The Cost & Sustainability of Bitcoin

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Data as at Block 534,240
(the 265th difficulty change)

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Foreword

To understand the nature of Bitcoin and its ties to *energy* (spelled with a lower-case e), one needs to understand the concept and nature of "Capital-E" *Energy*. *Energy* is the prevailing force in the universe - both *Father Time* and *Mother Nature.* It cannot be created or destroyed, only transformed from one state to the other. It is the finite but infinitely divisible, shape-shifting sole ingredient of the universe. Its force cannot be stopped, only harnessed through its good graces. The Big Bang can be considered the "Birth of all *Energy* and Laws of Nature". *Bitcoin's* "Big Bang" was the codified creation of 21 million coins, of which 50 were discovered in the mining of the *Genesis Block*. Since then, 17 million have been discovered, with the rest to be mined in a predictable manner over time.

Energy is split infinitely into units of lower-case *energy and mass* (calories, joules, pounds, kilograms etc.), just as *Bitcoin* is infinitely split into units of *bitcoin* – no *mass*, just *energy*. From here, the link between *Energy* & *Bitcoin* becomes evident when looking at *Nature and Life,* and the economic evolution of humans.

At the most primal level, the first instinct of *Life* is to survive. *Energy* is *Life*, and *Life* is sustained by *energy.* Plants get their energy from photosynthesis. Predators do this by consuming more calories than they used to hunt their prey. Human Civilisation has evolved to the point where we can transform *Energy* into a state of Power (fire, steam, coal, batteries, fuel cells, etc). This has taken us from harnessing fire to cook food millennia ago, to much more capable energy sources now. Thanks to all the energy we produce, Humans now expend their calories in the pursuit of *currency* and *money* to purchase their food calories and other things required for survival and store the rest for future use.

There are huge differences between *currency* and *money*. Money is finite, whereas currency is not, and can therefore be compared to *energy*, and retains its stored energy over time. When the Gold Standard was abandoned, our paper currency became backed by nothing but promises. Ever since then, the value of currency has tended to zero, and money to infinity. Currency violates the rules of *Energy* by being created out of nothing (aside from the comparatively infinitesimal *energy* used to print out currency and mint coins). Disrespecting nature has led to dangerous levels of global wealth and income inequality, and widespread social and economic suffering. No form of life has defied *Energy* and survived in the long term, and this has been the case for billions of years.

Cryptocurrency is the "*Life*" of money, of which Bitcoin was "first-life" – literally converting energy into money. It has evolved to keep meeting market needs and sprouted a thriving cryptocurrency ecosystem. *Bitcoin* was designed to last as long as humans do, wherever they are in the universe with a communications link. Obviously, in the distant future, if humans have stood in the face of *Energy* and not harnessed it in a clean and renewable way, they will perish. Therefore, as we continue to advance technologically, the Bitcoin Blockchain will be a permanent emissionless store of "*monetary energy*" – money secured and proven to be both finite, and earned through hard work (literally, "Proof of Work"), using massive amounts of *energy* in the process.

Executive Summary and Preface

All data used in this paper is as at Block 534,240, mined on 29 July 2018. Network Difficulty was roughly 5.95 trillion. Hash Rate was roughly 42.6 EH/s. Price on the Bitfinex exchange was roughly USD$8200. The changes in mining ecosystem metrics since January 2015 are shown below:

Metric	*January 2015*	*July 2018*	*Change*
$/GH	*$0.65*	*$0.037*	*-94%*
W/GH	*0.89*	*0.098*	*-89%*
Network Hash Rate	*295.4*	*42587.7*	*14317%*
Price	*$200*	*$8,200*	*4000%*

This paper serves to update the assumptions used in a prior version of this research from February 2015[1], and provides a systematic methodology of modelling the environmental and economic costs of Bitcoin. Furthermore, the paper will provide a thorough discussion on the economics of Bitcoin mining to support the underlying model assumptions. Comparative data with the Gold Mining industry will also be revisited.

Based on the assumptions set forth in this paper, the model has estimated the average cost to mine one bitcoin to be roughly $6,450. It should be noted that this research is an inductive, bottom-up estimate, with the intent to provide a ball-park estimate. A sensitivity analysis has also been undertaken to demonstrate range of costs under different scenarios, which shows a realistic range of **average** mining cost of between **$5400** (driven by aggressive electricity price assumptions), and **$7500** (driven by hash rate increase assumptions). Due to the nature of competition in the Bitcoin mining market, costs that are significantly higher than the market price of Bitcoin can generally be ignored in the short term.

Major Assumption Updates

- The previous version of this research omitted the cost and impact of air-conditioning to the network, so the tonnage of CO_2 was underestimated by over a third. It also did not capture the impact of manufacturing, packaging and air-freight transportation of ASIC mining rigs, or the impact involved in the resource extraction or recycling process. The new methodology set forth in this paper captures these items, and the result is a **Bitcoin network that exhales 63 million tonnes of CO_2 per year – about 0.12% of global greenhouse gas emissions[2,3,4] (37 Gt CO_2 + 16.5 Gt CO_2e). Of the 160,000 TWh of energy generated globally each year[5], the Bitcoin Network chews through about 105 TWh/year (0.0661%). It should be noted that all figures include the impact of the manufacture of ASICs, which represent over 50% of all emissions generated.**
- In early 2015, the fee market was almost non-existent. In 2015, the average daily miner's fee revenue was 22.4 BTC. For the six years between 2009 and 2015, the average was only about 15 BTC. In the past 6 months, daily revenue has been very consistent, hovering at just under 50 BTC/day. To that end, this extra revenue has been accounted for in this update.

