BITCOIN MINING ECONOMICS

Explore the fundamentals of bitcoin mining

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Foreword: **JASON LES – CEO, RIOT**

BRAIINS Insights

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Contributors:
Drew Armstrong, Karim Helmy, Tom Masiero,
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BRAIINS

Braiins, established in 2011 and based in Prague, Czech Republic, is a global leader in the field of bitcoin mining.

The company specializes in the **development of software and hardware tools for bitcoin miners**, including the world's longest-running bitcoin mining pool and the first custom OS for bitcoin mining computers. Braiins' tools are used on hundreds of thousands of devices around the world.

You can learn more about the company and our offerings at braiins.com

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FARM TOOLBOX

STRATUM V2

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Foreword

Bitcoin has been an unstoppable force since its inception, having a profound impact on how the world perceives and interacts with money. At the core of this transformative new financial system is the innovation of proof-of-work mining. The application of mining in Bitcoin is what makes trustless consensus possible. It drives the decentralized issuance of supply to prevent the seigniorage of profits, and with the brilliant utilization of a difficulty adjustment algorithm, it ensures consistent timing of the Bitcoin blockchain regardless of conditions external to the network. Miners are responding to economic incentives, but their work ensures the foundation on which the Bitcoin blockchain drives forward.

As the CEO of Riot Platforms, Inc., one of the largest publicly traded Bitcoin mining companies, I have had the privilege of witnessing firsthand the remarkable growth and evolution of the Bitcoin mining industry. From its humble beginning of hobbyists mining on their laptops, Bitcoin mining has evolved to a multi-billion industry comprised of continuously improving technology, industrial-scale operations, publicly traded companies, and partnerships with the world's largest energy players.

Readers of "Bitcoin Mining Economics" will find a comprehensive exploration of the core concepts, intricacies, and cutting-edge developments that shape this dynamic new field. The goal of this book is to demystify the complexities surrounding Bitcoin mining and better explain its economic foundations, offering an insight into this captivating realm as the reader enters their own journey in Bitcoin mining.

The fundamentals of mining economics are critical to understanding how the Bitcoin mining industry functions and to better inform the reader on how to evaluate investing in their own or others' mining operations. Concepts such as hashprice, its determinants, factors influencing its volatility, and the strategies employed to optimize mining operations are critically important to finding success in this competitive ecosystem. Through detailed analysis and real-world examples, this book provides readers with the tools and insights needed to effectively navigate this rapidly changing landscape.

I can speak firsthand to the pivotal role capital markets play in the expansion and growth of Bitcoin mining. During the bear market of 2022, we, as an industry, witnessed numerous bankruptcies and restructurings amidst a challenging market environment. This book explores the dynamics of capital allocation within the mining industry, the intricacies of financing operations, and emerging trends in the market. The authors examine the complexities of navigating this unique landscape to give readers a heads-up perspective of both the challenges and opportunities that lie ahead.

One of the central themes explored in this book is the relationship between Bitcoin mining and energy sources. While the energy-intensive nature of Bitcoin mining has sparked debates about sustainability, the true story is the remarkable positive impact it has on stabilizing power grids and supporting generation development. The authors dive into these topics, examining the impact Bitcoin mining has on power grids and how, as an industry, we are transforming not only how we think about money, but energy markets as well.

“Bitcoin Mining Economics” celebrates the entrepreneurs, pioneers, and visionaries who have shaped this industry and continue to push the boundaries of what is possible. It is a testament to the power of Bitcoin and its supporting technologies, as well as the resilience of human ingenuity. It is therefore my hope that this book serves as a valuable resource for readers, whether they are seasoned professionals seeking to deepen their knowledge or curious minds eager to grasp the intricacies of this fascinating new industry. Together, let us advance the proof-of-work infrastructure of Bitcoin and drive human prosperity and freedom globally.

Jason Les, CEO Riot Platforms
June 15, 2023
Costa Mesa, CA

Preface

In the *Bitcoin Mining Handbook*, we aimed to help general bitcoiners, new mining industry professionals, and perhaps a proof-of-work-curious politician or two build a foundation of knowledge about how bitcoin mining truly works. Much of that content was originally created to clear up common misconceptions about proof-of-work (e.g., that finding a block is solving one big, ultra-complex math problem) and explain how various aspects of the mining industry and the bitcoin network function under the surface.

In *Bitcoin Mining Economics*, it‘s time to go deeper.

There are two really big trends right now in bitcoin mining that are shaping its future.

One is the continued blurring of the line between the bitcoin mining industry and the energy industry. In the last few years, we’ve seen major companies from the oil and gas, hydro, wind, solar, and nuclear sectors work directly with bitcoin miners to colocate mines that can improve the economic efficiency and overall production of their energy generation assets. At Braiins, we’ve also spoken to countless groups and individuals from the energy industry who are realizing how mining can help them build new generation projects that are more attractive to investors and less dependent on the accuracy of complex long-term market forecasting to ensure their economic viability. In short, miners are getting increasingly educated on energy, and vice versa. This trend is going to accelerate rapidly in the event that the bitcoin price follows past trends and sets new all-time highs in the future, perhaps during the 5th halving epoch that is expected to begin in March of 2024. It feels like we are just a short time away from seeing major energy companies begin to acquire bitcoin mining companies and build their own mining subsidiaries, and this will undoubtedly have a huge impact on the future of mining.

The other major trend is the maturation of the mining industry from a business and financial perspective. The majority of publicly traded mining companies have been experiencing their first brutal bear market during this 4th halving epoch, and nearly all of them are learning some lessons the hard way—from reduced or canceled growth forecasts and liquidated BTC treasuries to debt holes so deep that bankruptcy was the only way forward. With hindsight, it's easy to look back and pick apart all the bad deals and poor treasury management choices, but doing so wouldn't really be fair. Mining companies have been following their incentives, and due to the unsophistication of the investor market that's trading public miner stocks, the only way to keep up with the competition was to forecast huge hashrate growth and accumulate as much BTC on the balance sheet as possible. Now everybody is suffering the consequences of high time preference stock price maximization, and the survivors will likely be better for it. On top of that, the incredible drop in hardware prices (90%+ from peak for new-gen models) has created an opportunity for new entrants to come in and build during the bear market, hopefully learning from the mistakes of their wounded and fallen predecessors without needing to repeat too many mistakes themselves.

Some obvious takeaways that the industry has learned so far are: it's great to be off-grid / behind-the-meter, but if you're on-grid you‘d better make sure you have electricity prices locked in or hedged; locating all your hashrate in a place where the government actively works against you is asking for trouble; massive loans for machine and infrastructure financing are really risky without a good hedge on hashprice (wen hashrate marketplaces?); and of course, try to buy low and sell high next time ;-)

With that, let's get into some bitcoin mining economics! In this book, we're going to go into topics including mining with intermittent energy sources as well as utilizing stranded natural gas that might otherwise be flared or vented, the merits of immersion vs. air cooling infrastructure, the past, present, and future of debt capital markets in bitcoin mining, and the future of mining revenue as it becomes increasingly transaction fee-based in the halving cycles ahead. Some of this content was originally published two or more years ago, but it has all been reviewed and edited to be relevant at the time of publication in 2023. We hope you learn a lot and enjoy the bitcoin mining insights.

FUNDAMENTALS OF MINING ECONOMICS

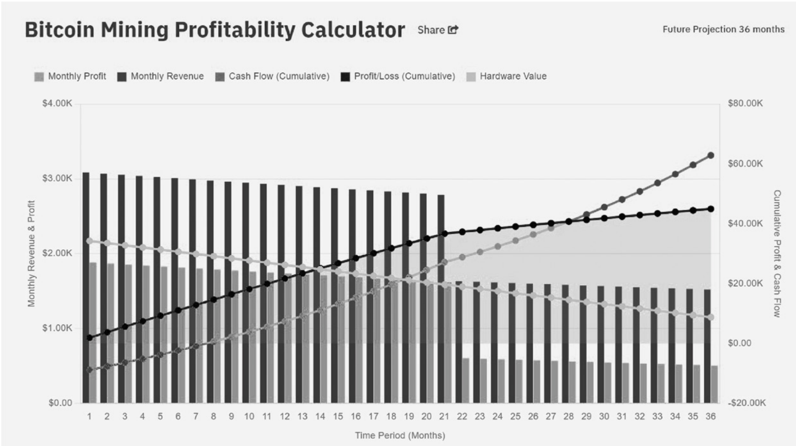
Your models are only as good as your assumptions.

At Braiins Insights (https://insights.braiins.com), we provide a Bitcoin Mining Profitability Calculator and Cost to Mine 1 BTC tool to help you model out your mining economics in great detail for various market conditions. However, these tools are dependent on the user to make realistic assumptions and to run multiple possible scenarios in order to get a decent big-picture overview of how viable a mining operation is and what can be done to optimize it.

Contrary to what the name may suggest, we aren't going to spend a lot of time in this section going over the basic inputs for our analysis tools one-by-one. Rather, we will hone in on a few of the most critical aspects of making useful future projections, such as the historical rates of change for network difficulty and BTC price, the correlation between hardware prices and hashprice in USD and BTC terms, and the difference between a miner's marginal and total cost to mine 1 BTC.

Hashvalue, Hashprice, and Rigprice

The key metrics at the heart of mining economic calculations, how they have changed over time, and how they might change in the future.



For those who aren't already accustomed to thinking in terms of hashprice and rigprice all the time, this will be a crash course to get you up to speed. And for those who are already well-versed, there might be some new things in here even for you. We'll start by breaking everything down into two parts—revenues and costs—and then take it from there.

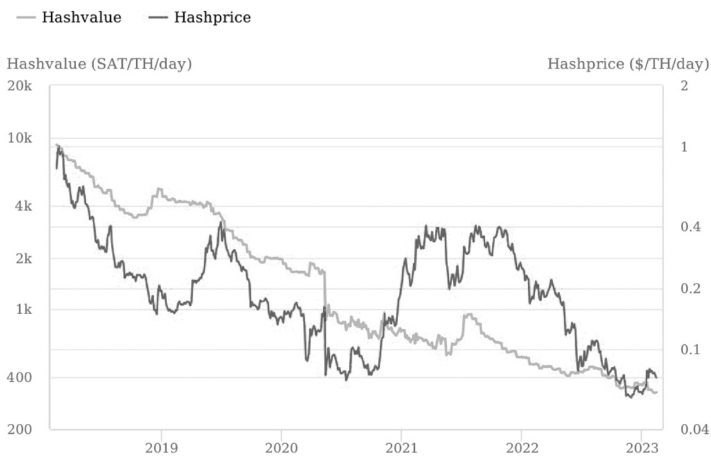
MINING REVENUE ACCOUNTING

A bitcoin miner's revenue is based on two things: the value of the blocks being mined and the amount of hashes they must compute to mine a block. In other words, the value of the block reward and the network difficulty target.

When you combine these two things together, you get a single metric, called ***hashprice***, which represents the $/TH/s/day that a miner earns, i.e. the daily amount of value that a miner will generate for every terahash/second of hashrate that they control.

Now, a lot of people have gotten confused over the years by the use of “price” in the name of a revenue metric. All this author can say is, I understand the confusion. Long story short, companies in the mining space (Braiins included) have been working for a while now on the very difficult task of building hashrate marketplaces for buying and selling physical hashrate, as well as trading hashrate derivatives. In that context, hash “price” makes a bit more sense, as it can signify the actual cost that a buyer is willing to pay for a unit of hashrate either on a spot (real-time) or forwards (long-term) market. Nonetheless, this author prefers the more intuitive term “hashvalue”, and as a result, the BTC-denominated version of hashprice (BTC/TH/s/day) is in fact called ***hashvalue*** on Braiins Insights.

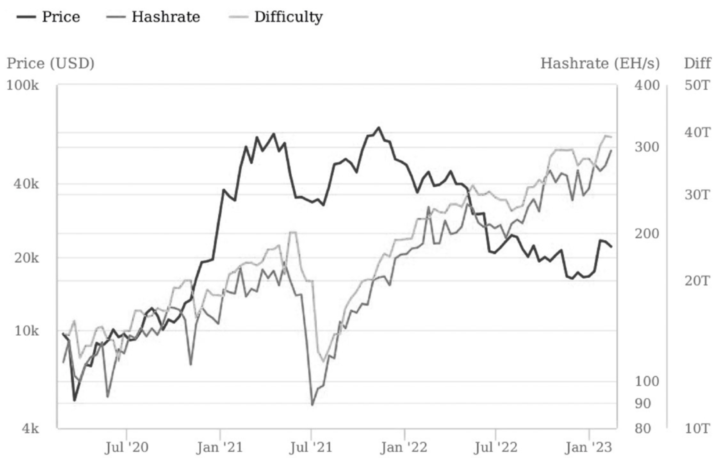
In the following chart, you can see hashvalue and hashprice on a logarithmic scale from 2018-2023. You’ll notice that hashvalue is far less volatile, which makes sense because it is impacted only by changes in network difficulty and the block reward value, where the block reward value is only fluctuating due to changes in the average transaction fees per block within a given halving epoch. Meanwhile, hashprice is much more volatile, as it’s the hashvalue multiplied by BTC price to get into fiat units.



Braiins Insights Chart showing Hashvalue and Hashprice on a Log Scale

There are a couple of key moments to point out in this chart. First is May 2020, in which you can see the steepest drop for both hashprice and hashvalue. This drop is a result of the 3rd halving that took place at block height 630,000 and cut bitcoin's block subsidy from 12.5 BTC per block to 6.25 BTC.

The second key moment occurs in mid 2021, when China began banning bitcoin mining in certain provinces before ultimately banning it outright just as the rainy season in China's hydropower-abundant Sichuan province was ramping up. While this didn't completely stop mining in China, and it's a safe bet that there are still many exahashes of hashrate running there today, it did make a sizable dent. As a result, network difficulty dropped from then all-time highs of just over 25 trillion to a low under 14 trillion, sending hashvalue up by nearly 50% in the process.



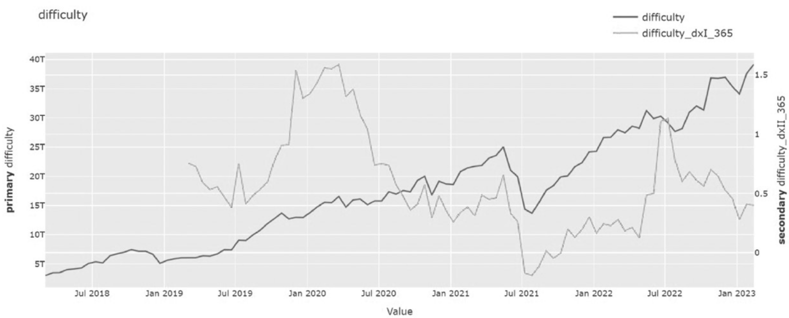
Braiins Insights Chart showing BTC Price, Hashrate, and Difficulty on a Log Scale

However, what you can also see is that bitcoin price dropped from highs just over $60k to the low $30k range before the massive drop in hashrate took place thanks to China's ban. So even as hashvalue practically doubled in a matter of weeks, hashprice merely recovered to where it had been before the latest 50% price drop. For miners who already had hashrate online outside of China when the ban occurred and who had the goal of accumulating as much BTC as possible, this was perhaps the greatest of all timelines. Just about 6 months later, difficulty was already pushing back towards new highs and lower transaction fees meant that hashvalue was trending towards all-time lows.

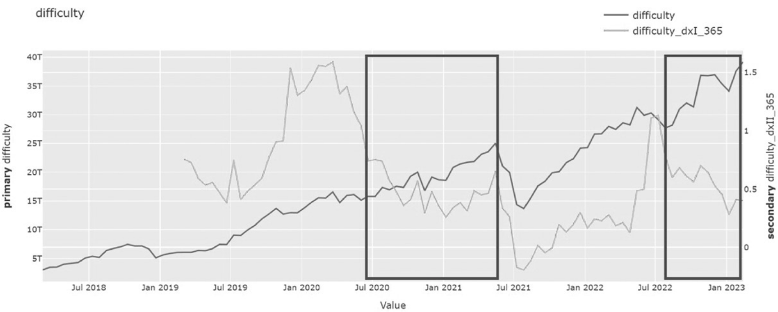
FUTURE RATES OF CHANGE IN BTC PRICE AND DIFFICULTY

When your goal is projecting future mining economics for a given operation, the most important assumptions that you'll make are for the changes over time in BTC price and network difficulty, as these will mostly determine the future hashvalue and hashprice. (The other factors are halvings every 4 years and transaction fees per block, which have been 1-2% of the total block reward for the majority of the time since July 2022.)

This means that we want to know more about the rate of change of network difficulty and BTC price in recent history. In the following chart, we calculated the 1-year rate of change in difficulty since 2018 and plotted it on the right y-axis, where a 0 value means 0% annual change and a 1 value means 100% annual increase.



Of course, the China mining ban adds an extra element of volatility to this data that isn't super likely to be seen again, at least not at such a big scale. Even so, we can see that the average annual change in network difficulty since the May 2020 halving is around 50%/year, with a brief period of being negative after the China ban and an equally brief period over 100%/year after a full year had passed following the ban and difficulty had recovered to new all-time highs



To mining industry veterans, 50%/year difficulty increases will sound quite tame—perhaps even too much so.

In the very early days of mining, network difficulty shot up exponentially as more people were learning about bitcoin and eventually using GPUs to mine instead of CPUs. Then ASIC hardware hit the market in 2013, and the efficiency gains in ASIC chips were so rapid and so large that most machines were made obsolete in well under 1 year as difficulty skyrocketed. Finally, with the launch of the Antminer S9 in late 2016, things started to slow down a bit and hardware lifespans extended into multiple halving epochs. In fact, there are still tens, if not hundreds of thousands of Antminer S9s brrrring away as these words are being typed, much to the chagrin of bitcoin mining e-waste alarmists including a certain integrityless Dutch central banker who publishes misinformed bitcoin hit pieces on the blog formerly known as Dogeconimist. Anyways...

Our takeaway is that the rate of change in network difficulty is slowing down as hardware efficiency gains decrease from one generation to the next, and as the scale of necessary energy capacity and infrastructure needed to increase network hashrate by 1% have become quite substantial. For more context on this, an average of approximately 6 EH/s of hashrate came online per month in 2022, and an average of nearly 10 EH/s of hashrate has come online per month from the lows of July 2021 until the highs at the time of writing in early 2023.

What does that look like in terms of power capacity?

Well, if we take the most popular hardware model online today, the Antminer S19j Pro, then 6 EH/s/month of hashrate equals around 200 MW of new power capacity every month. With total network hashrate now exceeding 300 EH/s (as of February 2023), this same monthly growth rate in absolute terms would require around 2.4 GW of new power capacity for miners for the year and would only result in about a 25% increase in total network hashrate.

Bitcoin ASIC Hardware & Power Capacity Calculator

☐ Show All | Filter Bitmain | Capacity 200 MW

Hardware Name	Consumption	Hashrate	# of Units	Total Hashrate
Antminer S9	1.16 undefinedkW	13.50 TH/s	155172	2.095 EH/s
Antminer T17	2.2 undefinedkW	40.00 TH/s	81818	3.273 EH/s
Antminer S17	2.52 undefinedkW	56.00 TH/s	71428	4.000 EH/s
Antminer S19 XP	3.01 undefinedkW	140.0 TH/s	59800	8.372 EH/s
Antminer S19j Pro	3.08 undefinedkW	104.0 TH/s	58441	6.078 EH/s
Antminer T19	3.15 undefinedkW	84.00 TH/s	57142	4.800 EH/s
Antminer S19	3.25 undefinedkW	95.00 TH/s	55384	5.261 EH/s
Antminer S19 Pro	3.25 undefinedkW	110.0 TH/s	55384	6.092 EH/s
Antminer S19j	3.25 undefinedkW	90.00 TH/s	55384	4.985 EH/s

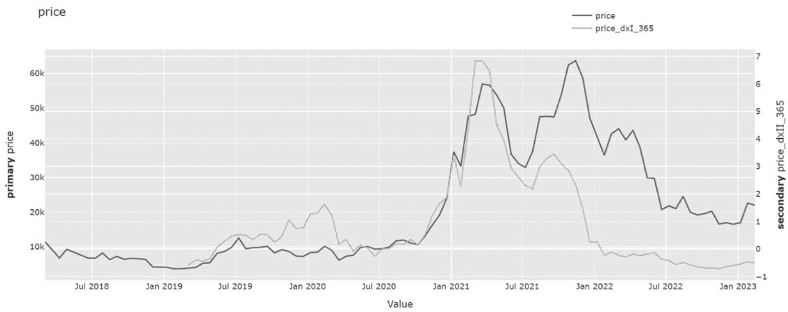
If we assume that all new hashrate will be from the most efficient hardware on the market today, Antminer S19 XP or equivalent 21.5 J/ TH efficiency, it would still take about 3.5 GW of new power capacity just to increase network difficulty by 50% from here (40T -> 80T).

The point is, even in the event that BTC price moons again in the future, bringing a significant amount of hashrate online to send difficulty soaring (but still lagging price) is going to be immensely difficult and time consuming.

At the same time, there are still a lot of stranded and underutilized energy resources all over the world, from flared and vented natural gas in North America, Siberia, Nigeria, and the Middle East to abundant hydropower in places like Paraguay, Ethiopia, and Kenya, not to mention new energy projects that this author believes will bring bitcoin mining to territories not yet tapped. There's plenty of space for difficulty to go up from here if price incentivizes it, but the 100%+ annual growth rate of the past is unlikely to repeat itself in the future.

For baseline estimates, 50%/year seems like a good guess for difficulty, with lows around 20%/year and highs of 80%/year. It's also important to keep in mind how far away the halving is, as it's pretty much guaranteed to have some hashrate drop off right after the halving unless price has recently done a 2x. (This is why there is a *Halving Difficulty Drop* input on the Braiins Profitability Calculator, so you can interrupt the long-term upward trend to reflect inefficient hardware being made obsolete by the halvings and miners with non-competitive electricity prices being forced to shut down.)

As for the other variable in hashprice, the price of bitcoin, we're probably still a couple decades away from low volatility. And the same 365-day rate of change calculation for BTC price that we did for difficulty doesn't help much.



Translating boom-and-bust cycles into a single value for annual rate of change is tricky. The method that this author is most fond of is broken down based on where we currently are in the cycle:

BTC in sustained time period below all-time high
Look at when price has exceeded the previous all-time highs in past market cycles and set a BTC price increment such that the timing is about the same but slightly more conservative. For example, BTC price hit a new all-time high above $20k in December of 2020, 3 years after it first set the high and 7 months after the halving. It set the most recent all-time high of $69k in November 2021, and November 2024 will fall 7 months after the anticipated date of the 4th halving. Given a price of $23k and 19 months until November 2024 at the time of typing, then we could conservatively guess 24 months to reach new all-time highs and put a 100%/year price increment. In this case, I'd consider 50%/year highly conservative and 150%/year as an attainable upper bound on bullishness.

BTC currently above last cycle's all-time high
Despite all the proclamations of "this time is different" and "we might enter a supercycle", the last cycle's bull market was not sustained. Granted, we've since learned that there was a huge exchange selling BTC which they didn't actually own to their customers, so we don't know where price would be today without this artificial inflation in bitcoin's liquid supply, but let's not digress further. As a mining analyst

or decision maker at a mining company, it's reckless to expect the good times to roll on for a long time when they never have in the past. Therefore, if there has been a new all-time high BTC price set in the last ~6 months, it's probably advisable to plan for a 2-3 year painful bear market to come in which network difficulty continues catching up to recent price gains while Number go Down for a while. In other words, plan for a repeat of 2022 with all-time low hashprice the next time we're in a bull market like 2021.

Align difficulty and price increments

One last point to mention is that difficulty and price are correlated, even though difficulty moves much, much slower. If you're doing a long-term profitability projection, it makes sense to adjust your expectation for the average annual change in difficulty based on your price increment. For instance, if I model a bullish scenario with 150%/ year average annual price growth, I should also assume difficulty will grow as fast as physically possible, which is maybe 80%/year given all the factors discussed earlier in this chapter. Meanwhile, a bearish long-term scenario for price should mean slower difficulty growth. Unless, that is, the industry average cost to mine 1 BTC is well below the current BTC price after a recent bull market, in which case you could accompany a 0% price increment with a 50% difficulty increment to prepare for some pain.

And speaking of industry average cost to mine 1 BTC... let's move on to the other side of the equation in bitcoin mining economics: costs.

Rigprice and Marginal vs. Total Cost to Mine 1 Bitcoin

In the previous chapter, we mentioned that there was some confusion about the "price" in hashprice and what that term refers to. When people were hearing hashprice and thinking of a cost, the metric they were thinking of is what we're going to refer to as ***rigprice***: the $/TH capital expenditure for purchasing mining hardware. For example, a 140 TH/s Antminer S19 XP with a rigprice of $35/TH would have a total unit price of $4900 per machine (140 TH/s * $35/TH).

Rigprice and hardware CapEx in general are going to come up again throughout the remainder of this book, as their importance tends to be less understood by new professionals in the mining industry, analysts covering the space, and curious bitcoiners dipping their toes into mining relative to the importance of electricity price. That's especially true if you care about your bitcoin-denominated cash flow and return on investment—things like when, if ever, you'll mine more bitcoin with a certain mining rig than you could have just bought if you invested the money directly into bitcoin and never mined.

Pretty much everybody who's familiar with Proof of Work knows how important it is to get cheap power. We have metrics like Break Even Electricity Price to track the shut-off price for each popular hardware model at its stock efficiency level, and we went into depth about optimizing that efficiency through things like 3rd party firmware with autotuning in the *Bitcoin Mining Handbook*.

HW Model	Break-Even Electricity Price
[Bitmain] Antminer S9	0.03 USD/kWh
[Bitmain] Antminer S17	0.06 USD/kWh
[MicroBT] Whatsminer M21S	0.05 USD/kWh
[MicroBT] Whatsminer M20S	0.06 USD/kWh
[MicroBT] Whatsminer M31S	0.07 USD/kWh
[Bitmain] Antminer T19	0.08 USD/kWh
[MicroBT] Whatsminer M30S	0.08 USD/kWh
[Bitmain] Antminer S19	0.08 USD/kWh
[MicroBT] Whatsminer M30S+	0.09 USD/kWh
[Bitmain] Antminer S19j Pro	0.10 USD/kWh
[Bitmain] Antminer S19 Pro	0.10 USD/kWh
[Bitmain] Antminer S19 XP	0.13 USD/kWh

Rigprice, though, is a whole other ballgame. Overpaying for hardware near the peaks of a bull market has sent many a mining company to the gallows over the years, some recently bankrupt mining companies included (although variable power prices played a part in several cases as well). On the other side of the coin, a well-timed bear market hardware purchase can outperform buying bitcoin directly in the short-term, even without accounting for the mining revenue from running the machines.

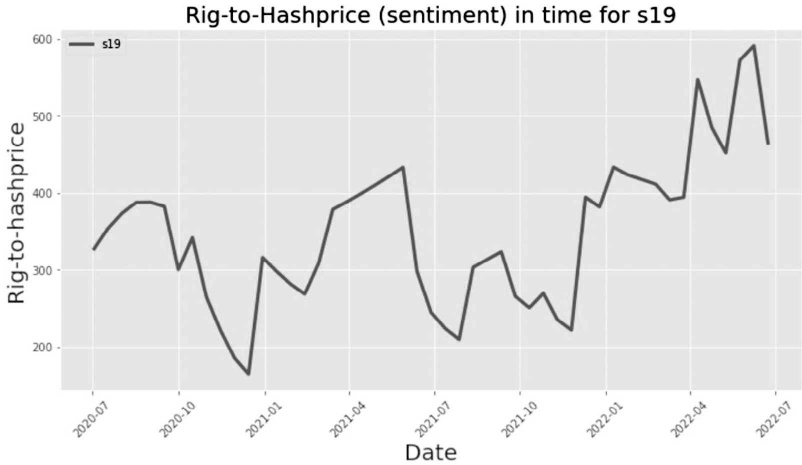
In fact, one of the underappreciated reasons for why China dominated mining throughout the ASIC era up until the CCP's ban was that Chinese miners had a huge advantage due to their proximity to hardware manufacturers. They received the best rig pricing, lowest shipping costs, and they could plug machines in much sooner than western miners after ordering them because they didn't have overseas shipping and delays at customs to worry about. Even if Chinese miners hadn't had access to such cheap power, their advantage on rig prices would have made them a mining powerhouse.

RIG-TO-HASHPRICE SENTIMENT ANALYSIS

There's a problem that miners have faced since the early days, but which has become far bigger in recent years. That is, when it's the best time to expand (bear market), capital is scarce because investors and the general public begin doubting bitcoin's resilience, whereas when it's the best time bolster the balance sheet with a bunch of BTC and cash (bull market), capital is flying around and funding an expansion is far easier.

This was especially true in the past couple of years with public mining companies, as the market rewarded them for future hashrate projections and BTC on the balance sheet without care for how that was being achieved or what risk management strategies were in place in case of a bear market.

