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Hanna Halaburda
David Yermack

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ABSTRACT

This paper studies the operations and financial valuations of 13 cryptocurrency mining companies that are listed on the NASDAQ stock exchange and have facilities in North America. We find that miners using Texas wind power are offline more than other miners, in a more erratic pattern, while receiving significant revenue augmentations from "curtailment" payments by electric utilities. Despite having relatively low activity levels, these Texas miners are more profitable than those using more stable sources of energy such as hyrdo power or solar power, as reflected in significantly higher enterprise values. We find a negative and significant beta between crypto mining stocks and an index of electric utilities, suggesting that ownership of a crypto mining company might provide a useful channel for risk management in the electric power industry.

Hanna Halaburda
Stern School of Business
New York University
44 W 4th St.
New York, NY 10012
hhalaburda@gmail.com

David Yermack
Stern School of Business
New York University
44 West Fourth Street, Suite 9-160
New York, NY 10012
and NBER
dyermack@stern.nyu.edu

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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 emerged as 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]

Many U.S. bitcoin miners have elected to organize themselves as listed companies on the NASDAQ stock market, and by the end of 2022 more than a dozen publicly traded crypto mining companies, representing about 24% 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. For

[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. The evolving global footprint of proof-of-work mining is tracked by the Cambridge University Centre for Alternative Finance at https://ccaf.io/cbeci/mining_map, which shows the rearrangement of hashrate shares among countries since May 2021 in slow-motion animation.

stockholders and bondholders, agreeing to become risk-sharing investors in crypto mines might have seemed unusual, since the essential task in proof-of-work mining involves little more than guessing random integers in an attempt to solve puzzles by trial-and-error. The comparative advantage of crypto miners lies in their ability to guess random integers rapidly, akin to somebody skilled at approaching a lottery kiosk and buying many tickets very quickly.

Disclosures by the publicly traded crypto miners have provided new transparency into the operating risks, leverage, cost structure and supply chain relationships in the mining industry. Our paper studies how outside shareholders have valued bitcoin miners, and how the publicly traded mining companies have adapted their strategies in an environment that requires regular shareholder reporting and interaction with Wall Street analysts. Along with daily stock prices and standard disclosures such as Forms 10-K, 10-Q, and 8-K, we rely heavily on monthly reports of mining success that all of the crypto miners now publish via press releases shortly after the end of each month. Our study covers a particularly difficult period for the mining industry, as the plunge in cryptocurrency prices in 2022 badly hurt miners' revenue, such that by late 2022 one of the mining companies was operating in Chapter 11 bankruptcy and several others had undergone debt restructurings or announced intentions to renegotiate with creditors.

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 that 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 6.25 bitcoins, or about $125,000 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.

Due to the absence of skill required in mining, we examine other possible sources for a company's comparative advantage that might create investor demand for its shares. Two explanations are related to procurement: companies may have priority access to scarce mining equipment, or they may secure relationships with cheap and reliable energy providers. A third possibility is that a miner may have superior engineering skill that keeps its machinery consistently online. A fourth hypothesis is that miners may accumulate bitcoin over time in such a way that they begin to resemble bitcoin closed-end funds, thereby attracting investors.

We can quickly rule out the value of access to mining hardware, at least during the crypto bear market that has characterized most of our sample period. When improved models become available, miners' specialized hardware can be highly sought-after, particularly those models manufactured by market leader Bitmain Technologies Ltd. in China. Among our sample companies, we observe many shareholder communications

[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). Lehar and Parlour (2021) study the possibility of collusion among miners to induce bitcoin customers to pay higher user fees.

during the 2021 crypto bull market that give great attention to the status of their Bitmain orders, including the quantity of mining rigs ordered, the expected delivery schedule, the actual shipment and delivery events, and the schedules for planned installation and activation of newly received machines. However, by the Fall of 2022 the mining market had become saturated with Bitmain's newer models,[3] and some mining companies were canceling orders or re-selling units at fire-sale prices.[4]

We also see little evidence that mining companies build large inventories of bitcoin in order to become surrogate closed-end funds. Only one company in our sample, Hut 8 Mining Corp. of Canada, follows this strategy on a sustained basis, and by the end of 2022 it held $150 million worth of bitcoin in inventory and had an enterprise value (debt plus equity) of about $200 million, implying that the bitcoin represented three-quarters of the value of the firm. The alignment between Hut 8's daily stock returns and the bitcoin price index, as measured by a linear regression also including the NASDAQ market index and an electric utility industry index, is estimated at 0.67, but this value is not very different from the estimates for most other companies in the sample, all of which have much smaller bitcoin inventories relative to the size of the company. A few other firms did purport to follow accumulation or "hodl" strategies of retaining their mined bitcoin during part of the sample period, but all of them except Hut 8 abandoned this strategy during 2022, often selling their bitcoin at depressed market prices in order to raise cash to forestall financial distress.

[3] See, e.g., Eliza Gkritsi, "A Huge Glut of Bitcoin Mining Rigs Is Sitting Unused in Boxes," *Coindesk*, October 14, 2022.

[4] 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.

We therefore focus on miners' relationships with electric utilities as sources of comparative advantage. 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.

Most of the miners in our sample claim to be engaging in "green" or environmentally friendly energy use, but experts have been skeptical (Solomon 2022), and many of the companies' claims often apply to plans for future electrical installations not yet operating. One environmentally friendly strategy adopted by several companies in our sample involves "load balancing," whereby they agree to become customers of utilities that produce erratic sources of renewable energy, especially wind power. Under a load balancing strategy, a miner provides a stable source of demand for electricity but agrees to shut down operations when demand from other sources spikes upward, essentially becoming a buffer between the utility and the broad consumer market. Under a load balancing contract with a utility, the crypto miner may receive a rebate or subsidy when it curtails its consumption at the utility's request.[5]

The presence of a crypto miner 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). The state of Texas, which already obtains about one-fourth of its electrical power from wind, has taken a special interest in crypto mining for this reason and is actively encouraging mining companies to locate there, even if Texas' hot weather is less than ideal for keeping mining rigs cool.

Our paper presents a basic model of a miner's choice between sustainable energy and conventional sources of electric power, and we identify market conditions under which a sustainable miner may be more profitable even when required to curtail its operations intermittently to accommodate demand surges by other customers, such as on days with very hot weather when air conditioning is used widely. The model generates several predictions that we test using data from the 13 publicly traded mining companies, four of which currently rely upon wind power in Texas. As predicted by the model, we find that these miners are less productive due to frequent shutdowns of their operations, but because they receive compensation for these "curtailment" episodes, they trade at higher market valuations on the stock exchange. We also analyze the structure of daily stock returns for all mining companies. We find positive market reactions to monthly mining reports that indicate high efficiency. Miners' stock returns exhibit strong positive alignment with the NASDAQ market index, which is heavily weighted with technology stocks, and also with the daily returns on bitcoin. After controlling for moves in the

[5] 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.

NASDAQ market and bitcoin, mining stock returns exhibit significantly negative associations with an index of electric utility stocks. This result suggests that crypto mining offers a natural hedge for the risks of operating an electric utility, implying that direct ownership of proof-of-work miners by utilities may be optimal for risk-sharing purposes (see the analysis of the Brazilian market in Bastian-Pinto *et al*., 2021). We observe "behind-the-meter" installation of crypto mines at some electric utilities that bypass the consumer transmission grid and appear to represent risk-sharing joint ventures.

By studying the demand side of the market for renewable energy that is subject to irregular fluctuations in supply, 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 and Yates (2022); and Niaz, Liu, and You (2022).

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

2. Model

A. Environment

To illustrate the forces at play, consider a market environment which includes three types of miners. The miner types differ by the electricity price they face and barriers to entry:

- individual miners, who use electricity at a retail price p_I;

- conventional energy powered mining facilities, who pay a commercial rate $p_C < p_I$;
- sustainable energy powered mining facilities, whose electricity cost p_S depends on the energy state.

Electricity from sustainable sources has a high variability of supply depending on the weather, season, or hour of the day: more water for hydro power is available in the spring, more sunshine for solar power occurs during the day, and wind power generation rises and falls according to the daily weather. We define the energy state as good (*G*) when the supply of sustainable energy is abundant, and this good state occurs with frequency α. In a bad energy state (*B*) the supply of sustainable energy is low and its price will be higher. In a good energy state, $p_S(G)$ is lower than the price of conventional energy, but not so in a bad state.