Acknowledgements

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Bitcoin Economics

Organizational decision-makers set their strategies in line with their firm's microeconomic, macroeconomic, and global competitive contexts. In the case of a Bitcoin mining firm, the context is as follows:

- Microeconomy: All other Bitcoin mining firms
- Macroeconomy: All other Bitcoin ecosystem members
- Global-Macroeconomy: All other digital and non-digital assets and global fiat monetary systems

This chapter defines the nature of competition within these three contexts and will assert that the nature of competition in the Bitcoin mining industry is perfectly competitive in the long term. This will lead into discussion on the strategic machinations of bitcoin mining firms, through comparison of empirical data and academic theory on firms in perfect competition.

Bitcoin Mining in the Global Monetary Macroeconomic Context

The Global Macroeconomy (GM) is the all-encompassing sum of all monetary systems, from traditional "analogue" financial systems, to digital ones like Bitcoin. All exchanges of value, legitimate or not, occur within it. Firms within the Bitcoin mining market service the Bitcoin ecosystem and depend on it being healthy and diverse in order to prosper[6].

"*[Accelerated] globalization [has] yielded conditions of considerable oligopoly in the world economy*"[7]. Some criticize the legacy system as the inadvertent/deliberate proprietor of global inequality[8, 9], with ever-mounting barriers to entry deterring the emergence of competing monetary systems. History shows that Schumpeterian gales of creative destruction eventually blow these barriers away[10]. In the case of the GM, this was the invention of The Blockchain, of which Bitcoin[11] is the first and largest implementation[12]. At that moment in history, the GM effectively split into the pre-2009 "analogue" GM, and the parallel digital one. Due to age, complexity, and nationalistic necessity, the legacy GM can only experience bursts of improvement[13] and remain a "closed ecosystem"[14,15]. In the highly competitive-yet-collaborative open-sourced decentralized digital ecosystem, anyone in the world can collaborate with others or create new or copycat ecosystems through the open-source software movement[16], ensuring evolution and adaption to changing market needs.

To that end, Bitcoin mining firms operate almost exclusively within the digital Global Macroeconomy, and the Bitcoin Mining Market in particular. They have an eye towards alternative digital ecosystems that are gaining traction in the wider free market, and whether their mining equipment can also mine these alternative digital currencies. The competitive cycle between them and their peers resets roughly every fortnight[17].

Bitcoin Mining in the Bitcoin Macroeconomic Context

The Oxford Dictionary defines an economy as "*the state of a country or region in terms of the production and consumption of goods and services, and the supply of money*". Since "country" or "region" do not apply to digital ecosystems, it is difficult to use traditional macroeconomics which rely exclusively on the concept of an influential controlling body to analyse them.

Bitcoin's monetary policy is highly predictable and based on a consensus-based, cryptographically secure, self-managing algorithm[18]. Bitcoin firms can move to the physical jurisdictions that provide the best incentives (i.e. low power, favourable business and tax laws, etc.). In the legacy global financial system, this option is only available to large multinational corporations[19], with most consumer-level participants lacking the mobility to move to the jurisdiction of their choosing[20]. This is inherently different in a permissionless, online, jurisdiction-agnostic environment.

Bitcoin's ecosystem is still small and fragile, but its incentive structure becomes more robust as more participants are attracted to the ecosystem[6]. Rational Bitcoin miners want to see the demand for their commodity grow organically and sustainably, but this is difficult. Miners mine an intangible digital commodity whose fundamental *value* relies on a consensus-based economic protocol and network. Its market *price* is based on the whim of the market. Every shock to the ecosystem, such as failure of wallet services and product providers[21], at least 36 exchanges[22] including the disastrous MtGox collapse[23]; online drug markets[24], Government crackdowns[25] and auctions[26]; scam-coins[27], developers[28], even miners themselves[29], and everything else in a long list of Bitcoin disasters, has in several cases caused dramatic and sudden movements in the price of the commodity[30]. Considering the evidence, Bitcoin is an example of an anti-fragile[31] system, with bitcoin achieving year-on-year growth in most key metrics[32,33]despite the numerous aforementioned setbacks. When and if the market becomes large enough to be less vulnerable to shocks, consolidation through means of integration and merger-and-acquisition activity amongst firms will be witnessed[59], as will be discussed in the next section.

Perfect Competition & Bitcoin Microeconomics

The example of "the hypothetical firm in a perfectly competitive market" is taught in most introductory economics classes. A literature review of primary academic texts[34,35,36,37,38,39] identifies nine conditions that define a perfectly competitive market:

- Homogeneous products
- guaranteed property rights
- non-increasing returns to scale
- zero transaction costs
- perfect factor mobility
- no barriers to entry or exit
- many buyers and sellers
- perfect information
- no externalities

When compared with real world data, the Bitcoin mining market (BMM) does not meet all aforementioned conditions of perfect competition, due to a relatively low number of ecosystem participants, currently resulting in wealth and information asymmetry. However, the BMM is trending towards becoming perfectly competitive as the wider Bitcoin macroeconomy grows, which will now be demonstrated.

As at date of writing, the BMM satisfies six criteria of a perfectly competitive market. Bitcoin's nature as an open-source, encrypted, distributed ledger means that the blockchain guarantees **property rights** and **homogeneity**, at zero or **near-zero transaction and storage cost**[40]. The **factors of production** (labour, equipment, and capital) **are mobile** to the extent that only a communication link and a power source is required to participate in the ecosystem. Due to its economic incentive mechanisms[11], any mining entity approaching 50% of network hash rate (NHR) would experience **non-increasing returns to scale**, if not jeopardize its own existence, as witnessed during the GHash.io saga of 2014[41]. Developing on top of Bitcoin requires no permission, and if entrepreneurs have a good enough idea, securing start-up capital is not a difficult barrier to entry to overcome, with over one billion US dollars invested in Bitcoin start-ups to date[42]. Low barriers are also commonplace in very young markets, with imitative entry into the market quite rampant[43]. Conversely, **barriers to exit** are quite low for most market participants except for heavily leveraged or undiversified miners, who risk holding highly specialized computing equipment that may be unable to mine other digital commodities. This is no different to traditional undiversified commodity miners[44].