While it may not be reasonable to expect the general public to get a lot smarter about mining, this author has no doubts that those in the industry have learned valuable lessons. One of the things that I wanted to do in 2021 and 2022 as I saw people around me taking big bets by buying hardware at $70+/TH was to develop some simple metric for quantifying sentiment on mining hardware. That led to the calculation of **rig-to-hashprice** and **rig-to-hashvalue**, where rig-to-hashprice is the hardware rigprice ($/TH) divided by hashprice ($/TH/s/day) and rig-to-hashvalue is the hardware rigprice (BTC/TH) divided by hashvalue (BTC/TH/s/day).



In a nutshell, the lower the rig-to-hashprice or rig-to-hashvalue, the better the timing probably is to buy hardware. With rigprice in the numerator, higher hardware prices translate to higher rig-to-hashprices. With hashprice / hashvalue in the denominator, higher daily revenue per terahash translates to lower rig-to-hashprices / hashvalues. If hashprice and rigprices go up or down at exactly the same rate, it basically means that the expected CapEx break even period (assuming a constant hashprice after purchase) for that hardware is staying the same.

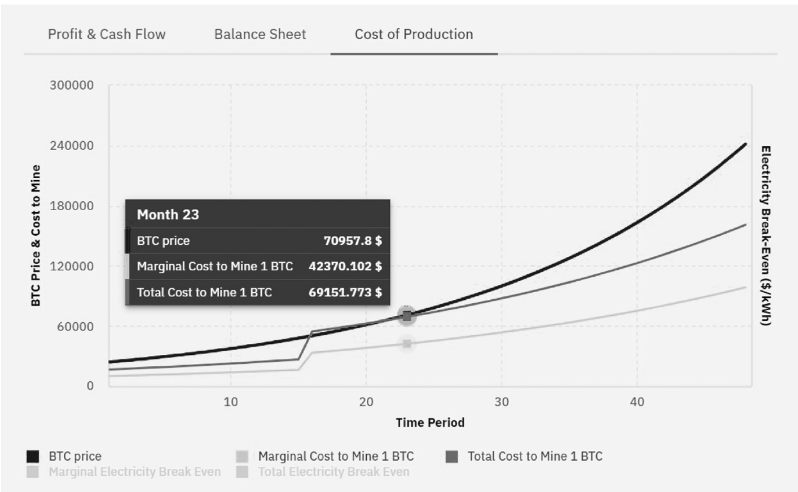
These metrics are unitless, but what they are really showing is market sentiment. *What are miners willing to pay for hardware relative to the current revenue that hardware can produce?*

By looking at the metric historically, we can put hardware prices into better context with market conditions and sentiment at the time, as rigprice takes care of the cost side and hashprice / hashvalue takes care of the revenue side.

INCORPORATING HARDWARE CAPEX INTO COST OF PRODUCTION

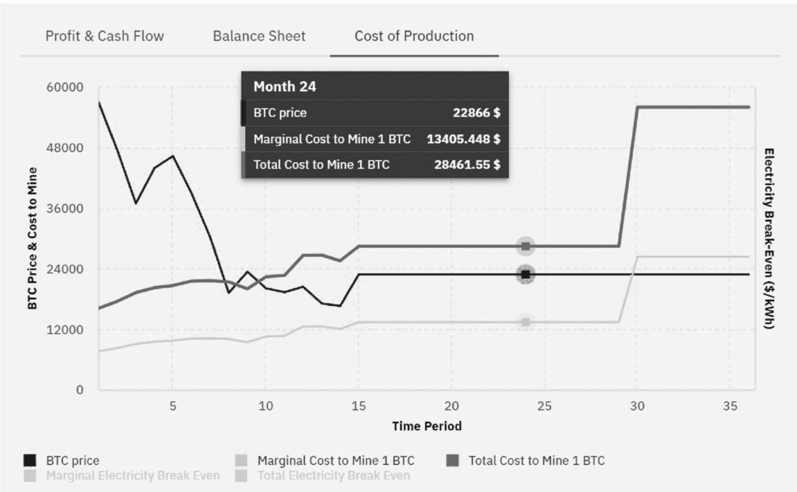
As for making decisions about hardware purchases today, one of the best ways to do it is to model both your ***marginal*** and ***total cost to mine 1 BTC***. The *marginal* cost to mine 1 BTC stat is computed very simply by dividing your monthly OpEx (all-in electricity costs) by monthly BTC mined (after revenue fees such as pool and dev fees). *Total* cost to mine 1 BTC includes the marginal cost but adds to it the depreciation of assets in order to factor in CapEx.

For example, if you spent $200,000 on hardware that will fully depreciate in 5 years, then the total cost to mine will include an additional $3,333 per month ($200,000/60 months) in your costs. To visualize this, let's suppose that the $200,000 for hardware CapEx is purchasing 40 of the 140 TH/s Antminer S19 XPs at $35/TH, plus a small cushion for shipping. We'll assume an electricity price of $0.06/kWh, starting BTC price of $23k, difficulty of 40T, a price increment of 80%/year, and a difficulty increment of 50%/year.



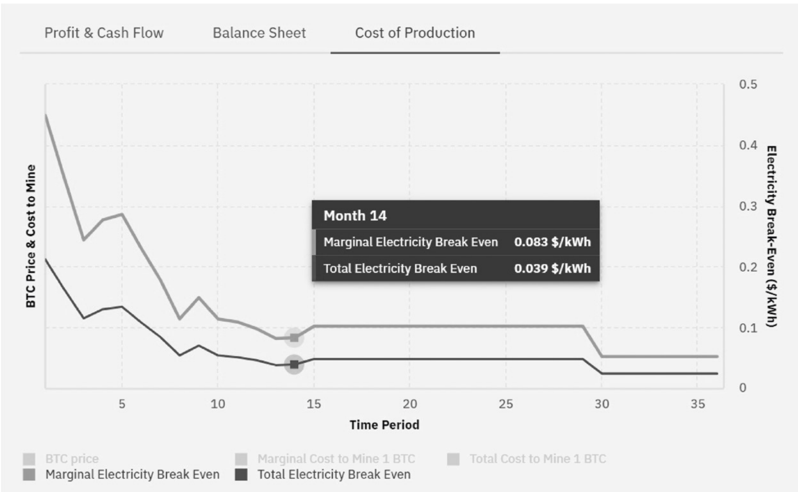
You can see that BTC price growth outpaces the increase in this miners' cost to mine 1 BTC. There is a 6-month period after the halving during which the BTC price is below the miner's total cost to mine 1 BTC, meaning that they would record a net loss after depreciation for those months while still bringing in solid profits on their marginal cost to mine 1 BTC.

However, what might this look like for a miner who was anticipating a bear market in 2021 when hardware prices for new-generation models were exceeding $100/TH? Well, let's take the same $200,000 and invest it into 22 104 TH/s S19j Pros at $86/TH in December 2021 to find out. This simulation will use historical data until the current month, then it will have price and difficulty increments of 0%, meaning that hashprice would stay flat.



Now we can see more clearly how much hardware prices matter. The miner's margins are getting squeezed from the first month of deployment, and by Month 8 the BTC price has dropped below their total cost to mine 1 BTC. Unless they've already paid off the $200k—not the case here, as cumulative profit is only $92,000 in Year 1—they are now operating on too slim a margin to keep up with their hardware payments. And that's in an impossible hypothetical scenario where they have a 0% interest loan with a period of 5 years. Now consider the 12-24 month loans with 8%+ interest rates that were more common at that time, and it becomes pretty clear why so many miners have liquidated their treasuries, sold off assets, put a halt to scaling plans, and even filed for bankruptcy.

Incidentally, this also helps explain why total network hashrate has continued climbing to above 300 EH/s at the time of writing even though price remains 70% down from all-time highs. Miners don't shut off when their total cost to mine 1 BTC is below the BTC price, only when their *marginal* cost to mine is below the BTC price. A miner who paid $80/TH for some S19j Pros in late 2021 is certainly feeling the pain in early 2023… but as long as their electricity price is below $0.08/kWh, they'll keep their machines brrrring along and keep chipping away at initial CapEx investment, albeit far too slowly to see positive returns anywhere on the horizon.



Once deep into a bear market, it’s just a game of survival. Those with strong balance sheets will acquire machines and infrastructure on the cheap from those who are hanging on to the edge of the cliff by their fingertips, just hoping to hang on until Number go Up bigly. Others will continue to build and scale quietly, positioning themselves for the next bull run.

One can only hope that the analysts and investors who allocate capital to miners will have learned some lessons for the next bull run as well.

DEBT CAPITAL MARKETS FOR BITCOIN MINERS

In this two-part series, we will provide a high-level overview of the past, present, and future of debt in bitcoin mining. Part I explores the genesis of debt in bitcoin mining and the most common structures. Part II discusses key considerations for borrowers and lenders, the effects of leverage on returns, and how the market might evolve in the future.

This content was originally written for the Braiins blog by Drew Armstrong. Drew is the President and COO of Cathedra Bitcoin, a company that believes sound money and abundant energy are the keys to human flourishing. Prior to joining Cathedra, he was a founding member of Galaxy Digital’s bitcoin mining team and helped build out Galaxy's mining equipment finance product. Drew began his career at Barclays' investment bank, where he focused on the origination of esoteric securitized products, such as data center securitizations and collateralized fund obligations. His views here do not reflect those of any of his past, present, or future employers.

At the end of this section, we’ll also include a chapter about analyzing bitcoin mining pool and miner holding / spending behavior, originally written for Braiins by Karim Helmy. Karim has a background in statistics and machine learning, and previously spent time on the research teams at Coin Metrics and Galaxy Digital.

The History of Debt in Bitcoin Mining: Part 1

Disclaimer: this series is biased toward western markets (specifically North America). While China was the Mecca of bitcoin mining long before industrial-scale projects arose in the US, the author and audience alike are likely more focused on the western hemisphere. As such, we will focus exclusively on the debt capital markets in North America, despite the fact that many similar products were offered in China and other countries.

In the 14 years since the Bitcoin network launched, we have seen bitcoin miners evolve from cryptography enthusiasts hashing with CPUs, to profit seekers investing in more and more efficient hardware (i.e., the lowest energy consumption per hash). From CPUs, miners quickly moved to GPUs, FPGAs, and finally to their own application-specific hardware, bitcoin mining ASICs.

In these early days, there was little to no debt financing available to bitcoin miners. The reasons were various:

1. The useful life of mining hardware was very short, with certain models remaining competitive for only 6 – 18 months before newer, more efficient models rendered them economically obsolete.

2. The short lifespan of ASICs paired with bitcoin's price volatility led to highly volatile returns for mining investments, making assets and projects very difficult to underwrite.

3. Most lenders didn't understand bitcoin or bitcoin mining. And with bitcoin mining being such a small market (annual mining

revenue didn't exceed $1 billion until 2017), there was little incentive for lenders to pay attention.

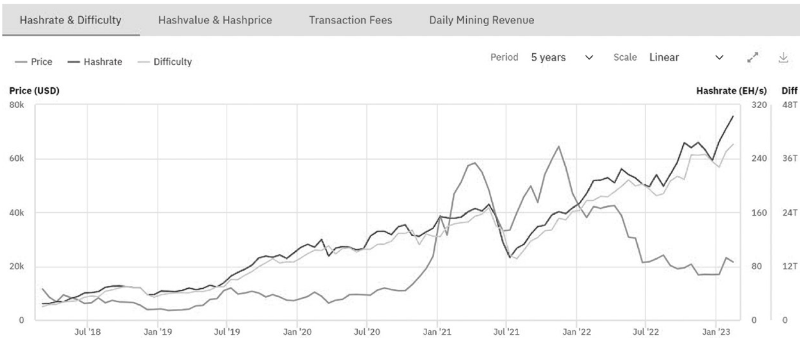
4. The "industry" was still immature; participants were aggressive, and often unprofessional. Many of the new mining companies and hardware manufacturers proved to be outright scams (I leave the reader to judge how much this has changed).

For the above reasons and others, bitcoin mining has tended to lag the rest of the "crypto" industry in terms of debt products. Debt has long been available for traders on offshore exchanges looking to lever up 100x on perpetual swaps, but it took until 2017 for bitcoin-backed debt to become available en masse to retail and institutional borrowers in the US. Retail bitcoin-backed debt was pioneered by companies like Unchained Capital and BlockFi, while trading houses like Genesis and Galaxy Digital provided the early collateralized debt products for institutions. In this era, most large bitcoin-backed loans were bespoke trades offered to hedge funds and sophisticated high net worth individuals, but the ultra-low interest rate environment and bitcoin's utility as pristine collateral attracted more capital and lenders to the asset class. The price appreciation of bitcoin ("number go up") also played a role, as more individuals and institutions looked to borrow against their bitcoin.

In the mining world, the 2017/2018 era also saw the first publicly traded bitcoin miners, with the likes of Riot Blockchain (which pivoted from a pharmaceutical technology company to bitcoin mining in 2017), DMG Blockchain, Hive Blockchain (which pivoted from a minerals exploration company in 2017), Hut 8, and Fortress Blockchain (now Cathedra Bitcoin) leading the charge. Others soon followed, with Bitfarms going public in 2019 and Marathon Digital completing its pivot in 2020 (after an initial bitcoin mining pilot in 2017). Outside of public markets, this era also saw the rise of then-private, "institutional" bitcoin miners in North America like Argo, Compute North, Core Scientific, Griid, Greenidge Holdings, and others.

These companies were primarily financed with equity; however, debt financing for bitcoin miners also began to emerge. In 2018 Galaxy Digital issued a $16m term loan to Hut 8 to finance new mining infrastructure, collateralized by bitcoin and infrastructure. The year 2018 also saw the founding of Arctos Capital and Blockfills, early pioneers in ASIC-backed debt in North America. Shortly thereafter DCG and Galaxy Digital both spun up their own mining businesses each with their own financing products for miners (Foundry (2019) and Galaxy Digital Mining (2020)).

From 2019 through 2020, a variety of smaller debt transactions were executed, as capital-deprived miners sought whatever forms of financing they could during the bear market. The lower velocity of the bear market also provided lenders the opportunity to fine-tune their structures, underwriting, and servicing capabilities.



Data from Braiins Insights

The growth of debt during this period was enabled by a variety of factors:

- Commoditized hardware. The 2018 crash drove many hardware manufacturers out of business (or at least atrophy into insignificance). By summer 2019, the hardware market was dominated by Bitmain, Canaan, and MicroBT. This greatly simplified the buying and selling of machines, with "rigs" becoming increasingly fungible. These manufacturers released roughly similar machines (in terms of efficiency) on roughly similar timelines.

- Longer ASIC lifespans. The Bitmain Antminer S9 was first released in 2016 but was still in wide use up until the 2020 halvening (arguably, it still is). This suggested that ASICs were now investible for the long-term, and that step-changes in hardware efficiency were perhaps a thing of the past. Tangentially, these first two factors also led to an increasing focus on power costs in mining, as access to the latest hardware no longer provided a durable competitive advantage.

- The growth of mining in North America. Due to its permissionless nature, anyone can mine bitcoin anywhere in the world. However, the United States and Canada's robust capital markets, abundant energy, and respect for property rights led to a meaningful increase in mining investments here from 2017 onward. This growth accelerated in 2021 following a bitcoin mining ban in China, as miners sought refuge in the regulatory environment of North America.

- Near-zero interest rate environment. As mining became more and more common in the epicenter of the global financial system, pockets of yield-starved capital salivated at the prospect of 8 – 30% debt (despite the obvious risks).

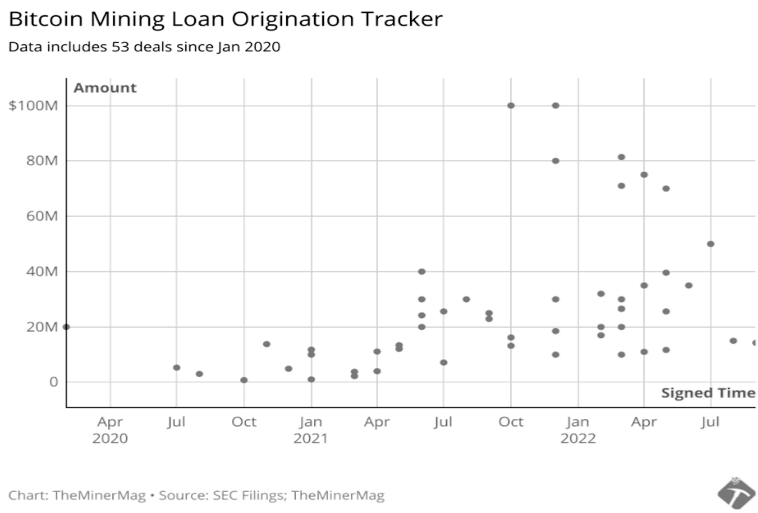
- Industry "maturation." The emergence of the aforementioned "institutional" mining companies gave the sense that this was now a real industry that could be trusted with credit. Many of these companies were run by converts from the 2017 bull run, bringing with them corporate sensibilities and relationships from other industries. Many thought the days of Shenzhen "chicken shack" mining were over, the network instead to be dominated by "Big Box Miners," with hyperscale data centers built atop freshly waxed floors.

- Number go Up (“NgU”). After bouncing back from the bottom of $3k in Q4 2018, it became increasingly clear that bitcoin was here to stay. And the rally in 2019 gave many hope that they would see the moon once again (soon™).

By the end of 2020, bitcoin mining debt capital markets had expanded to include a variety of competing lenders (Foundry, Galaxy Digital, NYDIG (which acquired Arctos), BlockFi, and others) offering a variety of debt products.

The foundations were laid. So, when bitcoin price took off in Q4 2020/Q1 2021, a boom in mining investments followed. Throughout 2021, equity capital flocked to bitcoin miners, pumping mining stonks in the process. These rising asset and equity values enabled miners to access increasing amounts of debt. Highlighting this point, several large equity raises of 2021 were accompanied by large debt facilities. As this period also saw the rise of ASIC “futures orders,” it even became possible to secure debt financing on machines that had not yet been delivered. The “old” generation of “institutional miners'' used this as an opportunity to catapult themselves to hyperscale. Simultaneously a variety of new entrants jumped onto the scene with multi-billion-dollar SPACs on zero deployed hash rate.

One can’t help but admire the supporting macro factors that contributed to the perfect storm of this capital binge for North American miners. The COVID stimulus left many markets flush with capital. Energy prices remained low as the commodity bear cycle played out its final act. Bored Patagonia-clad PE bros with a recently piqued interest in “crypto” sought to take advantage of the public/private market arbitrage of hash rate valuations, in hopes their returns might bankroll yachts and bottle service at E11even. All while China banned bitcoin mining, suppressing hash rate during bitcoin’s scenic route from $60k down to $30k and then back up to $69k



Source: TheMinerMag

But like all binges, the bitcoin mining hype cycle of 2021 was followed by a brutal hangover. The bear market of 2022 has seen many darlings of the last few years turn into distressed assets. Several large-scale public miners have been forced to restructure their balance sheets or file for bankruptcy.

And while debt may have been a new tool for bitcoin miners, credit markets have been around for thousands of years, and the key principles of debt are largely unchanged. In this next section, we will explore these principles, before evaluating the current array of bitcoin mining debt products.

PRINCIPLES OF DEBT

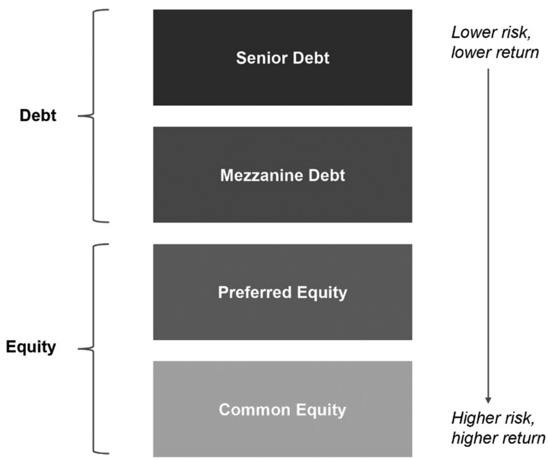
If you consider yourself fluent in the concepts and parlance of corporate fuh-nance, feel free to skip this section.

Wikipedia defines “debt” as “an obligation that requires one party, the debtor, to pay money or other agreed-upon value to another party, the creditor.” Such obligations can take many forms, but there are a few key principles that underly any piece of debt.

CAPITAL STACK OVERVIEW

To understand debt, first one must understand the idea of the “capital stack.”

For our purposes, all forms of financing can be grouped into two buckets: debt and equity. Debt holders are considered “contractually senior” to equity holders. This means that debt holders have first claim to the assets and are therefore paid out first in the event of a bankruptcy or liquidation. As a result, debt is considered “less risky” than equity, and therefore has a lower expected return. The debt and equity portions of the capital stack can be segmented further; in order of seniority: senior debt, junior or mezzanine debt, preferred equity, and equity. There could also be multiple types of debt or equity that have the same level of seniority or “pari pasu” with each other.



The main reason you would try to fund an enterprise with debt instead of equity is to enhance returns. If you want to buy a $10 project, you can either use $10 of your own money, or you can borrow $5, and—so long as you service the debt—can keep all profits (after debt service) for yourself (on a lower denominator of invested capital). We will explore the impact of leverage on bitcoin mining returns in more detail in a later section.

Lenders structure debt facilities with the goal of getting paid back full principal and interest regardless of other exogenous factors. To do so, lenders seek to give themselves as much protection as possible; “protection” meaning tools that allow them to minimize the risk of not getting their money back. These tools are frequently referred to as “credit enhancements” and come in several forms.

Creditworthiness

The lender will first evaluate the overall creditworthiness of the borrower. Creditworthiness is a measure of the borrower’s ability to pay back the lender. Less “creditworthy” borrowers will typically have additional credit enhancements to increase the lender’s comfort in getting repaid.

Collateral

The simplest form of “credit enhancement” is collateral. Lenders often require borrowers to pledge assets to “collateralize” the loan. This means that if the borrower were to fail to repay (or “service”) the debt, the lender could claim and liquidate the collateral. For example, if you buy a house using debt financing from a bank (take out a mortgage), you pledge your home to the bank. If you fail to make good on your debt payments, the bank can reclaim your house (foreclose).

Debt that is backed by a specific asset (a car, house, or bitcoin mining ASIC) is typically referred to as “asset-backed,” though like all finance jargon, the boundaries of the definition can be murky. In general, if debt is being used to finance the purchase of an asset, lenders will require that asset to be part of the collateral, but lenders might also request additional collateral. Additionally, just because a loan is “asset-backed” doesn’t mean the creditworthiness of the borrower is no longer relevant; asset-backed lenders focus on the overall creditworthiness of the borrower plus the valuation of the underlying assets.

The value of collateral relative to the amount of debt is very important. This ratio has a variety of names, but the most common is Loan-to-Value or “LTV” for short (other variations include “collateralization ratio” and “advance rate”). LTV is calculated as the size of the outstanding principal (the “L”) divided by the value of the collateral (the “V”). This provides a simple way for lenders to calculate their protection in the event they had to foreclose on the loan. For example, if a lender had to foreclose on an 80% LTV loan and liquidate the collateral, the asset price could fall by 20% before the lender took a hit. In other words, the higher the LTV, the riskier the loan. This example also demonstrates the importance of collateral liquidity and volatility; the more liquid and less volatile the collateral, the less risky the loan.

Some loans do not require collateral to be pledged to the lender; these are called “unsecured” loans as the debt is not “secured” by any collateral. Lenders will still consider the borrower’s assets and credit worthiness when sizing and pricing unsecured loans, the lender just has no specific legal claim (or “perfected lien”) against any assets. These loans are typically only available to people and organizations with strong credit credentials, as a loan secured by specific collateral has a lower risk of loss than an unsecured loan. Such loans are rarely available to bitcoin miners.

Covenants

As means of further protection, lenders often also stipulate specific rules around what a borrower can and can’t do; such rules are called “covenants.” Covenants might stipulate the exact use of an asset, certain rules around other activities of the borrower, or might require certain actions from the borrower should things happen that are entirely outside of their control (e.g., margin calls or uptime requirements).

Cost of capital
The above will all help determine the cost of debt (the interest rate). This cost of debt stems from the time value of money. The lender needs to be compensated for giving their capital to the borrower. The amount they need to be compensated is based on the probability of repayment. The riskier the debt is perceived to be, the more expensive that debt will be. In the words of Art Lyon, "There's no bad risk, just a bad price." Notably, the price of risk varies dramatically with market conditions.

Likewise, a lender's cost of capital is also important in determining the interest rate a borrower pays. A lender can only offer loans at a cost of capital that is higher than the cost they pay. In fact, a lender's whole business model is lending out money at a higher interest rate than their own cost of capital; the difference between their interest income and interest expense is their profit, or in debt-speak their "net interest margin" ("NIM" for short). For this reason, in emerging debt capital markets, the cost of capital is typically high as the first lenders likely have higher cost of capital themselves. As the market matures, larger lenders with lower cost of capital often push out these pioneer species by undercutting their rates.

Back-end financing
To this end, the existence of a secondary market for loans in an asset class can influence the cost of debt for those loans. If a lender can sell loans to other investors, then they can lock in a return and free up capital to generate more loans, which can drive down the cost of debt for borrowers. This is the principle behind securitization markets, and is a large reason why certain forms of debt like car loans and mortgages are so cheap. The larger the secondary market for these loans, the easier it is for lenders to originate and distribute, earning net interest margin in the process.

DEBT PRODUCTS FOR BITCOIN MINERS

The above principles underly all debt, but most industries have a limited array of readily available debt products, typically tried and true structures that have stood the test of time. We will now walk through the existing universe of debt products available to bitcoin miners.

Asset-backed debt As a reminder, asset-backed debt refers to loans backed by a specific asset. There are three main categories to consider: bitcoin-backed, ASIC-backed, and infrastructure-backed.

Bitcoin-backed debt is one of the oldest structures available to bitcoin miners. The logic is simple: a miner can deposit bitcoin as collateral to the lender and receive a fiat-denominated loan in exchange. Bitcoin has many properties that make it particularly attractive collateral; it's a digital bearer asset that trades 24/7 on a variety of highly liquid venues. As a result, it typically offers the lowest cost of capital for bitcoin miners. However, bitcoin's price volatility means LTVs can fluctuate dramatically; for this reason, lenders often have margin call provisions (if bitcoin falls below a certain price, the borrower needs to contribute additional collateral or repay part of the loan). The interest rates for these loans vary depending on the lender and market conditions, ranging from 4 – 12%. The loans have varying terms, but they typically don't amortize, meaning there may not be any mandatory principal payments until the maturity date.

ASIC-backed debt emerged as the structure du-jour during the last bull market. These loans typically had 18-month terms for an all-in cost of capital ranging from 13 – 28%. This is notably more expensive debt than bitcoin-backed loans, but it gave new miners without large bitcoin treasuries access to a new pocket of capital. In some transactions, miners could even finance machines before they were delivered (e.g., if a miner entered into a futures order, they could secure debt financing before the machines were deployed). However, once the financed machines are plugged in, the loans start amortizing (meaning principal is paid down gradually over the term). Similar to bitcoin-backed debt the value of the collateral (ASICs) can be quite volatile, resulting in similar LTV fluctuations. Unlike bitcoin-backed debt, however, it's hard to employ a margin call on ASICs. This has caused some lenders to offer low LTVs (sub 50% in some cases), but even still, the market turmoil of H2 2022 has resulted in many such loans becoming undercollateralized (LTVs > 100%). In terms of covenants, these loans might stipulate certain uptime requirements, prohibit the use of firmware and immersion, or other operational rules to ensure the value of the collateral is preserved.

Infrastructure-backed loans for bitcoin miners also appeared in the last 24 months, allowing miners to gain financing on the supporting infrastructure at a mining site. The loans range from utilities financing substations to mining savvy lenders providing leverage against containerized data centers. Infrastructure-backed lending (or "project financing") is quite common in other industries (including and especially energy), however these traditional lenders typically are not comfortable lending to bitcoin miners. Legacy industries are often able to borrow against infrastructure at higher LTVs, lower interest rates, and over longer terms (up to five years). But given the volatility of bitcoin mining, miners likely only have access to such loans at materially worse terms than traditional industries like energy. The primary lenders currently serving bitcoin miners with infrastructure-backed debt are either the small subset of legacy institutions who have gotten comfortable with bitcoin mining risk (e.g., certain utilities and energy infra lenders) or smaller lenders who are comfortable taking a bitcoin miner's power or data center infrastructure as collateral. Infrastructure-backed debt is similar to ASIC-backed debt in that the collateral is a physical asset that can be liquidated (in theory at least), but there is much wider variance in the terms. These loans have yet to become a meaningful portion of the market, but they do exist.

