figures show monthly installed hashrates for 14 publicly traded bitcoin mining companies during the period April 2021 through December 2024. Data is obtained from monthly operating reports released voluntarily by each company. By late 2022 Texas mining locations accounted for approximately half of the overall total, a ratio that remained relatively constant throughout 2023 and 2024. All other locations include sites in the remaining 49 U.S. states and Canada, and a few companies have minor operations in other parts of the world. The total hashrate of the 14 companies represented a negligible portion of the worldwide hashrate in April 2021, when China unexpectedly banned cryptocurrency mining. By the end of 2024 the companies' operations had grown to account for approximately 30% of the global hashrate.

mining capacity throughout the sample period, despite the economic difficulties brought on by events of the 2022 "crypto winter," in which bitcoin's market price – and the miners' revenue – dropped three-quarters from a high of about $65,000 on November 10, 2021, just prior to the collapse of FTX, to a low of $16,439 on December 29, 2022. Investment in hashing power also continued unabated despite the "halving" of bitcoin rewards that occurred algorithmically in mid-April 2024, reducing the miners' fees per block from 6.25 to 3.125 bitcoins (not including a much smaller amount paid as voluntary user fees by individual customers seeking priority processing).

Importantly for the analysis in this paper, Figure 2 vividly shows the dominance of Texas in the portfolio of the 14 companies' mining sites. During 2023 and 2024, the last two years of the sample period, Texas mining locations accounted for approximately half of the overall total hashrate, with the remainder almost entirely in the U.S. and Canada except for a minor amount located abroad. The companies' monthly operating reports, which are the source of the data in Figure 2, often contain updates on the construction

installed hashing power, but as discussed below, some of this capacity will inevitably be off-line part of the time for maintenance or due to agreed curtailment of operations at times of peak electricity demand.

or expansion of mining facilities, especially in Texas, including land acquisition, erection of buildings, and most critically, connections to the electrical grid. Obtaining trunk line utility connections "behind the meter" had become a critical point of delay in many companies' expansion plans by 2024, as electrical grids in Texas and the rest of North America faced unprecedented rising demand for electricity to power data centers after years of relatively low growth. The surging demand for electricity was attributed not only to cryptocurrency mining but also to the growth of artificial intelligence (AI) services. In addition to waiting periods for electrical connections, a further brake on the growth of bitcoin mining occurred due to procurement delays for state-of-the-art mining rigs. Many companies report monthly on their positions in the delivery queue of Bitmain, the leading supplier, although during the 2022 crypto winter a number of companies were forced to abandon or re-sell their pending orders due to liquidity problems brought on by the falling retail price of bitcoin, the mined commodity.[9] Bitmain and various electrical power providers became significant creditors of certain leveraged mining companies that had difficulty making scheduled payments for electricity or hardware especially in the bear market of 2022.

The 14 companies in our sample exhibit very different strategies for financing their growth. A majority have low to moderate debt on their balance sheets and would appear to have low bankruptcy risk at the end of 2024, and many of them had a significant portion of their equity represented by accumulated bitcoin inventories that they had mined and not yet liquidated. For a minority of the miners, borrowing is sometimes aggressive, often with bitcoin held in inventory being pledged as collateral for loans that in turn are used to put down deposits on new orders of mining rigs or to finance construction of additional data centers. These strategies provide considerable leverage that amplifies profits when bitcoin prices are rising, while accelerating descent into financial distress when bitcoin prices are dropping, as was the case with a number of firms by the end of 2022. Many companies that had moderate leverage in mid-2022 had backed into highly leveraged capital structures by year-end due to the declines in the market values of their equity, even as new borrowing had largely been cut off by the debt markets after bitcoin's retail price collapsed.[10]

[9]For example, see the January 12, 2023 announcement by Iris Energy, stating that it had purchased and immediately re-sold miners previously ordered from Bitmain, with the transaction reducing prepaid expenses by $8 million on its balance sheet while improving its cash position by $6 million; this appears to represent the liquidation of its Bitmain deposits at 75 cents on the dollar. See also Eliza Gkritsi, "A huge glut of bitcoin mining rigs is sitting unused in boxes," Coindesk, October 14, 2022.

[10]A detailed analysis of mining companies' capital raises and indebtedness, including commitments for equipment financing, is provided by Luxor Technology Corp. in its 2022 year-end report, available at

Measuring the profitability of the 14 mining companies in either economic or accounting terms has been challenging. During the sample period companies have had to record bitcoin on their balance sheets as an intangible asset, with carrying value equal to the fair market value when mined. When the market price of bitcoin falls during a fiscal quarter, companies record "impairments" of bitcoin values as costs against earnings, but they are not permitted to book earnings gains by marking bitcoin inventories to market during quarters when prices rise (a change in these accounting rules is pending, which will move accounting to a mark-to-market basis in both directions). Data in Table 2 show that a minority of companies respond to the implied costs of these accounting rules by selling mined bitcoin immediately and retaining virtually none in inventory, while other companies do the opposite, accumulating large quantities of bitcoin earned from mining and occasionally using capital raises to buy more bitcoin on the open market. This aggressive accumulation of bitcoin fueled the growth in market values of some companies such as MARA Holdings (formerly Marathon Digital Holdings), which had a horde of more than 44,000 bitcoin worth about $4.2 billion at the end of 2024, accounting for the majority of the company's estimated enterprise value of slightly less than $6 billion. In addition to the rapidly changing valuations of bitcoin inventories, companies' earnings reports are further clouded by the rapid obsolescence of bitcoin mining rigs, which frequently are written off and replaced prior to the end of their estimated useful lives due to rapid technological innovation that causes companies to scrap their installed hardware and upgrade to newer models.