The satisfaction of the final three conditions relies solely on the growth of the network and passing of time. The current size of Bitcoin's user base is speculative, and always will be due to its pseudonymous nature. CNBC reported[45] that 8% of American adults had invested in cryptocurrency (or, 8% of 250 million people[46] = 20 million). Yahoo Finance reported[47] that 16.3 million Americans buy and sell bitcoin frequently. Coinbase reports that they have over 20 million users[48]. Meanwhile, in some parts of Europe is estimated that an average 4% of consumers use cryptocurrency as a payment method every day as of 2016, with Eastern Europe leading the charge at 11%[49]. The numbers play out as follows[50]:

Country / Region	Adult Population (millions)	Users as % of Population	No. Bitcoin Users (million)
USA	250.0	8%	20.0
Eastern Europe	260.7	11%	28.67
France	56.8	4%	2.27
Germany	73.4	2%	1.47
UK	57.6	1%	0.58
Spain	41.5	2%	0.83
Switzerland	7.6	2%	0.15
Benelux	25.8	2%	0.52
			Total 54.5

Table 1 - No. of Bitcoin Users - High Estimate

When adding US and European numbers, and noting that data for Asia, Africa, Latin America, and Oceania are omitted, a high estimate of over 50 million users can be made. Although this sounds like a market with "many buyers and sellers", 50 million people only accounts for 0.8% of the World's adult population[50]. A much lower estimate of between 2.9 million and 5.8 million has been highlighted in a very detailed assessment of the global cryptocurrency market produced by Cambridge University in April 2017[51] (granted, things have changed dramatically since April 2017 when price was only USD$1000, right before the "big hype" of late 2017, where a significant number of new users would have come into the ecosystem).

From a commercial markets point of view, a strong case can be made that a few participants have an inordinate, albeit *temporary*, grip over **pricing** and **information**. The temporary nature is shown in the table below, comparing wallet balance distribution since December 2014. We can see that there has been a flatting of the distribution of coin holdings away from large wallet balances to much lower balances. As can be seen, coins held in wallets with balances containing between 0.001 to 10 BTC have grown dramatically, and it could be expected to resemble a normal distribution as the decades move on.

	Dec-2014[52]	Jun-2018[53]	
Balance	% of all BTC	% of all BTC	Δ
0 - 0.0001	0%	0.01%	-
0.001 - 0.01	0.02%	0.12%	500%
0.01 - 0.1	0.16%	0.73%	356%
0.1 - 1	0.85%	3.23%	280%
1 - 10	4.76%	8.70%	83%
10 - 100	26.73%	25.57%	-4%
100 - 1,000	23.40%	21.80%	-7%
1,000 - 10,000	23.40%	19.92%	-15%
10,000 - 100,000	17.02%	17.28%	2%
100,000 - 1,000,000	3.66%	2.64%	-28%

Table 2 - Distribution of Coins (by wallet balance)

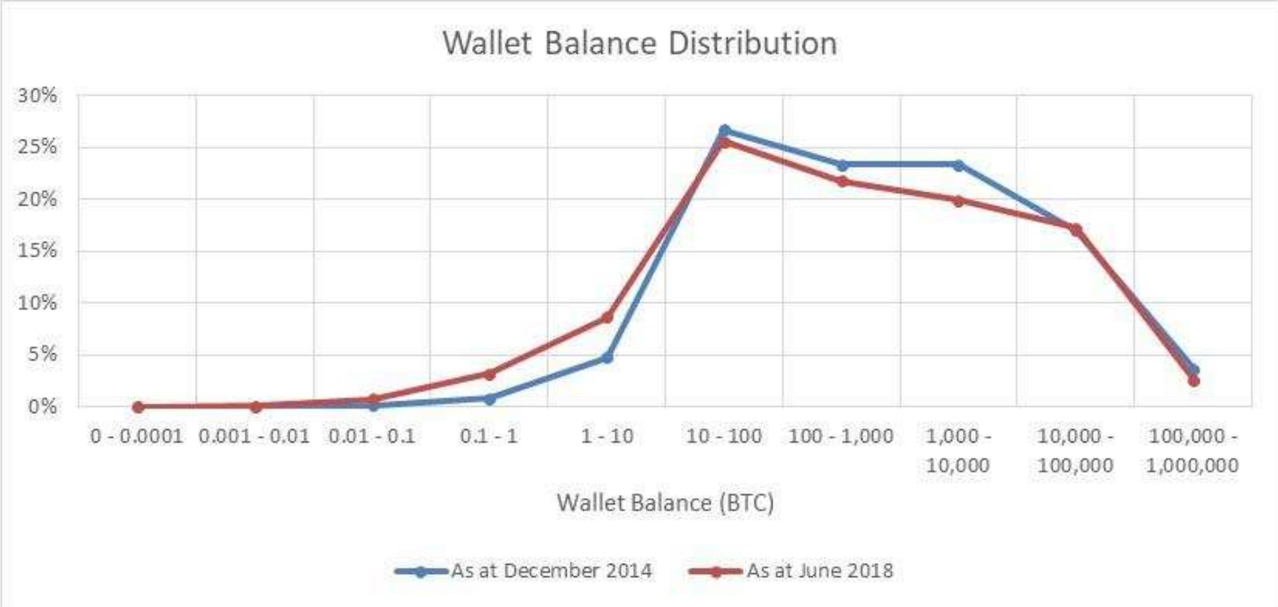

Figure 1 - Distribution of Coins (by wallet balance)

It should be noted that **all** wallets with a balance of over 100,000 coins belong to identified exchanges / custodial wallets[53]. The identifiable custodial wallets, alongside their "total wallet balance rank", is as follows:

Rank	Custodian	Qty BTC
1, 441	Bitfinex	175,172
2	Binance	174,759
3	Bittrex	117,203
4	Huobi	98,042
5	Bitstamp	97,848
28	Coincheck	34,277

Rank	Custodian	Qty BTC
55, 58, 117, 125, 167	Kraken	70,805
177, 447	Xapo	8,911
264	AnxPro	4,712
353	Bitmain	3,372
255	BitX.co	4,966
Identifiable Coins in Custody		**790,067**

Table 3 - Bitcoin Held in Identifiable Custodial Accounts

The above table does not include coins held in custody by other major custodians such as BitMex, Poloniex, Coinbase, and others. It is expected that a lot of wallets with very large balances are custodial wallets, especially as those wallets have several hundred inputs and outputs over a short period of time, which means that the distribution may be even flatter than demonstrated above. A study of Bitcoin Unspent Transaction Outputs (UTXO) by Unchained Capital[54] studying the shift of old coins into new hands over time, noted that 15% of BTC moved out of wallets that had been dormant for 2 to 5 years during the 2017 Bitcoin rally. This trend of a flattening in distribution is expected to continue, as spent bitcoin is spent forever, and needs to be earned back.

Bitcoin's current major externality is the CO_2 emitted by hardware operating and securing the network, which is discussed in depth over the next few chapters. Therefore, as the world moves towards carbon-free energy sources over the coming centuries, in additional to cleaner and more efficient mineral mining and e-waste recycling technology, Bitcoin's CO_2 emission **externalities** will eventually tend towards **zero**. Based on strong and predictable trends indicating technological improvements driving down costs of renewables[55], as well as the potential for fossil fuels to be priced fairly (i.e. more expensively) under future carbon trading schemes[56], we may witness a more expedient migration to renewables. As history has shown several times, the death of an incumbent technology is swift when displaced by something better[57].

Bitcoin is not perfectly competitive in its current state but is very close to becoming so. The first six of the above conditions are met in the short-term, with the last three destined to be met (if not already partially met), should Bitcoin have a “long-term”.

Most importantly, in a perfectly competitive environment, marginal cost to produce a good (MC) is equal to the marginal revenue from selling that good (MR), i.e., in long-term equilibrium, cost to mine will be equal to the price of a bitcoin, and in the short term, this equilibrium point will be established by the market.

Perfect Competition & Managerial Economics

The Porter’s Five (or Six) Forces[58] framework is a mainstay of the MBA Curriculum. The forces within the Bitcoin mining market are illustrated below.