CORPORATE DEBT

Instead of borrowing against a specific asset, miners also might choose to borrow money at the corporate level. A common example of this would be a "Senior Secured Term Loan," which typically involves an "all asset lien," meaning that the lender would take substantially all the borrower's assets as collateral. These loans can also have more complex features, such as rules around accessing some proceeds only after certain operational achievements. There are a few benefits from the lender's perspective: first, the structure is simpler as there is little risk of multiple pieces of debt that may be in conflict with each other; second, the lender has a claim to all cash flows from the business not just specific assets; and third, if the borrower does default, the lender can just take ownership of the existing operations without being forced to sell collateral on a potentially illiquid market. From a borrower's perspective, these loans are a simple way to get debt financing, but they offer less flexibility. These loans are typically only available to large miners and may have unique covenants and rules around unlocking proceeds. It's worth calling out that such loans have not been the primary forms of debt financing for bitcoin miners, but they may become more common in the future.

There are other types of corporate debt as well (e.g., convertible debt and other bespoke structures), but they are not common enough to warrant evaluation in this essay.

SUMMARY COMPARISON

It is worth flagging that this table is obviously prone to fluctuations in the market (bitcoin price, mining economics, broader macro factors, etc.) as well as borrower-specific considerations. This overview of different structures should be viewed as a high-level map, outlining the current landscape of debt for bitcoin miners (and perhaps provide context for some of the recent news in bitcoin mining).

Next, in Part II, we will look at some high-level considerations for lenders and borrowers alike, play with some math to see the effects of leverage on bitcoin mining operations in a variety of market conditions, and lastly reflect on how the market could evolve in the near to medium term.

	BTC-Backed Debt	**ASIC-Backed Debt**	**Infra-Backed Debt**	**Senior Secured Loan**
Collateral	Bitcoin	Bitcoin mining ASICs	Supporting infrastructure (containers, transformers, etc)	All assets
Cost of Capital	4–12%	13–28%	5–25%	varies
Typical Term	3–12%	18 months	varies	varies
Typical Convenants	• Deposit BTC w custodian • Margin calls	• Site approval • Firmware/ immersion restrictions • Uptime requirements • Rules around corporate indebtedness	• Site approval • Rules around infrastructure use • Rules around corporate indebtedness	• Rules around corporate indebtedness • Lender approval of operational decisions • Cash flow restrictions

Debt Capital Markets in Bitcoin Mining: Part 2

In Part 1 of this series, we reviewed the history of debt in bitcoin mining, examined key principles of debt, and looked at some of the most common structures available to bitcoin miners. Now that we understand the landscape, we will take a look at the considerations for borrower and lender alike, the effect of leverage on mining returns, and discuss how the future of the market might look.

KEY CONSIDERATIONS

From a Lender's Point of View

Many of the lenders in bitcoin mining have been viewed as predatory, gouging hard-working hashers at usurious interest rates and driving miners into bankruptcy. But your humble author believes this critique to be a bit unfair. The last 6 months suggest that bitcoin mining lenders were perhaps not conservative enough in their underwriting practices, and perhaps should have demanded even more protection or higher interest rates (remember the mantra, "there's no bad risk, just a bad price").

So let's examine the key considerations for a lender to better understand where they are coming from. When evaluating the below considerations, instead of saying certain aspects of a loan make it "better" or "worse," we will instead discuss them as having more or less "risk."

Primary Goal: the lender's primary goal is to earn attractive risk-adjusted returns ("return on capital"). This means AT LEAST receiving their principal back ("return OF capital"), and this latter concern is the motivating force behind most lender considerations.

Loan Considerations:

- Creditworthiness of borrower: the less leveraged, the more "trustworthy," experienced, and profitable the borrower, the less risk

- Loan-to-Value: the lower the LTV, the less risk

- Collateral: the more (and more liquid) the collateral, the less risk

- Term: the shorter the term, the less risk, as the lender gets their money back faster and uncertainty increase as you move further out into the future (not to mention halvings)

- Covenants: the more rules and restrictions that protect the lender, the less risk (an oversimplification but directionally correct)

- Interest rates: the higher the interest rate, the more attractive the loan, as the interest rate is the key determinant of lender returns. If other aspects of the loan increase its risk, the lender is typically compensated with a higher interest rate (remember the mantra of debt)

- Debt service coverage (cash flow divided by debt service expense): the higher the coverage, the less risk

- Balance sheet: the lower leveraged the borrower (and the more unrestricted cash), the less risk

- Sizing: the work required to originate a $1 million loan vs. a $100 million loan is surprisingly similar; thus, lenders often have minimum loan sizes to ensure that the juice is worth the squeeze

- Operations: lenders want to lend to borrowers who are operationally sound and profitable, as this reduces the risk of the borrower being unable to service the debt. In the case of bitcoin mining, this means miners with a proven track record and low-cost power

Other Considerations:

- Portfolio construction: the more diversified the portfolio, the less risk. As stated above regarding sizing, while lenders might have minimum loan sizes, the desire for a diversified portfolio can impose maximum loan sizes as well. That way no single bad loan will cause their ruin

- Syndication: as discussed in Part 1 (see the "Back-end financing" section), the lender might have separate "investors" who purchase or lend against these loans once they are originated. This lies at the heart of the lender business model: a lender borrows at X% and lends that same money out at X+Y%, where Y% is their net interest margin. This consideration can lead to "origination targets" where a lender will seek to issue a given amount of loans in order to satisfy an agreement with investors

Key Considerations for Bitcoin Miners

Now that we understand the considerations for lenders, we will examine how miners should approach these structural features. To simplify things, we will consider a loan to be "more attractive" from a borrower's perspective if it comes with less restrictions thereby providing them more flexibility.

Primary Goals:

- Capital-efficient expansion: the ability to finance larger operations and/or take on less equity dilution

- Enhanced returns: we will discuss this more in the Case Study section below

Loan Considerations:

- Proceeds: miners will often seek to borrow as much as they can, but this can be a double-edged sword as it can both reduce net cash flows and increase balance sheet fragility

- Collateral: the less collateral pledged, the more attractive the loan

- Term: the longer the term, the more attractive the loan, as it gives the miner more time to pay back principal. In the case of an amortizing loan, this means lower the monthly payments

- Covenants: fewer covenants make for a more attractive loan; borrowers want freedom to act however they see fit, and covenants (especially operational covenants) can get in the way of this

- Interest rate: the lower the interest rate. the more attractive the loan. Miners are incentivized to seek the lowest cost of debt possible; this often is the key point that makes a miner choose one structure over another (if you have a bitcoin treasury, why borrow against ASICs at 15% when you can take out a bitcoin-backed loan at 5%?)

- Debt service coverage: while miners typically want to maximize their debt proceeds, they should also be conscious of the fact that too much debt can be a burden on cash flows

- Balance sheet: much like debt service coverage, balance sheet considerations are also a rare moment when borrower and lender incentives are aligned; too much debt can cause borrowers to become insolvent

- Hidden fees: another key consideration for borrowers are the hidden fees that lenders often structure into loans. Borrowers typically only think of the headline interest rate, but these fees can cause meaningful changes to the overall “cost of debt”

- Upfront or origination fees: typically 1 - 2%, these fees are the difference between the cash proceeds disbursed to a borrower and the outstanding principal amount on origination

- Warrants: some lenders might also ask for warrants (contracts granting the right to buy the borrower’s equity at a specified price) as a way of providing additional upside

- Related transaction fees (e.g., hedging): some lenders to bitcoin miners will offer a “discount” on the interest rate in exchange for guaranteed fees to other parts of the business

Other Considerations:

- Initial diligence: given the asymmetric downside lenders face, they require borrowers to go through an extensive diligence process to ensure they are operationally and financially sound. From a miner’s perspective, the colonoscopy of due diligence is often worth it, but would-be borrowers should expect to disclose nearly every material aspect of their business to the lender prior to receiving a dollar of proceeds

- Firmware and advanced cooling technologies: loans with ASIC collateral often prevent the use of aftermarket firmware or advanced cooling technologies (e.g., immersion) without lender approval. These restrictions are intended to minimize potential damage to machines and maximize their fungibility on the secondary market, but they may hinder a miner’s ability to optimize their operations

- Operation simplicity: loans typically all come with their own operational and reporting requirements. The administrative work to fulfill these requirements on even one loan can be burdensome, let alone multiple

CASE STUDY

The following section illustrates the effect of leverage on the returns of a bitcoin mining operation. The outputs were created using a simple cash flow model which can be accessed by scanning the QR code below. The curious reader is invited to download a copy to play around with the model and explore the impact of leverage on various mining scenarios.

Before we dive into the details of the case study, we will state a few simplifying assumptions that are unrealistic, but helpful for purposes of forecasting.

- We assume a flat hash price during the entire forecast period

- We assume that capital is deployed during month zero, and hash rate is live the following month. In reality, this is also unlikely, but it is similar to a miner purchasing a completed site from a third party and commencing operations immediately

- We ignore corporate overhead

- We look at everything on a pre-tax basis

- Lastly, this case study considers a typical loan that might have been issued prior to the severe deterioration of mining conditions in mid 2022. The illustration of these terms does not suggest that such loans are readily available to miners

The operation assumptions are fairly simple:

- We assume that a new project is built for $2.4m

- 1,000 S19J Pros purchased at $15 / TH ($1.5m in total)

- Supporting infrastructure costs $300k / MW ($900k in total for an assume 3MW site)

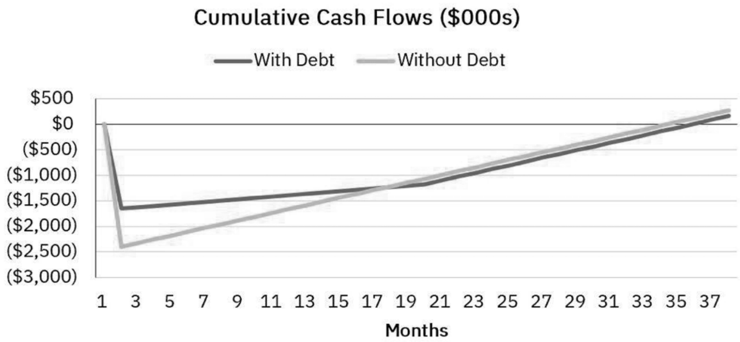
- For simplicity, we assume that an S19J Pro pulls 3,000 watts

- We forecast cash flows over a period of 3 years (conservative estimate for the lifetime of an ASIC)

- We assume the site has 95% uptime and $55 / MWh all-in operating costs

Now, we will consider the effect of adding an ASIC-backed loan with a ~50% LTV ($750k of debt proceeds, prior to a 2% origination fee). We assume this $765k loan has an interest rate of 15% and an 18 month term.

For three hash price scenarios we will examine the following output. The top half of the analysis shows the monthly cash flows, and the bottom half shows the returns over a 3 year forecast period. The left and right columns show the results of the miner taking on that leverage (LHS) vs. the results if the miner never took on leverage in the first place (RHS). Notably, when looking at the monthly cash flows for the miner that did not take on debt ("unlevered"), the reader can see the cash flow profile of the levered miner after the debt is paid off.

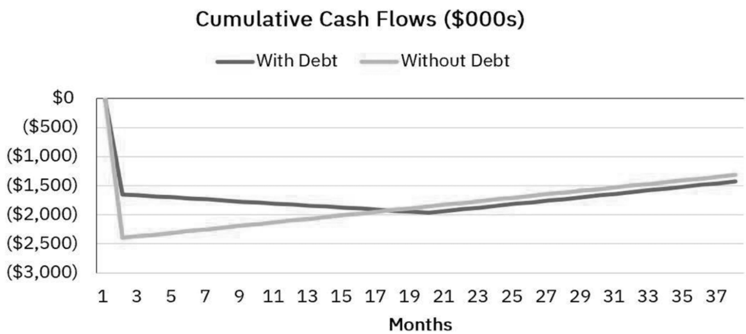


Notes:

- Cumulative cash flow is based on total pre-tax returns over term
- Payback (months) is the # of months required to recover the equity investment
- Multiple on invested capital is the total cash profits divided by the equity investment
- Internal rate of return is the discount rate at which NPV of investment = $0

As the "Base Case" we will look at the approximate 3 month trailing average hash price (~6.5 cents / TH / s / day). Under these conditions, the returns from a mining project with the above specifications are marginal. It takes nearly the entire 3 year period for the miner to recover their initial equity investment. This helps illustrate the brutality of recent bitcoin mining conditions.

Now, if hash price fell to 5.0 cents (the approximate hash price if bitcoin fell to $15.3k and the network held at 280 EH/s), the debt service exceeds the operating profit, resulting in the miner hemorrhaging cash until the debt is paid off. The returns in this scenario are even worse, with the levered miner never recovering more than 14% of its invested capital, while the unlevered miner earns only 45% of the invested capital. This highlights the role that leverage can play in harming the cash flow profile of a miner.



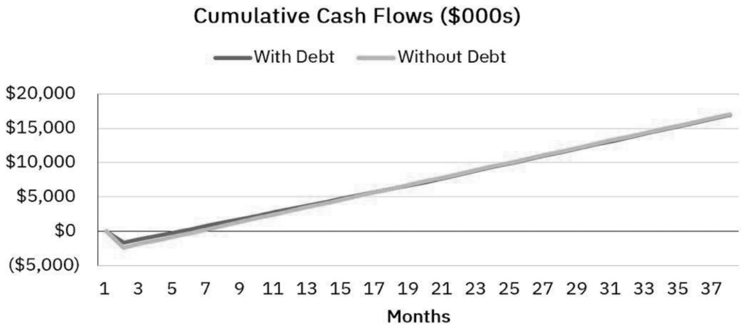
In reality, however, it is unlikely a miner would continue to hemorrhage cash by servicing this debt until maturity. Typically, one or more of the following would occur: restructuring, default, or bankruptcy. The field of distressed debt is highly complicated and nuanced but below is an oversimplified discussion of each (disclaimer: the only true experts in this subject are practitioners with years of experience in navigating restructurings and bankruptcies).

- **Restructuring**: a miner might "restructure" their existing loan, by renegotiating terms with its existing lender and/or refinancing their debt with a new lender, to reduce the ongoing debt service burden. Typically, restructuring consists of some combination of the following: prepayment from the borrower (either from balance sheet cash, the sale of assets, or potentially new, more punitive debt), extension of the loan term (perhaps in exchange for contributing additional collateral), and/or conversion of debt to equity. Restructuring is always a negotiation between the borrower and the lender and is therefore unique to each situation

- **Default**: when a borrower fails to perform its obligations under a loan, a lender can trigger a "default." Events of default are explicitly stated in loan agreements. Sometimes different events of default allow the borrower a certain amount of time to "cure" them, thereby preventing an actual default. But if the borrower does not, a lender has the option to foreclose on collateral and force certain actions from the borrower (e.g., the return of collateral). A default can also either lead to restructuring or bankruptcy

- **Bankruptcy**: there are various different types of bankruptcies (often referenced by different chapters of the U.S. Bankruptcy Code), but in general it is a process where companies seek relief from debt that it cannot repay. This can either be imposed by a lender or entered into voluntarily from a borrower. The bankruptcy rabbit hole is far too deep to go down in this piece

The reason many miners took such risks, however, was the effect leverage can have on returns (though some might claim ignorance played a role as well). To better understand, let us consider the returns if bitcoin pumped back toward its previous all time high of $69,420 the day after the loan was issued and the capital invested. This would result in ~23 cent hash price (assuming network hash rate stayed flat).



In this scenario, the levered miner earns a return on their invested capital 3x higher than that of the unlevered miner. And the operating cash flow so vastly exceeds the debt service, that the monthly payments are inconsequential. Looking at this scenario, it's not surprising that so many miners aped into machines in 2021. Few other physical asset classes have the potential to offer returns like these (though it's worth noting that the price of machines and infrastructure would likely inflate as well if mining conditions improved so drastically, but this is intended to be a simple model, so we try to minimize the number of changing assumptions).

The TLDR is perhaps unsurprising: leverage offers miners the ability to amplify returns and expand faster, but it comes at the cost of fragility during bear markets. Those seeking to understand the effect of different assumptions and added complexities on returns are invited to play around with the open-sourced model.

THE FUTURE OF DEBT IN BITCOIN MINING

The Shortcomings of ASIC-Backed Debt

Two years ago, if you, dear reader, had asked me, your humble author (a former asset-backed securities investment banker and ASIC-backed lender) how debt capital markets in bitcoin mining would evolve, I would have said debt in bitcoin mining would evolve just like many other asset-backed credit markets with specialty lenders.

In these markets, when a new asset class emerges, originations start with smaller lenders offering new debt products at high interest rates. Over time people get more comfortable with the asset class and interest rates decline (as underwriting prowess increases and perceived risk decreases). Eventually other financial institutions agree to purchase these loans (back-end financing), changing the business model of the lenders to become "origination platforms," collecting a fee on the loans they originate and then sell. Banks then facilitate the issuance of "term" asset-backed securities to other investors (largely insurance companies, seeking a fixed return over a fixed term). So the "origination platform" creates the loan and takes a spread, the bank takes another spread for packaging the asset-backed security, and the investor enjoys the rest of the loan's economics. This is how securitization markets work. And given the parallels to other securitized asset classes (e.g., traditional equipment finance), I would have said that ASIC-backed debt would follow this same path.

But such securitization markets take years to develop, and the boom and bust of ASIC-backed debt in the last 12 - 24 months has highlighted many shortcomings of the structure that your humble author and many lenders did not predict. These shortcomings call into question the long-term viability of the structure, and are as follows:

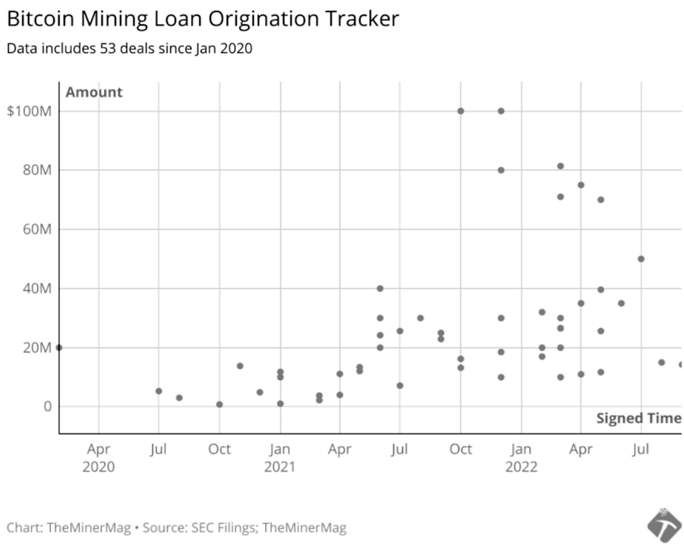
- **Correlation**: in simple terms, as bitcoin price falls, so too do ASIC prices (the collateral value), and the profit margins of miners (their ability to service the debt). This means if a lender were to foreclose because a borrower is unable to service the debt, it is likely that the collateral, the very thing which was supposed to give the lender additional security, has also lost value

- **Volatility**: it would be one thing if the highly-correlated bitcoin and ASIC prices were stable, but recent history has shown us this is far from the case as both witnessed ~80% + drawdowns.

In dollar terms, ASICs are volatile assets that people buy in hopes of producing another volatile asset (bitcoin)

- **Liquidity of ASICs**: unlike bitcoin, ASIC orderbooks can be quite thin, so if a lender is forced to repossess ASICs, it is unclear whether they will be able to sell them quickly (and without meaningful slippage in price)

The cost of capital for ASIC-backed debt also poses an issue. It is unclear if the interest rates of ASIC-backed debt will ever be competitive with bitcoin-backed debt. Perhaps this is unsurprising, as bitcoin is the best form of collateral in human history. For this reason, it seems unlikely that bitcoin-backed debt will ever go away entirely (in fact, the author expects this market to expand by many orders of magnitude over the next few decades). But even setting other structures aside, the macro backdrop of rising interest rates may hit ASIC-backed debt harder than bitcoin-backed debt, as a ~5% increase in ASIC-backed debt could take interest rates as high as 20-30%.



The above reasons cast doubt as to whether ASIC-backed debt will reemerge as the dominant structure when conditions improve. But what will replace it? While the exact structures are uncertain, the cost of capital will remain king. If miners do decide to employ leverage, they will continue to seek the cheapest and least onerous form of debt.

Cost of Capital is King

Perhaps instead of ASIC-backed debt lenders will make a push for large corporate debt facilities with all-asset liens (i.e., bitcoin, ASICs, infrastructure, and any PPAs) or even site-specific loans. Such structures may offer a lower cost of capital perspective, as in an event of default, a lender could foreclose on an entire mining operation and run it themselves. The lender would then earn all associated free cash flow while they look to liquidate the site (if they want to liquidate at all). In such a scenario, a lender-cum-miner would have far more flexibility than they would if they were forced to liquidate a portfolio of offline ASICs. The desire for “self-sufficient” collateral may mean that hosted data centers are the best lenders of ASIC-backed debt for their customers, as foreclosure on collateral is trivial (the lender just needs to redirect the ASIC to the mining pool of their choice).

One other interesting manifestation of this theme is that retail miners with good credit scores (who often do not have access to ASIC-backed debt) may be able to take out personal loans to finance machines, which are sometimes priced at lower interest rates than ASIC-backed debt (if ASIC-backed debt is available to them at all).

The quest for interest rate arbitrage could also give an advantage to would-be-miners from other industries that have lower cost of capital. For example, an energy super major has far more debt products available to them at a lower cost of capital. Energy companies could use this to their advantage if and when they enter into bitcoin mining in earnest.

From a lender's perspective, cost of capital is equally important. Only lenders with access to cheap capital will be able to compete in offering debt financing to miners. Imagine two lenders: one is a venture-backed startup the other a large bank. There is little chance a venture-backed startup will be able to provide loans at a lower interest rate than banks with access to the fiat debt capital markets (even when subsidized by fiat VC funding). The only way to win in financing businesses is to have the lowest cost of capital.

The Forever Forthcoming Hash Rate Marketplace

Perhaps instead miner financing will be dominated by entirely novel structures. One debt-like product that might play a role is hash rate-based financing. While the market has yet to settle on one dominant structure, the crux of hash rate financing is that miners should be able to sell their future production similar to other commodity producers. The benefit is twofold:

1. Hash rate financing is non-dilutive (similar to debt)

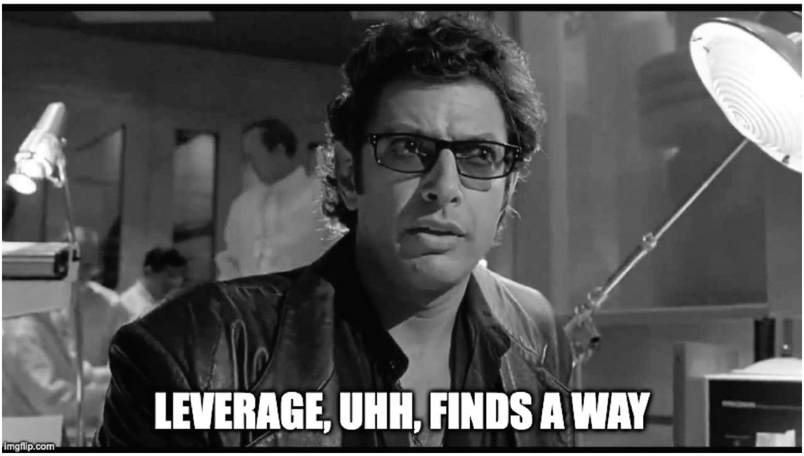
2. Such products can also allow miners to hedge some of their future production

Famously, hash rate marketplaces have been 6 - 12 months away for the last 3 or so years; however, Q4 2022 saw a new push of such products. This form of financing would be entirely new to bitcoin mining, and, at time of writing, it remains unclear whether there is sufficient demand for hash rate to allow this market to flourish.

Only Time Will Tell

But regardless of what debt products dominate bitcoin mining in the future, at time of writing (January 2023), it seems likely that we will see far less debt in the near term, as miners and lenders alike have been burned in this downturn. Moving forward, miners will likely be more hesitant to use leverage and thereby increase the fragility of their businesses. Likewise, many lenders have left the asset class either due to poor loan performance or because they've gone out of business altogether (e.g., BlockFi and Celsius). Those lenders who do remain will likely be far more conservative moving forward (though the next bull run may see a return to similarly aggressive lending practices from new entrants).

This highlights one last key similarity with other credit markets. During bull markets, things are fine and everyone makes money; but during bear markets and recessions, many borrowers, lenders, and investors get burned, resulting in a decrease in originations and an increase in interest rates. This will persist for a while, until conditions improve. Optimism is regained. And the cycle repeats again.

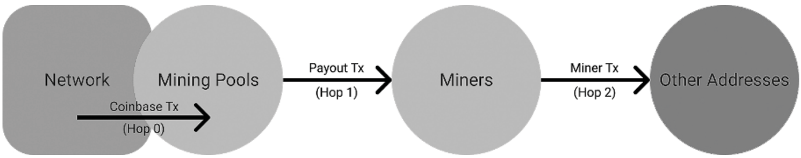


Like other industries, there will be a diversity of attitudes toward debt. Looking back to the energy sector again, many energy companies choose to stay away from debt altogether because of volatile commodity prices. On the other hand, some energy companies binge on debt, a decision which can be wildly successful or catastrophic depending on market timing and execution. Only time will tell which strategies will succeed.

Understanding When and Why Bitcoin Miners Sell Their BTC

During the bear market from 2018-2020, it was commonplace to see people blaming negative price action on miners selling all their coins and citing metrics such as “Miners Rolling Inventory” that measured the flow of BTC in and out of addresses that received mining rewards via the coinbase transaction. Of course, what these metrics were actually showing in 99% of cases was the inflows and outflows from mining pool wallets, not miners themselves.

Fortunately, this misconception is far less common these days, and it’s thanks in large part to Coin Metrics and other blockchain data analysis platforms for developing sound methodologies to measure true miner transaction flows by looking at what happens to coins once they’re 1-hop away from the original coinbase transaction.

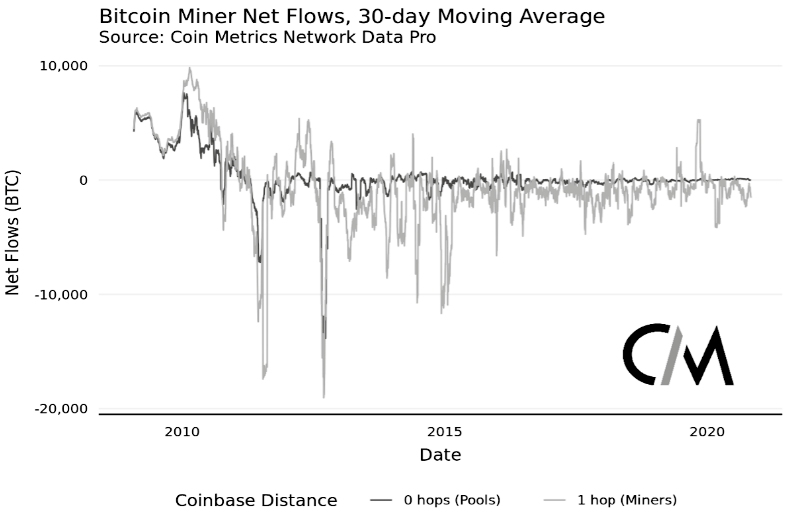


The following chapter was originally written in November of 2020 by Karim Helmy, formerly of Coin Metrics and Galaxy Digital, to provide more insights into what we can learn from this data and to discuss when and why miners sell their bitcoin.

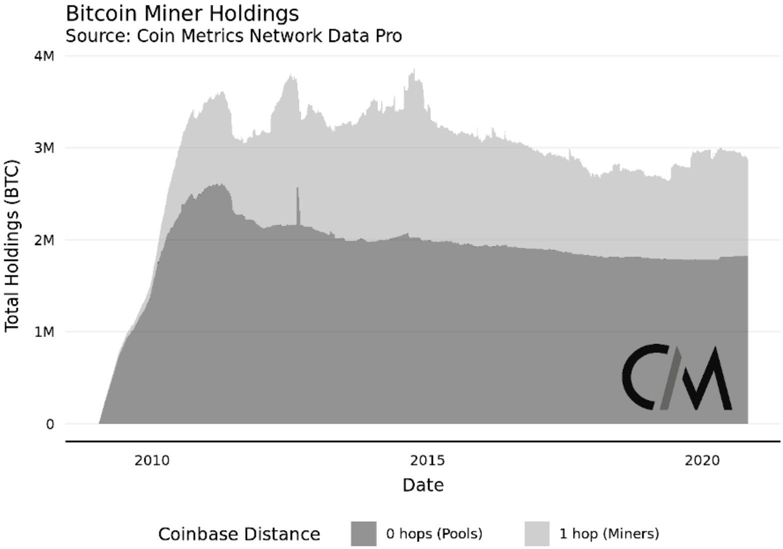
Note: Coin Metrics has continued refining their methodology for analyzing mining pool and miner transaction flows. If you’re interested in learning more, search online for Coin Metrics’ State of the Network: Issue 160.

WHAT CAN THE AVERAGE BITCOINER LEARN FROM FOLLOWING MINER FLOWS?

Bitcoin miners have a huge impact on liquidity, so analyzing their flows gives you a better understanding of the markets. What we see on a macro level is that their influence on the network is gradually declining, with net outflows becoming less volatile over time. Given that several halvings have now reduced issuance dramatically, this lines up with what we'd expect.