4 Analysis

We begin our analysis by studying the relations between daily company stock price returns and relevant market indexes. Table 3 contains regression analysis for a pooled sample of the 14 companies during a period beginning on May 3, 2021, and continuing to December 31, 2024 (most companies were not publicly traded for the entire sample period). We report

hashrateindex.com/blog/content/files/2023/01/Hashrate-Index-2022-Year-In-Review–FINAL-.pdf. In one of the more unusual capital raises by mining firms, Marathon announced a $500 million convertible debt offering in November 2021 that it twice expanded, reaching a final total of $747.5 million for five-year bonds with a 1% coupon and the right to convert into Marathon stock at a price of $76.17 per share. Shareholders registered sharp displeasure with the terms of the issue, sending Marathon's stock into a nosedive from $75.92 to $55.40 per share. See https://www.fool.com/investing/2021/11/15/why-marathon-digital-plummeted-more-than-20-today/. The company nevertheless pushed ahead with the bond sale and used the proceeds to place a large order for more bitcoin mining equipment.

t-statistics based on standard errors clustered by company, and due to the relatively small number of clusters, Table 3 includes a second set of t-statistics calculated according to methods introduced in Ibragimov and Müeller (2016). In the first four columns, we regress daily stock returns against the daily returns on the NASDAQ market index, bitcoin, the SP500 Electric Utilities Index, and the S&P Global Clean Energy Transition Index, respectively (for bitcoin, returns on weekends and market holidays are incorporated into the observations of the next Wall Street market day). In the fifth column, all four indexes are included together. Focusing on the fifth column, we see a very strong association between mining stocks and movements in the NASDAQ index, with an estimated market beta of 1.23, and not surprisingly a strong association also exists between the bitcoin return and the bitcoin mining stocks. For the electric utility industry, we obtain a negative estimate that is not significant under the corrected t-statistic. The most interesting result in the table is the significantly positive association between the mining company stock prices and the index of clean energy companies, suggesting that companies in these two industries exhibit a complementary or symbiotic economic relationship.

We next move to investigate the predictions from our model introduced in Section 2 above. All of our main predictions differentiate miners that use sustainable energy from those using conventional energy sources. In practice, it can be impossible to observe the mix of energy used by any single miner, and mining companies themselves may not know the mixes of energy used by their electricity providers on a day-to-day basis. For our purposes we will compare Texas-based mining companies with those elsewhere. Figure 2 shows that the hashing power in our sample is almost evenly divided between facilities in Texas and facilities elsewhere in North America. Texas regulators have been aggressive in offering attractive curtailment payments to bitcoin miners as inducements for them to locate in the Lone Star State in order to provide load balancing for the fast-growing renewable energy industry. While certain other jurisdictions in North America may also enter into curtailment schemes with bitcoin miners, they are infrequent relative to those in Texas not often disclosed by the companies in our sample.

4.1 Sustainable Miners' Down Time

Our Proposition 1 states that miners using sustainable energy sources will periodically shut down (or decrease) their mining operations, resulting in mining fewer coins than their hashing

Dependent variable: Daily stock return					
Intercept	-0.0025 (5.58) *** (1.50)	-0.0026 (5.62) *** (1.54)	-0.0018 (3.71) *** (0.94)	-0.0005 (1.00) (0.24)	-0.0024 (5.51) *** (1.58)
NASDAQ return	2.2104 (27.88) *** (7.99) ***				1.2251 (15.61) *** (4.49) ***
Bitcoin return		1.0018 (43.48) *** (11.16) ***			0.7581 (34.33) *** (9.46) ***
Utilities return			0.7167 (32.04) *** (8.14) ***		-0.3833 (8.29) *** (1.33)
Clean energy return				1.4107 (28.08) *** (3.29) ***	0.4480 (10.33) *** (2.58) **
Observations	11,712	11,712	11,712	11,712	11,712
R^2	0.1713	0.2273	0.0114	0.0857	0.2881

*** Significant at 1% (***), 5% (**), and 10% (*) levels

Table 3: **Analysis of mining company stock returns.** The table presents ordinary least squares estimates of daily stock returns of 14 publicly traded bitcoin mining companies between May 3, 2021, and December 31, 2024. Explanatory variables include the daily returns on the NASDAQ market index, bitcoin, the SP500 Electric Utilities index, and the S&P Global Clean Energy Transition Index. The first t-statistic for each estimate is based on standard errors are clustered at the company level. The second t-statistic is calculated according to Ibragimov and Müeller (2016) to adjust for the relatively small number of clusters.

power would support. We define a measure of capacity utilization, mining success, which measures the number of coins mined per company per month, compared to the number that would be predicted by the company's installed hashrate relative to the global hashrate. The right column of Table 2 shows the average monthly success rate for each of the 14 companies in our sample. None of the companies achieves 100 percent mining success, which would be indicated by a statistic of 1.00, because all of them will inevitably have equipment offline for maintenance reasons, disruptions in electricity supply, and so forth.[11] Mining success also has a luck component, as a company could exceed the 1.00 success rate if it is especially fortunate in guessing the correct nonces to complete blocks in the global proof-of-work mining competition. Because many Texas miners go offline periodically due to contractually agreed curtailment schemes related to load balancing, we would expect lower success rates for Texas

[11] An an example, for December 2022 the mining companies Argo Blockchain (Texas), ClearSpark (Georgia), Core Scientific (various), Hive Blockchain (Quebec), and Riot Blockchain (Texas) all reported being knocked temporarily offline during a severe winter storm that disrupted the electric utility industry especially in the central U.S. and upstate New York.

miners than for those not in Texas.