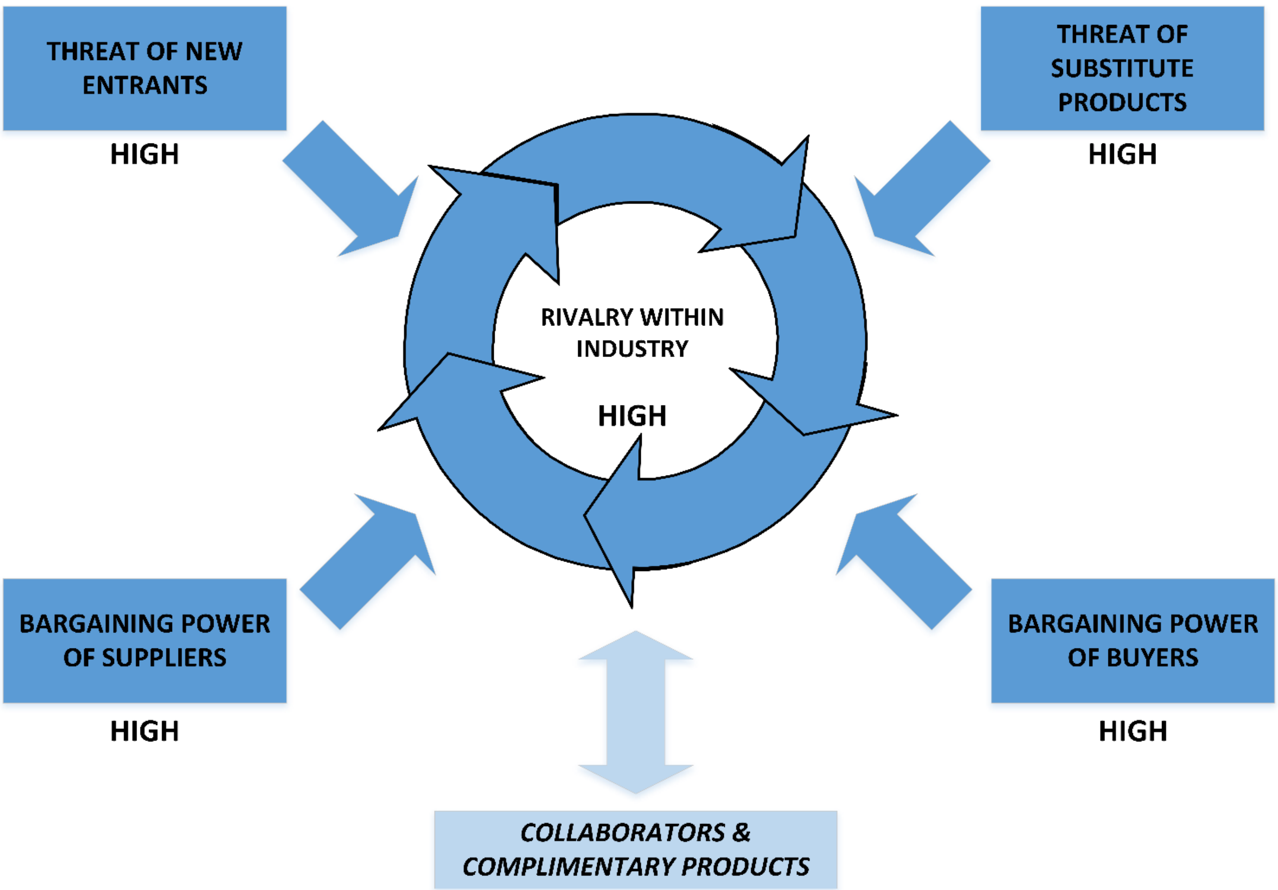

Figure 2 - Porter's Five Forces Analysis of the Bitcoin Mining Industry

Mapped out, prospects look quite daunting for an industry competitor. They cannot easily protect themselves from new miners or substitute products such as other digital currencies. They are price takers with little power over their buyers, and unless they are an innovation leader in the fields of hardware manufacture and research-and-development, data centre ownership, and/or electricity provision, they have little control over their suppliers too. As mentioned previously, collaborators (i.e. other ecosystem participants) currently have equal potential for benefit and detriment whilst the market is still susceptible to shocks. Competition is stiff within the mining industry, and a prompt extinction awaits if you are not a cost or innovation leader[57]. **This is expected - economic profit tends to zero in long-term equilibrium in a perfectly competitive landscape [34], and the marginal cost of producing and the market price oscillate around an equilibrium point[34], with evolution and improvement the only way to stay in business**. In such competitive markets, there is also a natural tendency for the market to be dominated by three or four players[59,60]. The Pareto Principle, also known as the 80/20 rule[61], states 20% of the market participants control 80% of the market. In November 2015, the 5 largest pools provided 79% of mining power. In June 2018, the largest 5 provided 70% of hash rate, with 78% of power coming from the top 6. That said, the pools are not monolithic entities.

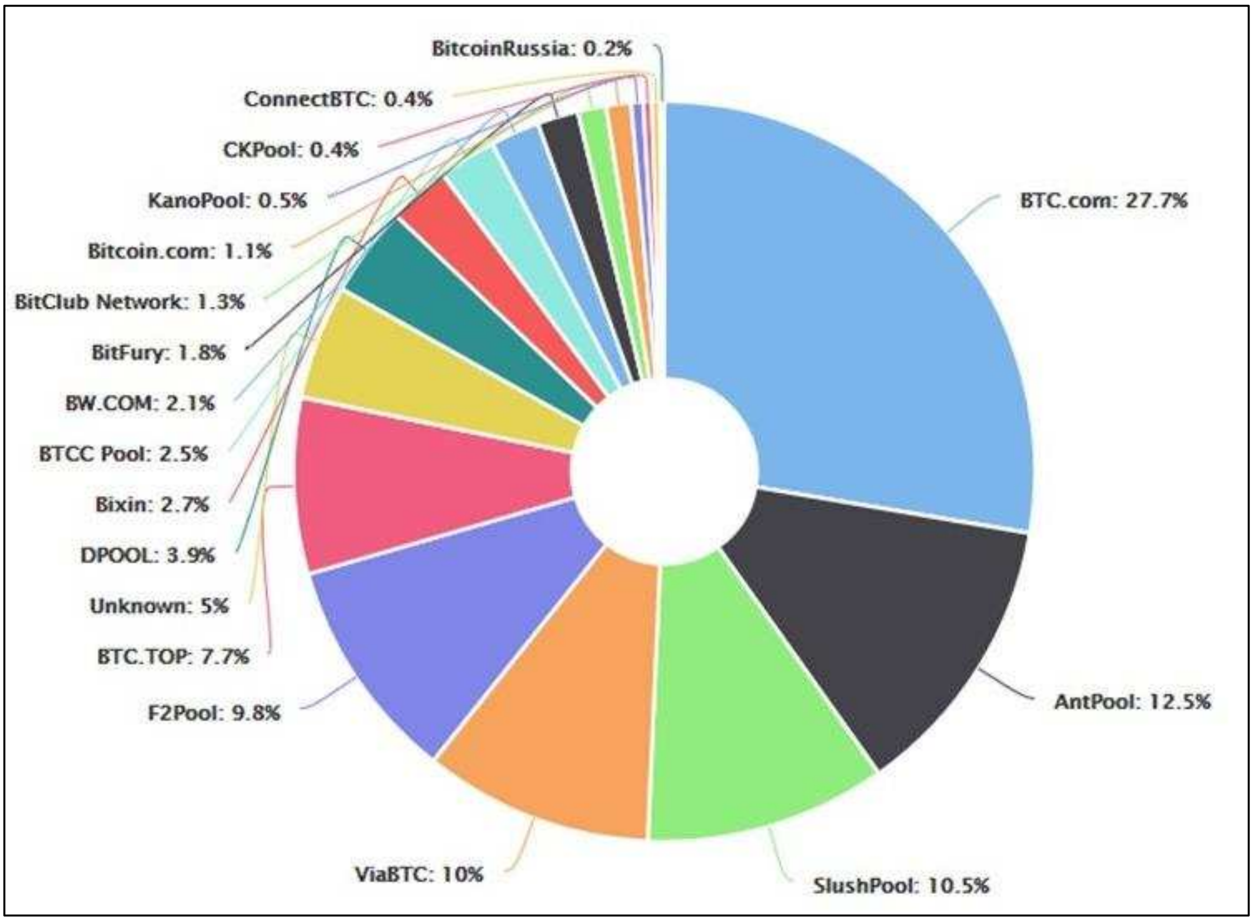

Figure 3 - Bitcoin Network Hash Rate (NHR) Distribution[62]

In a perfectly competitive market, a firm's decisions are predictable. All firms need to decide to start up, how to run their business as cost-effectively as possible, and whether to stay in business or not. In the Bitcoin world, the decision-making process relies on market price of bitcoin, operating expenditure, and the network hash rate, i.e., how much competing "mining" power exists on the network. It also indirectly relies on the continued faith and investment of miners in the value of their commodity i.e. continued research, development, capital expenditure, and strategic partnerships with collaborators. Table 4 shows the relationship between hash rate and price and shows the outcomes for miners in six different scenarios.