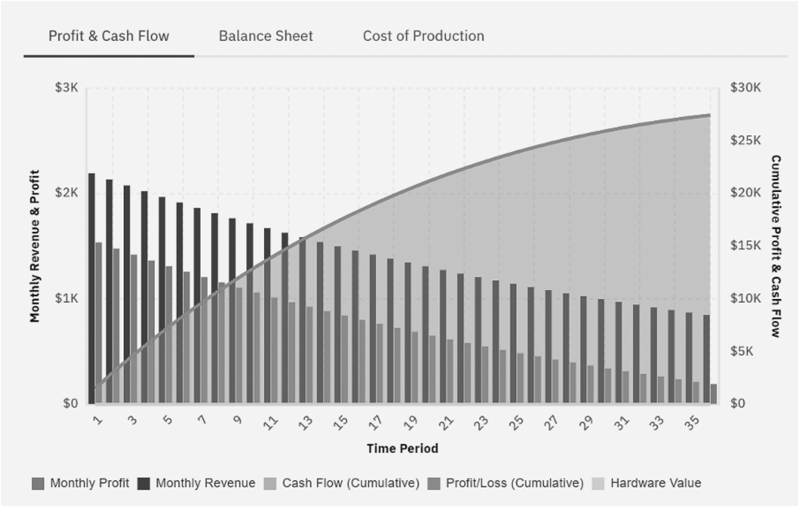
By tracking miners' flows and holdings, you can also see some interesting short-term trends, like how miners accumulated over 380,000 BTC in the year leading up to the halving. This buildup was mostly confined to 1-hop addresses, so previous methodologies would've missed it. On a micro level, this could be a useful trading indicator, though it hasn't been tested for that purpose to our knowledge.



WHEN AND WHY DO MINERS SELL THEIR BTC?

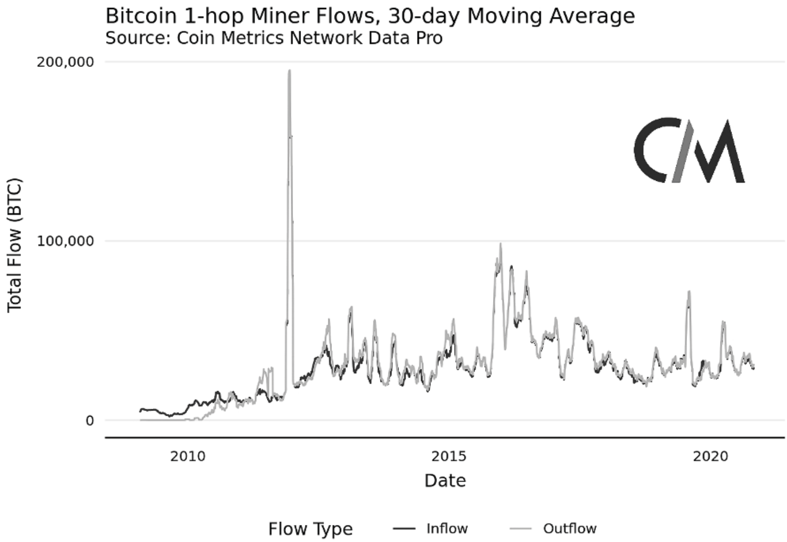
The short answer is that miners sell to cover costs and take profits. Miners' expenses, including electricity and rent, are mostly fiat-denominated, but their revenues are earned in bitcoin. This leaves them exposed to the price of bitcoin, which can heavily impact their profitability.

Below you can see an example of a 36-month cash flow analysis for a hypothetical Bitcoin mining operation with 1000 TH/s of hashrate, 30 J/TH efficiency, and paying an electricity fee of $0.03/kWh. With difficulty rising (+80%/year) faster than price (+20%/year) in the example, the net profit per month is an increasingly smaller percentage of mining revenue over time. This means that the miner would need to be selling a larger portion of their BTC mined each month to cover costs.



This is what Bitcoin miner cash flows look like the majority of the time. The exception is during intense bull markets, during which network difficulty rises less quickly than price and miners are able to cover costs with a smaller portion of the coins they mine each month. Depending on their fund management strategies and the amount of BTC exposure they're willing to carry, though, some miners may actually sell more coins at these times to realize the gains on coins mined and held through the bear market.

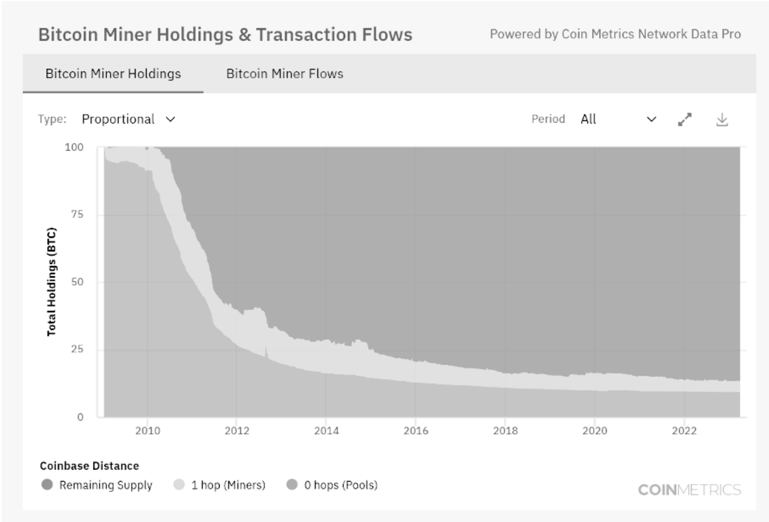
This model is confirmed by the analysis, which shows that 1-hop inflows and outflows have typically tracked one another closely and that the spread between them has generally tightened.



Surveys such as one conducted in the 3rd Global Cryptoasset Benchmarking Study by the University of Cambridge Centre for Alternative Finance showed that most miners don't employ advanced hedging strategies, meaning holding and selling are how they get to their desired level of risk. I expect we'll see more adoption of loans and derivatives in the not-so-distant future. However, even then, selling coins will continue to be how miners realize their profits.

YOU CAN FIND THESE MINER FLOW METRICS ON BRAIINS INSIGHTS

Thanks to our friends at Coin Metrics, we are also displaying some of these metrics on real-time and historical miner transaction flows on Braiins Insights. For example, in the Proportional Bitcoin Miner Holdings chart, you can see the percentages of the total BTC supply over time that have never moved from the coinbase transaction, have moved once, and have moved 2+ times.



With the knowledge that 0 hops (Pools) will include the approximately ~1 million coins mined by Satoshi and never moved, we know that there are only about ~800k other BTC remaining in that category, most of which were also mined in the early days and many of which may be lost forever.

ENERGY SOURCES DEEP DIVE

At the time that most of the content in this section was originally written, the hashrate exodus from China was just beginning, and the public mining companies of North America were still relatively small players on a global scale. Much has changed about the distribution of network hashrate since then, as well as the prevalence of miners participating in grid balancing programs where they shut off during times of peak demand or setting up behind-the-meter at energy generation sources to soak up surplus supply.

While there's certainly temptation to wax poetic on how misunderstood bitcoin mining is by the majority of the journalists, politicians, and general public that discuss it, this is a book on economics. So instead, I'll take this opportunity to tie in some Economics 101: Supply & Demand.

A fundamental concept that anybody wishing to discuss bitcoin mining accurately must understand is that miners require cheap power to be profitable, and, by definition, this means that miners want power that is in surplus supply relative to demand, as this will always be the cheapest power. Whether it's excess solar on a sunny day, excess wind on a windy day, excess hydro during the wet season, stranded gas that's uneconomic to take to market, or even excess grid power during times of low demand, bitcoin miners can utilize that oversupply of energy that would otherwise be stranded. On the other hand, any time that demand is high relative to supply, bitcoin miners will reduce consumption or turn off completely, as the power is worth more to somebody else than it is to the miner.

This makes bitcoin miners unique compared to just about every other energy consumer profile out there. Even similar industrial consumers differ in that they typically require many minutes, if not hours, to fully ramp up or down their consumption, while bitcoin miners can do this in a matter of seconds.

Obviously, this Economics 101 concept has significant implications for bitcoin mining's role in the energy industry and society as a whole, and it's this unique energy consumption profile that makes a continued blurring of the lines between the energy industry and the mining industry practically inevitable. To have an opinion on bitcoin mining without this basic understanding and its implications for funding new energy generation projects, maintaining grid stability, and harnessing stranded energy assets is foolish.

Economics of Bitcoin Mining with Solar Energy

An economic analysis of bitcoin mining when using an intermittent, renewable energy source like solar power without a grid connection. The original was published in June 2021 and remains intact on the Braiins blog. The chapter following this one is a "Part 2" expansion discussing mining with solar and a grid section.

In December 2020, I wrote an article for Bitcoin Magazine titled *The Next 10 Years of Bitcoin Mining*, which described how the mining industry is rapidly evolving as large institutions, energy producers, and governments become increasingly involved.

A lot has happened since then. China banned mining, Ripple is spending millions on lobbying to spread mining FUD in Washington D.C. and online, politicians across the world are criticizing bitcoin for its energy consumption, and the typical person today who knows anything at all about bitcoin mining likely thinks it's an environmental catastrophe.

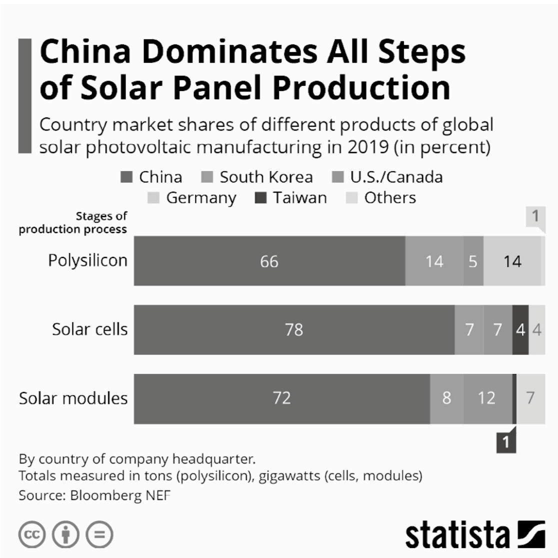
All of this shined a spotlight on mining and made once-rare knowledge about the industry's dynamics now somewhat commonplace for Bitcoiners. Among this knowledge is the possibility for bitcoin to incentivize renewable energy development around the world by providing a means to monetize surplus energy that would otherwise be wasted.

While I'm already aware of bitcoin mining being used to monetize surplus hydro, geothermal, and even some wind energy, I hadn't heard of it being done at any noteworthy scale with solar. And so, as I saw solar getting mentioned more often in 2021, my curiosity got the best of me, and I decided to do some analysis to determine its viability. In this article, I'll share my findings along with some commentary on the whole "green" bitcoin topic.

MISSING CONTEXT IN THE "GREEN" ENERGY CONVERSATION

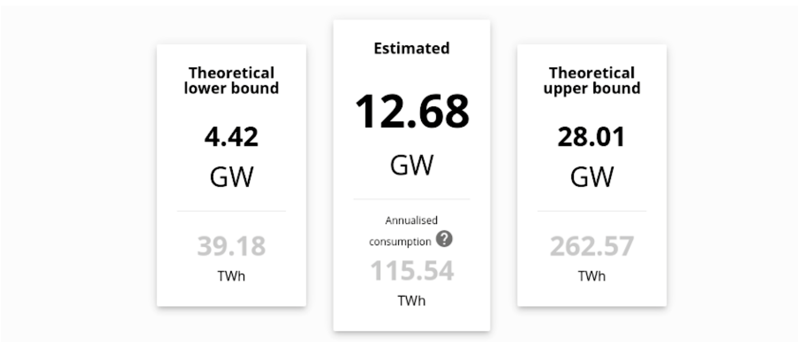
One important point to mention before we get into the financial analysis is that the "clean" and "dirty" descriptions of various energy sources can be misleading without deeper context. For example, manufacturing and deploying solar panels and batteries requires energy-intensive mining for minerals from the earth, using toxic chemicals, and burning significant amounts of energy in the manufacturing process as well. Once manufactured and transported, solar panels can produce clean energy for many years, but there are still noteworthy environmental and social costs to be paid, which are rarely mentioned in the public discourse.

In fact, one of the biggest production centers for solar panels in the world is Xinjiang, China, which is largely due to the fact that Xinjiang has cheap coal that can be used in the manufacturing process, which brings down the cost of production. Incidentally, "cheap" labor may be another not-so-convenient factor that's bringing down the cost of production in Xinjiang, but that's a whole other topic.



Ironically, bitcoin critics frequently singled out Xinjiang because of the region's extensive use of coal to power bitcoin miners from October to May during China's dry season (at least before the latest ban may have put an end to mining in Xianjiang for good). More generally, however, the most commonly cited metric when looking at bitcoin mining's environmental impact is the percentage of total network hashrate that's powered by fossil fuels. This, too, can be misleading without more context.

For instance, the US Energy Information Administration estimated that the amount of natural gas being flared and vented in the US is around 1.48 billion cubic feet per day (Bcf/d), equivalent to about 1.52 trillion BTUs/day (British Thermal Units). In more common terms, this amount of natural gas could be used to generate roughly 162 TWh/year of electricity. Based on the latest figures from the Cambridge Center for Alternative Finance shown below, waste gas in the USA alone is likely enough to power the entire Bitcoin network, which consumes an estimated 116 TWh per year. Not to mention the venting and flaring that doesn't get reported or the waste gas in other countries around the world.



Source: CBECI figures at the time of writing, May 29, 2021

Combusting natural gas and using the electricity produced to mine bitcoin prevents that gas from being flared or vented, which in turn prevents methane emissions, which are estimated by the Environmental

Protection Agency to be 25 times worse for the environment than CO_2 over a 100-year time span and 80 times worse over a 25-year time span.

All of this is not to say that efforts to transition more bitcoin hashpower to renewable energy sources are pointless or bad. To the contrary, any scenario where bitcoin mining can be used to help build and scale up our energy generation capacity with greater economic efficiency is exciting. Rather, our goal is simply to help everybody approach this topic with a nuanced perspective, understanding that raw energy consumption amounts and even the denomination of that energy, which is renewable, do not actually tell us everything about the final environmental impact of bitcoin mining.

With that context in mind, let's shift our focus now to the topic of bitcoin mining being used to help scale solar energy projects.

BCEI WHITEPAPER SUMMARY AND ASSUMPTIONS

The Bitcoin Clean Energy Initiative (BCEI) led by Square and ARK Invest, recently published a whitepaper (April 2021) that explains how bitcoin mining can be added to solar power and battery systems to help scale them beyond what would be possible if there was no way to monetize the surplus energy produced during peak sunny hours. Since I'm no expert on solar power, I'll be relying on their data to get realistic inputs for my own mining profitability analysis.

Specifically, there are two points that are extremely relevant.

1. Levelized Cost of Energy (LCOE): the total lifetime cost of building and operating a power generation asset divided by the total amount of energy it produces. In other words, this metric essentially tells us the cost to produce a kWh of energy with a given power source, which we can use as the electricity price for the mining profitability calculations.

2. Solar energy production is intermittent: the sun only shines for part of every day, and the amount of sunshine varies seasonally. Meanwhile, batteries are still far too costly and inefficient to store and transport significant amounts of surplus energy, resulting in much of the energy produced by solar panels going to waste.

The paper includes the $/kWh electricity price for solar using the LCOE metric, so setting an electricity price for this hypothetical mining operation is easy. I'll just take the average from the range, which is $0.035/kWh.

LCOE by Energy Source

In Price per kWh

Hydro	~.01 – .04	**Nat. Gas**	~.04 – .07
Wind	~.02 – .05	**Geothermal**	~.05 – .10
Solar	~.03 – .04	**Coal**	~.06 – .07

All but Hydro, Lazard. *Hydropower,* IRENA – International Renewable Energy Agency.

Source: BCEI Whitepaper, page 2

The much bigger challenge is determining how much uptime the mining machines would have, given the intermittent nature of solar energy generation and the fact that most of the energy it produces would be consumed by the grid or stored in batteries rather than used for mining. **A key thing to note from the BCEI whitepaper is that the miners run entirely on solar power, not using grid power during unproductive solar hours**.

In typical mining applications, it's assumed that the ASICs will be running basically 24/7. There are exceptions, such as load balancing programs in which miners power off during times of peak demand, but generally even these will have 80%+ uptime. This is important because there is one big external cost in all of this that could make or break the use case for bitcoin mining: capital expenditure (CapEx) for purchasing hardware.

ASIC hardware has historically depreciated over longer periods of time as the network difficulty increases (i.e., the BTC mined per terahash of hashrate goes down), so downtime is extremely costly as it pushes out the date to break-even on that initial CapEx. In a case of too much downtime, it's possible that bitcoin mining will be a net negative for an energy project, meaning that it never produces enough profit to pay off the initial investment.

Estimating ASIC Uptime with Solar Energy

BCEI's paper links to an open-source model incorporating real-world data that serves as a proof-of-concept for a solar system that integrates bitcoin mining. The model is *backtesting* the use case with historical Bitcoin network data and incorporating it into a much more complex financing scenario, which is beyond the scope of this piece.

The purpose of this analysis is to isolate the bitcoin mining portion of the project and see how competitive it would be with more typical mining operations. Instead of backtesting with historical data, I will be making forward projections incorporating data from ARK's model into standard bitcoin mining profitability calculations.

A key excerpt from the model's README is the following:

"The logic of the model is optimized to prioritize meeting grid demand. That is, the sun's energy will not be used to mine bitcoin unless the demand from the grid is first met. Once grid demand is met, the model assesses whether it is more profitable to store energy in the battery or mine bitcoin based on trailing profitability levels."

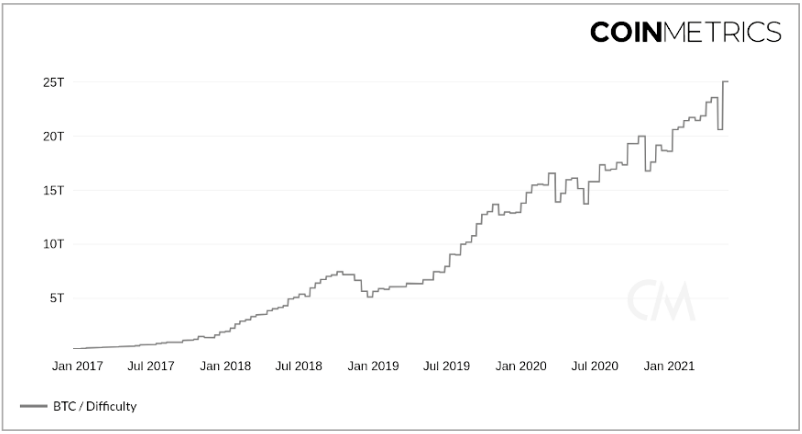
Basically, the model is making a sophisticated calculation about what to do with surplus energy at any given time. This makes the ASIC uptime calculations very complex as the deployed hashrate is fluctuating hour-by-hour, whereas our goal is to get a single figure that we can use to approximate the average hashrate for the operation over the total time period being analyzed.

In order to get a realistic value, I simply took the average of all the hourly values in the *Deployed Hashrate* column of the model, resulting in a final value of 1.923 EH/s. Since the maximum hashrate for the operation is 5.449 EH/s, this average hashrate estimate equates to 35% uptime for the deployed ASICs at the mining farm. Put another way, calculating the mining revenue for a 1.923 EH/s operation that mines 24/7 will give us more or less the same results as for a 5.449 EH/s operation that mines for about 8 hours per day on average.

Now we have all the information we need to carry out some basic financial projections.

BITCOIN MINING PROFITABILITY WITH INTERMITTENT ENERGY SOURCES

One of the critical components of forward financial projections for bitcoin mining is the network difficulty. This is because the mining revenue generated per unit of hashrate goes down as difficulty goes up, which it has done at a rapid pace, as shown below.

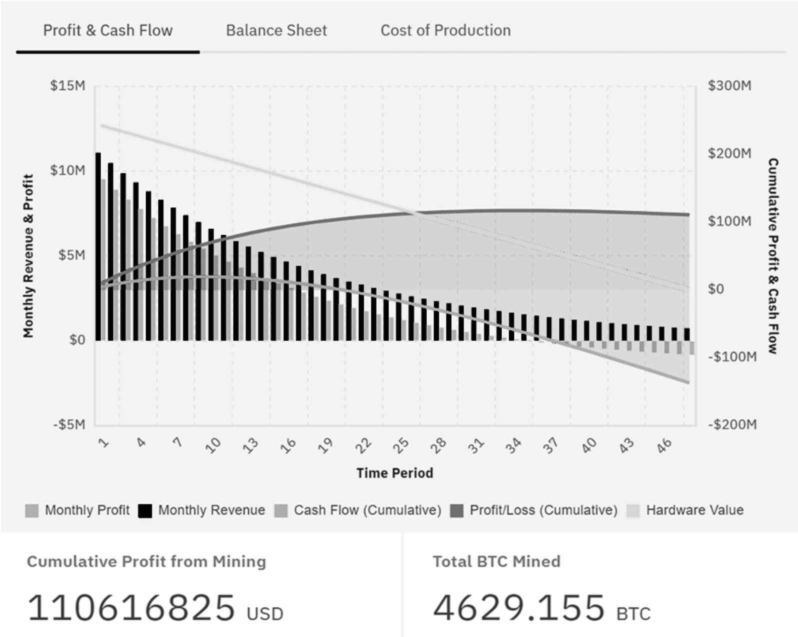


Source: Coin Metrics Network Data

Since 2017, network difficulty has increased from 317 billion to 25 trillion, equaling a 164% annual increase over the past 56 months. Considering the current semiconductor chip shortages and unknown future price action, I'll conservatively set the annual difficulty increment to just 100% in my calculations to simulate difficulty doubling each year. Meanwhile, I'll start with the price held constant at $40,000 per BTC.

Note that I will set $30,000 for monthly OpEx (operating expenses), which is also a very conservative estimate for all the costs involved in staffing a 170 MW facility and maintaining the hardware in it.

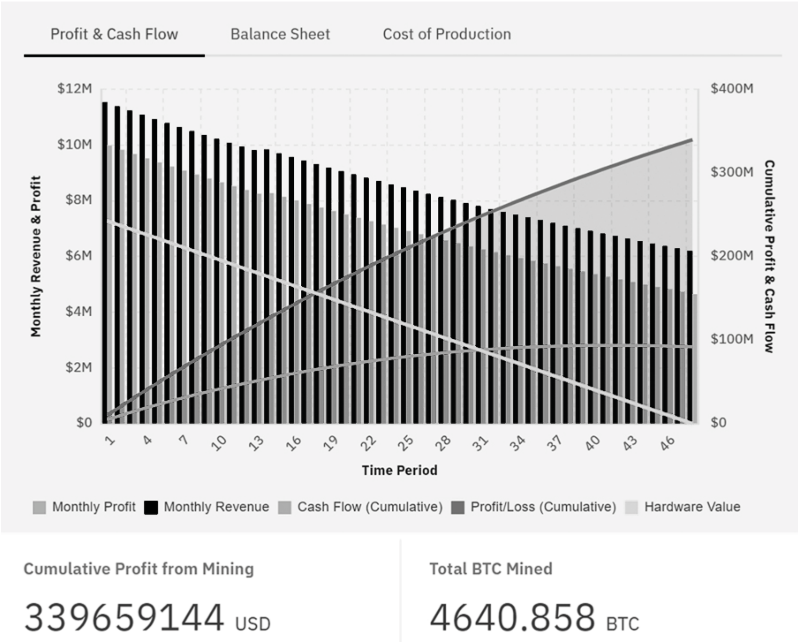
Below is a 4-year cash flow analysis that uses the CapEx and ASIC specifications from the open-source model. Power consumption is set to 35% of the maximum consumption in order to maintain the same average efficiency (~31 J/TH) of the ASICs used in ARK's calculations.



We find that with difficulty approximately doubling every year while price remains constant, this investment performs poorly, with nearly $100 million in negative cumulative cash flow by Month 34, when mining becomes unprofitable on a marginal basis (assuming hardware fully depreciates in 48 months)—and it does not factor in the halving that would occur about 3 years into the analysis. This is our baseline, but it's not actually very realistic. Difficulty is unlikely to keep going up at the historical pace for 4 years if the price doesn't also perform similarly as it has in the past.

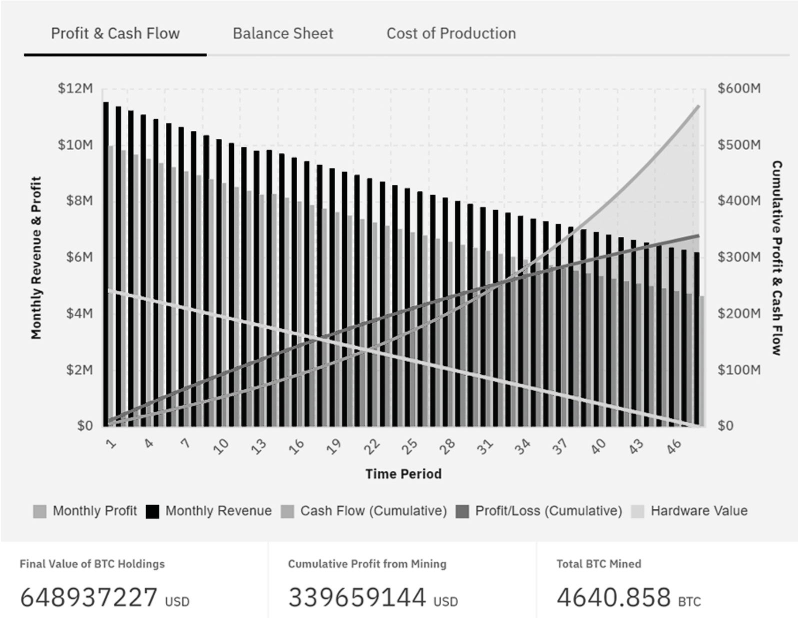
Still, improving ASIC efficiency and today's large profit margins for miners mean that difficulty is likely to continue going up rapidly for at least the next 1-2 years in all but the most extreme bearish scenarios. In other words, even if the BTC price remained constant for 2 years, difficulty would continue increasing until the average cost of production for bitcoin miners equaled the actual BTC price.

But what about a more bullish scenario where BTC price also increases rapidly? Well, let's set a 70% annual price increment and find out.



Now we see that mining remains profitable, albeit at an ever-decreasing rate, for the entire 48-month period (again, the halving is not factored in). Furthermore, the initial CapEx investment is actually paid off near the end of the 3rd year of operations. This tells us that adding bitcoin mining to this solar project would be rational only if the investors believed that the BTC price was going to increase significantly in the next 4 years.

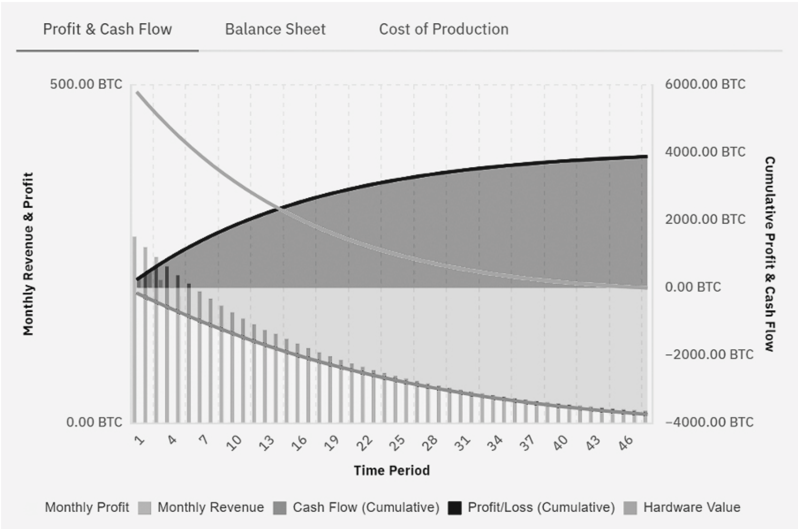
And since that's the case, we might as well check what would happen if the miners were to HODL some portion of the BTC they mine, say 50%, rather than cashing it out entirely to fiat each day.



Now we're talking! By setting a HODL Ratio of 50%, the CapEx break-even point is shortened to less than 2 years, and the final cash flow of the operation, including the value of the ASIC hardware inventory, reaches nearly $600 million. The takeaway is simple: the success of this hypothetical mining operation is highly dependent on the BTC price. No surprises there.

But wait, there's one more caveat here. Given the initial BTC price of $40,000, we should also compare how this hypothetical investment would perform vs. simply buying and holding BTC with the $247,680,000 CapEx. In the mining scenario, a total of 4,641 bitcoins are mined (see *Total BTC Mined* in the STATS part of the image above) over the first 4 years of operations (not accounting for the halving around the end of Year 3). But at $40,000 per BTC, the $247,680,000 could be used to purchase 6192 bitcoins with no OpEx for simply holding them. Phrased differently, the miners never break even on the CapEx in BTC terms.