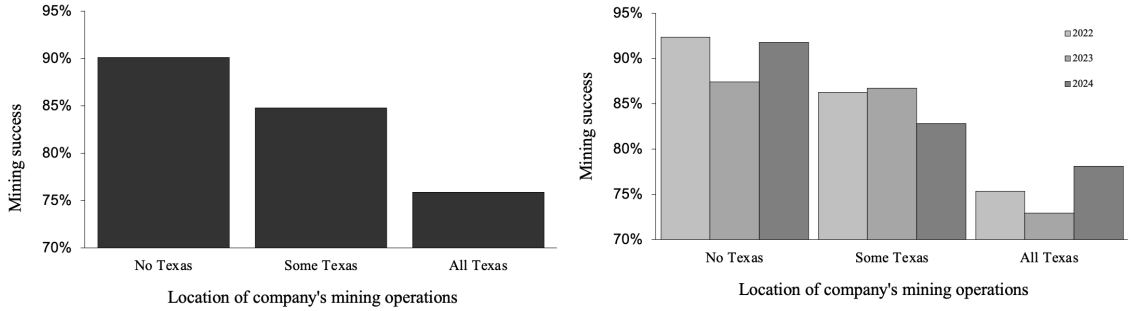


Figure 3: **Monthly success rates of bitcoin mining companies.** The graphs show information about monthly success rates of bitcoin mining companies, based upon the geographic location of their facilities. Success is definted as the number of coins mined per month relative to the number expected, based on the company's hashrate relative to the global network hashrate.

We use companies' monthly operating reports to infer their mining success. These reports generally disclose the number of coins mined per month and the month-end installed hashrate, and we benchmark each company's success based on data about the global hashrate and total global mining rewards which are widely available from blockchain explorer websites. In Figure 3 we group the monthly observations of mining success into three subsamples: those for companies with no presence in Texas, those partly in Texas and partly elsewhere, and those entirely in Texas. The data in the left half of the figure show a monotonic decline in mining success based upon presence in Texas, as companies outside Texas exhibit approximately 90% success during our 2021-2024 sample period, those partly in Texas have 85% success, and those entirely in Texas have approximately 76% success. The right panel of Figure 3 shows a disaggregation of the data by year, which reflects the same pattern annually for 2022, 2023 and 2024 (we omit 2021 due to the small number of observations). T-tests indicate that the sample mean of the success variable is greater for companies outside Texas compared to the group that are either partly or entirely in Texas; this result holds below the 1 percent level for the overall sample and in the 2022 and 2024 sub-groups, though not in 2023.

4.2 Higher value of sustainable miners

Proposition 2 states that miners using sustainable energy sources may be more profitable despite their periodic shut-downs. As discussed in Section 3 above, observing the profitability

of miners is difficult due to the accounting treatment of bitcoins, which are not marked to market when their value increases, and also because of the frequent writeoffs of mining equipment before the end of its operational life. Rather than focusing on accounting profits, the analysis in this section instead studies the market valuation of bitcoin mining companies.

We estimate a regression model of the fair market value of the mining businesses of the 14 companies in our sample. using month-end observations calculated according to the method described in Section 3 above. We have a total of 465 usable observations for the 14 companies during the intervals that they were publicly traded between the start of our sample in April 2021 and the end of the sample in December 2024. The explanatory variables in our model include each company's installed hashrate, obtained from companies' monthly operating reports, and the month-end market price of bitcoin, the commodity mined by these firms.[12] Results appear in Table 4.

Estimates in the left column of Table 4 show positive and strongly significant estimates for the installed hashrate and the market price of bitcoin, with standard errors clustered according to whether companies have some or all of their operations in Texas. The Texas subsample includes 243 of the 465 observations, or slightly more than half the sample. In the second and third columns we estimate the regression separately for the Texas and non-Texas subsamples, using ordinary least squares, and in the right column of Table 4 we show t-statistics testing whether the Texas and non-Texas estimates are significantly different from one another. We calculate these t-statistics using the method described by Ibragimov and Müller (2016) to adjust standard errors in models with a small number of clusters. These t-statistics indicate that, despite relatively large differences in the economic magnitudes of the coefficient estimates, we cannot reject the null hypothesis of equality between them in the Texas and non-Texas subsamples.

Figure 4 uses the estimates from the second and third columns of Table 4 to show the value of a mining business as a function of bitcoin's market price. For this figure, we assume that the company has an installed hashrate of 10 Eh/s, which is very near the median for the 14 companies in our sample. Figure 4 illustrates that the estimated value of a mining business increases with the price of bitcoin both inside and outside Texas, but the lines cross at a market price of approximately $56,000. Because Texas-based miners receive curtailment payments and go offline a relatively high proportion of the time, the value of those businesses

[12] A detailed analysis of the association between bitcoin mining stocks and the price and volatility of bitcoin itself appears in Baur et. al (2023).