HASH RATE \ PRICE	INCREASE	CONSTANT	DECREASE
INCREASE	• Short-term profit • New miners enter	• Leaders emerge • Profits Decrease	• Inefficient miners exit • Miners buy coins instead of mine them
DECREASE	• High Short-term profit • New miners enter	• Short-term profit • New miners enter	• Miners exit until some are profitable

Table 4 - Price - Hash Rate Relationship Matrix

Effectively, if price of the commodity (i.e. demand) increases well beyond the cost to mine the commodity, miners will enter the market until the price and cost are equal. If price decreases, miners leave the industry until there are only profitable miners (i.e. either cost or innovation leaders) remaining. If price is dramatically lower than cost to mine, some miners may elect to simply buy bitcoin up to the current cost to mine. If the market is flat, profit tends towards zero until the market is shaken up again. This is similar to the workings of physical commodity miners in the commodity[63] and oil[64] industries. The difference is that a Bitcoin firm's decisions take hours and days to implement, and days and weeks to take effect, instead of months and years. The same is true regarding the time taken to reach equilibrium after a price shock; "two-to-four times the duration of the production-to-storage cycle" (i.e. months to years) for commodities[65], weeks for Bitcoin.

Trends & the Future

Since the future appears full of opportunities for the digital macroeconomy, one should expect digital microeconomies to become more perfectly competitive as time passes. Should long amounts of time, say, 50 years pass, when all bitcoins have effectively been mined, and the ecosystem is still healthy and has entered the redistribution stage, microeconomies such as the bitcoin mining market will start to resemble the textbook examples of perfect competition. In time, miners will vertically integrate backwards[66] by acquiring data centres, chip fabricators, research-and-development teams, and renewable power plants; and integrate forwards by acquiring exchanges, brokers, and other places to sell what they have mined. They can horizontally integrate[66] by acquiring entities that enrich the value of their commodity such as wallet hardware and other product manufacturers, financial services companies, and media outlets. 80% of the market will be controlled by the 20% of the largest and most integrated market participants[61], with the other 80% providing the niche and evolving needs of the market. As time goes on, the makeup of the microeconomy will evolve until its extinction and replacement[10].

Now that you have a very thorough understanding of the market, and what is going through a miner's mind, the focus of the paper will shift to the cost of mining Bitcoin.

The Evolution of the Bitcoin Mining Industry: January 2015 – Now

Mining Technology

Since the last analysis, Bitcoin mining technology has improved dramatically. The benchmark used back then was Bitmain's Antminer S5. We will look at the S5 compared to its current successor, the Antminer S9i[67].

	January 2015	June 2018	% Change
Network Hash Rate	295.4 PH/s	36346.2 PH/s	+12,200%
Retail-Best Miner	Bitmain Antminer S5	Bitmain Antminer S9i	
$/GH (RRP)	$0.65	$0.047	-94%
W/GH	0.89	0.098	-89%

Table 5 - Evolution of Mining Technology

Further to the above, one of Bitmain's closest competitors, Canaan Creative, comes in with a lower $/GH rate ($0.044) when excluding PSU costs from both rigs, but a 15% higher W/GH value (0.109)[68]. As the market will tend to gravitate towards the lowest total price available, it's expected that Bitmain controls and ships significantly more hardware than Canaan[91].

Hash Rate Growth

The dramatic drop in $/GH and W/GH shown in Table 5 has spurred extraordinary hash rate growth. That said, this is not a new phenomenon.

Figure 4 shows hash rate growth since the Genesis Block in 2009[69], showing steady and consistent exponential growth of the network. One of the main drivers of investment in mining equipment is expected hash rate growth from one difficulty cycle to the next. We will explore this concept in further detail in the next chapter. Table 6 shows how consistent fortnightly hash rate growth has been over the past 6 and a half years. Network difficulty grows directly in line with hash rate growth.

	2012-Current	2013-Current	2014-Current	2015-Current	2016-Current	2017-Current	YTD
Average	9.0%	9.9%	7.0%	5.3%	5.9%	6.8%	7.2%
St Dev	9.9%	10.2%	7.3%	6.1%	6.4%	6.7%	5.7%
Sample Size	187	161	130	100	73	46	17

Table 6 - Average Difficulty Change Data

As a result of the constant hash rate increases, the difficulty cycle is rarely 14 days, and based on rough year to date data (7.2% increase per cycle), the difficulty cycle is closer to 14 days x (1 – 7.2 %) = 13 days, or 312 hours.

Should Bitcoin ever scale and reach its potential, it is almost certain that mining equipment will exponentially increase in processing efficiency in line with Moore's Law for at least another 5 years[70] and exponentially increase in power efficiency in line with Koomey's Law for at least another 25 years[71].