Individual miners face no barriers to entry (Prat and Walter, 2021, Budish 2022, Halaburda et al 2022), hence more will enter if they find mining profitable. We consider them in aggregate and denote this aggregate as *I*.[6] Mining facilities, however, face some barriers to entry, related for example to contracting with a limited number of electricity providers, and thus there is an upper limit on how many can be present in the market. We assume that there is one conventional-energy-powered mining facility *(C)*, and one sustainable-energy-powered mining facility *(S)*. All miners use the same equipment, assumed to be available in unlimited quantity, so that a miner's relative usage of electricity is proportional to its relative hashing power employed, h_i.

[6] Results change somewhat if we introduce barriers to entry for the individual miners.

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.

B. Participation and profitability of a sustainable-energy mining facility

Within this environment, we ask two questions:

1. When is it worthwhile to mine with sustainable energy rather than not mine at all?
2. When is mining with sustainable energy more profitable than mining with conventional energy?

Case i: No contracting frictions

Baseline without S.

Consider first the baseline case without the sustainable mining facility, i.e., when only individual miners and the conventional mining facility are in the market. Note that for any level of $H_{-I} = h_C$ that is less than R/p_I, the individual miners find it profitable to enter, and therefore increase I's electricity use until approximately $h_I + H_{-I} = \frac{R}{p_I}$. That determines the total use of energy for mining in this baseline equilibrium to be $H_0 = \frac{R}{p_I}$.[7]

[7] This may be lower if there are barriers to entry for individual miners.

In equilibrium, the conventional mining facility maximizes its profits by using

$h_C^*(H_0) = \left(1 - \frac{p_C}{p_I}\right)\frac{R}{p_I}$ energy, obtaining profits $\pi_C^*(H_0) = \left(1 - \frac{p_C}{p_I}\right)^2 R$. While each individual miner uses an infinitesimal amount of energy and breaks even, in the aggregate they use $h_I^* = \frac{p_C}{p_I}\frac{R}{p_I}$.

Prediction 1. *The effect of changes in electricity prices (p_I, p_c) and bitcoin price (R) on electricity consumption without S:*

- *An increase in R directly increases H_0 as well as both $h_C^*(H_0)$ and h_I^*.*
- *An increase in p_I directly decreases H_0 and h_I^*. Its effect on $h_C^*(H_0)$ is ambiguous: $h_C^*(H_0)$ is decreasing in p_I when $2p_C < p_I$, but increasing otherwise.*
- An increase in p_c has no effect on overall electricity consumption H_0, as it shifts the electricity consumption from C to I.

Participation of the sustainable miner (S).

Whenever $p_S < p_I$, the sustainable mining facility finds it profitable to mine rather than not mine. S's entry has a differential impact on the equilibrium and participation of other miners depending on whether $p_S < p_I - p_C$ (which we will call *very low* p_S) or the reverse (which we call *higher* p_S). Whether S is more profitable in mining depends on the relative costs p_S and p_C as well as the proportion of good weather state, α.

If there is already H_0 electricity consumed for mining in the market, then S finds it profitable to add more electricity if $\pi(h_S, H_0) = \frac{h_s}{h_s+H_0}R - p_s h_s > 0$ which is equivalent to $\frac{R}{p_S} - H_0 > h_S$. Therefore, for any $p_S < p_I$, the sustainable mining facility finds it profitable to enter the market. The lower the p_S, the more additional hashing power S will add. Other miners adjust their electricity use in response. The overall electricity consumption exceeding H_0 makes individual miners not-profitable. Some or all of them exit, depending how low p_S is.[8]

For *higher* p_S, i.e., $p_S > p_I - p_C$, if sufficiently many individual miners exit, the remaining ones are borderline profitable (or indifferent). That implies that the overall use of energy in the market is the same as before S's entry, $H_0 = \frac{R}{p_I}$.[9] In this equilibrium, the sustainable mining facility obtains the highest profits, $\pi_S^*(H_0) = \left(1 - \frac{p_S}{p_I}\right)^2 R$ at the electricity consumption level $h_S^*(H_0) = \left(1 - \frac{p_S}{p_I}\right)\frac{R}{p_I}$. The electricity consumption and profitability of C does not change: $h_C^*(H_0) = \left(1 - \frac{p_C}{p_I}\right)\frac{R}{p_I}$ and $\pi_C^*(H_0) = \left(1 - \frac{p_C}{p_I}\right)^2 R$.

[8] An implication of this analysis, which we do not pursue in the paper, is that windy days will often draw more miners into the network, increasing its security. Conversely, when the weather is not windy, network security may degrade. This exogenous impact of the weather upon network security would be mitigated if the network's footprint were diversified geographically.

[9] This value may be higher than H_0 if individual miners face different costs of retail energy, or if there were entry frictions for individual miners in the baseline case before S's entry.

Now the individual miners in aggregate consume $h_I^* = \frac{p_C + p_S - p_I}{p_I}\frac{R}{p_I}$, each one breaking even.

When p_S is *very low*, i.e., $p_S < p_I - p_C$, a sustainable mining facility finds it optimal to use so much energy that even when all but one individual miners leave, the last one will not be profitable. Therefore, all individual miners leave, and only S and C remain in the market. In this equilibrium the remaining miners use more overall energy than in the presence of individual miners; the overall energy used is $H_1 = \frac{R}{p_C + p_S}$. Note that $H_1 > H_0$, as long as $R > 0$.[10] Within H_1, S uses $h_S^*(H_1) = \left(1 - \frac{p_S}{p_C + p_S}\right)\frac{R}{p_C + p_S}$ and $h_C^*(H_1) = \left(1 - \frac{p_C}{p_C + p_S}\right)\frac{R}{p_C + p_S}$, yielding profit $\pi_S^*(H_1) = \left(1 - \frac{p_S}{p_C + p_S}\right)^2 R$ and $\pi_C^*(H_1) = \left(1 - \frac{p_C}{p_C + p_S}\right)^2 R$.

To compare energy consumption and profits as p_S varies, recognize that p_S may represent different values in these formulas. Therefore, we use p_S^H to denote *higher* values of p_S and p_S^L to denote *very low* values of p_S. By these definitions, $p_S^H > p_I - p_C$ and $p_S^L < p_I - p_C$.

[10] When R=0 and electricity prices are positive, then all h values are 0, as all miners exit and no electricity is consumed for mining.

If we hold p_I and p_C constant while varying p_S, then for *R*>0, then

$\pi_S^*(H_0) = \left(1 - \frac{p_S^H}{p_I}\right)^2 R < \left(1 - \frac{p_I - p_C}{p_I}\right)^2 R = \left(\frac{p_C}{p_I}\right)^2 R$, and at the same time,

$\pi_S^*(H_1) = \left(1 - \frac{p_S^L}{p_C + p_S^L}\right)^2 R = \left(\frac{p_C}{p_C + p_S^L}\right)^2 R > \left(\frac{p_C}{p_I}\right)^2 R$. Therefore, $\pi_S^*(H_1) > \pi_S^*(H_0)$, i.e.,

the sustainable mining facility's profit always increases as p_S decreases. At the same time, the profit of the conventional mining facility does not change with small changes in p_S as long as p_S is *higher*. But once p_S drops to *very low*, C profit decreases, i.e., $\pi_C^*(H_1) < \pi_C^*(H_0)$, and it keeps decreasing as p_S decreases within the *very low* range.

Prediction 2. *Participation decisions of miners solely depend on the electricity prices, p_S, p_C and p_I, and are independent of the value of block reward (via bitcoin price), R*:

- *I participates when $p_I < p_C + p_S$,*
- *S participates when $p_S < p_I$,*
- *C always participates, since $p_C < p_I$.*

Prediction 3. *The level of electricity consumption, and the profitability of miners, depend both on the electricity prices and the value of the block reward (via price of bitcoin), R*:

- *The electricity consumption (and profit) of each miner increases as R increases.*
- *Decreasing p_i increases h_i^* (and π_i^*) and decreases h_j^* (and π_j^*) for all $j \neq i$.*

The model predicts electricity consumption will drop as the bitcoin price falls. However, it is not so much due to exit as decreased intensity of the same miners. When *R* decreases, each of the miners is decreasing their electricity use proportionally. And if all miners respond optimally, it turns out that each miner's *proportion* of the electricity use remains the same, and only depends on the relative electricity prices, while the overall electricity use declines.[11]

Relative profitability of the sustainable miner (S):

Per analysis above, the sustainable mining facility is profitable whenever $p_S < p_I$. Moreover, it is more profitable than conventional mining facility in every period it operates when $p_S < p_C$. If p_S were always lower than p_C, then we would get a straightforward result that S is more profitable than C. However, p_S depends on the sustainable energy state, and it may be higher than p_C, or even not available at all in bad states. Thus, whether S is more profitable than C overall depends on $p_S(G)$ and $p_S(B)$ relative to p_C, as well as α.