In fact, we can check the BTC-denominated version of the profitability calculator to see the full impact—accounting for each monthly OpEx bill having been used to simply buy BTC as well. This shows that the mining strategy ends with nearly negative 4,000 BTC in cash flow, meaning that putting CapEx and OpEx into buying BTC would have resulted in a hardware wallet stuffed 4,000 BTC fuller than the mining scenario.



To summarize:

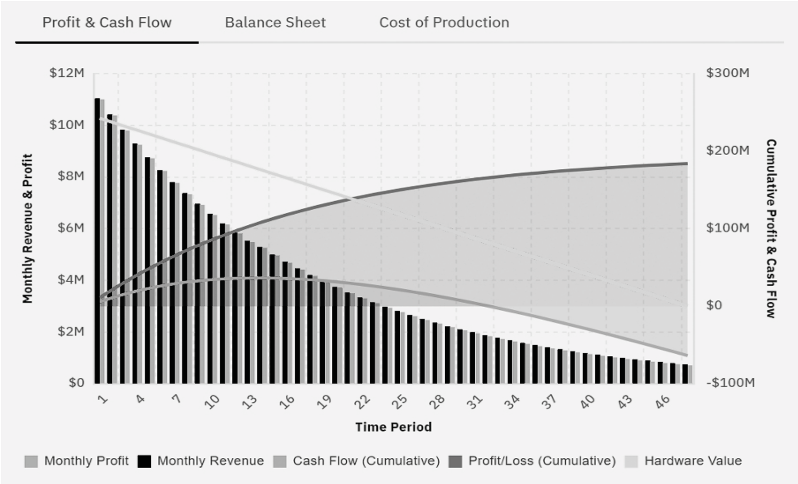
- If the miners are not long BTC, this investment probably doesn't make sense because it's unlikely to perform well in fiat terms if BTC price doesn't appreciate significantly.

- If the miners are long BTC, they would be better off just buying bitcoin rather than investing in a complicated and risky mining operation because they are unlikely to mine more BTC than they can buy with the initial investment amount.

This conclusion holds well in different projected scenarios because the BTC price and difficulty are correlated to each other. So if difficulty doesn't increase as quickly as projected, it very likely means the price has performed poorly and the investment doesn't do well in fiat terms. If the price does increase substantially, difficulty will likely continue increasing at about the same pace as it has for the past 5 years, in which case the investment doesn't do well in BTC terms.

One other point to reiterate is that the analysis here is isolating the mining portion of the solar + battery + bitcoin mining project. Although these numbers may not look attractive, there are other factors not taken into account, such as the possibility of government subsidies for renewable energy projects as well as access to extremely cheap capital, which can make this look more reasonable to large companies with big balance sheets who are able to tolerate more risk and longer payback periods on investments of this size. Basically, those trends I talked about in *The Next 10 Years of Bitcoin Mining* are becoming more noticeable. Most importantly, a grid interconnection to actually buy power for mining during non-sunny hours and maintain competitive uptime is not discussed here, although it will be a big part of the *Optimizations for Bitcoin Mining with Intermittent Energy Sources* chapter.

Anyway, before moving on to the last part of this analysis, I want to drive home just how much of the risk-reward ratio depends on the bitcoin price. So let's look at one more visualization—this time with FREE electricity and a constant BTC price. One could argue that the surplus energy produced by the solar panels during peak sunny hours would otherwise go to waste and have zero economic value, so we should consider (almost) all mining revenue as profit. In this case, what would we find?

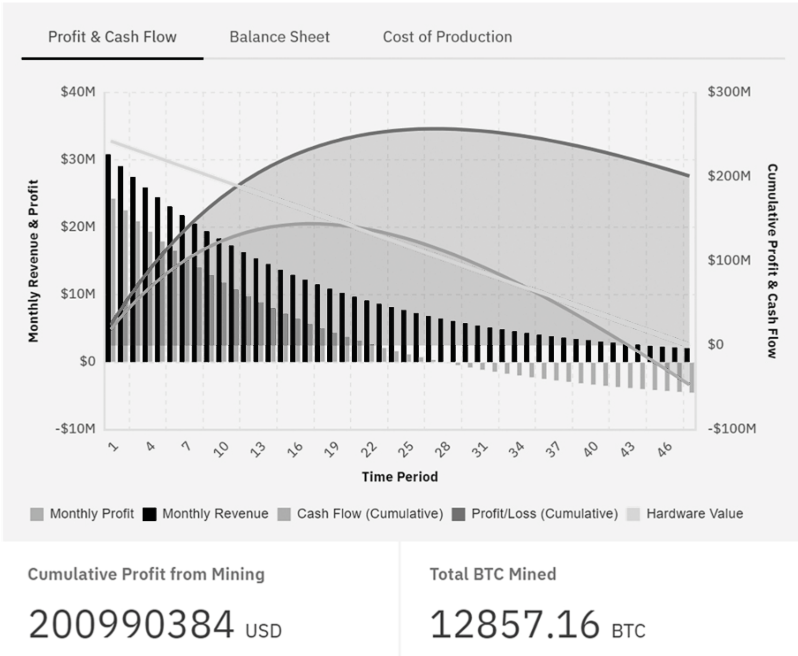


Unfortunately, even with free electricity, the operation never breaks even on the initial fiat CapEx investment unless BTC price goes up substantially.

COMPARING THE SOLAR MINING OPERATION TO A MORE CONVENTIONAL MINING FARM

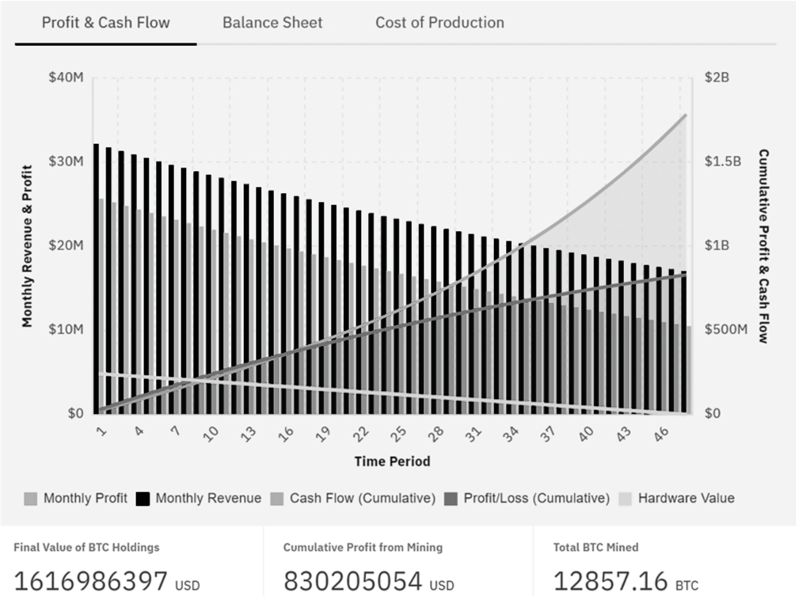
One more thing worth looking into before we wrap this article up is a comparison of the same hypothetical bitcoin mining operation as above, but with a constant energy supply rather than an intermittent one. Hypothetically, this could even be the same mining operation, just with a grid interconnection to maintain uptime during off-peak solar hours.

This means that we will use the maximum hashrate and power consumption from the model, 5448960 TH/s (5.45 EH/s) and 178 MW respectively, as well as the same CapEx. However, to make things more interesting, we'll increase the electricity price of the hypothetical full-uptime operation to $0.05/kWh and keep the $30,000 monthly OpEx.



We can see that even without any BTC price appreciation, the operation breaks even during Year 2 and remains profitable for about 2.5 years. Assuming the miners were to simply liquidate their hardware inventory and stop mining when they are no longer profitable, they would have a final cash flow of $205 million—not bad for a $247 million initial investment. This is a significantly less risky investment than the 35% uptime operation.

And if we add the 70% annual BTC price appreciation and 50% HODL Ratio into the calculation that we used for the most profitable scenario with the solar project, the upside is... very nice.



USD CapEx break-even occurs in just 9 months, and the final cash flow of the project exceeds $1.7 billion. The total BTC mined over 4 years is close to 13,000, more than double the amount that could have been bought with the initial CapEx investment amount.

In summary, a mining operation with $0.05/kWh electricity and full uptime drastically outperforms one with $0.035/kWh electricity or even free electricity but 35% uptime.

One other variable not discussed here that could be interesting to play with is the type of ASICs used. In the model from the BCEI paper, a mix of old-generation (Antminer S9), mid-generation (Antminer S17 and Whatsminer M20S), and new-generation (Antminer S19 and Whatsminer M30S) is used. If the goal is to minimize risk, the investors could avoid expensive new-generation miners, sacrificing some efficiency and longevity in order to have a much lower initial CapEx investment. Perhaps with excellent timing (e.g., purchasing

50,000 Antminer S9s around the halving in May 2020 when they were selling for $20-$40 each), it could work out well.

Furthermore, the miners in the model are only running when there is surplus energy to consume directly from the solar panels. If the miners were to use battery power or a secondary energy source to increase uptime, particularly in the early months of the operation before network difficulty has increased significantly, that could also improve the probability of breaking even on the mining CapEx.

The table below shows the months to break even on the CapEx for the mining operation analyzed in this article with a range of electricity prices and ASIC uptime amounts. (*Note: NaN means that the CapEx break-even does not occur in the first 48 months analyzed*.)

CAPEX Break Even (months) for Bitcoin Mining ASICs														
Elektricity Price	**Percentage Uptime**													
	35%	**40%**	**45%**	**50%**	**55%**	**60%**	**65%**	**70%**	**75%**	**80%**	**85%**	**90%**	**95%**	**100%**
FREE	NaN	NaN	38	28	23	19	17	15	14	12	11	11	10	9
1 ¢/kWh	NaN	NaN	NaN	36	27	22	19	16	15	13	12	11	10	10
2 ¢/kWh	NaN	NaN	NaN	NaN	36	26	21	18	16	14	13	12	11	10
3 ¢/kWh	NaN	NaN	NaN	NaN	NaN	NaN	26	21	18	16	14	13	12	11
4 ¢/kWh	NaN	NaN	NaN	NaN	NaN	NaN	NaN	28	22	18	16	15	13	12
5 ¢/kWh	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	24	19	17	15	14
6 ¢/kWh	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	22	18	16

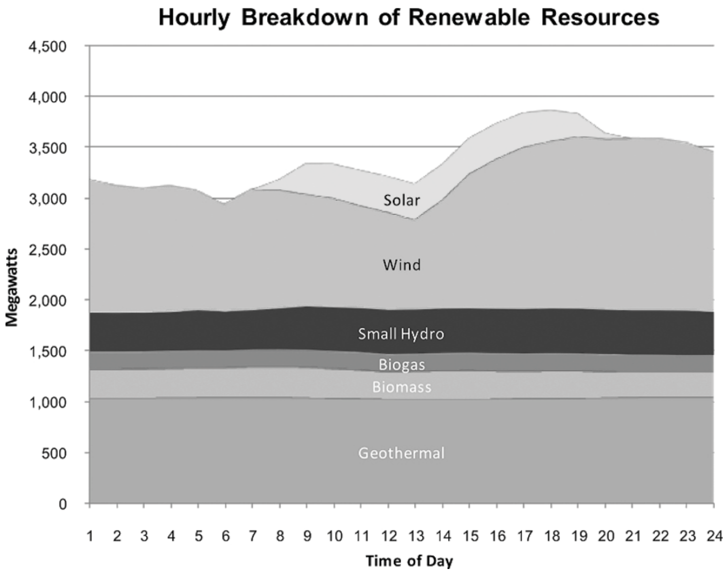
Other data: BTC price: $40k, Difficulty: 25.05T, Monthly Difficulty Increment +100%/year, ASIC Efficiency: 32.6 J/TH

Mining farms with 90%+ uptime are likely to break even within the first 2 years of operations with electricity prices at the high end of the spectrum, while extremely cheap electricity prices are not enough to make most operations viable with less than 60% uptime.

THE FUTURE OF "GREEN" BITCOIN

This article may not paint such a rosy picture of bitcoin mining being integrated into solar projects, but all hope is not lost for a relatively green future for bitcoin mining around the globe. Market conditions can change to make this more feasible in the future than it is today, such as a decrease in hardware prices if more manufacturers can become competitive with MicroBT and Bitmain.

Meanwhile, other renewable energy sources such as hydro and geothermal are already a big part of the bitcoin mining landscape, and wind energy is potentially more realistic as well because it can have more consistent generation than solar. And of course, adding a grid connection to the mix for a solar mining project to increase uptime can make it viable, as we will discuss more in this book.



Source: California ISO

At the time of this writing, hundreds of thousands of ASICs have recently been deployed in the Sichuan and Yunnan provinces of China, where they will be consuming surplus hydroelectric power produced by excess hydro capacity from the overbuilding of dams there. In Russia, Canada, the USA, and potentially elsewhere, miners are consuming increasing quantities of surplus natural gas, which would otherwise cost energy producers money to flare and vent while also emitting harmful methane. Load-balancing programs for urban energy grids are gaining popularity as well, making grids more efficient and robust so that they are capable of handling periods of peak demand without as much stranded or curtailed energy (i.e. economic inefficiency) the rest of the time.

The energy consumption of the Bitcoin network may be trending up, but that ultimately does not tell us much about its actual environmental impact. Even the denomination of hashrate powered by renewable energy fails to account for use cases like consuming waste gas or reusing the low-grade heat output from ASICs for other residential and industrial applications. This is all very complex and nuanced, but one thing is clear: we need proof-of-work to have a meaningfully decentralized global monetary network.

**Additional note: The average efficiency of the ASICs used in these calculations is 32.6 J/TH. This is most similar to an Antminer S19 or Whatsminer M30S+, which are the current newest-generation of mining hardware at the time of writing. Based on market prices for these hardware models in June 2021 of $80-100/TH ($ per terahash), the CapEx for hardware in the analysis done above would be $400MM-$550MM, as opposed to $248MM (the figure used).*

Optimizations for Bitcoin Mining with Intermittent Energy Sources

Exploring methods to reduce capital expenditures (CapEx) and operational expenditures (OpEx) as well as improve ASIC hardware lifespan for bitcoin miners with intermittent power supplies. This content was originally published in July 2021 and modeled Antminer S17s, but the economic analysis has been updated in 2023 for Antminer S19s and more current (i.e. depressed) mining economics.

Since Bitcoin entered the ASIC mining era in 2013, the lion's share of advancements have happened with hardware. The first ASIC—the Avalon1 released by Canaan in 2013— had a hashrate of 60 GH/s and a consumption of 595 W. In today's efficiency terms, that's just under 10,000 J/TH.

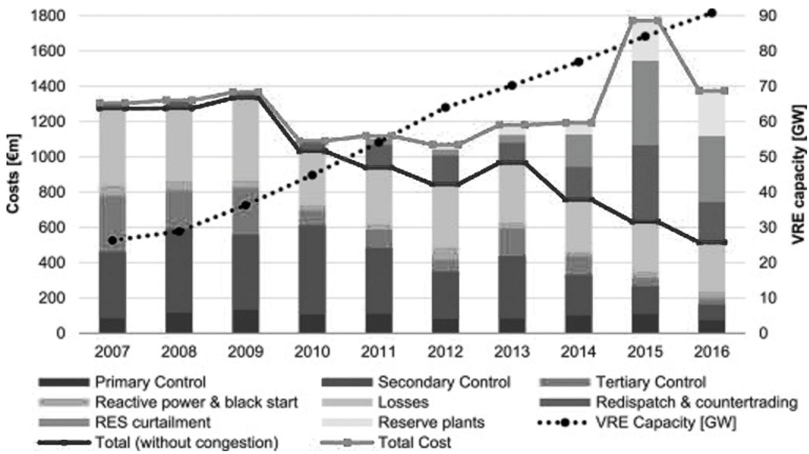
In the next four years, efficiency improved by two orders of magnitude as the release of the Antminer S9 in 2016 took us below 100 J/TH. However, efficiency gains are now beginning to slow down significantly. The best ASICs of 2021 hash at around 30 J/TH and are only ~10-20 J/TH more efficient than their mid-gen predecessors.

As the playing field gradually levels out for hardware, one of the ways miners are finding competitive advantages now is via more sophisticated Power Purchasing Agreements (PPAs) and by setting up next to intermittent power sources to consume surplus energy. For example, several miners in Texas are now acting as Controllable Load Resources in the ERCOT (Electric Reliability Council of Texas) system, meaning that they agree to consume less power when there is high demand from the grid, and in exchange they pay much lower prices (e.g. 1-3 ¢/kWh) for their electricity the rest of the time.

With these inconsistent and intermittent energy supplies, miners must develop customized strategies to determine how much energy they consume at any given time. In this article, we'll discuss some of the basic optimizations these miners can make in planning and running their operations to maximize profitability.

THE RISE OF INTERMITTENT ENERGY

The chart below shows the growing capacity of Variable Renewable Energy (VRE) in the UK and Germany from 2007 to 2016, and with it the growing amount of curtailment (i.e., reduction in power output below what could have been produced) occurring in order to balance energy supply and demand. Similar trends are taking place all over the developed world.



Source: https://www.sciencedirect.com/science/article/pii/S1364032118300091

As discussed in the *Economics of Bitcoin Mining with Solar Energy* chapter, plugging bitcoin miners in to consume surplus power (e.g., RES curtailment in the chart above) is not always a straightforward win. Miners need to have high uptime; otherwise, there is a significant risk that the ASICs will never reach a positive ROI, even with extremely cheap or free electricity.

From the moment they purchase hardware, miners are on a time crunch to maximize their BTC mined, no matter how cheap their electricity may be. This is because, with the exception of the months following China's mining ban, the bitcoin network difficulty has been steadily climbing to the tune of ~8% monthly increases during the modern ASIC era. In other words, the BTC mined per terahash of hashrate has been decreasing by approximately 8% per month during that time.

As difficulty climbs and hashvalue (BTC/TH/day) decreases correspondingly, the returns generated from the initial CapEx investment into ASIC hardware slow down. For example, the chart below compares the returns over 24 months for an ASIC with 100% uptime vs. 70% uptime. While the revenue from the ASIC with 100% uptime exceeds the cost of the ASIC (in BTC terms) during Month 12, the same never occurs for the ASIC with 70% uptime. This simply illustrates that it doesn't matter how low your operating costs are if you sacrifice too much revenue.

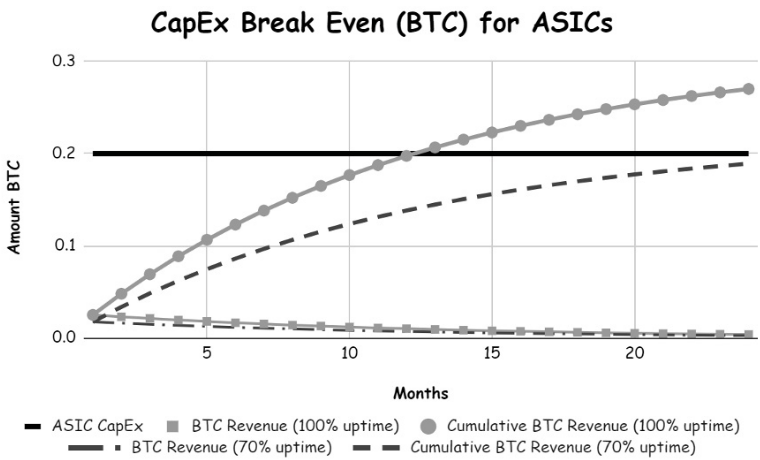


Chart: Hypothetical CapEx Break Even with an ASIC cost of 0.2 BTC

If the total mining revenue produced by an ASIC never exceeds the initial amount paid for it and the costs to run it (in BTC terms), then it would be better to simply buy BTC in the beginning and not mine. Of course, there are plenty of reasons (mainly to do with fiat financing) why these mining farms get built anyway, but I digress.

So, what can be done to improve the economics of this new generation of mining operations using intermittent energy sources and participating in load balancing programs?

(RELATIVELY) MORE EXPENSIVE ENERGY IS BETTER THAN NO ENERGY

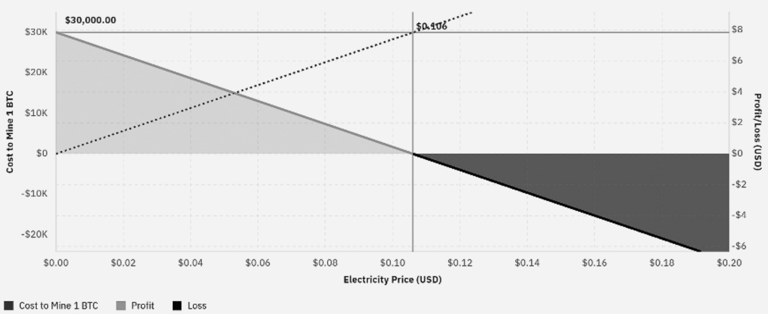
The simplest way to make a mining operation viable with a highly intermittent energy source is by using another energy source the rest of the time, such as natural gas, grid power, or some of the power stored in batteries from the intermittent source (e.g., solar or wind).

In that scenario, it's unlikely that the secondary energy source will be cheap relative to the primary one. Natural gas, even if stranded, will likely have higher CapEx to set up the necessary infrastructure, while grid energy and battery power will have other sources of demand to drive the spot price higher.

For the sake of this analysis, suppose that a miner gets an average of 8 hours per day of "free" electricity from solar panels during peak production, but they then have to pay the same price as regular industrial consumers, say 8 ¢/kWh, for their energy during the remaining 16 hours per day.

With the BTC price at $30k and network difficulty nearing 50T at the time of (re)writing, only hardware with efficiency better than 35 J/TH will really suffice. So we'll start by looking at an Antminer S19j Pro with free electricity for 8 hours per day and 8 ¢/kWh the remaining 16 hours.

Cost to Mine | Monthly Cost to Mine



[Bitmain] Antminer S19j Pro

Hardware Efficiency 29.6 J/TH	Break-Even Electricity Price 0.106 USD	Cost of Production for 1 BTC 28.3 USD
Margin 29971.7 USD	BTC Mined per Day 26152 SAT	Profit per Day 7.84 USD

Source: Braiins Insights Cost to Mine 1 BTC calculator

And keeping all the inputs the same except for paying $0.08/kWh for electricity.

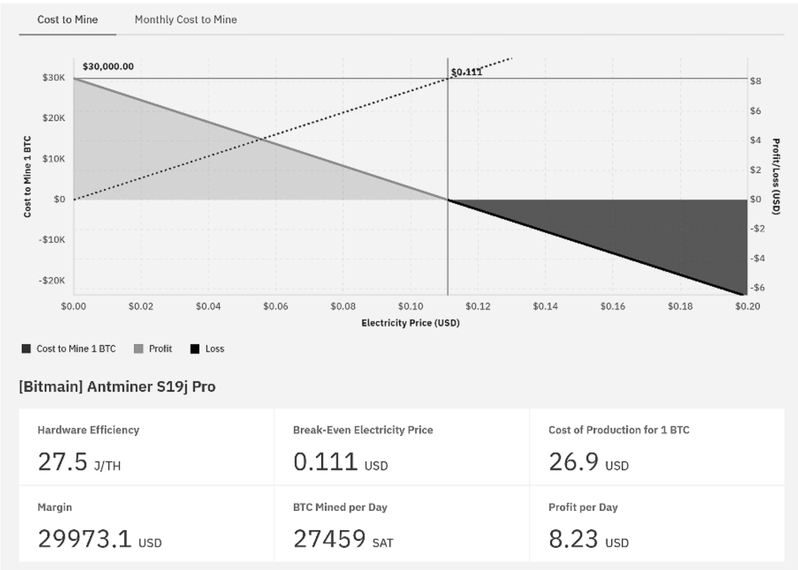
[Bitmain] Antminer S19j Pro

Hardware Efficiency 29.6 J/TH	Break-Even Electricity Price 0.106 USD	Cost of Production for 1 BTC 22612.8 USD
Margin 7387.2 USD	BTC Mined per Day 26152 SAT	Profit per Day 1.93 USD

This means that you would make $2.61 (⅓ * $7.84) of profit each day during the 8 hours with free electricity, and $1.30 (⅔ * $1.93) of profit the other 16 hours, for a total of $3.90. Put another way, you increase your daily profit by nearly 50% by running the miners on the more expensive electricity rather than just shutting them off for those 16 hours.

Scenario	Energy source Debt	Electricity Price	Hours/ day	24-hr Profit	Daily Profit
Stock firmware & no secondary energy source	1st: Intermittent	$ 0.00	8	$ 7.84	$ 2.61
	2nd: None	$ -	-	-	-
	Average/Total	$ 0.00	8		$ 2.61
Stock firmware & stable secondary energy source	1st: Intermittent	$ 0.00	8	$ 7.84	$ 2.61
	2nd: Grid	$ 0.08	16	$ 1.93	$ 1.29
	Average/ Total	$ 0.00	8		$ 3.90

But let's not stop there. In a future scenario where mining is ultra-competitive once again, the efficiency gains and added flexibility of an autotuning firmware can make a huge difference. Enter Braiins OS+.



During the 8 hours per day of free electricity, running Braiins OS+ and improving efficiency by 2 J/TH while at the stock power consumption limit (3080 W) boosts profitability from $7.84 to $8.23 per 24 hours after factoring in the 2.5% firmware devfee deducted from revenue.

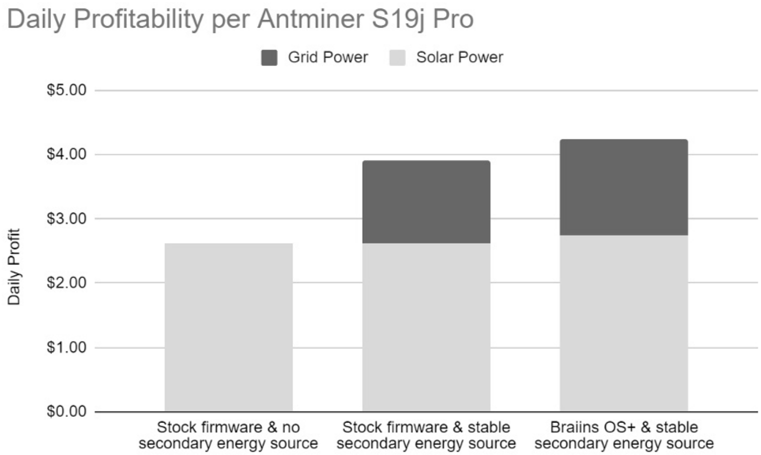
But the real magic is in the remaining 16 hours, when ASIC efficiency matters more due to the much higher electricity costs. With autotuning and a high efficiency profile (2200 W power consumption), the S19j Pro can produce approximately 88 TH/s at 25 J/TH for a profit of $2.25 per 24 hours of operation with $0.08/kWh electricity.

[Bitmain] Antminer S19j Pro

Hardware Efficiency	Break-Even Electricity Price	Cost of Production for 1 BTC
25 J/TH	0.123 USD	19578.2 USD
Margin	**BTC Mined per Day**	**Profit per Day**
10421.8 USD	21575 SAT	2.25 USD

Adding up our two time periods again, we get $2.74 of profit each day for the free 8 hours and $2.25 of profit the other 16 hours, for a total of $4.24 per day—a 12% profitability increase compared to stock firmware and a 62% profitability increase compared to stock firmware without a secondary energy source, not to mention an extra 800 satoshis mined per machine each day.

Scenario	Energy source Debt	Electricity Price	Hours/ day	24-hr Profit	Daily Profit
Braiins OS+ & no secondary energy source	1st: Intermittent	$ 0.00	8	$ 8.23	$ 2.74
	2nd: None	$ -	-	-	-
	Average/Total	$ 0.00	8		$ 2.74
Braiins OS+ & stable secondary energy source	1st: Intermittent	$ 0.00	8	$ 8.23	$ 2.74
	2nd: Grid	$ 0.08	16	$ 2.25	$ 1.53
	Average/ Total	$ 0.00	8		$ 4.24



It's worth mentioning that using this high-efficiency mode can not just lower total monthly power bills for the grid power utilized but, in some cases, may actually bring down the price of electricity itself. This is because it's very common to be charged a rate that has two components: a base charge and a demand charge based on your peak power consumption in a short time interval for the entire month or billing period. By consuming less power per miner, the peak consumption drops, causing a chain reaction of a lower demand charge and thus a lower overall $/kWh electricity price. Not to mention that you mine more BTC per watt of electricity consumed thanks to the improved efficiency of the hardware.

The downside here is mining less BTC relative to mining with a higher power input, but after subtracting out BTC sold to pay power costs, it's a net positive.