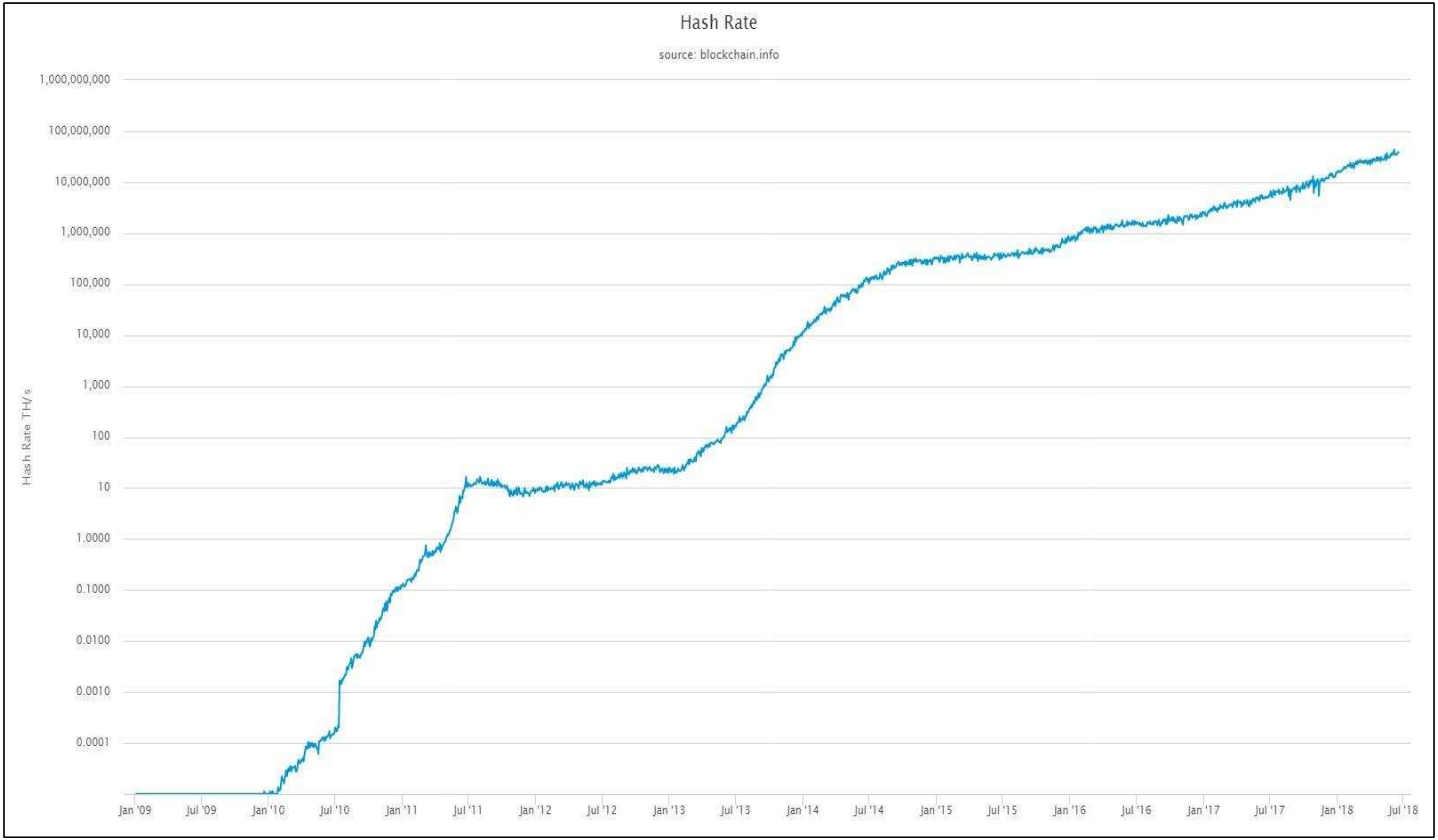

Figure 4 - Network Hash Rate - All-time Data (Log Scale)

Understanding the Cost of Bitcoin – Inputs & Drivers

Calculating the costs of Bitcoin can be modelled quite simply through the relationship of the 7 variables defined below.

Economic Cost Inputs / Drivers

CAPEX

CAPEX is the capital expenditure required to maintain a proportional share of mining rewards upon an increase in difficulty. This is typically the purchase of additional GH/s at a particular $/GH rate. This is demonstrated in the below example, assuming the average of 7.2% difficulty increase discussed above:

	Current Difficulty Cycle	Next Cycle (Predicted)
Network Hash Rate	1000 PH/s	1072 PH/s
Hash Power Provided by Miner / Mining Pool	300 PH/s	321.6 PH/s
% of Hash Rate provided by miner	30%	30%

Therefore, for the example mining pool to maintain their 30% slice of the pie, they need to bring on 21.6PH/s of hash power.

There are other elements of CAPEX whose life-cycles are much longer than mining equipment. These elements of CAPEX can also be deemed as "sunk costs" in many cases, and don't affect future decisions. The CAPEX categories are as follows:

- Bitcoin Mining Equipment (typically last for only a few months before they're unprofitable)
- Power Supply Units (PSU) for mining equipment typically last as long as the mining equipment due to planned obsolesces, with hardware manufacturers regularly changing the required PSU wattage with each new generation of miner.
- Server Racking / Data Centre Construction & Fitout Costs (typically last for decades). Server Racks / Data Centres could also come under Operational Expenses (OPEX) if the Data Centre is being rented / leased. Regardless, these costs are negligible compared to the costs of electricity.

OPEX

OPEX is the expenditure required to remain operational. At scale, this is effectively just the cost of power to the mining equipment and air conditioning within a data centre. It is estimated that cooling can consume 30[72] to 40%[73] of overall energy consumption, with 21% a benchmark for the most efficient cooling systems[74]. Technologies such as immersive cooling will reduce energy consumption as a trade-off for a large initial capital outlay. One should take in account the "Iceland Factor", where Bitcoin mining uses as much power as all of Iceland's homes[75] due to it being cold enough for data centres to meaningfully reduce cooling costs and having clean and cheap hydro-electricity. At 840 GWh/yr., tiny Iceland would account for about 1% of the world's mining power. While Iceland is only a very small share of the market, miners have access to several other cold places with cheap electricity[76]. **For the purposes of this model, we will assume cooling contributes to 20% of the total power consumption**, in line with the laws of perfect competition and the technological gravitation towards maximum efficiency.