Dependent variable: Market value of bitcoin mining company ($ millions)

	Full sample	Texas subsample	Non-Texas subsample	Texas vs. Non-Texas
Intercept	-75.23	10.48	-216.00	
	(0.69)	(0.09)	(1.85)*	(2.43)**
Hashrate (Eh/s)	72.73	80.72	46.63	
	(6.40)***	(12.21)***	(4.38)***	(0.64)
Bitcoin price	0.013	0.009	0.019	
	(2.88)***	(3.27)***	(6.27)***	(0.45)
Observations	465	243	222	
R^2	0.4604	0.5036	0.3413	

*** Significant at 1% (***), 5% (**), and 10% (*) levels

Table 4: **Value of a bitcoin mining company.** The table presents estimates of the market value of a bitcoin mining company, as a function of its installed hashrate and the market price of bitcoin. The sample includes monthly observations for 14 publicly traded bitcoin mining companies beginning April 30, 2021 and continuing until December 31, 2024, although most companies are not publicly traded at the beginning of the sample period and are added to the analysis after their shares are listed on the NASDAQ exchange. The dependent variable, the market value of the mining business, equals the market values of its equity plus debt, minus the value of cash and the market value of its bitcoin held in inventory. The market value of each company's debt is estimated using the KMV method with assumptions described in the text. Companies disclose data quarterly about their debt and cash positions, and values are interpolated for the two month-end dates between each quarterly disclosure. Bitcoin inventories are based on monthly company operating reports or interpolated from balance sheet data about digital asset holdings. The model in the first column of the table shows least squares estimates for the entire sample, with standard errors clustered according to a Texas indicator variable that equals 1 if the company has some of all of its mining operations in Texas. The second and third columns show least-squares estimates for the Texas and non-Texas subsamples. The t-statistics for the first column are calculated according to the method of Ibragimov and Müeller (2016) to adjust for the relatively small number of clusters. The fourth column contains t-statistics testing the equality of the parameter estimates for the second and third columns, also calculated following Ibragimov and Müeller (2016).

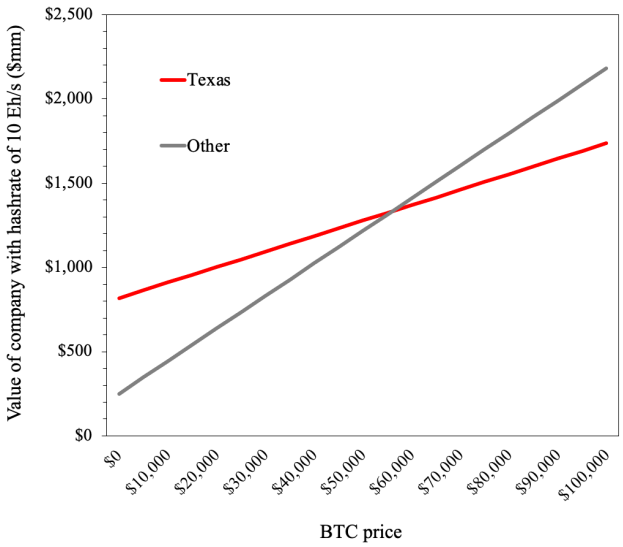


Figure 4: **Market value of a typical bitcoin mining company.** The graph shows the estimated market value of a representative bitcoin mining company with a hashrate of 10 Eh/s, which is close to the median value for the 14 companies in our sample. The schedules for Texas and non-Texas companies are based on regression estimates shown in Table 4, based on a sample of month-end observations of company values between April 2021 and December 2024. Mining company value equals the market values of equity plus debt, minus the values of cash and bitcoin held in inventory.

exceeds the value of non-Texas businesses when the price of bitcoin is low; intuitively, this would represent the "bad" state in our model in Section 2, although the model defines a "bad" state in terms of higher cost rather than lower revenue. In contrast, at high values of bitcoin the opportunity costs of not being able to mine due to energy curtailment becomes higher, and the non-Texas business that are not as vulnerable to curtailment become relatively more valuable.

4.3 Curtailment schemes

Our Proposition 3 states that sustainable energy utilities may find it profitable to set up curtailment schemes, inducing periodic shut-downs. These curtailment schemes may increase profitability of the affected mining companies.

Three companies in our sample, all with the majority of their hashing power located in Texas, provide detailed monthly information about rebates, curtailment payments, or other economic benefits received from their electricity suppliers. We cannot directly observe the incidence and value of these payments in any individual company's financial statements,

since they may be variously accounted for as revenue or reductions in energy expense and are generally not broken out, but based on the narratives in companies' public communications, it is clear that many, if not most of them receive periodic curtailment payments in some form from their electricity providers.

Cipher Mining since June 2023 has provided monthly estimates denominated in BTC of the revenue it receives from foregoing mining from time to time and selling power back to the electrical grid at the prevailing retail price. Cipher engaged in much more of this activity in 2023 than in 2024, as bitcoin values were significantly higher by 2024 and the opportunity costs of not mining would have been greater than in 2023. Over the 19 months between June 2023 and December 2024, the company estimated that it sold 266 bitcoins worth of electricity back to the grid, about 4.8% of the total number of bitcoins that it mined during the same period.

Figure 5 shows monthly data from two companies, Riot Platforms and Core Scientific. Riot provides a monthly estimate of the value it receives from power curtailment credits and so-called "demand response credits," which amount to rebates credited to its electricity bill in return for shutting down temporarily either on a voluntary basis or at the direction of its power suppliers. The left half of Figure 5 shows the sum of these two payments each month from May 2022 to December 2024. Core Scientific's disclosures occur in a different format, providing the number of megawatt hours (MwH) of electricity consumption avoided during its periods of shutdown. These data appear in the right half of Figure 5 for the period from January 2022 to December 2024. The scale of companies' curtailments varies over time in part due to the growing size of their operations. Both companies' graphs reflect that curtailment activity is highest during the summer months of July and August, when demand for energy will be highest in Texas and the generation of wind power will be reduced. The value of the curtailment credits is evident in the financial statements published by Riot Platforms.[13] In 2023 the company received $71.2 million worth of curtailment credits which represented 38% of its EBITDA of $189.6 million. In 2024 it received $36.9 million of credits, which represented 12% of its EBITDA of $297.0 million.