In summary:

- Mining with intermittent energy sources makes a lot more sense if they can be supplemented by another energy source to maintain uptime

- Autotuning firmware can increase flexibility, allowing for a significant reduction in energy consumption when electricity costs are higher and improving efficiency across the board

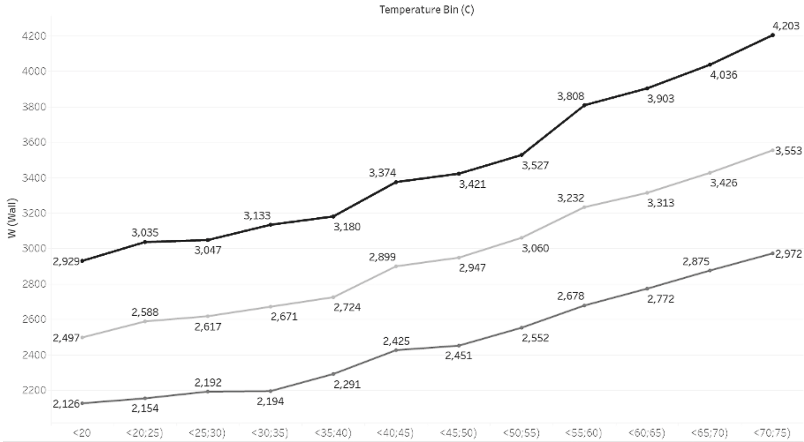
This second point is worth diving deeper into, as it can also apply to miners participating in load balancing programs for another reason besides immediately reducing operating expenses.

EFFECTS OF HEAT ON ASIC HARDWARE EFFICIENCY AND LIFESPAN

One other factor to note is that it’s not just the time spent on and off that matters for long-term ASIC profitability, but also the number of times you transition between the two states. The hashing chips in an ASIC are made of silicon, and this material operates at quite high temperatures during mining (optimally 70-85oC or 158-185oF). Then, when the ASIC is powered off for a while, the chips return to ambient temperatures. The process of heating up and cooling down the material is called thermal cycling, and it can result in an accelerated degradation of the silicon chip's quality.

There is no public data (yet) to help quantify the effect of frequent thermal cycling on any popular ASIC models, so we’re not going to estimate the months it may take off of an ASIC’s life or the loss in efficiency it may cause during its lifespan. However, it’s safe to assume that less frequent thermal cycling is better than more frequent thermal cycling for hardware lifespan, all else being equal.

Additionally, research by Braiins published in 2022 demonstrated that, when all other factors (voltages and frequencies) are equal, hardware efficiency for the Antminer S19 generation significantly decreases at higher temperatures. In other words, you consume more power to produce the same amount of hashrate as the ambient temperature in your mining environment increases. This relationship is likely less significant for hardware from MicroBT, but still applicable.



Power Consumption (y-axis) vs. Hashboard Temperature (x-axis), constant 13.5V, and comparing 450 (bottom), 550 (middle), and 650 MHz (top) frequencies.

Imagine a mining operation that runs on solar power during sunny hours and powers off the rest of the time. The best days for power generation would be the worst days for mining efficiency due to the heat. And the ASIC chips would degrade significantly faster than the industry standard per hash that they compute, as they would be operating in high heat during the day and then fully cooling off after the sun goes down, only to repeat the whole process the next day.

If only there was a way to make it work that we were going to talk about in the next chapter...

From Flare to Fortune: Mining Bitcoin Off-Grid with Stranded Gas

An introduction to bitcoin mining with natural gas to illustrate bitcoin miners' relentless appetite for cheap and abundant energy. This article gives a general overview of the market landscape, the economics of mining with methane, and an outlook for the future.

The world of bitcoin mining is continually evolving, and one development that has captured the attention of both the oil and gas industry and bitcoin miners alike is off-grid natural gas mining. As the name suggests, off-grid mining utilizes energy sources that are disconnected from the central power grid, often in remote or hard-to-reach locations. In this chapter, we will explore the world of mining bitcoin using stranded and flared gas.

Stranded gas refers to natural gas deposits that, due to their remote location or low production volumes, aren't economically viable to transport to the market using traditional infrastructure. Flared gas, on the other hand, is a byproduct of oil production that is either vented or, more often, burned off into the atmosphere for safety reasons, mainly to manage pressure levels and reduce the risk of explosions.

Traditionally, both stranded and flared gas have been considered waste products in the oil and gas industry. However, this perception is changing. A growing recognition of the potential these resources hold as a low-cost power source for bitcoin mining is slowly reshaping how industry players view these gas forms, in many cases shifting them from a liability into an asset.

A PRIMER ON THE OIL AND GAS INDUSTRY

Before delving further into the details, it's crucial to understand how the oil and gas industry—which can be divided into upstream, midstream, and downstream sectors—works. Upstream refers to the exploration and extraction of oil and gas; midstream denotes the processing, storage, and transportation; and downstream encompasses the refining of petroleum crude oil and the processing and purification of raw natural gas.

Stranded gas largely originates from the upstream sector. Its abundance results from geographic and infrastructural constraints that render the gas too costly to bring to market. These challenges include the absence of pipelines due to the remoteness of the gas fields, regulatory hurdles, and low production volumes that don't justify the infrastructure investment required to bring the gas to market.

Flared gas is a waste byproduct of oil production, and the flaring practice also represents a significant consideration from both the economic and environmental sides. Flaring gas not only contributes to greenhouse gas emissions, but also squanders a valuable energy resource.

THE PREVALENCE OF STRANDED AND FLARED GAS

Both stranded and flared gas are underutilized resources of immense value, largely due to the geographical and logistical challenges their usage presents.

So, why are these gases so prevalent? The answer lies in the complex nature of oil and gas extraction. In many cases, gas deposits are discovered in conjunction with oil reserves. When these fields are located in remote regions, the logistical and financial burden of transporting the gas to market becomes prohibitive, leading to its classification as stranded. Similarly, flare gas is an unavoidable byproduct of maintaining safe pressure levels in oil wells. The gas that can't be efficiently captured or utilized is flared (burned off), resulting in vast quantities of wasted energy.

In spite of these challenges, stranded and flared gas present an extraordinary opportunity for bitcoin miners due to their appetite for low-cost power and ability to set up in remote locations with mobile, modular infrastructure and hardware that can adapt to variable power supplies.

THE ECONOMICS OF STRANDED AND FLARED GAS

It is estimated that as much as 30% of the over 7,257 trillion cubic feet of known natural gas reserves on earth are stranded. This includes huge reserves in places such as Prudhoe Bay in Alaska and the Mackenzie Delta in Canada. For context, in 2022, the USA consumed 32.31 trillion cubic feet of natural gas. It goes without saying that if companies could economically capture and utilize stranded gas, they could tap into a significant revenue stream.

Flaring is a widespread practice in the Bakken Shale formation in North Dakota. Despite being one of the largest oil-producing regions in the U.S., the lack of natural gas infrastructure has led to high flaring rates. The U.S. Energy Information Agency reports that around 19% of all natural gas produced in the state in 2019 was flared, the equivalent of about 0.56 billion cubic feet per day. Flaring this gas not only wastes a valuable resource but also attracts fines under environmental regulations, adding another layer of cost for producers.

These examples highlight the market value of stranded and flared gas. However, to fully appreciate the economics at play, we must consider the costs involved. These include capital expenditure (CapEx) for infrastructure, operational expenditure (OpEx) for maintenance and operations, and the potential fines and taxes imposed by regulators.

For instance, let's consider the cost of pipeline construction, a primary method for transporting natural gas. The U.S. Energy Information Administration estimated that in 2020, new pipeline construction costs would average $7.65 million per mile. For a stranded gas field 100 miles from the nearest pipeline, the cost of constructing a new connection would be $765 million—not a small sum.

Additionally, companies face fines and taxes for flaring. For instance, in the first ten months of 2022, oil & gas companies in Nigeria were fined a total of $341 million for flaring. The fines range from between $0.5-$2 per thousand cubic feet (Mcf) depending on the amount of oil they produce. With a current gas price of around $2.7 per Mcf, it's clear that the financial impact of fines can quickly surpass the value of the flared gas itself.

A glance at some news headlines reveals the intertwined narratives of flared and stranded gas' economic and environmental impacts and the recent pivot to harnessing this energy for bitcoin mining.

THE BUSINESS OF MINING BITCOIN WITH STRANDED AND FLARED GAS

In my opinion, one of the most important superpowers of flare gas mining is the distributed nature of these types of mining operations. Off-grid flare deployments typically have less than a megawatt of capacity, which makes off-grid mining the most decentralized hashrate on the bitcoin network.

Although choosing this path involves many trade-offs, it hones one's skills and business acumen, which leads to wiser decisions with regards to choosing a business model, your oil and gas partners, equipment such as hardware and containers, as well as generators. During my time at Great American Mining, we would often debate the merits of these different choices.

Would we build our own mining containers or buy containers so we could deploy quickly? Ultimately, we chose to vertically integrate our operations at Great American Mining, mainly because we needed to control operations remotely and meet the stringent safety requirements of being on active oil and gas well pads.

Would we use the newest generation machines or choose cheaper older generation miners that we could pick up on the cheap? We chose the Whatsminer M20s model, which was best in class at the time. If you are trying to accumulate as much bitcoin as quickly as possible, you are almost forced to get the newest generation of machines. In retrospect, I wish we had cut our teeth on older-generation machines.

What would we pay for the gas from the oil and gas operators who had these flaring issues? Back when we first started, it was common to get the gas for free, and in some cases, miners even got paid to take the gas! Nowadays, miners typically pay an average of $1mcf/d, which is roughly equivalent to $0.01 kw/h.

Do you buy the power generation or lease it? Again, tradeoffs have to be considered. Most folks getting into mining aren't well-versed in operating natural gas generators. So for most miners, leasing or renting units from service companies like Mesa, Moser, or Baseline Energy was the easy choice. When we first got started, it was common to be able to rent a generator for less than $0.03 kw/h, that allowed off-grid miners to mine bitcoin in the $0.04-0.05 kw/h range—a very competitive rate without a ton of strings attached. It is possible to invest the CapEx to own the generation and essentially drive down the OpEx costs to only pay for maintenance and gas. This model is more prevalent in stranded gas deployments, and is what we currently do at Standard Bitcoin for our off-grid operations.

One of the major drawbacks of choosing the flare gas model is that miners are exposed to not only the dynamics of bitcoin's volatility but also the market conditions of Oil and Gas producers. In the spring of 2020, Oil and Gas prices went negative at one point and forced many operations, including one site we were on, to turn off operations as it became unprofitable for the oil and gas operators to extract their molecules profitably. We soon found ourselves in the unenviable position of not having ownership rights to the gas we needed to operate. This forced us to find another source for gas and live to fight another day. Ironically, the bitcoin market was brutal during that period. We had just entered a new halving epoch, and the price had crashed to the $4,000 range.

One of the rules I try to tell new miners is to just make sure they're plugged in and in a position to never have to turn off. Most folks who've been mining for a long time have made it through bear cycles by just staying alive. If you are alive when a bull cycle hits, you are golden. However, if you are trying to plug in during a bull market, there is a very high likelihood that you are going to get REKT due to everyone and their mothers trying to plug in as well, which drives up pricing on ASIC's, containers, services, etc.

Another important consideration, especially in the context of rule #1 above (staying alive), is whether to mine in hot climates. Texas has become a hotbed for both on-grid and off-grid miners. Heat is NOT a miner's friend, especially the West Texas heat. Machines tend to have their lifespan affected in these environments, which must be considered before committing to buy machines and fund a deployment. Now don't get me wrong, cold climates offer their own set of challenges to overcome as well, but that’s a topic for another day.

While I was at Great American Mining between 2019 - 2021, I saw a bunch of unique business models adapted. From a straight deal that would consist of an off-take agreement for the gas to sophisticated revenue share deals with producers and even generator service providers that wanted exposure to bitcoin. One of my favorite parts about off-grid mining is the flexibility one can have in terms of figuring out how to get a site live.

In 2022, I started Standard Bitcoin along with former GAM team members Marty Bent and Matt Adkins. It started out innocently enough: we had access to older legacy gas wells that were stable but small in size.

Instead of going all in and building out specialized containers, we opted to buy Upstream Data's Hash Huts. These hash huts are basically a generator and mining unit in one box. This allowed us to deliver the hash hut to our gas wells, plug-in and start hashing. It was magic. Being that we didn't have to worry as much about the volatility that a typical flare gas operation has, we didn't need to have all the bells and whistles for our operation.

With the advent of Starlink, bitcoin miners can quickly set up mining farms in remote locations. Get yourself a $200 laptop from Amazon and you can remotely manage the hash hut as well. The industry is likely to see continued growth and innovation in this space.

Off-grid miners also have an amazing community, and we have some incredibly talented companies operating in the very nascent stages of what will be a massive industry in the years to come.

MINING BITCOIN WITH STRANDED AND FLARED GAS: CASE STUDIES

Now, let's explore a few real-world examples to illustrate the complex considerations, strategies, and trade-offs involved in leveraging stranded and flared gas for bitcoin mining.

1. Great American Mining (GAM), an early pioneer of off-grid mining, faced a steep learning curve. With their initial strategy of using top-tier mining equipment, the company suffered during the market downturn due to their high operation costs. The valuable lesson was that the latest equipment might not always be the best choice. Instead, lower-cost, older-generation mining machines could provide a buffer against market fluctuations. GAM's strategy of vertical integration allowed them to control operations remotely and meet safety requirements necessary for active Oil and Gas well pads.

2. Standard Bitcoin, started by former GAM members, took a different approach. With access to stable but small legacy gas wells, we opted for Hashhuts from Upstream Data. These units, combining a generator and mining machine in a single box, made it simple to get plugged in and start hashing onsite. This approach allowed us to operate without worrying about the usual volatility of flare gas operations, focusing on a more streamlined, efficient process.

3. Crusoe Energy, a significant player in the space, showcases the ability to scale flared gas mining operations. They deploy modular data centers directly at oil well sites, converting flared

gas into electricity onsite. They represent a model of what large-scale flare gas mining could look like, and their approach has managed to attract substantial investment.

Through these case studies, we can see that business models and strategies can vary significantly in the field. Whether it's a decision about which equipment to use, how to structure the business operation, or how to navigate the volatility of gas supplies and bitcoin prices, these companies have charted their courses in the dynamic landscape of flare gas bitcoin mining. Each has adopted different strategies to maximize their opportunities and manage risks, providing valuable lessons for future players in this space.

TRENDS TO WATCH

As we have seen, the practice of using stranded or flared gas to mine bitcoin is more than a novel innovation; it's a potentially transformational approach that can address perceived and real environmental issues, create new value from waste, and contribute to the decentralization and security of the bitcoin network. But what does the future hold for this emerging sector?

1. Technology Evolution: Advances in mining equipment, energy conversion technology, and data center designs will continue to impact the economics and feasibility of off-grid bitcoin mining. For example, higher-efficiency ASICs could make it possible to extract more value from a given volume of gas. At the same time, better energy conversion systems could make it easier to operate in remote locations with low-quality gas.

2. Regulatory Environment: The regulatory environment can significantly impact this sector. On one hand, stricter regulations on flaring could increase the cost of waste gas, making bitcoin

mining more attractive. On the other hand, regulatory uncertainty around bitcoin itself poses risks.

3. Market Dynamics: The volatile nature of both the gas and bitcoin markets will undoubtedly continue to play a role. Fluctuating gas prices and supplies can influence the cost and availability of inputs for mining operations. Meanwhile, bitcoin's price swings can dramatically affect the profitability of mining operations.

4. Environmental Impact: As awareness and concern over climate change grows, the ability to convert waste gas into a valuable resource could become more attractive. This approach can help reduce CO2 emissions, turning a problem into an opportunity.

The future of off-grid bitcoin mining is still unwritten, but the potential is vast. In a world seeking innovative solutions to hard problems, the ability to convert waste into value while bolstering the security of a growing bitcoin network is an opportunity that is worthy of pursuit.

To finish off this chapter, I'd like to leave you with another couple of rules:

1. NEVER host for off-grid. (Uptime % can vary based on factors outside your control. You will get REKT)

2. NEVER EVER buy machines in a bull market. Trust me and thank me later. Get creative and get whatever hash rate you can online and be ready to buy ASIC's when things crash.

Stay Hashing!

MINING INFRASTRUCTURE AND STRATEGY

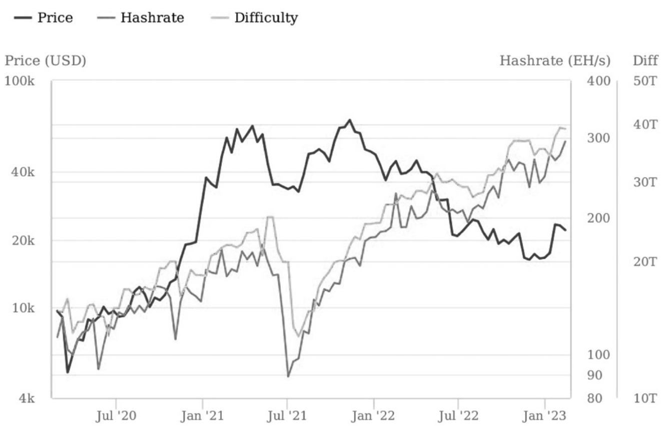
Although cheap electricity is obviously essential to bitcoin miners, the importance of CapEx should not be understated. As we showed in the Economics of Bitcoin Mining with Intermittent Energy Sources, even free electricity is not enough to compensate for overly expensive hardware ($/TH) and infrastructure ($/MW). In large part, CapEx for bitcoin miners is just a function of timing and cost of capital, but not entirely.

In this section, we'll explore how miners can improve their economics by utilizing liquid cooling (i.e. immersion or hydro) to bring total CapEx down even as their $/MW bill for infrastructure increases. In bear markets when hardware is cheap, this strategy isn't as attractive unless your mining farm is located somewhere with a difficult climate, such as the American South or Paraguay, for example. However, it has historically been the case that miners see their access to capital greatly reduced while their cost of capital skyrockets in bear markets, so chances are that at some point every miner will be faced with the difficult decision of how to deploy capital when hardware prices are elevated. Liquid cooling is one of the ways to add flexibility and strategy to this process when the timing is out of your control.

Economics of Immersion Cooling for Bitcoin Miners

An analysis of the big question: "Is immersion cooling worth it?" with long-term profitability projections for Antminer S19 series hardware in immersion using stock firmware and Braiins OS+. This analysis was originally published in May 2022 with future projections for all of the mining profitability calculations. Here, the same exact inputs are used, but the profitability projections utilize real historical data for May 2022 - May 2023 so that you, the reader, can see how things are working out so far for these hypothetical operations.

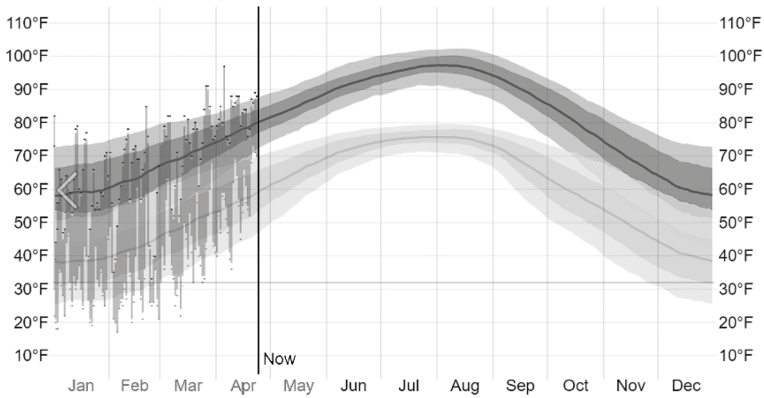
The day is June 18th, 2021. China is extending its provincial cryptocurrency mining ban in Xinjiang and Inner Mongolia to be nationwide, just as the ultra-profitable rainy season in hydropower-dense Sichuan province is getting going. Network hashrate—once practically a sure bet to exceed 200 EH/s by mid-year—now drops back below 100 EH in July. The miners who have hash online in the summer of '21 see their revenue temporarily double in bitcoin terms, from under 500 satoshis/TH/day to nearly 1000 sats/TH/day.



Fast forward to late May 2022. Resilient miners in China have gotten smarter about their network infrastructure and security so that they can continue hashing away, although not nearly at the same scale as before. While some employees of a leading Chinese hardware manufacturer have suggested in friendly conversations that as much as 30-40% of network hashrate remained in China as of mid-2022, this author (with almost no contacts in China) believes it's more likely below 20%.

Meanwhile, total network hashrate is pushing to new all-time highs. The 30-day moving average for hashrate has been sitting above 200 EH/s for a couple of weeks now, and the estimated real-time network hashrate is 208 EH/s at the time of writing. As for where the new hashrate is coming online, there is simply no debate. North America has picked up China's slack and then some, with Texas becoming the clear global frontrunner in terms of hashrate/m2 (even though Texas is huge).

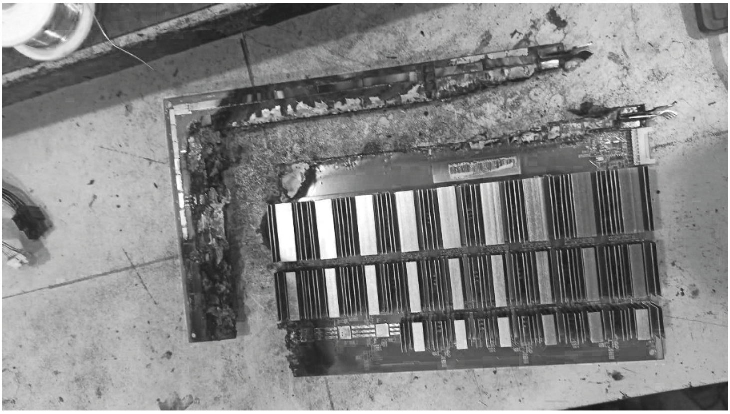
With this hashrate migration to North America and Texas in particular, we are in for an interesting summer. West Texas, the home of much intermittent solar and wind energy, is about to get hot. Like, swelteringly hot.



The daily range of reported temperatures (gray bars) and 24-hour highs (red ticks) and lows (blue ticks), placed over the daily average high (faint red line) and low (faint blue line) temperature, with 25th to 75th and 10th to 90th percentile bands.

Source: WeatherSpark.com

This presents a problem for bitcoin miners. When it's really hot outside, mining hardware runs less efficiently and has a greater risk of failure. The consequences can cause downtime and loss of revenue due to machines automatically turning off once temperature readings reach dangerous levels. Additionally, it can lead to fried hashboards and other permanent hardware damage if the machines don't shut down in time. (Braiins OS+ Dynamic Power Scaling feature fixes this.)



To make matters worse, the most popular ASIC hardware family today is the Antminer S19 series, which is extremely sensitive to heat relative to older miners like the S9 and Whatsminer M20S. As described in the Braiins research article, *Impact of Temperature on Efficiency of Antminer S19's*, the power consumption of Antminer S19 models can increase by 40%+ with higher temperatures even as frequencies are constant (and thus hashrate is constant as well), meaning that the J/TH efficiency of the machines suffers significantly.

It's no surprise, then, that many public miners are exclusively building immersion cooling infrastructure for their new miners coming online in Texas and elsewhere in the hot and humid southern United States. Immersion cooling alleviates the majority of the temperature impact on mining operations. Rather than worrying about your mining fleet's uptime, power consumption, and lifespan, you can respond to temperature rises by increasing pump speeds and running dry coolers / cooling towers harder, keeping your total hashrate and power consumption much stabler and decreasing operational risks. For well-capitalized miners operating in hot climates, it just makes sense.

But what about the pleb miners with a machine or two or five at home? What about the miners with 1-6 MW operations in Paraguay or Mexico? For that matter, what about the miners in Wyoming, Montana, and the Dakotas where it's very cold for a good portion of the year but those few summer months can see temperatures exceed 100oF (38oC) on rare occasions?

Does it make sense for any of those miners to invest in immersion cooling? Well, let's find out.

BENEFITS OF IMMERSION COOLING FOR BITCOIN MINERS

Before getting into the economic analysis, it's important to understand the advantages of immersion compared to air cooling that help justify its higher up-front cost. To briefly summarize, immersion cooling offers the following benefits:

- **More effective heat dissipation**: the fluids used in immersion, called dielectric coolants, are much more thermally conductive and dense than air, making them better at absorbing heat and moving it quickly away from the miners.

- **Increased hardware lifespan**: small vibrations and rapid temperature fluctuations degrade hardware lifespan, and immersion cooling greatly reduces both of these because the fluid temperature is more stable than air and the fans, which produce the vibrations in air, can be removed in immersion.

- **Better operating conditions**: the immersion fluid prevents dust and debris from getting into the hardware, decreasing cleaning and maintenance requirements. Also, the removal of the fans and density of the fluid practically eliminate the noise, which can be deafening for miners in air.

- **Improved Efficiency (J/TH)**: on a new-generation miner like an Antminer S19, the 4 fans consume roughly 35 W each, accounting for ~5% of the machine's total electricity consumption in air. Removing them to run in immersion means that the 5% energy savings can go towards more hashing, improving the J/TH by roughly that amount.

- **Safer Overclocking (more TH/s)**: the more effective heat dissipation and operating conditions in immersion also enable miners to overclock their machines to a very significant degree, as we'll see later in this article.

All of these benefits make immersion cooling superior to air cooling, regardless of the climate that the miner is operating in. However, it comes at a much higher up-front cost, so there's still a question of whether or not immersion cooling is worth it. While that will depend largely on the local climate of the operation, this article will outline the structure for making this determination and all of the not-so-small details to consider with it.

MINING INFRASTRUCTURE CAPEX: IMMERSION VS. AIR COOLING

As is the case with all future profitability calculations we do for bitcoin miners, we're going to have to make a lot of assumptions and generalizations here in order to get anywhere.

Honing in on a narrow price range for building mining infrastructure just isn't possible. It depends on all sorts of factors that change over time and across different locations, as well as the size of the operation being built. For example, labor in Paraguay and Mexico is relatively cheap compared to the US and Canada. On the other hand, many of the parts required for infrastructure would need to be shipped internationally, which may also include extra import costs. And modular, mobile infrastructure (i.e. mining containers) will generally cost more per MW than large static facilities that can host 10+ MW worth of miners.

So, let's simplify matters and just lay out some assumptions. Building air cooled infrastructure can cost anywhere from **$150-400k/MW**, depending on everything described above. Some portion of that cost is for cooling, including wet curtains and industrial-sized intake and exhaust fans, as well as insulative material to separate hot and cold aisles. All together, those cooling components will rarely account for more than 10% of total infrastructure CapEx, while the more common case is probably at or below 5%. Meanwhile, the lion's share of the costs will be from labor, materials, and electrical equipment and wiring.

Immersion mining infrastructure will still have nearly all the same costs as air cooled infrastructure, minus about 5% ($7.5k-20k/MW) for the cooling components that are no longer needed. However, immersion will add all sorts of new and costly components to the infrastructure:

- Dry coolers / cooling towers
- Tanks and frames
- Pumps and pipes
- Heat exchangers
- Dielectric coolant
- Sensors and monitoring / control systems

After analyzing dozens of different immersion systems varying in size from small DIY tanks with 2-4 mining machines to industrial-scale facilities, we've found that the extra CapEx for building immersion infrastructure is almost identical to the original air cooling CapEx range, $150k-350k per MW, not including shipping costs. This means that the total cost for immersion infrastructure should be somewhere in the wide range of $280k-730k/MW, although the upper portions of both the air cooled and immersion ranges are generally for modular containers, which wouldn't be combined with each other. More realistically, then, let's say that the total immersion cost should be somewhere in the **$280-600k** range.

Now, all that's left to do is answer the question of whether that extra CapEx is worth it for all the benefits immersion provides.

MINING PROFITABILITY PROJECTIONS FOR IMMERSION COOLING VS. AIR COOLING

Finally, we've made it to the fun part. Let's lay out the rest of our assumptions and crunch the numbers.

First, some arbitrary inputs to narrow down the scope:

- **Price and Difficulty**: $40,000/BTC and 29794407589312 difficulty (as of early May 2022)

- **Power Capacity and Time**: 10 MW of available power capacity for 4 years

- **Safety Margin**: 5% of the power capacity will be set aside for running cooling equipment (fans, pumps, dry coolers, etc.) and as a safety margin, leaving 9.5 MW for mining

- **Hardware and Rigprice**: The mining hardware used will be exclusively 104 TH/s Antminer S19j Pro's with a total machine cost of $8500/unit (rig price $81.7/TH) and stock power consumption per unit of 3068 W

- **Infrastructure Cost**: Air cooled = $250k/MW, or $2.5MM total for 10 MW; Immersion = $450k/MW (air cooling + $200k/MW), or $4.5MM total for 10 MW

- **Hardware Depreciation**: There will not be a difference between air cooled and immersed hardware depreciation rates; 20%/year for both even though immersion miners should have a longer operating lifespan; more on this in the Out-of-Scope Considerations section at the end of the article.