Suppose now that $p_S(B) > p_I$, or equivalently that S has an obligation to stop mining in a bad state. Both have the same effect that S is only active in the good state and gets 0 profit in the bad state. Then, using simply $p_S(G) = p_S$, we find that S is more profitable than C when

[11] This is consistent with the main result in Arnosti and Wineberg (2022).

$$\alpha > \begin{cases} \left(\dfrac{p_I - p_C}{p_I - p_S}\right)^2 & \text{for } p_S > p_I - p_C\,, \\ \dfrac{(p_I - p_C)^2(p_C + p_S)}{(p_C - p_S)p_I^2 + (p_I - p_C)^2(p_C + p_S)} & \text{for } p_S < p_I - p_C\,. \end{cases}$$

In both cases the threshold for α is less than 1. That means that

Prediction 4. *S may be more profitable than C, even though it is mining fewer bitcoins than its mining power capacity.*

Seasonality of sustainable energy supply.

Sustainable energy supply varies not only in a given period (day or hour), but the number of "good" periods also varies with the season. For example, for wind electricity, the oversupply is more likely to happen in spring and fall than in winter and summer. For solar, the oversupply is more likely to happen during the day. And for hydro, the oversupply is more likely to happen in the spring than in the fall (e.g. Niagara Falls has more water throughput during spring when parts of the glaciers up north are melting, and clearly less in late fall and winter when the glaciers are frozen again).

To account for it, we take an interval of periods, like a year (Y) is divided into a "good" season (like fall or spring for wind, y_F), or a "worse" season (like winter or summer for wind, y_W). Correspondingly, the probabilities of a good supply state are $\alpha_F > \alpha_W$.

Then the condition above takes the form

$$\frac{\alpha_F y_F + \alpha_W y_W}{Y} > \begin{cases} \left(\dfrac{p_I - p_C}{p_I - p_S}\right)^2 & \text{for } p_S > p_I - p_C\,, \\ \dfrac{(p_I - p_C)^2(p_C + p_S)}{(p_C - p_S)p_I^2 + (p_I - p_C)^2(p_C + p_S)} & \text{for } p_S < p_I - p_C\,. \end{cases}$$

It still shows that S may be more profitable that C, even though it is mining fewer bitcoins than its mining power capacity. And the difference between the capacity and the actual bitcoins mined will be larger in a "bad" season.

Moreover, if we consider a possibility of an accidental shut down, the cost of such a shut-down differs by season. Every period of accidental shut down in season j results in lost profits of

$$\begin{cases} \alpha_j \left(1 - \frac{p_S}{p_I}\right)^2 R & \text{for } p_S > p_I - p_C\,, \\ \alpha_j \left(\frac{p_C}{p_C + p_S}\right)^2 R & \text{for } p_S < p_I - p_C\,. \end{cases}$$

Since $\alpha_F > \alpha_W$, then for any p_S, this loss is higher in a "good" season than in a "bad" season.

This analysis can be extrapolated to "bad" realizations of α_F and α_W. The α's represent probability of good supply states. Suppose, however, that in a subset of periods in season j, the realized frequency of good states, $\hat{\alpha}_j$, is lower than the expected, i.e., $\hat{\alpha}_j < \alpha_j$. Then:

Prediction 5. *For every non-activity period below the expectation, α_j, the penalty on the earnings expectations is higher for $j = F$ than for $j = W$.*

<u>*Case ii: Energy contracting frictions*</u>

We have assumed that a miner can obtain as much energy as he needs and pays his respective rate only for what he uses. Next, we analyze how the mining equilibrium changes when the electricity contract includes binding limits on the electricity and when the mining facility needs to pay (or is paid) for electricity not used.

Limits to Energy Use.

Suppose that S has limit $\bar{h}_S$ on its electricity use, while I and C have no limits.[12] We find that S would never find a binding limit $\bar{h}_S$ profitable. That is, S is always better off if it can consume h_S^* electricity as characterized above, with either no limit or a limit that never binds. Our earlier results show that as p_S decreases, S's profit-maximizing electricity consumption h_S^* increases, and so do profits, π_S^*. This is true whether lowering p_S allows the individual miners to stay in the market or pushes them out. Thus, limiting the electricity consumption below h_S^* at any price p_S lowers S profits, by definition of the optimality of h_S^*.

Unused Energy – Penalty or buy back.

Suppose now that the sustainable mining facility's electricity contract specifies that it has access to energy up to $\bar{h}_S$ at price p_S but must pay a penalty p_P for any "unused" energy. S's optimization problem is then

$$\max_{h_S \leq \bar{h}_S} \left\{ \frac{h_S}{h_S + H_{-S}} R - p_S\, h_S - p_P \left(\bar{h}_S - h_S \right) \right\}$$

which is equivalent to

[12] Notice that it is a limit on the use of electricity. It may come from two sources: either from the electricity provider, or from insufficient equipment availability.

$$\max_{h_S \le \bar{h}_S} \left\{ \frac{h_S}{h_S + H_{-S}} R - (p_S - p_P)\, h_S - p_P \bar{h}_S \right\}$$

Following the same analysis as before, we find it is optimal for S to consume $\min\{\bar{h}_S, \hat{h}_S(p_P)\}$, where

$$\hat{h}_S(p_P) = \begin{cases} \left(1 - \dfrac{p_S - p_P}{p_I}\right) \dfrac{R}{p_I} & \text{when } p_S - p_P > p_I - p_C\,, \\ \left(1 - \dfrac{p_S - p_P}{p_S - p_P + p_C}\right) \dfrac{R}{p_I} & \text{when } p_S - p_P < p_I - p_C\,. \end{cases}$$

In all cases, $\hat{h}_S(p_P) > h_S^*$. Thus, when $\bar{h}_S > h_S^*$, then the higher the penalty, the larger is the electricity consumption above the optimal level. It is still possible, however, that the mining facility is paying the penalty $p_P < p_S$, even while using more than h_S^* electricity. That happens when $\bar{h}_S > \hat{h}_S(p_P)$.

Such high $\bar{h}_S$ is damaging to S's profitability. So the question arises, why would S sign a contract with such a high $\bar{h}_S$ in the first place? The answer may lie in the volatility of bitcoin prices. Overall electricity usage depends on the value of the mining reward R. When the bitcoin price and thus the value of mining reward is high (R^H), S wants to be able to use $h_S^*(R^H) = \left(1 - \frac{p_S}{p_I}\right) \frac{R^H}{p_I}$ at a preferred rate p_S. So it sets $\bar{h}_S = h_S^*(R^H)$ and does not pay any penalty. But when the bitcoin price falls to R^L, S may prefer to pay the penalty p_P when

$$\left(1-\frac{p_S}{p_I}\right)\frac{R^H}{p_I} > \left(1-\frac{p_S-p_P}{p_I}\right)\frac{R^L}{p_I} \Leftrightarrow \frac{R^H}{R^L} > 1+\frac{p_P}{p_I-p_S}.$$

(This calculation is for $p_S - p_P > p_I - p_C$, but the result qualitatively holds for other cases.)

Prediction 6. *As the bitcoin price decreases, S is willing to pay higher penalties for not using its quota of electricity.*

Under certain contracts, p_P may be negative, and the electricity provider would be paying the mining facility not to use electricity (i.e., S sells the unused electricity back to the provider). It follows directly that such a buy-back scheme results in less than h_S^* electricity used by S.

C. Partial Welfare Effects

New coins created.

Changing energy prices should have no effect on the number of new coins created if the difficulty adjustment works reasonably well. This is because the network is programmed to issue the same number of bitcoins is created within a given time interval – currently 6.25 bitcoins per 10 minutes – independent of the overall electricity consumption.

Overall energy consumed.