[13]See Shawn Tully, "How Riot Blockchain capitalized on a hot Texas summer to make more money selling power than mining crypto," Fortune, August 13, 2022.

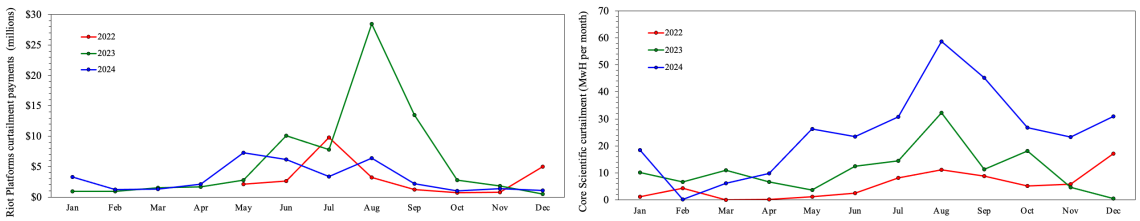


Figure 5: **Monthly curtailment activity of two mining companies.** The graphs show information about monthly reductions in electricity use by Riot Platforms (left panel) and Core Scientific (right panel), obtained from company operating reports. Riot reports the value of credits received each month for voluntary power curtailment and participation in Texas demand response programs, and the graph shows the sum of these two values. Core Scientific reports the megawatt hours (MwH) of electricity use avoided due its periods of operating curtailment.

5 Discussion and conclusions

This paper studies the operations and financial valuations of 14 publicly traded cryptocurrency mining companies operating mainly in North America. About half their total hashrate is concentrated in Texas, where sustainable energy providers offer contracts with curtailment payments to miners who shut down operations during peak demand. These miners help stabilize demand on the electrical grid, thereby providing incentives for the green energy facilities that use wind power.

We present a model showing potential advantages of bitcoin mining using sustainable energy, as these miners will benefit from lower prices when energy is abundant during times of high wind and will collect rebates or subsidies for going offline when energy is scarce due to lack of wind. Although they will participate less regularly in the mining industry than their counterparts using conventional energy, the miners using sustainable energy may be more profitable due to the structure of their contracts with energy providers.

We collect monthly data from a new source, operating reports that the mining companies publish on their websites with data about bitcoins mined, hashrate installed, equipment ordered, bitcoins retained in inventory, and construction plans for new facilities. We find that miners using Texas wind power are offline more than other miners as predicted by our model, and that they receive large curtailment rebates in seasonal patterns that account for a significant part of their operating cash flows. Analysis of miners' valuations implies that those using sustainable energy achieve higher valuations when bitcoin market prices are low, but that this pattern reverses when prices are high and the opportunity costs of foregone

mining increase.

References

Arnosti, Nick S. and Matthew Weinberg, 2022, Bitcoin: A natural oligopoly. Management Science 68, 4755-477.

Bastian-Pinto, Carlos L., Felipe V. de San Araujo, Luiz E. Brandão, and Leonardo L. Gomes, 2021, Hedging renewable energy investments with bitcoin mining, Renewable and Sustainable Energy Reviews 138, 110520.

Baur, Dirk G., Jonathan R. Karlsen, Lee A, Smales, and Allan Trench, 2003, Digging deeper: Is bitcoin digital gold? A mining perspective, unpublished manuscript, available at ssrn.com/abstract=4407838.

Benetton, Matteo, Giovanni Compiani, and Adair Morse, 2021, When cryptomining comes to town: High electricity-use spillovers to the local economy, unpublished manuscript, available at ssrn.com/abstract=4469901.

Bruno, August, Paige Weber, and Andrew J. Yates, 2022, Can bitcoin mining increase renewable electricity capacity? Unpublished manuscript, available at ssrn.com/abstract=4241613.

Bharath, Sreedhar T., and Tyler Shumway, 2008, Forecasting default with the Merton distance to default model, Review of Financial Studies 21, 1339-1369.

Budish, Eric, 2022, The economic limits of bitcoin and anonymous, decentralized trust on the blockchain, unpublished manuscript, available at ssrn.com/abstract=3197300.

Carter, Nic, Shaun Connell, Brad Jones, Dennis Porter, and Murray A. Rudd, 2023, Leveraging Bitcoin miners as flexible load resources for power system stability and efficiency, available at SSRN 4634256.

Cassauwers, Tom, 2021, An environmental upside to bitcoin? Sierra, March 30.

Cong, Lin William, Zhiguo He, and Jiasun, Li, 2021, Decentralized mining in centralized pools, Review of Financial Studies 34, 1191-1235.

Congressional Research Service, 2019, Bitcoin, blockchain, and the energy sector, report no. 45,863, August 9.

Easley, David, Maureen O'Hara, and Soumya Basu, 2019, From mining to markets: The evolution of bitcoin transaction fees, Journal of Financial Economics 134, 91-109.

Halaburda, Hanna, Guillaume Haeringer, Joshua Gans, and Neil Gandal, 2022, The microeconomics of cryptocurrencies, Journal of Economic Literature, 60(3), pp.971-1013.

Ibragimov, Rustam, and Ulrich K. Müller, 2016, Inference with few heterogeneous clusters. Review of Economics and Statistics 98, 83–96.

Lehar, Alfred, and Christine A. Parlour, 2021, Miner collusion and the bitcoin protocol, unpublished manuscript, available at ssrn.com/abstract=3559894.