- **Electricity Price**: All-in electricity rates will be a fixed $0.05/kWh with 24/7 uptime

- **BTC HODL Ratio**: All miners have the goal of maximizing their BTC holdings, so the HODL Ratio will be 100% of profits in all cases

- **Simplification**: Although heat impacts Antminer S19 efficiency and summer months would likely cause a decrease in profitability for the air cooled operation, we will not factor that in and assume that hashrate and consumption are stable year-round (giving a small, unrealistic advantage to the air cooled operation)

Next, the ever-important assumptions of hashprice rate of change a function of difficulty and price rates of change:

- **Moderately bullish case**: May 2026 values of $400k/BTC and 182.3T difficulty, meaning that difficulty increases 70%/year and price increases 80%/year; 0. BTC transaction fees per block, 20% halving difficulty drop as less competitive miners shut down; of course, BTC price could (and historically did) increase faster than this, but in that case all miners will do extremely well and this analysis isn't very interesting

- **Moderately bearish case**: May 2026 values of $95k/BTC and 98.7T difficulty, meaning that difficulty increases 50%/year and price increases 25%/year, 0.1 BTC transaction fees per block, 30% halving difficulty drop as less competitive miners shut down; of course things could get more bearish than this, but if you think BTC won't go up at least 25% year on average over a 4-year period, then save yourself the time now and don't invest in mining

Note that the bullish case will result in less BTC mined because large BTC price increases will incentivize more hashrate to come online, causing difficulty to increase faster.

One interesting way to put the infrastructure CapEx into perspective is by comparing it to the hardware CapEx. If we assume stock power consumption of 3068W per S19j Pro and a 5% buffer in total power consumption, that means that we will have 325 S19j Pro's per MW. At a unit cost of $8500, the hardware CapEx is $2.76MM/MW—approximately 10x the air cooling infra cost and 5.5x the immersion cooling infra cost. Just food for thought.

With these assumptions, we'll analyze the bullish and bearish cases for each of 6 different scenarios:

1. Air-cooled, stock firmware

2. Air-cooled, Braiins OS+ and stock power consumption

3. Immersion cooled, stock firmware

4. Immersion cooled, Braiins OS+ and stock power consumption

5. Immersion cooled, Braiins OS+ and 4000W power consumption

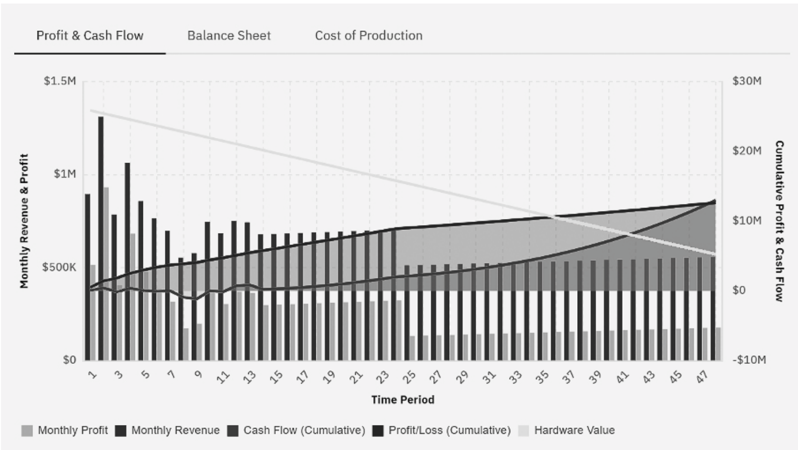
6. Immersion cooled, custom PSU, Braiins OS+ and 5500W power consumption

Note: All profitability projections have been updated with 1 year of historical data since this content was originally published, but the final difficulty and BTC price for May 2026 are kept the same as the original analysis (i.e. the difficulty increment and price increment have been adjusted from the original analysis to still result in the same ending values for May 2026).

Case 1: Air-cooled running stock firmware

To fill 9.5 MW at the stock power consumption of 3068 W, we can purchase 3,096 S19j Pro's for a total hardware CapEx of $26.32MM. This brings our total CapEx for the 10 MW air-cooled operation to **$28.82MM** (720.5 BTC). Our total **hashrate is 322 PH/s** and our pool fee is 1%.

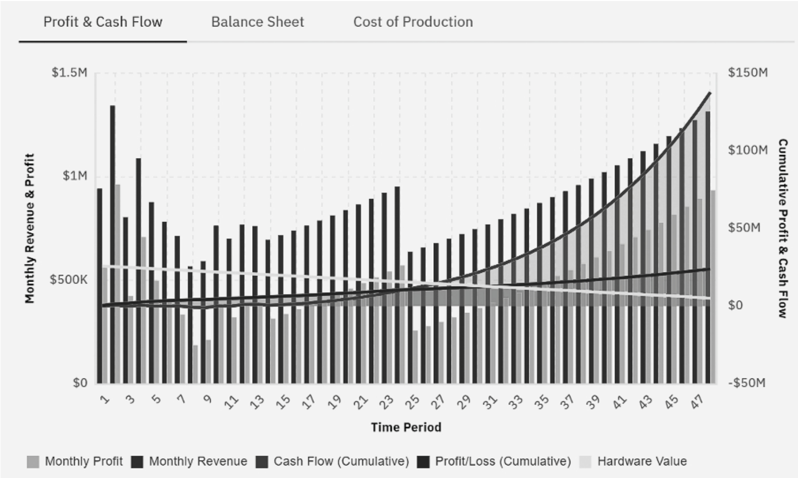
Bearish Case



USD CapEx Break Even	43 MONTHS	BTC CapEx Break Even	--- MONTHS	IRR	14 %
Final Value of BTC H...	34558772 USD	Cumulative Profit fro...	12642915 USD	Total BTC Mined	910.351 BTC
Hardware Fully Deprecia...	--- MONTHS	Avg. Cost to Mine 1 BTC	20038 USD	Electricity Break Even	0.085 USD

With a 100% HODL Ratio on our profits, we end up with $34 million worth of BTC at the end of the 4 years and 910 total BTC mined.

Bullish Case

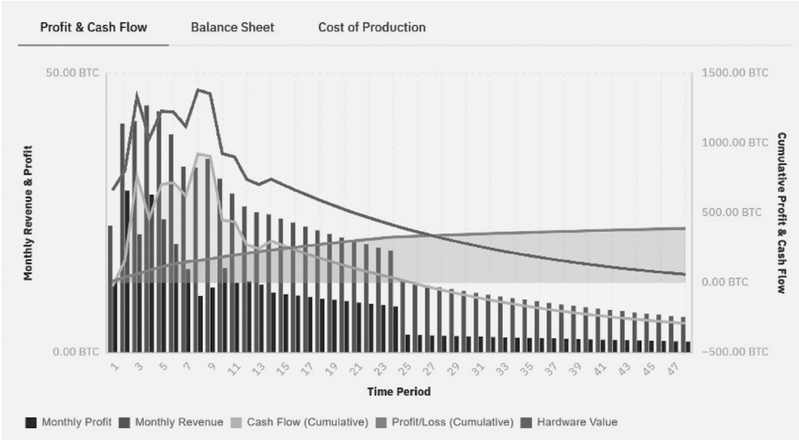


USD CapEx Break Even	27 MONTHS	BTC CapEx Break Even	--- MONTHS	IRR	19 %
Final Value of BTC ...	159316095 USD	Cumulative Profit fro...	23948253 USD	Total BTC Mined	839.509 BTC
Hardware Fully Deprecia...	--- MONTHS	Avg. Cost to Mine 1 BTC	21728 USD	Electricity Break Even	0.116 USD

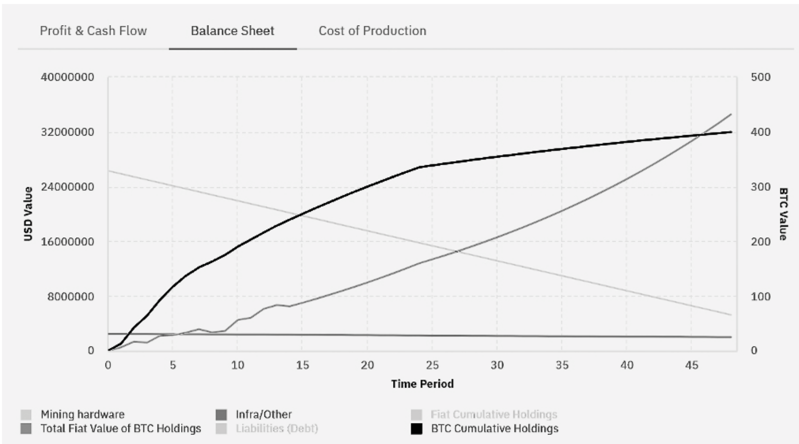
In the bullish case with significant appreciation in BTC price, we end up with nearly $159 million worth of BTC holdings and over 837 total BTC mined.

It’s fair to say that both the hypothetical bullish and bearish cases for an air cooled operation work out well in fiat terms, even with the poor hashprice performance over the last 13 months of historical data. This will be our baseline for comparing the projections with different immersion solutions factored in.

Let’s not move on too fast, though. This is an economic analysis of immersion cooling for *BITCOIN* miners, not *FIAT* miners. If we take a look at the profitability calculations in BTC terms, we see a different story.

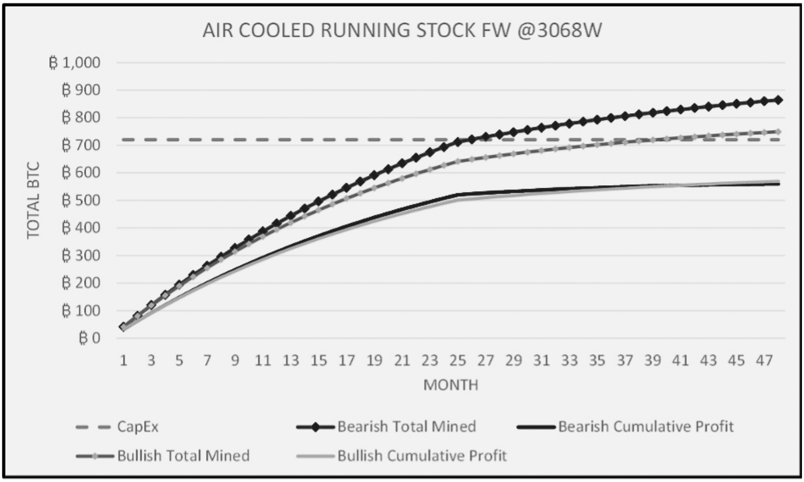


Assuming that we only sell the amount of BTC necessary to cover our OpEx each month, our Cumulative BTC Holdings after 48 months in the bear are just under 400 BTC (pictured), 320 BTC short of our original CapEx spend. Thanks to wider profit margins, we get to 440 BTC in the bullish case, but still well below CapEx breakeven in BTC terms.



This means that the only way this operation could out-perform a simple buy and hold BTC strategy is if it's financed (e.g. with BTC-collateralized loans) such that the miner doesn't need to sell BTC to cover the OpEx or if the BTC-denominated resale value of the hardware at the end of the analyzed period can make up the difference.

You can see the impact of the all-time low hashprice in the past 13 months of historical data by looking at the original projections from May 2022 for BTC mined and held in these scenarios shown on the following chart. While we're now projected to mine about 100 more BTC in total for each case, our holdings are around 100 BTC lower due to the thin margins forcing us to sell more of the BTC mined.



The next step is to re-run this same analysis with bull and bear cases for five other scenarios:

Case 2: Air cooled running Braiins OS+ at stock power consumption
CapEx is the same as in the first scenario, but the improved efficiency from autotuning brings total hashrate to **340.5 PH/s**. The 2.5% firmware devfee is factored in for all projections with Braiins OS+.

Case 3: Immersion running stock firmware
We add $2 million to the total CapEx, giving us **$30.82 million (770.5 BTC)**. With the fans removed, there's about 5% more power

to go towards actually hashing, making the hashrate per machine approximately 109 TH/s. This brings the total hashrate to **338.1 PH/s**.

Case 4: Immersion running Braiins OS+ at 3068 Watts
CapEx remains $30.82MM, but running Braiins OS+ at the stock power consumption in immersion brings the hashrate per S19j Pro to 114.5 TH/s, for a total hashrate of **354.5 PH/s**.

Case 5: Immersion running Braiins OS+ at 4000 Watts
The immersion miner running stock firmware is not taking full advantage of the infrastructure that they spent $450k/MW to build, as they are not using the immersion systems to overclock their miners at all. Let's see what happens when they run Braiins OS+ on their S19j Pro's at 4000 W with autotuning. If the PSUs are immersed along with the miners, the stock PSUs can safely run in this range.

Based on our data, a typical S19j Pro in immersion can hash at around 136 TH/s with a power consumption target of 4000 W, although this is fairly conservative and we've seen some hashing above 140 TH/s in ideal conditions. *(Disclaimer: results vary for each hardware device and depending on the temperatures maintained by your immersion system. Always measure power consumption at the wall and hashrate on your pool account.)*

Since we are planning to consume 4000 W per machine, we won't buy as many miners to fill the available 9.5 MW of capacity. Rather than 3,096, we will only need to buy 2,375 S19j Pro's. This brings our hardware CapEx to $20.19 million and our total CapEx to **$24.69 million (617.25 BTC)**. Total CapEx is actually far lower than an equivalently sized air cooled operation because, even though the immersion infrastructure costs more, it enables us to reduce the more significant cost factor, our hardware. At 136 TH/s per machine, our total hashrate is **323 PH/s**.

Case 6: Immersion with custom PSUs running Braiins OS+ at 5500 Watts

When you can safely overclock to much higher power limits via immersion cooling, you'll find that there is A LOT of hidden potential in Antminer S19 models. In fact, they can run at 6000, 7000, or even 8000 W per unit if you want to really push them. However, the stock PSUs that come with these miners cannot run nearly that high. To push the limits of the ASICs, you'll need PDUs and PSUs that can supply more than 4000 W per machine.

Custom PSUs can vary a lot in price and are subject to some of the same supply chain issues as pretty much everything else in mining these days. That said, a typical price for custom 6 kW PSUs in recent weeks has been about $500/each, so we can just add this to our S19j Pro cost and bring it to $9000/machine.

Running at 5500 W each, we need 1727 S19j Pro's with custom PSUs to fill our 9.5 MW available capacity. This gives us a hardware CapEx of $15.54 million and a total CapEx of **$20.04 million (501 BTC)**. If we assume a hashrate of 160 TH/s at 5500 W (34.4 J/TH), this gives us a total hashrate of **276.3 PH/s**. (Note: it is possible to get higher hashrate than 160 TH/s at 5500 W with Braiins OS+, but we are being conservative in these estimates, as was the case with the 4000 W projections.)

The Results

With the inputs for each of our six case studies calculated, we ran the numbers through the profitability calculator and put the key metrics into a summary table for easy comparison.

Bearish Case						
Scenario	**Total BTC Mined**	**Final BTC Holdings**	**Total BTC Mined - CapEx**	**Cumulative Profit ($mm)**	**USD CapEx Breakeven (Months)**	**Avg. Cost to Mine 1 BTC**
Air-Cooled Stock FW	₿910.4	₿399.6	₿189.9	$12.6	43	$20,038
Air-Cooled BOS + Stock Consumption	₿962.7	₿437.4	₿242.2	$13.9	41	$19,240
Immersion Stock FW	₿955.9	₿445.2	₿185.4	$14.2	42	$19,083
Immersion BOS + @3086W	₿1,002.3	₿491.5	₿231.8	$15.8	40	$18,201
Immersion BOS + @4000W	₿906.0	₿395.0	₿288.5	$12.5	39	$20,143
Immersion BOS + @5500W	₿769.3	₿258.6	₿268.3	$7.9	45	$23,711

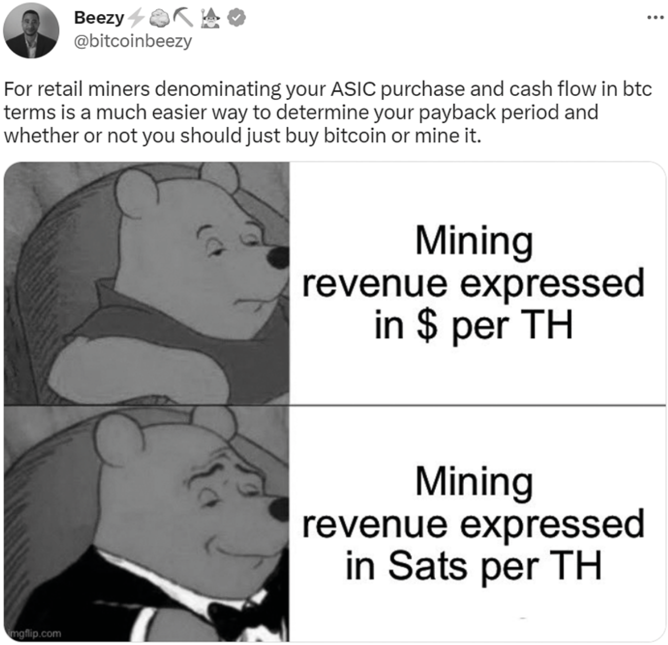
Bullish Case						
Scenario	**Total BTC Mined**	**Final BTC Holdings**	**Total BTC Mined - CapEx**	**Cumulative Profit ($mm)**	**USD CapEx Breakeven (Months)**	**Avg. Cost to Mine 1 BTC**
Air-Cooled Stock FW	₿839.5	₿442.4	₿119.0	$24.0	27	$21,728
Air-Cooled BOS + Stock Consumption	₿887.7	₿490.7	₿167.2	$26.4	26	$20,548
Immersion Stock FW	₿881.5	₿484.4	₿111.0	$26.1	27	$20,694
Immersion BOS + @3086W	₿924.2	₿527.2	₿153.7	$28.2	26	$19,736
Immersion BOS + @4000W	₿857.3	₿460.0	₿239.8	$26.9	25	$21,287
Immersion BOS + @5500W	₿713.1	₿316.0	₿212.1	$17.6	27	$25,581

One of the first comparisons to look at is *Air Cooled with Stock Firmware* vs. *Immersion with Stock Firmware*. This is taking custom firmware and overclocking out of the equation for a moment and asking the question whether or not the efficiency gain of operating in immersion offsets the extra CapEx paid up front. The answer to that question has remained the same from the original analysis to this edition that incorporates 13 months of real data: immersion performs better—more BTC mined in total, more BTC in holdings after paying for OpEx, and higher cumulative profit.

Another thing you'll likely notice right away looking at the tables is that *Immersion with BOS+ at 5500 Watts* performs poorly on every metric except *Total BTC Mined - CapEx (in BTC terms)*. This is exactly what we'd expect given the bearish hashprice. The only scenarios where overclocking to that significant of a degree will work out well are (1) miners with extremely cheap power, (2) ultra-bullish time periods where revenue gets to be upwards of 30¢/kWh with more efficient hardware, or (3) miners with flexible balance sheets that can cover their OpEx without selling a large portion of BTC mining rewards, enabling them to hold until the bull market. (Scenario (3) is why the Total BTC Mined - CapEx metric is interesting.)

MINING PROFITABILITY IN BITCOIN TERMS

You probably noticed that none of these hypothetical mining operations have final BTC holdings after four years that are greater than their CapEx in bitcoin terms. In other words, even though some scenarios perform well in fiat terms, they do not outperform the alternative of using the initial CapEx amount and the monthly OpEx amounts to simply buy and hold bitcoin.



Some thoughts on this:

- If BTC price increases significantly faster than difficulty, it widens mining profit margins and can also help close this gap. We've analyzed essentially the opposite scenario by using historical data for May 2022 - May 2023.

- The two best performing scenarios in terms of BTC-Denominated CapEx vs. Cumulative Profit are the two with autotuning and overclocking (4kW and 5.5kW), both in the bear and bull cases. This makes perfect sense, as autotuning and overclocking essentially produce a discount on the rigprice ($/TH) of your hardware.

- One could conclude that mining bitcoin rarely outperforms simply buying and holding it, but this leaves out something very important: *financing*. Many mining operations today are funded via debt financing or by raising money from investors, and in such cases, it's usually not possible to simply buy bitcoin with the funds. Additionally, many miners today are using these financing methods to cover operating expenses in order to hold all of their BTC mining revenue, not just the profit. The method of financing and balance sheet management ultimately make a big difference for profitability in bitcoin terms.

Other Out-of-Scope Considerations

There are some nuances that would be too complex to include in the mining profitability projections but that miners should be aware of if they're considering immersion.

First of all, **the analysis assumes constant hashrate and power consumption year-round**. This may roughly be the case in places like Iceland and Siberia that never get too hot, but it's not realistic for places like Texas and Paraguay, where heat in the summer would result in increasing power consumption and worse efficiency for air-cooled miners. Since immersion would enable more stable operating conditions year-round, regardless of weather conditions, immersion should compare even more favorably than what we've shown in the projections above for miners who operate in hotter climates.

For both air cooled and immersion operations, **miners can use saved autotuning profiles on Braiins OS+ and sophisticated power management strategies to optimize their operations on a much more granular basis**. For example, they can optimize for efficiency during the hot hours of the summer, optimize for maximizing hashrate during the coldest hours of the winter, and so on. And as difficulty continues to go up over time and their profit margins shrink, they can respond by shifting from a general strategy of maximizing hashrate to a more efficiency-focused strategy. Of course, most PPAs are for a specific amount of power, so this flexibility isn't possible for a large portion of miners, but it's something that retail miners especially can take advantage of to try to compensate for likely paying higher electricity prices.

Also worth mentioning is t**he impact of immersion on hardware resale value**. Once hardware has been running in immersion, it probably shouldn't ever be run in air. For one thing, the thermal paste used in hardware, including Antminer S19s, will dissolve in most dielectric coolants, resulting in poorer thermal conductivity, which would make the machine dangerous to operate air cooled later on.

As a result, the future of **the secondary hardware market will likely be segregated between machines that have been used in immersion and those that have not** (but still can be in the future). It's hard to say whether the immersion machines will be worth more or less relative to the non-immersion machines. On the one hand, immersion should improve the lifespan and decrease wear and tear from months or years of operation, meaning that the machines are still in great condition when they hit the market. On the other hand, the buyers for those machines can only be miners who have available immersion capacity, and it's questionable whether or not it will make sense to put older hardware into immersion considering the higher infrastructure CapEx. Therefore, it seems possible that hardware running in immersion does have a longer operating life but is difficult to sell on secondary markets when it's 4+ years into that lifespan and effectively "old-gen" hardware.

Another out-of-scope factor to consider is that **immersion infrastructure won't become useless when the current new-gen machines are no longer profitable or stop working**. With proper maintenance, it should be the case that immersion systems can be used for multiple generations of hardware across 10+ years. Perhaps 3-5 years from now, you'll swap out your S19's or M30S's for the latest gen hardware, and you'll be able to operate it more efficiently and safely overclock it from the beginning because you already have the immersion systems ready to go. If the economics of immersion look good with a single generation of hardware, it's up only for multiple generations.

Lastly, **immersion systems are better at efficiently (and quietly) capturing the heat output of the miners and transporting it elsewhere**. The majority of the time, that elsewhere is a cooling tower or dry cooler, but sometimes it might be a swimming pool, a green house, or some other place that can use the heat from miners. If miners can find a customer for the heat (even if it's themselves), they are effectively dropping their electricity price by making the electricity count twice. Immersion helps enable more use cases for doing just that.

Last Word

Long-term, the winning strategy based on this introductory analysis is using immersion cooling infrastructure and running it around stock power consumption or stock efficiency levels (i.e. moderate overclocking) with autotuning firmware like Braiins OS+. This provides the best balance of total production (i.e. mining as much BTC as possible) and high efficiency (i.e. stacking the most sats per Watt of energy consumed).

Although the price tag of immersion seems extremely high for many miners, it will usually be relatively insignificant compared to the cost of new-gen hardware. (The exception being time periods like late 2022 - early 2023 with extremely cheap hardware.) If you don't have easy access to capital or you are building a smaller-scale operation and using older, less efficient mining machines, then immersion likely won't make sense. But for well-capitalized miners building industrial-scale operations, particularly in places with hot summers like Texas and the rest of the southern US, immersion is probably worth it. And of course, whether you overclock or not, you're missing out on extra BTC if you don't use Braiins OS+ to maximize ASIC efficiency at any power consumption level.

Oh, one final note: this analysis only compares immersion vs. air cooling but doesn't begin to analyze the third option: hydro cooling. In early 2022, large-scale hydrocooling solutions were practically unheard of, but they've since gained a decent amount of popularity. Many of the benefits of hydrocooling are similar to those of immersion, with the biggest advantage being that you don't need an expensive coolant for hydrocooling solutions like you do with immersion. However, the jury is still out on factors such as maintenance requirements and accessibility to the hardware for maintenance, longevity of the hydro cooling systems, and efficacy of the cooling when overclocking to the upper limits of the hardware.

The Emergence of Hydro (Water) Cooling

Some quick notes on hydro cooling options for bitcoin miners and how it differs from immersion cooling while offering many of the same general benefits compared to air cooling.

While it's likely that well over 1 GW of immersion cooling infrastructure has been built out by bitcoin miners in the last several years, hydro (i.e. water) cooling has been much slower to catch on. Bitmain released an 18 TH/s Antminer S9 Hydro in 2018 with minimal success, and then a few years passed with basically nothing happening on the hydro front.

However, both Bitmain and MicroBT have invested significantly in developing hydro-cooled variants of their hardware, and it seems likely that hydro will be receiving serious consideration from miners in 2023 and beyond.

HYDRO VS. IMMERSION AND AIR COOLING

The way that hydro cooling typically works in bitcoin mining is that water (potentially mixed with glycol) circulates through small tubes inside the hardware to cooling plates that are fixed to the hashboards. This is also called direct-to-chip or direct-to-plate cooling, as the cooling plates are directly next to the ASIC chips so that the cool liquid passing through can draw a substantial amount of heat off of the chips. Notably, this means that the chips and hashboards do not directly touch the fluid with hydrocooling the way that they do with immersion, which is why it's possible to avoid using a costly dielectric coolant as there is no need to worry about material compatibility for all of the components of the hardware.

Due to being a closed-loop system, hydro cooling also prevents exposure of the hardware to outside elements, meaning that dust and dirt aren't of concern. And, similarly to immersion, since powerful fans running at high speeds aren't necessary for cooling the hardware, miners can run practically silently.

However, the most significant benefits of hydro cooling are, of course, the potential performance improvements for the hardware. Specifically, safely achieving better efficiency and producing more hashrate. Therefore, the methodology used earlier in this section to analyze immersion vs. air cooling will similarly apply for hydro cooling. Essentially: *figure out how much more the hydro cooling setup + hardware costs vs. air cooling, then translate that to a total $/TH that takes into account the better performance of the liquid-cooled hardware*.

DATA CENTER STANDARDIZATION

One last interesting topic while on the subject of hydro cooling is the Whatsminer M53S Hydro from MicroBT, a 260 TH/s machine that consumes 6760 W at stock settings for an efficiency of 26 J/TH. The performance is quite good by 2023 standards, but it's not the most interesting thing about this particular machine in the big picture. Rather, it's the form factor that makes it stand out, due to the fact that it uses the "U" server sizing of traditional data center racks. ("U" is a unit of height in the rack, where 1U = 1.75inches (4.45cm) tall x 19in (48.26cm) wide.)

The M53S has a standard 2U size and can be placed in regular server racks that go in traditional data centers, assuming access to a sufficient water coolant supply. It's a move towards standardization that's interesting (some might even say encouraging) to see from a major manufacturer in the bitcoin mining industry, where popular machines have had the "shoebox" formfactor throughout the modern ASIC era.

In comparison, Bitmain also offers a couple hydro cooled variations of its Antminer S19 series with great performance specs as well as hydro-specific container infrastructure, but they've stuck with the shoebox form factor for these machines.

At the time of writing, it remains to be seen how the market will respond to these differing solutions and how they will hold up over time. Immersion has a significant head start in adoption, but hydro solutions will begin competing on cost, performance, and simplicity to set up and operate.

TRANSACTION FEES AND HALVING CYCLES

If you simplify the bitcoin mining business model down to a few basic principles, it is largely similar to the production of other commodities such as oil, gold, and corn… except for one unique difference: the halving. Every 4 years, new BTC issuance earned by miners gets cut in half. Historically, this new coin issuance—the block subsidy portion of the block reward—has accounted for the vast majority of total mining revenue, while transaction fees make up the rest.

Since the early days, people have speculated about whether or not transaction fees will increase enough in volume and stability to sustain the mining industry as the block subsidy decreases again and again and ultimately hits zero by the year 2140.

One of the nuances that's often missed in these speculative discussions is that there is no identifiable "correct" value in BTC or fiat terms for the block subsidy to be sufficient to ensure bitcoin's decentralization and resistance to attacks. The main purpose of the block subsidy is to incentivize honest miners to deploy and operate hashrate such that network difficulty is high enough to make it prohibitively expensive for attackers to even attempt amassing 51%+ of network hashrate or trying to censor transactions going into blocks, something we analyzed in much more detail in the Cost to 51% Attack chapter of the Bitcoin Mining Handbook.

The important clarification to make is that total mining revenue (often referred to as the security budget) doesn't necessarily tell us how distributed hashrate is geographically and politically, nor other aspects of the industry such as hardware manufacturing, firmware choices, mining pools, etc.—all factors that matter to bitcoin's overall decentralization and censorship resistance. Besides that, it seems almost pointless to have a discussion today about what bitcoin's transaction fees will be like in 20+ years considering that we're still in the "early adopter" epoch of bitcoin's maturation, and a decades-out future where bitcoin is still relevant almost certainly comes with a significant increase in demand for block space as well as an orders-of-magnitude increase in bitcoin's value against all the world's fiat currencies.