Lower electricity prices and higher bitcoin prices increase overall consumption of electricity for mining. Consider first the situation with no contracting frictions. The overall electricity consumption is

$$H_0 = \frac{R}{p_I}, \qquad \text{when } p_S > p_I - p_C \text{ or } S \text{ inactive}$$

$$H_1 = \frac{R}{p_C + p_S}, \qquad \text{when } p_S < p_I - p_C$$

It is straightforward that as p_S decreases from *higher* to *very lower*, the overall energy consumption increases, $H_1 > H_0$. Similarly, straightforward is that both H_0 and H_1 increase in *R*. In addition, penalties for not using the electricity, $p_P > 0$ may also further increase the overall energy consumed ($H = \frac{R}{p_C + p_S - p_P} > H_1$ if $\bar{h}_S$ not binding) when $p_S - p_P < p_I - p_C$.

Prediction 7. *We should expect a non-linear effect of lowering p_S on the overall consumption of electricity: For $p_S > p_I - p_C$, the overall electricity consumption stays constant at H_0 as p_S declines. Once $p_S < p_I - p_C$, the electricity consumption, H_1 increases as p_S declines, assuming a constant R.*

Conventional vs. sustainable energy consumed.

When p_S declines (holding R constant), less conventional electricity is used for mining, even though more overall electricity is used. At the same time, as R increases both types of electricity use increase.

Earlier results show that when p_S is *higher*, overall consumption H_0 does not change, but the market share of S increases at the cost of I. If at least some of I are using conventional energy, decreasing p_S results in decreasing use of conventional energy in the market.

For *very low* p_S, we cite an earlier result $h_C^*(H_1) = \frac{p_S}{(p_C+p_S)^2}R$. Note that for $p_S > p_C$, $\frac{p_S}{(p_C+p_S)^2}$ is increasing in p_S. Together with $p_S < p_I - p_C$, it yields $h_C^*(H_1) < \frac{p_I-p_C}{p_I^2}R = h_C^*(H_0)$. So even if all h_I^* is coming from sustainable energy, *very low* p_S results in lower conventional energy use. The effect is exacerbated if some of individual miners use conventional energy. Moreover, the result will increase with $p_P > 0$.

Prediction 8. *When p_S declines (holding R constant), less electricity is used for mining by miners other than S, even though more overall electricity is used.*

This implies that reports pointing to the damaging environmental impact of bitcoin mining may be misleading if only focusing on total electricity used.

Prediction 9. *When p_S declines (allowing R to move arbitrarily), a lower proportion of mining is done by miners other than S.*

3. Data description

We collect data on all publicly traded bitcoin mining companies with North American operations that are listed on the NASDAQ market during a sample period that begins in May 2021 and continues up to the present. We include only those companies that achieve market capitalizations of at least $100 million at some point during the sample period, 13 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,[13] has been public for more than five 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). Only two of the companies have operations outside North America, and just one represents a relocation of

[13] 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.

hardware that had previously been installed in China. The most popular location for mining is Texas (nine companies with facilities either in place or under construction), followed by Georgia (four companies), New York (four), and Quebec (three). Many (perhaps all) of the U.S. mining companies 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 since April 30, 2021. At the inception of the sample 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 the high watermark for the industry's market cap occurs in mid-November 2021, when 11 companies were public with an aggregate market cap of about $20.5 billion. As the market price of bitcoin has declined since November 2021, so too has the value of mining stocks, albeit at a somewhat faster rate. As of January 2023, 13 companies were listed with a collective market cap of about $3.4 billion, which represented a rebound from a low of $1.7 billion reached just two weeks earlier. The chart does not reflect the value of the entire U.S. mining industry since it only includes public companies and ignores some penny stocks. There are many more private companies and partnerships, including large firms such as Genesis Digital Assets Inc., which may be the biggest North American miner.

Table 2 provides information about the assets of the 13 public mining companies, including the total reported hashrates of their mining hardware 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 values are measured as of December 31, 2022. Not all companies report their bitcoin inventories, but in most of these cases other information suggests these undisclosed inventories are negligible.

While bitcoin prices had significantly dropped during the "crypto winter" of 2022, reducing the value of rewards earned by crypto miners, the industry nevertheless continued to expand its capacity with the global hashrate growing almost continuously during the year. As of January 2023, four companies in our sample – CleanSpark, Marathon, Riot, and TeraWulf – were actively building new facilities and/or installing new mining units, and their announced plans would add about 24.5 Eh/second of hashing power to the network by mid-2023, representing nearly a 10% increase of the global hashrate. However, companies had experienced difficulty in achieving their announced growth targets, for various reasons related to local permitting delays, supply chain bottlenecks, adverse weather events, and the like. Figure 2 shows the monthly evolution of hashrate targets announced and actually achieved by one of the larger companies, Marathon Digital Holdings, a firm that tends to make more complete disclosures than most other firms. As shown on the graph, Marathon in early 2021 announced a target hashrate of 10.37 Eh/second by early 2022, but its actual hashrate grew far too slowly to approach this goal. The company announced even greater goals of 13.3 Eh/second by mid-2022 and 23.3 Eh/second by early 2023, a date which was later pushed back to mid-2023. However, the actual hashrate of the company grew only slowly through May 2022, after which it dropped virtually to zero following a tornado that knocked offline its largest facility. In January 2023 the company was still announcing its intent "to have approximately 23 EH/s of capacity installed near the middle of 2023," according to its January 5 monthly mining update.

Companies' bitcoin retention policies vary considerably, and the time series of monthly bitcoins mined and sold is shown for three companies in Figure 3. The top company, CleanSpark Inc., tends to sell its mining output in real time, as its monthly sales track fairly closely the number of coins mined. For the most part, this policy resembles those of commodity mining companies that extract ores and minerals from the crust of the earth. The middle company, in Figure 3, Hut 8 Mining Corp., simply accumulates all the bitcoins it mines, following a policy known in the crypto community as "hodling." As noted above, Hut 8 is really in two businesses, (i) mining bitcoin, and (ii) speculating in the future appreciation of bitcoin. To the extent its bitcoin inventories grow over time, it might begin to resemble a closed-end fund focused on cryptocurrency, and it might attract an investor clientele seeking exposure to crypto assets via a surrogate for a bitcoin ETF, a product that the SEC has repeatedly refused to approve despite dozens of applications and evident investor demand. The company on the bottom of Figure 4, Core Scientific, had been following an accumulation policy similar to Hut 8's until it abruptly reversed course in mid-2022 and began to liquidate its inventories of cryptocurrency in order to create liquidity for addressing financial problems. By December Core Scientific was bankrupt and appeared to be selling off new bitcoin as quickly as it was mined in order to generate immediate cash.

The 13 companies in our sample have very different capital structure policies. Four out of 13 have little debt on their balance sheets and would appear to have very low bankruptcy risk. Among the other nine 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 mining sites. These strategies could provide considerable leverage that would amplify profits if bitcoin prices were rising, but they could accelerate a descent into financial distress if bitcoin prices were 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.[14]

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 all 13 companies during a period beginning May 3, 2021, and continuing to January 13, 2023 (most companies were not publicly traded for the entire sample period). Standard errors are clustered by company. In the first three columns we regress daily stock returns against the daily returns on the NASDAQ market index, bitcoin, and the SP500 electric utilities index, respectively (for bitcoin, returns on weekends and market holidays are folded into the next Wall Street market day's

[14] 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 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.

observations). In the fourth column, all three indexes are included together. Focusing on the fourth column, we see a very strong association between mining stocks and movements in the NASDAQ index, with an estimated market beta of 1.78, 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 significantly negative beta of -0.91 after controlling for movements in bitcoin and the overall market. This result indicates that cryptocurrency mining has the economic properties of a hedge against returns in the utility industry, a pattern that makes sense since electricity represents the main variable cost in crypto mining.

In the right column of Table 3, we augment the model with an indicator variable for those days (usually one per month) on which companies make public announcements about their mining results for the prior calendar month. We define a statistic of mining "success" equal to the ratio between a company's actual coins mined and the expected amount, with the expectation based upon the ratio between the company's own hashrate and the network hashrate, multiplied by the global bitcoin output during that month. To calculate the hashrate ratio, we take the starting and ending ratios for a company each month and average them together. Many companies' mining success values cluster around 1.00, but some are lower, a pattern we discuss further below.[15]

The regression estimates in the right column of Table 4 show positive and significant market reactions to announcements of successful mining months. While

[15] While many companies have mining success below 1.00, none of them exceed 1.00 which seems surprising, since by construction the statistic should equal 1.00 for the mining industry in aggregate. The most simple explanation is probably that some (or most) companies exaggerate their true hashrates. Conssistent with this possibility, in its recent *2022 Annual Crypto Review* (slide 14), Coindesk shows a disagreement between the calculated bitcoin network hashrate and the somewhat higher hashrates reported by major mining pools in the aggregate.

positive investor reactions to good operating performance are not surprising, we note that our result suggests that investors do not monitor the bitcoin blockchain with great attention. In principle, interested researchers should be able to identify the public keys of individual mining companies on the blockchain and take note of their mining progress in real time, so that month-end announcements of mining success shouldn't move the market.