Li, Jiasun, Hang Ren, and Ioannis Bellos, 2024, Bitcoin mining for carbon emission reduction, unpublished manuscript, available at ssrn.com/abstract=4986178.

Makarov, Igor, and Antoinette Schoar, 2021, Blockchain analysis of the bitcoin market, unpublished manuscript, available at ssrn.com/abstract=3942181.

Niaz, Haider, Jay J. Liu, and Fengqi You, 2022, Can Texas mitigate wind and solar curtailments by leveraging bitcoin mining? Journal of Cleaner Production 364, 132700.

Prat, Julien, and Benjamin Walter, 2021, An equilibrium model of the market for bitcoin mining, Journal of Political Economy 129, 2415-2452.

Shan, Rui, and Yaojin Sun, 2019, Bitcoin mining to reduce the renewable curtailment: A case study of CAISO, unpublished manuscript, available at ssrn.com/abstract=3452015.

Solomon, Marissa, 2022, ICYMI: Three new reports paint damning picture of climate-killing & community impacts of cryptocurrency mining, Earthjustice, October 18.

Sundaram, Rangarajan, and David Yermack, 2007, Pay me later: Inside debt and its role in managerial compensation, Journal of Finance 62, 1551-1588.

A Appendix: Proofs

Proof.[of Prop 1]

Electricity use optimization. Given the level of hashing power H_{-i} applied by the rest of the market, the profit miner i gets from applying h_i hashing power is

$$\pi(h_i, H_{-i}) = \frac{h_i}{h_i + H_{-i}} R - p_i h_i$$

where R is the value of the mining reward. Note that h_i and H_{-i} are at the same time measures of electricity used and hashing power.

Lemma 2 *Participation decisions of miners depend on the electricity prices, p_S, p_C and p_I:*

- *I participates when $p_I < p_C + p_S$,*
- *$i = C, S$ participates when $p_i < p_I$.*

Proof.[of Lemma 2] Each i participates when for $h_i > 0$, $\pi(h_i, H_{-i}) = \frac{h_i}{h_i + H_{-i}} R - p_i h_i \geq 0 \iff h_i \leq \frac{R}{p_i} - H_{-i}$. An individual infinitesimal I miner enters as long as $H_{-i} < \frac{R}{p_i} = H_0$. Thus, there will be some I miners participating (i.e., in aggregate $h_I > 0$) only if $H_{-I} = h_C + h_S < \frac{R}{p_I}$, and then $h_I + H_{-I} = H_0$.

In the case that individual miners, I, participate, C maximizes $\pi(h_C, H_{-C}) = \frac{h_C}{h_C + H_{-C}} R - p_C h_C$. The FOC: $R\left(\frac{H_{-C} + h_C^* - h_C^*}{(H_{-C} + h_C^*)^2}\right) - p_C = 0 \iff R(\frac{H_0 - h_C^*}{H_0^2}) - p_C = 0 \iff h_C^* = (1 - \frac{p_C}{p_I})\frac{R}{p_I}$.

Similarly, in the case that individual miners, I, participate, S maximizes $\pi(h_S, H_{-S}) = \frac{h_S}{h_S + H_{-S}} R - p_S h_S$. The FOC: $R\left(\frac{H_{-S} + h_S^* - h_S^*}{(H_{-S} + h_S^*)^2}\right) - p_S = 0 \iff R(\frac{H_0 - h_S^*}{H_0^2}) - p_S = 0 \iff h_S^* = (1 - \frac{p_S}{p_I})\frac{R}{p_I}$.

Then $h_C^* + h_S^* < \frac{R}{p_I} \iff (2 - \frac{p_C+p_S}{p_I})\frac{R}{p_I} < \frac{R}{p_I} \iff p_I < p_C + p_S$. Thus, when this condition holds, some I will participate. This proves the first part of Lemma 2.

Notice that in the case that I participates, $h_C^* > 0 \iff p_C < p_I$ and $h_S^* > 0 \iff p_S < p_I$. When no I participates, the total hash power used is $H_1 = h_C + h_S$. Then by FOCs $\frac{H_1 - h_S^*}{H_1^2} = \frac{p_S}{R}$ and $\frac{H_1 - h_C^*}{H_1^2} = \frac{p_C}{R}$, which in equilibrium yields $\frac{h_C^*}{H_1^2} = \frac{p_S}{R}$ and $\frac{h_S^*}{H_1^2} = \frac{p_C}{R}$, so that $H_1 = h_C^* + h_S^* = \frac{R}{p_C+p_S}$ and $h_C^* = \left(1 - \frac{p_C}{p_C+p_S}\right)\frac{R}{p_C+p_S}$, $h_S^* = \left(1 - \frac{p_S}{p_C+p_S}\right)\frac{R}{p_C+p_S}$, which are strictly positive whenever $p_S > 0$ and $p_C > 0$. Note that I does not participate when $p_I > p_C + p_S$, so that directly $p_I > p_S$ and $p_I > p_C$. This proves the remainder of Lemma 2. ■

By the nature of variable supply of sustainable energy, $p_S(B) > p_S(G)$. S enters the market when $p_S(G) < p_I$ (by Lemma 2), with $h_S^*(G) = \left(1 - \frac{p_S(G)}{p_I}\right)\frac{R}{p_I}$.

When $p_S(B) > p_I$, the miner shuts down in state B (also by Lemma 2), i.e., $h_S^*(B) = 0$. When $p_S(B) < p_I$, $h_S^*(B) = \left(1 - \frac{p_S(B)}{p_I}\right)\frac{R}{p_I}$.