Of course, from a miner's perspective, it's very simple: the bigger the security budget, the better. But once you get into ideas such as removing the 21 million supply cap and adding some small perpetual inflation, the nuance above should carry some weight.

As for the rest of this chapter, we're going to bring things back to mining economics and business models. Specifically, we'll be taking a look at every miner's and mining pool operator's favorite thing: variance.

Transaction Fee "Luck" for Bitcoin Miners

The future of variance risk and hedging for bitcoin miners and mining pools as transaction fees become increasingly important for miner revenue over time.

Throughout most of the latest bear market, transaction fees have made little difference in bitcoin mining profitability. Taking away the ordinal-fueled fee boom of Q2 2023, the average transaction fee amount per block over the past couple of years is 0.095 BTC—a mere 1.5% of the total block reward. Needless to say, fees weren't much of a liferaft for miners as they watched the BTC price sink and network difficulty climb during the past 2 years.

So, as many miners have been fighting to avoid bankruptcy and live to hash another day, what better time than now to distract ourselves with some speculation about what future bitcoin miners might be doing to survive in 10, 20, or even 50 years?

And no, we won't be discussing the sustainability of transaction fee revenue in this article, but if you're interested in that, you can check out *Understanding Bitcoin's Fee-Based Security*.

PREREQUISITE KNOWLEDGE: BLOCK FINDING "LUCK"

Most miners today are familiar with the concept of luck. It is another word for the variance in block finds that mining pools and solo miners experience relative to their expected block finding cadence given their hashrate and the network difficulty.

As a quick example, let's say that a mining pool has a static 10% market share of the total network hashrate. This means that they are expected to find 1 of every 10 blocks, or 1 block per 100 minutes given a 10-minute average block time. If they find exactly 1 block per 100 minutes, they have 100% luck. If they find more than 1 block per 100 minutes, they are "lucky" and have earned more BTC than expected. On the other hand, finding less than 1 block per 100 minutes is "unlucky" and means that they earned less BTC than expected.

In short time periods (days to weeks), it's quite common for luck to fluctuate significantly. Over long time periods (months to years), luck balances out towards 100%. For miners who don't want to stomach this short-term variance, many mining pools today offer a reward system called FPPS (Full Pay-Per-Share) that pays miners according to the expected value of their hashrate, regardless of the actual blocks mined by the pool. In this system, the pools are taking on all the short-term variance risk, which requires deep BTC reserves to remain solvent through bad luck periods.

In case you're interested in a more thorough lesson, our Mining Pools Explainer should get you fully up to speed.

TRANSACTION FEE “LUCK”

Hidden inside block finding luck is another form of variance that gets about 0.01% of the attention: transaction fee luck. This refers to the fullness of the mempool at the time of a block find and the resulting amount of transaction fees contained in that block relative to other blocks in the same time period.

In the context of transaction fee luck, finding a block very quickly after the previous block was found is “unlucky” because it will result in relatively lower fees, assuming the miner of the previous block included the highest-fee transactions possible. To the contrary, finding a block after a long network-wide block finding drought is “lucky” because it gives the mempool time to fill up with higher-fee transactions as users compete to get included in the next block.

For example, let’s look at transaction fee luck for some blocks between Block #764132 and #764145.

Blocks Mined

Block Height	Miner (Pool)	Time	Block Value	Block Value
764145	ViaBTC	2022-11-21 15:50:36	6.26858795 BTC	101269.04 USD
764144	F2Pool	2022-11-21 15:50:36	6.33486575 BTC	102339.76 USD
764143	BTC.com	2022-11-21 15:50:36	6.37794196 BTC	103207.86 USD
764142	Binance	2022-11-21 15:50:36	6.36470425 BTC	102993.64 USD
764141	Braiins Pool	2022-11-21 15:50:36	6.44039154 BTC	104218.42 USD
764140	BTC.com	2022-11-21 15:50:36	6.52686176 BTC	105617.68 USD
764139	Foundry USA Pool	2022-11-21 15:50:36	6.41517762 BTC	103810.40 USD
764138	Foundry USA Pool	2022-11-21 15:50:36	6.48544529 BTC	104947.48 USD
764137	ViaBTC	2022-11-21 15:50:36	6.54658927 BTC	105936.91 USD
764136	Braiins Pool	2022-11-21 15:50:36	6.70572926 BTC	108512.11 USD
764135	ViaBTC	2022-11-21 15:50:36	6.41545909 BTC	103449.28 USD
764134	AntPool	2022-11-21 15:50:36	6.51418027 BTC	105041.16 USD
764133	Braiins Pool	2022-11-21 15:50:36	6.51064599 BTC	104583.76 USD
764132	BTC.com	2022-11-21 15:50:36	6.26657529 BTC	100663.13 USD

1 – 15 of 150 items 1 of 10 pages

Braiins Insights: Recent Blocks Mined

The average block value in this stretch is 6.44 BTC, or approximately 0.19 BTC average transaction fees per block. Although there are no block durations particularly close to 10 minutes (the closest is Block #764141, 6:27 after the previous block), the average 1-block duration is still very close at 10:11. And do we find any relationship between long block durations and higher transaction fees?

Block #	Block Value (BTC)	1-Block Duration (sec)	2-Block Duration (sec)	3-Block Duration (sec)
764132	6.26657529	103	718	1543
764133	6.51064599	1123	1226	1841
764134	6.51418027	1044	2167	2270
764135	6.41545909	225	1269	2392
764136	6.70572926	3558	3783	4827
764137	6.54658927	273	3831	4056
764138	6.48544529	297	570	4128
764139	6.41517762	15	312	585
764140	6.52686176	967	982	1279
764141	6.44039154	387	1354	1369
764142	6.36470425	105	492	1459
764143	6.37794196	319	424	811
764144	6.33486575	141	460	565
764145	6.26858795	-3	138	457
Average	6.44093966	611	1266	1970

THE ANSWER IS A RESOUNDING YES.

By far the most valuable block in the batch, #764136, had an extremely long 1-block duration at 59:19 and racked up ~0.456 BTC of fees—over double the average. Even though it was followed by a block just 4:33 later, there were enough high-fee transactions leftover in the mempool to make that block the 2nd highest value in the batch with ~0.297 BTC of fees. The 2nd, 3rd, and 4th longest 1-block durations resulted in the 3rd, 4th, and 5th highest block values.

On the other end of the spectrum, the shortest block durations resulted in the lowest value blocks. 5 blocks were found within 3 minutes of the previous block, and these 5 blocks rank as the 1st, 2nd, 3rd, 4th, and 6th least valuable in the batch.

Side note: you may have even noticed a -3 second block duration for Block #764145. This is because the timestamp does not need to be exact, and modern-day miners actually alter it in 1 second increments on purpose to expand their search space in a process known as nTime rolling, providing more combinations to hash with each nonce (nonce range * ntime range). This makes our block durations imprecise, but chances are that our error margin isn't more than a few seconds.

THE FUTURE: HEDGING TRANSACTION FEE VARIANCE

Today, with transaction fees accounting for so little of total block rewards, block finding luck reigns supreme as the only luck metric that really matters. But as we progress through more halving epochs, will transaction fee luck begin to play an important role in mining economics?

Let's fast forward to the year 2034, when the block subsidy has halved 3 more times and sits at 0.78125 BTC. Supposing that transaction fees don't increase at all in bitcoin terms from the blocks analyzed above, what would be the difference between the luckiest and unluckiest transaction fee blocks?

Current Halving Epoch				*Halving Epoch #7 (Hypothetical Values)*			
Block #	**Block Value (BTC)**	**Tx Fee % of Block Reward**	**%Difference from Average**	**Block #**	**Block Value (BTC)**	**Tx Fee % of Block Reward**	**%Difference from Average**
764132	6.26657529	0.26%	-2.71%	1394132	0.79782529	2.08%	-17.94%
764133	6.51064599	4.00%	1.08%	1394133	1.04189599	25.02%	7.17%
764134	6.51418027	4.06%	1.14%	1394134	1.04543027	25.27%	7.53%
764135	6.41545909	2.58%	-0.40%	1394135	0.94670909	17.48%	-2.62%
764136	6.70572926	6.80%	4.11%	1394136	1.23697926	36.84%	27.24%
764137	6.54658927	4.53%	1.64%	1394137	1.07783927	27.52%	10.87%
764138	6.48544529	3.63%	0.69%	1394138	1.01669529	23.16%	4.58%
764139	6.41517762	2.57%	-0.40%	1394139	0.94642762	17.45%	-2.65%
764140	6.52686176	4.24%	1.33%	1394140	1.05811176	26.17%	8.84%
764141	6.44039154	2.96%	-0.01%	1394141	0.97164154	19.59%	-0.06%
764142	6.36470425	1.80%	-1.18%	1394142	0.89595425	12.80%	-7.84%
764143	6.37794196	2.01%	-0.98%	1394143	0.90919196	14.07%	-6.48%
764144	6.33486575	1.34%	-1.65%	1394144	0.86611575	9.80%	-10.91%
764145	6.26858795	0.30%	-2.68%	1394145	0.79983795	2.32%	-17.73%
Average	6.44093966	2.96%			0.97218966	19.64%	

In the (current) 4th halving epoch, the greatest percentage difference from the average block value is 4.11%. In the 7th halving epoch, the same difference in transaction fee values results in 5 of the 14 blocks having an over 10% difference from the average block value, and the 4.11% difference from Halving Epoch 4 becomes a 27.24% difference in Halving Epoch 7.

And if we fast forward another 3 halvings...

Current Halving Epoch				*Halving Epoch #10 (Hypothetical Values)*			
Block #	**Block Value (BTC)**	**Tx Fee % of Block Reward**	**%Difference from Average**	**Block #**	**Block Value (BTC)**	**Tx Fee % of Block Reward**	**%Difference from Average**
764132	6.26657529	0.26%	-2.71%	2024132	0.11423154	14.51%	-60.42%
764133	6.51064599	4.00%	1.08%	2024133	0.35830224	72.74%	24.15%
764134	6.51418027	4.06%	1.14%	2024134	0.36183652	73.01%	25.38%
764135	6.41545909	2.58%	-0.40%	2024135	0.26311534	62.88%	-8.83%
764136	6.70572926	6.80%	4.11%	2024136	0.55338551	82.35%	91.75%
764137	6.54658927	4.53%	1.64%	2024137	0.39424552	75.23%	36.61%
764138	6.48544529	3.63%	0.69%	2024138	0.33310154	70.68%	15.42%
764139	6.41517762	2.57%	-0.40%	2024139	0.26283387	62.84%	-8.93%
764140	6.52686176	4.24%	1.33%	2024140	0.37451801	73.92%	29.77%
764141	6.44039154	2.96%	-0.01%	2024141	0.28804779	66.10%	-0.19%
764142	6.36470425	1.80%	-1.18%	2024142	0.2123605	54.01%	-26.42%
764143	6.37794196	2.01%	-0.98%	2024143	0.22559821	56.71%	-21.83%
764144	6.33486575	1.34%	-1.65%	2024144	0.182522	46.50%	-36.76%
764145	6.26858795	0.30%	-2.68%	2024145	0.1162442	15.99%	-59.72%
Average	6.44093966	2.96%			0.97218966	19.64%	

In this hypothetical scenario, transaction fee variance matters a whole lot—total block values are > 20% away from the average in 10 of 14 blocks. However, I don’t see this extreme level of block value volatility as particularly realistic.

For bitcoin to still exist and be significant in 12 or 24 years, it will almost certainly have a much larger user base than it does today, resulting in far more consistent and substantial demand for block space. This should minimize the difference in block values between a 1 minute and a 20 minute block duration. On top of that, the way that we use the bitcoin blockchain will likely evolve towards more final settlement of large transactions and fewer time-sensitive small payments, as those will mostly happen off-chain.

These factors would result in less short-term variance in transaction fee amounts, preventing the occurrence of partially full blocks that sometimes get mined today when many blocks are found in quick succession.

Still, miners in the 2030's and beyond will want to reduce their exposure to transaction fee variance as much as possible. The two most likely ways they would do so are:

- **Hashrate forwards and hashvalue/hashprice futures**: miners can lock in their revenue weeks or months into the future with hashrate forward contracts and hashprice futures; where futures and forwards would primarily hedge BTC price volatility and difficulty increases today, they may primarily be hedging transaction fee volatility in the future, assuming that BTC price and difficulty will stabilize considerably as bitcoin grows.

- **Out-of-band payments**: miners can ensure more stability in their revenue by making agreements with block space consumers (e.g. exchanges) to include their transactions in blocks for a subscription-type fee paid separately (off-chain). Subscribers would limit their risk of paying higher transaction fees in the future if block space demand increases, while miners would limit their risk of shrinking revenue in the future if demand decreases. For more detailed analysis of this, search for the article *Stratum V2: Migration and Decentralization published on Derbit Insights*.

The biggest question mark for the long-term future in my mind is at the mining pool level. It's already very difficult to run a mining pool, especially in the FPPS era, which requires deep reserves to withstand bad luck periods. Transaction fee luck simply increases risk for pool operators with FPPS, potentially by a significant amount considering some of the numbers in the *% Difference from Average* column of the *Halving Epoch 9* table.

Importantly, this variance risk is different from the risk that miners themselves want to hedge. Miners care about hashvalue (BTC/PH/s/day) and hashprice ($/PH/s/day) revenue, as it's what sets their top line. For this, miners of the future will likely be able to hedge with hashvalue and hashprice futures, physically delivered hashrate forwards, and non-deliverable hashrate forwards. Pools care about this as well, but it's not as important as hedging the risk of owing the miners in the pool more BTC than the pool actually mined due to variance. Pools can do everything by the book and still become insolvent if their reserves are not deep enough to withstand bad luck, especially if they have bad block finding luck and bad transaction fee luck at the same time.

To the extent that pools can gain stability with out-of-band payments, they will have to figure out how to transparently pass along most of this revenue to miners in the pool to remain competitive against other pools. Hashvalue and hashprice would not be uniform values for all miners and pools anymore, as the off-chain fees miners receive will not be factored in. This leaves us with a few questions for which I don't have the answers.

What might the pools of Halving Epochs 7+ look like? Will FPPS still be the standard? Will pools pay each of their miners according to the value of the block templates they work on (Stratum V2 implementation, where shares are valued based on the block template value the miner is hashing regardless of which block gets mined and the value of block templates that other miners in the pool are hashing), or will the "full" portion of FPPS still be based on a 24-hour moving average of transaction fees per block? Will MEV (miner extractable value) and out-of-band payments become commonplace on bitcoin?

Only time will tell. Tick tock, next block.

A NOTE ON ORDINALS AND STRATUM V2

I originally wrote this article in late 2022, before ordinals were a thing. I will leave the g*ood for bitcoin/bad for bitcoin* debate about ordinals to others, but purely from a capitalistic miner's perspective, many more sats have been awarded to miners in the last few months than otherwise would have been the case had ordinals not become a thing, although fees have come back down to earth recently.

At the same time, we have moved much closer to answering the question I asked in the original conclusion to this article—*will MEV (miner extractable value) and out-of-band payments become commonplace on bitcoin?*—than I would have expected so soon. Out-of-band payments have undoubtedly increased significantly (albeit maybe temporarily) thanks to ordinals, as well as increased demand for transaction accelerator services where pools take an off-chain payment to prioritize a lower fee transaction in their blocks, a result of the increased mempool congestion from more transaction volume.

As somebody who has never personally written pool software (i.e. take it with a grain of salt), I strongly favor a transition to block-template based accounting by pools with Stratum V2. It solves a couple of problems:

(1) If miners who use Stratum V2 Job Negotiation to construct their own blocks are consistently selecting sub-optimal transaction sets that don't maximize transaction fees, they get paid less for their shares without punishing other miners in the pool who work on higher-value block templates. However, this creates yet another luck metric for pools in which they can get lucky when miners working on higher-value templates find proportionally more blocks than miners working on lower-value templates, as they don't have to pay the latter group of miners as much and get to keep the difference. Of course, this can go the other way too. So we'd have *block finding* luck, *transaction fee* luck, and *block template* luck. Variance^3. The mining pool business is rough.

(2) Template-based accounting would have a very interesting impact on the market for out-of-band payments. It would allow individual miners to participate and develop their own use cases and fee optimization strategies independently of their pools (without impacting other miners in the pool), and it would also enable miners who don't involve themselves in out-of-band payments to consistently hash higher-value block templates than those who do and get paid more per share accordingly. In the current FPPS-dominant landscape, a few out-of-band payments here and there won't impact the moving average for transaction fees very much, but the more commonplace off-chain payments become, the more they will be felt negatively by *all* miners getting paid with an FPPS method who don't benefit from those off-chain fees. Template-based share values are a way to reward miners who always optimize their transaction selection to maximize on-chain fees, and in my opinion, that's an important thing to do.

Of course, however pleasant those things sound ideologically, it's another thing to write the software that can do this extra-granular accounting for each share. It's my belief that there usually won't be significant variation between block templates for different miners in a pool, and therefore there won't be hundreds of different block template values for pools to account for differently at any given moment. Paying miners according to their template values would actually incentivize miners to update their block templates with new high-value transactions more frequently within a given round, resulting in more miners consistently working on the highest-possible-value blocks than there would be otherwise at any given moment.

Again, only time will tell.

HASHRATE AND HUMOR: MINING FOR MEMES

Bitcoin mining may initially appear to be an intricate, complex beast. The whirlwind of jargon, figures, calculations, strategies, and variables can feel overwhelming. But what if there was a lighter, more amusing way to delve into everything that this book covers?

Well, have you heard of the saying, "a picture paints a thousand words"?

That's exactly what memes do.

In the realm of internet culture, memes are utilized to articulate ideas, describe feelings, and depict scenarios. They're frequently snapshots from movies or TV shows, overlaid with a witty caption.

In this chapter, we offer you a respite from the dense and information-rich text that fills this book. We invite you to explore the lighter side of bitcoin mining economics - through the lens of memes. Using a meme or two, we aim to illustrate the key concepts covered in each chapter, injecting a dose of fun into the learning process.

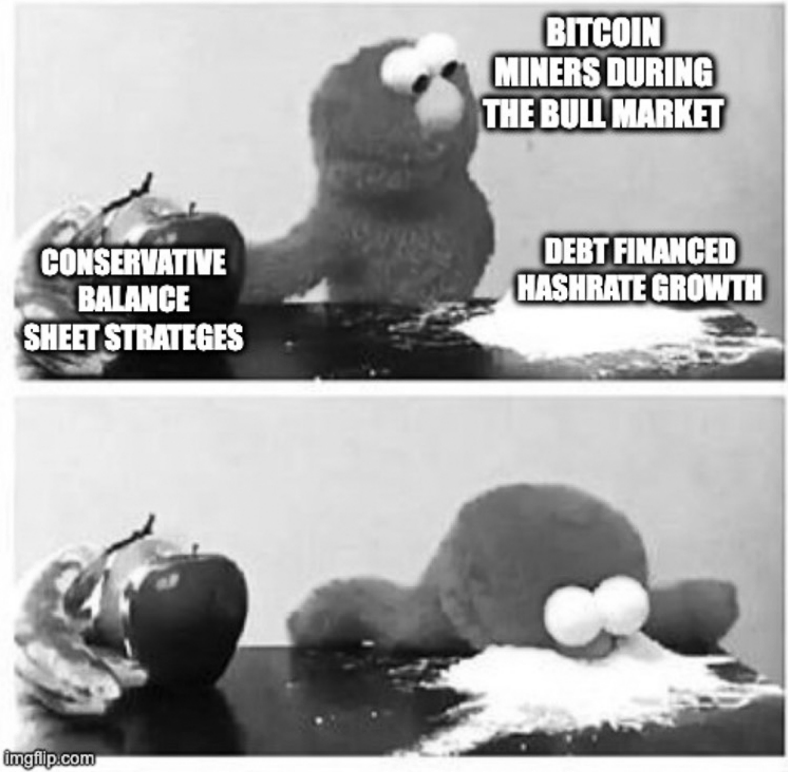
The past two years have been exceptionally rough for bitcoin miners. Prices have taken a nosedive, difficulty has surged with the increasing hashrate, and the return to a more typical demand for energy has driven the cost of power significantly upward.

However, the struggle isn't solely limited to these recent years; bitcoin miners have always faced a daunting environment. They must grapple with bitcoin-intrinsic factors like the difficulty adjustment and the halving, both of which influence their profitability, as well as extrinsic factors such as execution risks, bitcoin and equipment price fluctuations, regulatory risks, and changes in macroeconomic conditions such as energy prices or interest rates.

This intricate matrix of moving pieces, many of which are beyond a miner's control, could make one wonder why one wouldn't simply adopt a buy-and-hold strategy instead of venturing into mining. The reality is that only those equipped with the right operational and financial conditions can mine bitcoin profitably, particularly when measured in bitcoin terms.

Speaking of financial conditions, debt capital markets pose a dilemma for bitcoin miners. While it's easier to secure debt capital to finance hashrate growth during bull markets, that's when the rig price (the cost per TH of computing power) is highest. As seen in 2021-22, many mining companies, especially publicly listed ones, succumbed to the lure of easily accessible capital to purchase more hardware, driven by the market's tendency to boost share prices of companies with increasing hashrate.

However, when the inevitable bear market hits and operating conditions toughen, companies that overleveraged often struggle to stay afloat long enough to recover.

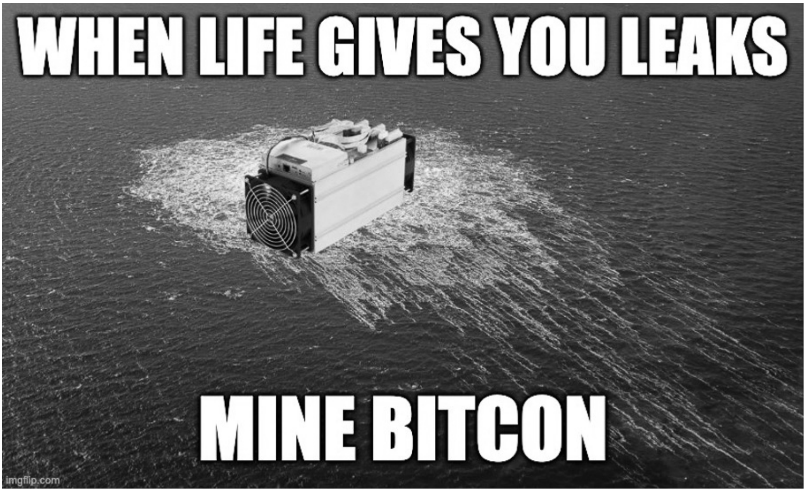


Watching your peers, who adopted conservative balance sheet strategies during the bull market, purchase cheap hashrate during the bear market can be a painful experience.

Nonetheless, surviving and thriving as a bitcoin miner isn't solely about price cycles and financing strategies. As we learned in the Fundamentals of Bitcoin Mining Economics chapter, a key factor of mining profitability is energy prices.

Few things delight bitcoin miners more than affordable energy. And what makes energy inexpensive? Surplus supply or low demand.

Bitcoin miners, who can be likened to dung beetles feasting on discarded energy, leverage this by setting up in remote locations where energy might otherwise go wasted due to a lack of economic viability for its use. They also take advantage of cheaper energy resulting from the lower demand during off-peak hours, acting as buyers of last resort when there are no other buyers for that energy. Bitcoin never sleeps.



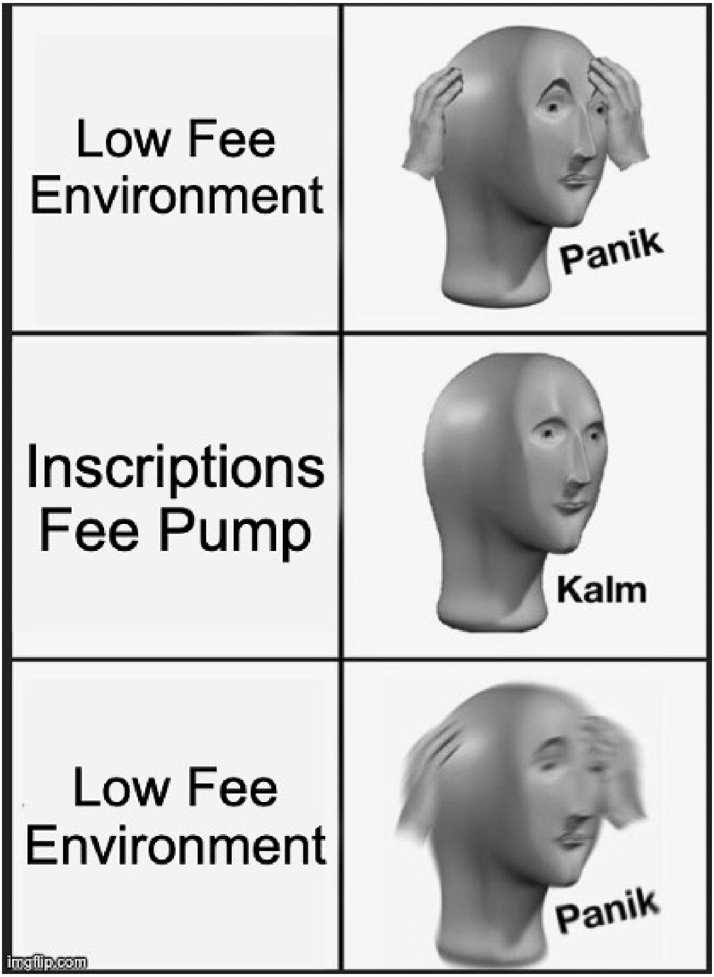
When it comes to the topic of infrastructure and strategy, the success of a mining operation hinges on the effective development of the right infrastructure, a significant part of which is the cooling method chosen for the machines. The most commonly used method is air, with immersion cooling considered more sophisticated (and rightly so), but liquid cooling is the new cool kid on the block.

Miners must also assess the jurisdictional risk when deciding the location of their operations. But as we saw with the China mining ban, the resulting dip in network hashrate was short-lived as miners relocated to friendlier jurisdictions, and new hashrate emerged elsewhere.

The "security budget" has been a topic of much discussion concerning the long-term sustainability of bitcoin in a low fee environment. With current fee levels and the block subsidy halving every four years, a massive increase in the dollar value of bitcoin will be required to maintain incentives for miners.

What constitutes "enough" fees to ensure adequate hashrate on bitcoin to deter potential 51% attackers remains uncertain. However, it's evident that as bitcoin adoption increases, demand for block space will primarily come from high-value transactions, leaving smaller transactions to other layers. Higher value transactions will be less price sensitive and more likely to lead to an increase in fees as these high-value transactions outbid each other to ensure inclusion in a block.

The recent spike in fees resulting from increased demand for bitcoin block space from inscribers gave us a glimpse into what a busier base layer would look like. Although short-lived, this period was a profitable one for miners, with transaction fees surpassing the block subsidy on occasion.



CLOSING THOUGHTS

A good portion of the content in this book was originally written when well over half of the global network hashrate was still located in China, along with essentially 100% of hardware manufacturing. It is, for lack of a better term, crazy to reflect on how rapidly the mining industry has changed in the two years since June 2021.

The United States became the new mining mecca of the world; Russian miners have been quietly accumulating many exahashes worth of hashrate; the Middle East has entered the scene as a major player; and Paraguay has developed into a Latin American mining hotspot despite the still-significant regulatory uncertainty there.

What's more, the narrative about proof-of-work's positive societal impacts is stronger than ever before. From miners providing hundreds of MegaWatts worth of controllable load resources (i.e., demand response) for energy grids to utilizing stranded natural gas and mitigating the associated methane emissions from flaring and venting that would otherwise occur. Even the once hypothetical narrative that bitcoin mining could help fund new energy generation projects now has real teeth, thanks to companies such as Gridless helping to electrify rural villages in Africa with small hydro plants that are made economically viable thanks to bitcoin mining soaking up and monetizing the excess energy production. That's just to name a few of the developments that have occurred or accelerated in the past couple of years, but there are many more.

Many things are sure to change in the years ahead. The current lack of regulatory clarity around the world for mining and bitcoin in general will likely be addressed, although positively or negatively in each place is anybody's guess. More energy companies will continue to slowly get involved with bitcoin mining, and more bitcoin miners will work towards securing their low-cost energy supplies long-term however they can. Hardware manufacturing will likely continue to ramp up in places outside of Asia, and more cooling method-specific hardware will be developed. Difficulty will go up, but hopefully not as fast as the BTC price. Who knows, we may even see another black swan event like China's ban in 2021 occur in the US if the Ripple lobbyists and anti-proof-of-work regulators get their way.

One thing is certain: the mining industry is going to continue to evolve rapidly for the foreseeable future, with a global free market responding efficiently to increasing political and financial volatility around the world while old institutions lag behind with no difficulty adjustment to correct their course. It will be incredibly interesting to play a small role in that evolution, and we hope this book has helped prepare you for the bear markets, bull markets, and halvings to come.

In the meantime, stay humble and mine the corn.

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