We next move to test some of the predictions from our model introduced in Section 2 above. Based upon Prediction 2, we conjecture that miners that are located in jurisdictions with large usage of wind power will have more variable success rates and will spend more time offline, because the generation of wind power is much more erratic than other sources such as fossil fuels, nuclear, or renewables including solar and hydro. Prices of energy should be much higher during periods in which the wind is not blowing, and when demand for energy is otherwise high due to the weather. Figure 4 presents information about the electricity market in Texas, showing the variability of the monthly demand for energy (the red series) and the availability of wind power (the blue series). Data are based upon daily observations in North Central Texas for the Load Mix and Native Load reports that are available on the website of the Electric Reliability Council of Texas (ERCOT). The red series in Figure 4 shows that demand for electricity is highest during the summer period of June-August, with demand also rising by a lesser amount in January-February during the winter. All else equal, the price of energy should be highest during these months. From the supply side of the market, the blue series in Figure 4 shows that the most abundant period of the year for generating wind power is the springtime, March through May, as well as the fall, October through December. During these periods, which could be interpreted as the "good" state *S(G)* in our model, the price of renewable energy should be lowest. Crypto miners engaging in load balancing strategies in Texas should therefore expect to be offline especially during the summer months, when relatively little wind power is available and demand for energy is high. These months would correspond to the "bad" state, *S(B)*, in our model. These miners should also exhibit a higher overall fraction of days off-line, which would translate into lower mining success rates.

In untabulated results, we augment the regression model in the right column of Table 3 by adding an interaction of the "success" variable with an index variable that reflects the average daily electricity demand in North Central Texas during that month, according to electricity usage data from ERCOT. We interact this electricity usage variable with the "success" variable as a way of testing Prediction 5. While we find a negative coefficient estimate as expected, it is not statistically significant.

We infer companies' offline behavior from their data for mining success, a variable that equals 1.00 if a company mines exactly the number of coins that would be expected given the size of its hashrate relative to the overall network hashrate. We have two companies mining the majority of their coins in Texas, Marathon Digital Holdings and Riot Platforms. Argo Blockchain and Bit Digital also have operations in Texas as well as other U.S. states and Canada. (Table 1 indicates that 9 of our 13 companies mine crypto in Texas, and in the cases of the other five companies, their Texas sites are under construction or under option for future development.) Table 2 shows that Riot and Marathon have two of the lowest success rates in our sample, indicating that they are often offline. In Figure 5, we plot the monthly success values for Riot against those for

BitFarms, a miner that mostly uses hydro power in Quebec. It is evident by inspection of the plot that Riot Blockchain is off-line far more frequently than BitFarms (in 15 out of 16 months) while exhibiting much greater variation in success; the standard deviations of the two monthly series in Figure 5 are 0.11 for Riot and 0.05 for BitFarms.

Though we are relying upon information from a small sample of companies, we interpret the lower and more variable success rates for Texas miners as being broadly consistent with Prediction 2 in our model, which implies that these miners will disconnect their machines on days with high external energy demand and/or low availability of renewable wind power. Riot has been very open about this behavior in its monthly reports. It generally discloses the value of rebates that it receives from local utilities due to periodic "curtailments" of mining. For example, in its July 2022 monthly mining update, Riot reported obtaining $9.5 million worth of power credits as compensation for not mining on certain days, an amount that significantly exceed its revenues from mining bitcoin during the same month.[16] Its most recent balance sheet, for September 30, 2022, shows a current asset of $40 million worth of future power credits which can be used to offset future electricity bills; the accounting is handled in a similar way to prepaid future revenue. Although other companies in the sample make occasional reports of earning these credits or similar subsidies, none of them appears to track them on its balance sheet as Riot does.

[16] 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. For December 2022, Argo Blockchain (Texas), ClearSpark (Georgia), Core Scientific (various), Hive Blockchain (Quebec), and Riot Blockchain (Texas) all reported curtailments of mining during a severe winter storm that disrupted the electric utility industry especially in the central U.S. and upstate New York.

Another implication of our model, stated in Prediction 4, is that miners with access to subsidies for curtailment periods may be more profitable than ordinary miners, even if they end up mining far less. While it is difficult for us to obtain data about the monthly profits of miners, we can observe the market values of these firms and examine whether they are valued more highly by the market.

Table 4 and Figure 6 investigate the recent value of the 13 companies in our sample as a function of their installed hashrates. We use the Merton-KMV model for this purpose. We observe the market value of equity for each company as well as the equity volatility over the past year. We assume that each firm has a default point equal to the value of short-term liabilities and one-half of long-term liabilities. We treat equity as having a one-year option to purchase the assets of the firm at an exercise price equal to the book value of total liabilities. The one-year U.S. Treasury bill rate serves as the risk-free rate.

Table 4 tabulates the market value of equity, book value of debt, and equity volatility (which exceeds 100% annually for every firm), along with the solution for the estimated market value of the entire firm. We subtract the equity market value from the firm's market value to obtain an estimate of the market value of debt. The table shows that some firms have debt with market values deeply discounted from book values, including Core Scientific, which has already filed for bankruptcy, and several others. Many of the firms' shares therefore trade in ways similar to out-of-the-money call options, a property that would appeal to risk-seeking investors of the type that also gravitate toward the cryptocurrency markets.

In Figure 6, we compare each firm's enterprise value with the hashrate of its mining equipment. Using the data from Table 4, we define enterprise value as the market value of equity plus the market value of debt, minus the market value of bitcoins, in order to capture the value of the underlying mining business independent of the value of any bitcoin inventory. January 13, 2023 serves as the measurement date. Note that not all companies disclose bitcoin inventories, and debt values are recorded on September 30, the most recent public disclosure date for most of the companies[17] (four of the 13 companies have low leverage and very little debt). We fit a regression line to the enterprise values of the different companies based upon their hashrates, and this line also appears in Figure 6. The regression has a good r^2 of 0.70. The two firms that are valued much higher than their predicted levels are Riot Platforms and Marathon Digital Holdings, which can be located on the graph to the north of the regression line. Marathon's market value is 135% higher than what would be predicted by the regression line, and Riot's is about 37% higher.

5. Discussion and conclusions

This paper studies the operations and financial valuations of 13 publicly traded cryptocurrency mining companies We find that miners using Texas wind power are offline more than other miners, in a more erratic pattern, while receiving significant revenue augmentations from "curtailment" payments by their power suppliers.

[17] Two of the companies that are based outside the U.S. file financial reports only semi-annually instead of quarterly, so these companies' most recent balance sheets are dated June 30, 2022. We also use the June 30 rather than September 30 balance sheet for Core Scientific, since its long-term debt was shown as having been accelerated to short-term status by September 30. Note 6 of Core Scientific's September 30 Form 10-Q indicates that this reclassification of debt from long-term to short-term took place because the company skipped several payments due to various lenders during October, subsequent to the end of the September 30 fiscal quarter but prior to the preparation of the balance sheet for the SEC filing.

Nevertheless these Texas miners are more profitable than those using more stable sources of energy such as hyrdo power or solar power, as reflected in significantly higher enterprise values.

One of the most intriguing results in the paper appears in Table 3, where regression estimates in the fourth column imply a strongly negative beta for crypto mining stocks with respect to an index of electric utilities. The estimate implies that owning a cryptocurrency mining unit would provide an effective hedge, or risk management tool, for utilities.

Our data also indicate that a subset of crypto miners actively pursue risky strategies involving high degrees of leverage and the pledging of bitcoins held in inventory.

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Table 1
Publicly traded bitcoin mining companies
The table lists 13 publicly traded bitcoin mining companies with the year of their NASDAQ stock market listing, country of corporate registration, and principal geographic locations of mining operations. Some mining sites are still under construction.