Either way, $0 \leq h_S^*(B) < h_S^*(G)$, which completes the proof of Proposition 1. ■

Proof.[of Proposition 2]

We focus the proof on the interesting case where $p_S(G) < p_C < p_S(B)$.[14]

First suppose that $p_S(B) > p_I$. In such a case, S is active in good state, but shuts down and gets 0 profit in bad state. So, S's profit is $\pi_S^*(\alpha) = \alpha(1 - \frac{p_S(G)}{p_I})^2 R$. At the same time, C's profit is $\pi_C^* = (1 - \frac{p_C}{p_I})^2 R$. Then, we find that S is more profitable than C when $\pi_S^*(\alpha) > \pi_C^* \iff \alpha(1 - \frac{p_S(G)}{p_I})^2 R > (1 - \frac{p_C}{p_I})^2 R \iff \alpha > \bar{\alpha} = \left(\frac{p_I - p_C}{p_I - p_S(G)}\right)^2$.

Notice that in such a case, while S's share of the mining power is $\frac{h_S^*(G)}{H_0}$, it mines only $\alpha\frac{h_S^*(G)}{H_0}$ blocks.

A similar result holds when $p_S(B) < p_I$, even though in this case S is limiting the use of mining power in state B, instead of shutting down. More precisely, $h_S^*(G) = \left(1 - \frac{p_S(G)}{p_I}\right)\frac{R}{p_I}$, $h_S^*(B) = \left(1 - \frac{p_S(B)}{p_I}\right)\frac{R}{p_I}$, $\pi_S^* = \alpha\left(1 - \frac{p_S(G)}{p_I}\right)^2 R + (1-\alpha)\left(1 - \frac{p_S(B)}{p_I}\right)^2 R$ and $\pi_S^* > \pi_C^* \iff \alpha > \bar{\alpha} = \frac{(p_I - p_C)^2 - (p_I - p_S(B))^2}{(p_I - p_S(G))^2 - (p_I - p_S(B))^2}$. Thus, S is more profitable than C when $\alpha > \frac{(p_I - p_C)^2 - (p_I - p_S(B))^2}{(p_I - p_S(G))^2 - (p_I - p_S(B))^2}$.

In such a case, S mines only $\alpha\frac{h_S^*(G)}{H_0} + (1-\alpha)\frac{h_S^*(B)}{H_0} < \frac{h_S^*(G)}{H_0}$.

In both cases the threshold $\bar{\alpha}$ is strictly less than 1, meaning that S mines fewer bitcoins, which completes the proof of the proposition.

[14]Otherwise, sustainable mining always dominates conventional when $p_S(B) < p_C$, and the other way around when $p_S(G) > p_C$.

■

Proof.[of Lemma 1]

Spot Buyout. By calculations in proof of Lemma 2, in the "bad" state with $p_S(B) < p_I$, mining brings profit $\pi_B = (1 - \frac{p_S(B)}{p_I})^2 R > 0$. Thus the spot buyout curtailment payment needs to be at least π_B to stop mining in that state.

Fixed Price contract with Shut-Down provision (FPwSD). FPwSD is a long-term contract where the utility offers a lower rate in G state, $p'_S < p_S(G)$, in return for shutting down mining upon request in B state.

The E utility prefers FPwSD scheme to Spot Buyout when

$$\alpha p'_S \left(1 - \frac{p'_S}{p_I}\right) \frac{R}{p_I} \geq \alpha p_S(G) \left(1 - \frac{p_S(G)}{p_I}\right) \frac{R}{p_I} - (1-\alpha) \underbrace{\left(1 - \frac{p_S(B)}{p_I}\right)^2 R}_{\text{Spot Buyout curtailment payment}}.$$

Thus, the min p'_S needs to satisfy equality condition

$$\alpha p'_{Smin} \left(1 - \frac{p'_{Smin}}{p_I}\right) \frac{R}{p_I} = \alpha p_S(G) \left(1 - \frac{p_S(G)}{p_I}\right) \frac{R}{p_I} - (1-\alpha) \underbrace{\left(1 - \frac{p_S(B)}{p_I}\right)^2 R}_{\text{Spot Buyout curtailment payment}}.$$

Notice that this minimal $p'_S < p_S(G)$.

S will prefer FPwSD scheme to Spot Buyout when

$$\alpha \left(1 - \frac{p'_S}{p_I}\right)^2 R > \alpha \left(1 - \frac{p_S(G)}{p_I}\right)^2 R + (1-\alpha) \left(1 - \frac{p_S(B)}{p_I}\right)^2 R$$

Thus, the max p'_S is characterized by

$$\alpha \left(1 - \frac{p'_{Smax}}{p_I}\right)^2 R = \alpha \left(1 - \frac{p_S(G)}{p_I}\right)^2 R + (1-\alpha) \left(1 - \frac{p_S(B)}{p_I}\right)^2 R$$

We find that $p'_{Smin} < p'_{Smax}$ and thus there is always room a FPwSD that is Patero improving on Spot Buyout (i.e. better for both S and E). To see that this inequality exists, notice that for min p'_S, the mining facility S is strictly better off under FPwSD than under