Company	Listed	Registered	North America sites	Other sites
Riot Platforms Inc.	2017	USA	Texas	
CleanSpark Inc.	2020	USA	Georgia, New York, Texas	
Bit Digital Inc.	2020	Caymans	Georgia, New York, Texas, Nebraska	(formerly China)
Marathon Digital Holdings Inc.	2021	USA	North Dakota, Texas	
Hut 8 Mining Corp.	2021	Canada	Alberta, Ontario	
BitFarms Ltd.	2021	Canada	Quebec, Washington	Argentina,
Hive Blockchain Technologies Inc.	2021	Canada	Quebec, Texas	Paraguay
Cipher Mining Technologies Inc.	2021	USA	Texas	Iceland, Sweden
Greenidge Generation Holdings Inc.	2021	USA	New York, Texas, South Carolina	
Argo Blockchain PLC	2021	UK	Georgia, Kentucky, Texas, North Carolina, Quebec	
Iris Energy Ltd.	2021	Australia	British Columbia, Texas	
TeraWulf Inc.	2021	USA	New York, Pennsylvania	
Core Scientific Inc.	2022	USA	Georgia, Kentucky, North Carolina, North Dakota	

Table 2
Mining data for publicly traded bitcoin mining companies
The table provides statistics about 13 publicly traded bitcoin mining as sourced from companies' monthly mining update press announcements. Each company's hashrate and BTC holdings are reported as of December 31, 2022, at which point these companies collectively accounted for 23.8% of the worldwide bitcoin mining hashrate. For each company, mining success equals the actual bitcoin 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.

Company	Hashrate	BTC held	BTC mined, 2022	Mining success
Riot Platforms Inc.	9.70 Eh/sec.	6,952	5,536	0.77
CleanSpark Inc.	6.20	228	4,621	0.95
Bit Digital Inc.	1.23	947	1,247	1.00
Marathon Digital Holdings Inc.	7.00	12,232	4,144	0.72
Hut 8 Mining Corp.	2.50	9,086	3,568	0.86
BitFarms Ltd.	4.50	405	5,168	0.99
Hive Blockchain Technologies Inc.	2.06	n.a.	3,270	0.97
Cipher Mining Technologies Inc.	2.80	n.a.	> 516	0.83
Greenidge Generation Holdings Inc.	2.50	n.a.	> 2,318	0.90
Argo Blockchain PLC	2.50	512	2,157	0.70
Iris Energy Ltd.	1.50	n.a.	2,295	1.00
TeraWulf Inc.	2.00	n.a.	495	0.75
Core Scientific Inc.	15.70	n.a.	14,420	0.90

Table 3
Analysis of mining company stock returns

The presents ordinary least squares estimates of daily stock returns of 13 publicly traded bitcoin mining companies between May 3, 2021, and October 14, 2022. Explanatory variables include the daily returns on the NASDAQ market index, bitcoin, and the SP500 Electric Utilities index. The indicator for monthly updates equals one on days in which companies report their mining results for the previous month. The success variable equals the company's monthly mining output divided by its expected output, based on the company's reported hashrate relative to the overall bitcoin blockchain hashrate. The growth variable represents the percentage increase in the company's hashrate over the prior month. Standard errors are clustered at the company level.

Dependent variable: Daily stock return

Intercept	-0.0049 ***	-0.0045 ***	-0.0067 ***	-0.0037 ***	-0.0038 ***
	(0.0010)	(0.0010)	(0.0010)	(0.0010)	(0.0011)
NASDAQ return	2.1543 ***			1.7733 ***	1.7757 ***
	(0.1075)			(0.1008)	(0.0992)
Bitcoin return		0.8983 ***		0.5481 ***	0.5470 ***
		(0.0411)		(0.0387)	(0.0386)
Utilities return			0.6316 ***	-0.9147 ***	-0.9140 ***
			(0.0420)	(0.0762)	(0.0779)
Update indicator					-0.0445
					(0.0283)
Update indicator x Success					0.0568 *
					(0.0317)
Update indicator x Growth					-0.0263
					(0.0272)
Observations	4,641	4,641	4,641	4,641	4,641
R^2	0.217	0.202	0.009	0.289	0.289

*** Significant at 1% level

Table 4
Estimated market values of crypto mining companies
The table shows the market value of equity and estimated market values for debt and the overall firm for a sample of 13 publicly traded bitcoin mining companies. Equity value equals the market capitalization on the NASDAQ stock exchange on January 13, 2023. Equity volatility is measured over one year prior to that date. Debt book value is obtained from the company's most recent balance sheet, in most cases dated September 30, 2023. The firm value estimate is derived using the KMV model, using a one-year U.S. Treasury rate and other assumptions described in the next. Implied debt value equals the difference between the firm value estimate and the equity market value. All dollar values are in millions.

Company	Equity market value	Equity volatility	Debt book value	Firm value estimate	Debt value implied
Riot Platforms Inc.	$926.4	1.03	$154.3	$1,064.7	$138.2
CleanSpark Inc.	106.5	1.02	48.6	150.9	44.4
Bit Digital Inc.	98.3	1.02	6.4	103.5	5.2
Marathon Digital Holdings Inc.	895.0	1.25	805.1	1,357.7	462.7
Hut 8 Mining Corp.	307.4	1.08	67.1	357.7	50.3
BitFarms Ltd.	225.1	1.14	113.9	331.2	106.1
Hive Blockchain Technologies Inc.	257.5	1.05	49.9	296.4	39.0
Cipher Mining Technologies Inc.	275.7	1.35	24.4	299.0	23.3
Greenidge Generation Holdings Inc.	44.8	1.44	217.8	222.0	177.2
Argo Blockchain PLC	70.2	1.50	138.5	194.5	124.3
Iris Energy Ltd.	97.0	1.26	133.1	218.2	121.2
TeraWulf Inc.	95.8	1.52	188.0	261.2	165.4
Core Scientific Inc.	30.4	2.80	1,428 7	1,076.0	1,045.6

Figure 1
Equity market capitalizations of crypto mining companies
The figure shows the equity market capitalizations of 13 publicly traded bitcoin mining companies between April 30, 2021 and January 13, 2023. 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.

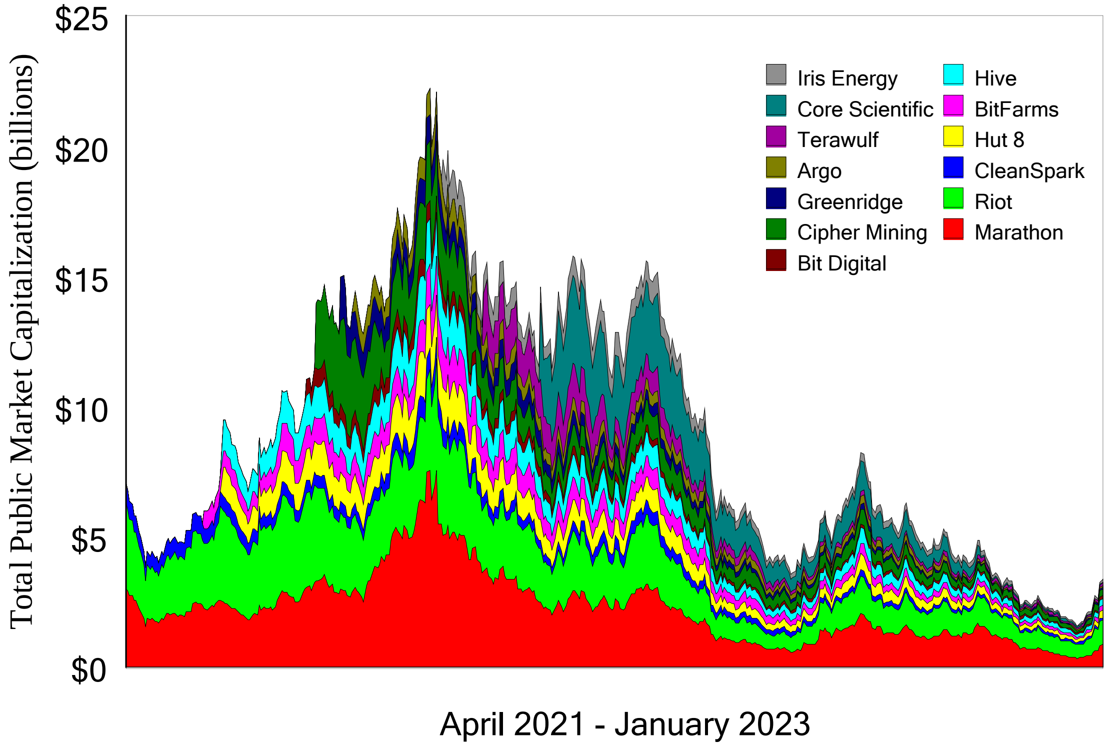


Figure 2

Actual and forecast hashrates for Marathon Digital, by month

The figure shows month-end hashrates reported by Marathon Digital Holdings Inc. in its monthly progress reports, along with future hashrate forecasts disclosed in the same reports.

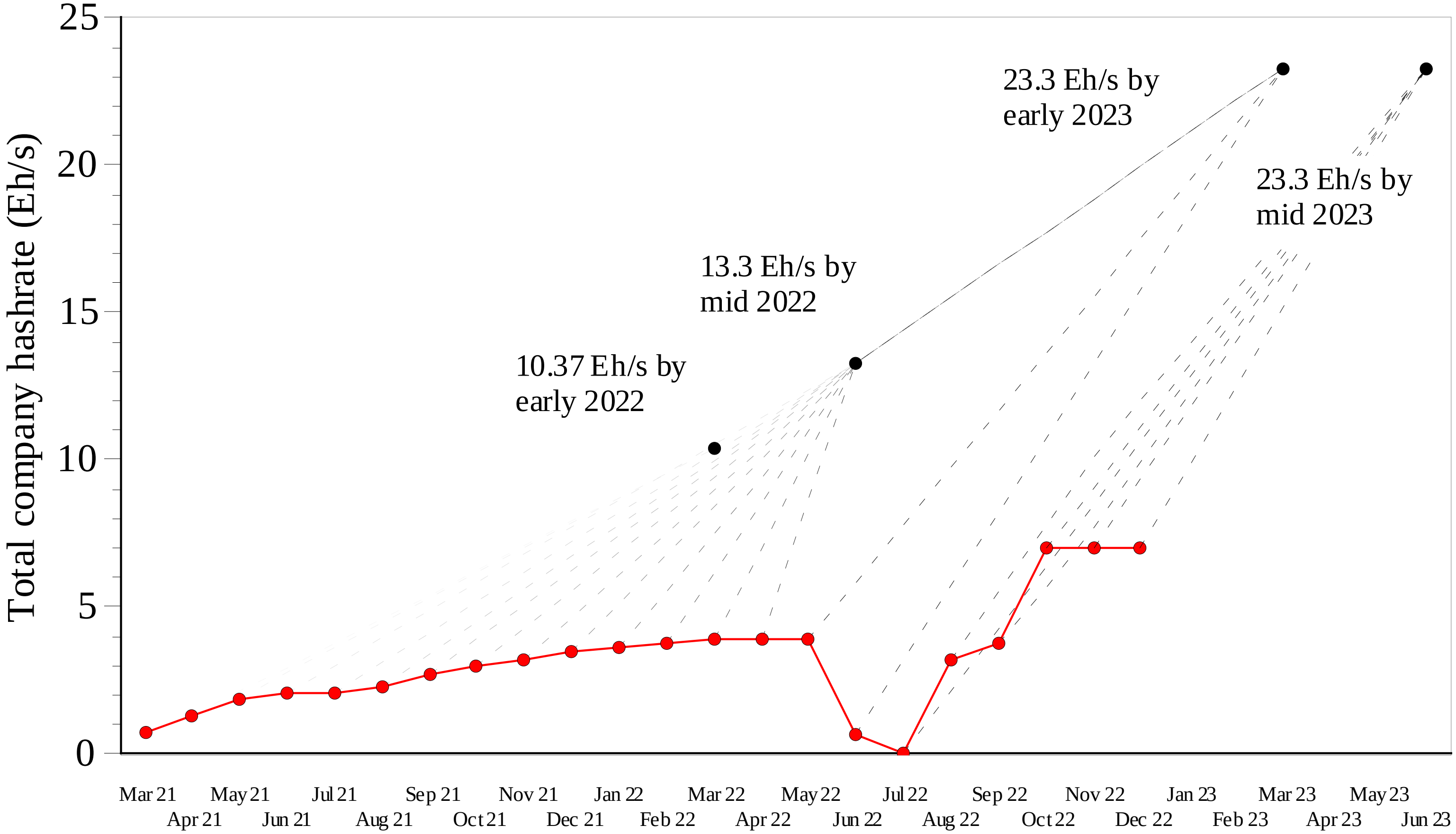
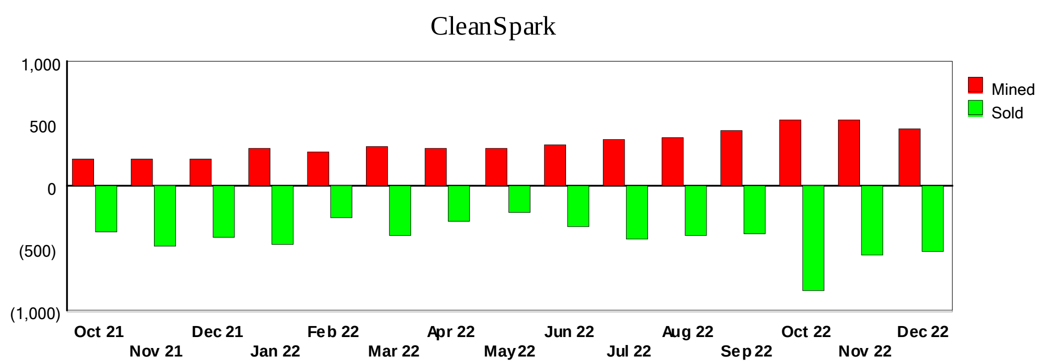
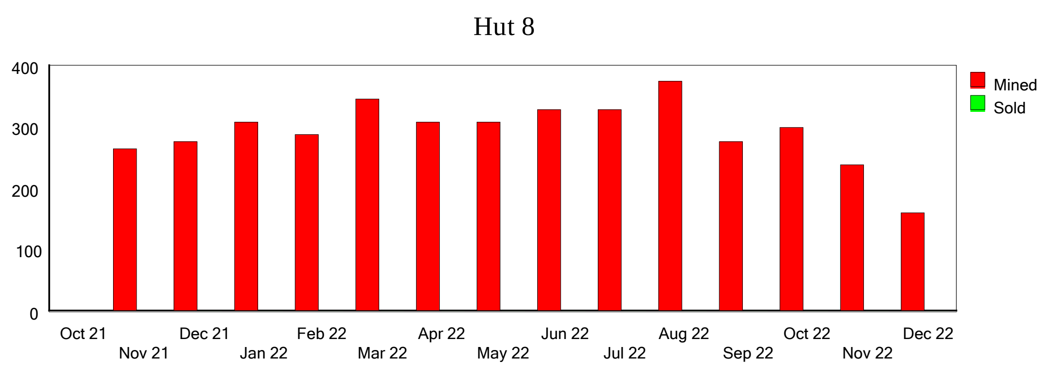


Figure 3
Examples of mining retention policies

The figures show monthly data for three companies during the 15 month period October 2021 through December 2022. In each graph the red bars represent new bitcoins mined during the month, while the green bars show bitcoins sold. The first company, CleanSpark Inc., follows a steady-state strategy of selling an amount each month that approximately equals its month mining output. The second company, Hut 8 Mining Corp., retains its entire mining output and accumulates an increasing inventory of bitcoins. The third company, Core Scientific Inc., also follows an accumulation policy until May 2022, when it abruptly liquidates most of its bitcoin inventory and switches to a steady-state strategy similar to CleanSpark's. Core Scientific omitted its November 2022 monthly mining report, filed for Chapter 11 bankruptcy protection on December 21, 2022 and did not disclose bitcoin sales when it resumed monthly reports in January 2023.