Spot Buyout scheme:

$$\alpha\left(1-\frac{p'_{Smin}}{p_I}\right)^2 R > \alpha\left(1-\frac{p_S(G)}{p_I}\right)^2 R + (1-\alpha)\left(1-\frac{p_S(B)}{p_I}\right)^2 R \iff$$
$$\alpha\left(1-\frac{p'_{Smin}}{p_I}\right)^2 R > \alpha\left(1-\frac{p_S(G)}{p_I}\right)^2 R + \alpha p_S(G)\left(1-\frac{p_S(G)}{p_I}\right)\frac{R}{p_I} - \alpha p'_S\left(1-\frac{p'_{Smin}}{p_I}\right)\frac{R}{p_I} \iff$$
$$\left(1-\frac{p'_{Smin}}{p_I}\right)^2 + \frac{p'_{Smin}}{p_I}\left(1-\frac{p'_{Smin}}{p_I}\right) > \left(1-\frac{p_S(G)}{p_I}\right)^2 + \frac{p_S(G)}{p_I}\left(1-\frac{p_S(G)}{p_I}\right) \iff$$
$$1-\frac{p'_{Smin}}{p_I} > 1-\frac{p_S(G)}{p_I} \iff$$
$$p_S(G) > p'_{Smin}\,.$$

Thus, there is always room for E to set p'_S such that it is strictly better off while keeping S also strictly better off than under Spot Buyout (the specific surplus sharing arrangements may vary). This completes the proof of Lemma 1. ■

Proof.[of Proposition 3]

First, if the sustainable electricity provider faces cost $L > \pi_B$ for overwhelming the grid in state B, it is better off inducing the miner to stop mining with Spot Buyout of π_B. By Lemma 1, the utility can offer a curtailment scheme FPwSD with p'_S that will benefit both the utility and increase profitability of the miner. That proves the statement of Proposition 3 for FPwSD. Moreover, in some environments FPwRO may offer further benefits to both the utility and the miner, but this is not always the case.

Fixed Price contract with Resale Option (FPwRO). FPwRO is a long-term contract where the miner commits to buying a certain amount of electricity at a fixed price $\tilde{p}_S$, but it can resell it at the market price.

By the formulas in the proof of Lemma 2, if S uses the energy for mining, it optimally uses $\left(1-\frac{\tilde{p}_S}{p_I}\right)\frac{R}{p_I}$ — and this is how much energy it will commit to buy under FPwRO. Using all this electricity brings profit of $\left(1-\frac{\tilde{p}_S}{p_I}\right)^2 R$. If instead it decides to resell this electricity at market price p, it earns $\left(1-\frac{\tilde{p}_S}{p_I}\right)\frac{R}{p_I}p$. Thus, the mining facility S decides to sell it when $p > p_I - \tilde{p}_S$. The electricity utility E, wanting to induce S to sell back to the grid in state B, needs to set $\tilde{p}_S > p_I - p_S(B)$. Also $\tilde{p}_S < p_I - p_S(G)$ needs to hold, otherwise the miner will never mine and instead will resell electricity in both states. The expected benefit of miner

S from such FPwRO contract is

$$\alpha\left(1-\frac{\tilde{p}_S}{p_I}\right)^2 R+(1-\alpha)\left(1-\frac{\tilde{p}_S}{p_I}\right)\frac{R}{p_I}p_S(B)$$

The electricity utility's profit from such a contract is

$$\left(1-\frac{\tilde{p}_S}{p_I}\right)\frac{R}{p_I}(\tilde{p}_S-(1-\alpha)p_S(B))$$

Given the payoffs under FPwSD in the proof of Lemma 1, E prefers FPwRO to FPwSD when

$$\left(1-\frac{\tilde{p}_S}{p_I}\right)\frac{R}{p_I}(\tilde{p}_S-(1-\alpha)p_S(B))\geq\alpha p'_S\left(1-\frac{p'_S}{p_I}\right)\frac{R}{p_I}$$

Such a contract can be preferred also by S (to FPwSD), when

$$\alpha\left(1-\frac{\tilde{p}_S}{p_I}\right)^2 R+(1-\alpha)\left(1-\frac{\tilde{p}_S}{p_I}\right)\frac{R}{p_I}p_S(B)\geq\alpha\left(1-\frac{p'_S}{p_I}\right)^2 R$$

These conditions are simultaneously satisfied if and only if

$$\left(1-\frac{\tilde{p}_S}{p_I}\right)\left(\alpha\left(1-\frac{\tilde{p}_S}{p_I}\right)+\frac{\tilde{p}_S}{p_I}\right)\geq\alpha\left(1-\frac{p'_S}{p_I}\right)$$

After solving the quadratic inequality, the condition becomes

$$\frac{\tilde{p}_S}{p_I}>\frac{1-2\alpha+\sqrt{(1-2\alpha)^2+4\alpha(1-\alpha)\frac{p'_S}{p_I}}}{2(1-\alpha)}$$

At the same time, the participation constraint requires $\tilde{p}_S<p_I-p_S(G)$. Thus, a FPwRO contract better than FPwSD with p'_S for both the miner and the utility exists only if

$$\frac{1-2\alpha+\sqrt{(1-2\alpha)^2+4\alpha(1-\alpha)\frac{p'_S}{p_I}}}{2(1-\alpha)}<1-\frac{p_S(G)}{p_I}$$

While there exist values for parameters α, p_I, $p_S(G)$ and p'_S that satisfy this inequality, that interval is more likely to be empty (i.e., there is no such FPwRO) when α is small, p_I is low, $p_S(G)$ is high and/or p'_S is low.

Thus, under some conditions, FPwRO is a viable curtailment scheme that benefits the

utility by inducing mining shutdown while increasing the profitability of the mining facility. Moreover, as shown earlier, FPwSD always benefits the utility by inducing mining shutdown while increasing the profitability of the mining facility as compared to no such curtailment scheme at all. This completes the proof of Proposition 3.

■