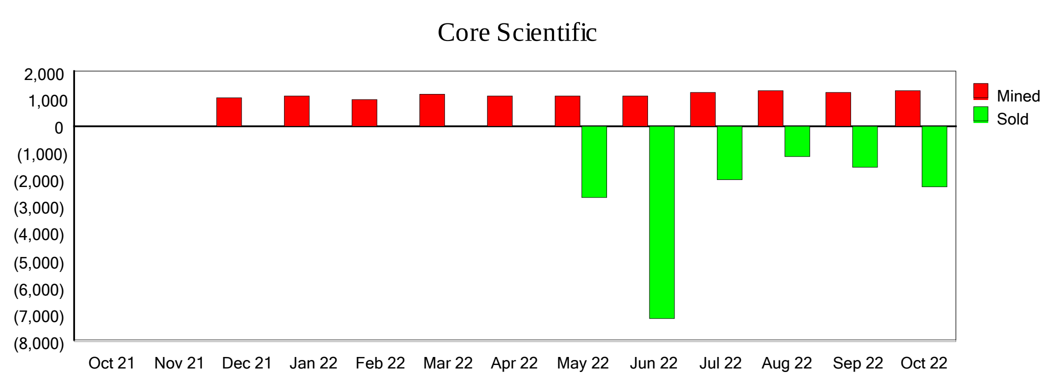


Figure 4
Monthly data from Texas electricity market
The graph shows monthly information about the availability of wind power and the demand for electricity in the state of Texas between January 2021 and July 2022. For each time series, the plotted value equals the percentage of the series' monthly average during the sample period. The supply of wind power is based on daily statewide data from the Fuel Mix report posted on the website of the Electric Reliability Council of Texas (ERCOT). The demand for electricity is based on the average of daily peak values within each month as reported in ERCOT's Native Load report using observations for the North Central market area.

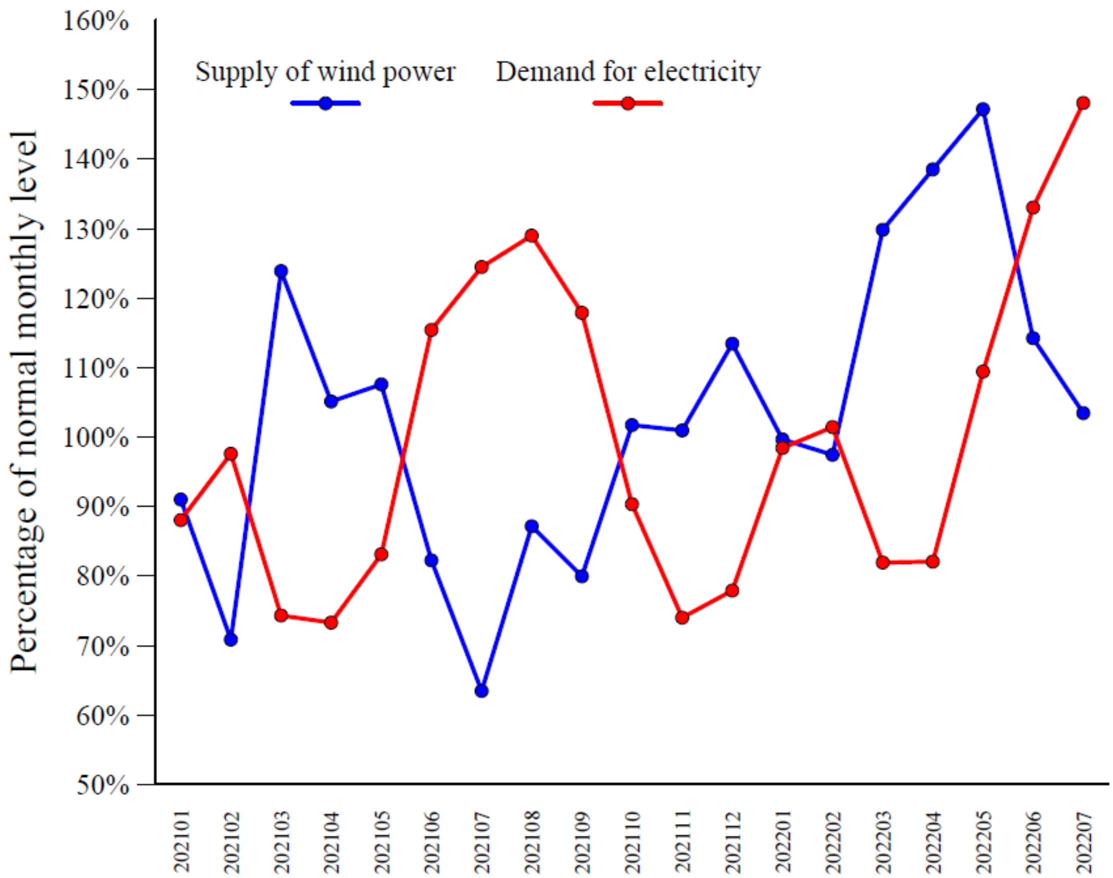


Figure 5
Monthly mining "success" for two companies
The graph shows monthly data for two companies' mining "success," which equals the company's monthly mining output divided by its expected output, based on the company's reported hashrate relative to the overall bitcoin blockchain hashrate. BitFarms uses mainly hydropower from facilities in Quebec and Washington State. Riot Platforms uses a mix of energy, including wind power, mainly at its mining site in Texas.

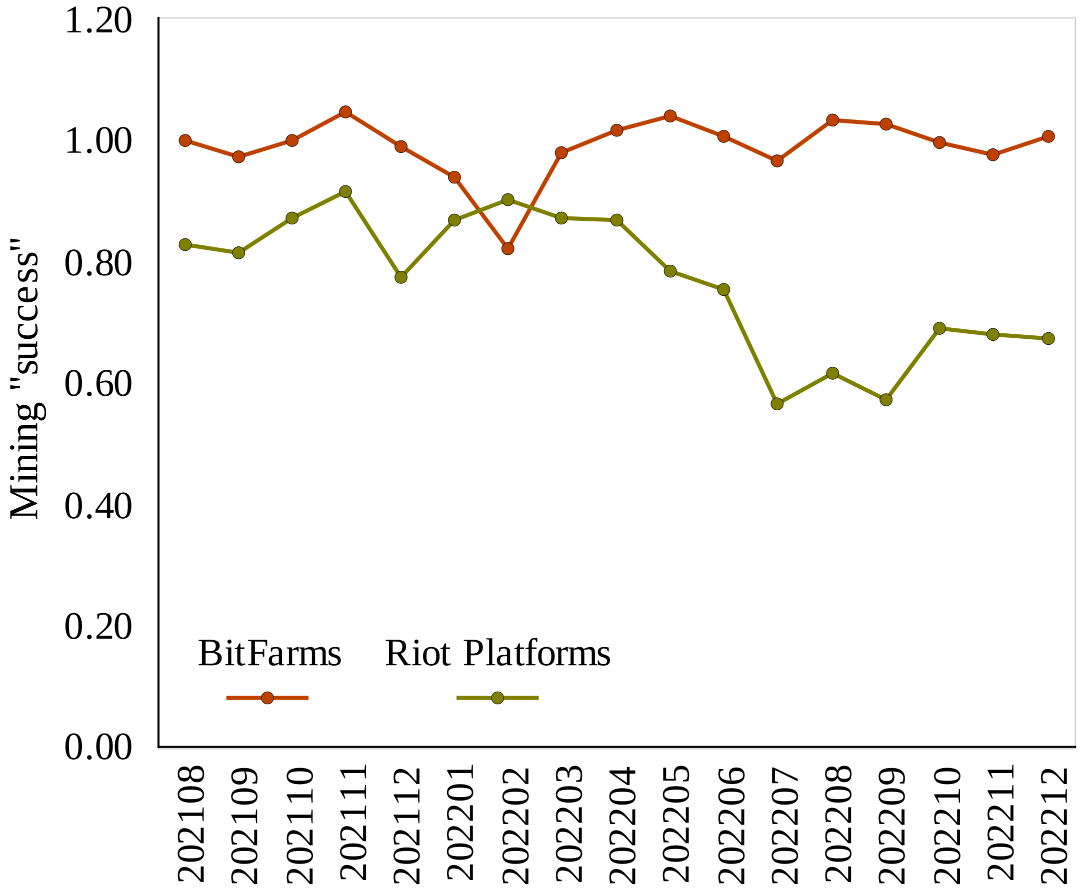


Figure 6
Enterprise value as a function of hashing capacity
The figure shows the estimated enterprise values (in millions) of 13 publicly traded bitcoin mining companies on January 13, 2023 as a function of their mining hash rates. Enterprise value equals equity value plus debt value minus the market value of bitcoin held in inventory. Debt value is estimated using the KMV model in Table 4, and bitcoin inventories are based on company reports and are assumed to equal zero for five companies that make no disclosures. The dark green line is a least-squares regression based upon the 13 company observations. The regression has an r^2 of 0.70.