Difficulty Cycle Length

Network difficulty changes every 2016 blocks. At a fixed hash rate, blocks will take 10 minutes (on average) to mine. This results in a difficulty cycle of 14 days. However, as the network hash rate increases 7.2% on average, blocks will be mined, on average, 7.2% quicker. Therefore, the time-period used to calculate the cost of mining a bitcoin will be the average time between difficulty changes will be taken as 13 days (14 days x 92.8% = 13.00), or, 312 hours.

Coins Mined

This is a fixed number – there are 2016 blocks of 12.5 bitcoins mined every difficulty cycle – 25,200 bitcoins. In addition to the mining rewards, mining fees are not insignificant either[77]. The SegWit Wars of the first half of 2017 had fees averaging over 200BTC per day, and the fee madness during the hype cycle of December 2017/ January 2018 had a revenue average of over 550BTC per day over those two months. With the SegWit wars over, and the hype now well settled, a relatively consistent 40 BTC per day has been earned in the 6 months leading to July 31, 2018 (st dev = 35, n=180). Daily average fee revenue trends over time are shown in the table below. For this model, we will use a figure of **650 BTC collected in fees each cycle** (i.e. about 50/day for the average 13-day cycle time).

	09-'12	2013	2014	2015	2016	2017	2018	Since Halving
Avg	6.57	43.31	12.92	22.42	62.38	273.51	105.45	177.93
St Dev	11.46	26.12	3.83	8.35	29.34	171.55	181.47	180.42
Sample Size	730	182	183	182	183	183	211	768

Table 7 - Daily average fee revenue over time

Power Cost & Emissions

To evaluate power costs and emissions, we don't have much of a choice but to use world-wide weighted average figures, due to the dispersion of miners all over the world. That said, thanks to the rules of perfect competition, particularly perfect factor mobility, miners will move to places with the cheapest electricity costs. The statistics are as follows[78,79,80,81]. The emissions figures consider CO2 equivalents, such as methane, and nitrous oxide.

Primary Energy Source	% Total PES	g CO_2e/kWh	Low Price ($/kWh)	High Price ($/kWh)
Biofuels & Waste	9.7%	18	$0.06	$0.11
Coal	28.1%	600 - 1001	$0.06	$0.14
Oil	31.7%	778	$0.07	$0.10
Natural Gas	21.6%	443	$0.04	$0.08
Nuclear	4.9%	66	$0.11	$0.18
Hydroelectric	2.5%	13	$0.02	$0.19
Other (Wind, Solar, Geothermal)	1.5%	20	$0.03	$0.11
Weighted Average (approx.)		**600**	**$ 0.06**	**$ 0.12**

Table 8 - World Power Costs & Emissions by Energy Source

**Note: When using Carbon Capture Systems (CCS), CO_2 emissions from Coal are reduced substantially.*

Although the average rate for US industrial companies is about $0.07/kWh[82], a safer assumption for Bitcoin miners would be closer to 3 or 4 cents, for the reasons mentioned above. There are several documented cases of the largest bitcoin mining operations paying $0.04/kWh[83], with reports that Bitmain was receiving a $0.02/kWh rate in their Yunnan facility[84], and one particular CEO claiming a cost of electricity of only 1.7 cents/kWh for their mining operation in Moses Lake, Washington, USA[85].

Mining Mix – "The Network Average Miner"

There are two types of miners; chip-fabricator miners, and retail miners. Retail miners can be split further into another two categories, large retail miners and small/individual miners. Small individual miners can also forego buying hardware themselves, and instead purchase mining contracts. Due to intellectual property and some economies of scale, chip-fabricators (chipfabs) can mine for significantly cheaper than retail miners. Typical gross profit margins in the semiconductor industry has averaged over 45% for a four-year period[86], with the most profitable ones close to 60%. The computer hardware industry averages around 35%[87]. Gross profit margins are used since operating expenses and depreciation are dealt with separately within the model. **It is assumed that miners pay no tax** (i.e. they retain all coins that are mined and/or asset depreciation costs are high enough to offset a large amount of tax on revenue from sold mining hardware). Due to the lack of competition in the ASIC hardware space, margins would likely be 50 to 60%. Obviously, there is a limit to the margin that can be made on mining hardware, as the customer base is quite savvy and can easily calculate profitability of their purchased miners at a particular price-point. **For the purposes of this study, it will be assumed that Bitcoin ASIC manufacturers make 60% gross margin on all hardware sold**.

Determining the number of non-chipfab large miners and individual miners is another area of speculation due to lack of robust market data. One half-insight can be gained from looking at the world's largest cloud-mining operation, Genesis Mining, who claim to have 2 million users[88]. Despite its MUCH higher price per GH/s (27c/GH (including electricity costs and incidentals)[89] vs Bitmain's 3.7c/GH), it may still be practical for many miners to opt for a cloud-based solution due to its "plug-and-play" nature, and more importantly, that it is an "instant-on" solution, so that you don't lose your most profitable days waiting for your miner to be shipped to you. That said, Genesis provides no data on their aggregate hash power, nor do they reveal details on the location of their server farms, or even which pools they mine on[90].

Next comes the question of chipfabs mining on their own equipment, and how much equipment has made it out into the market for large-scale and small-scale miners. According to an analysis by Sanford C. Bernstein & Co, it was estimated that Bitmain captured 75% of market share in hardware sales, Canaan Creative captured 15% of the market, and other manufacturers made up the remaining 10%[91]. Bitmain's CEO has stated that the company earned USD$2.5B in revenue for 2017[92], with the majority of that revenue earned through mining sales, as opposed to mining and selling Bitcoin directly. From this, we can size the market for mining hardware to be a maximum of USD$3.33bn, as some part of Bitmain's revenue would be mining based. Based on the

2017 average price of an S9 miner of around USD$3000[93], this means that Bitmain shipped over 800,000 units. If Bitmain's revenue of $2.5B was a 75% share of the market, then Canaan Creative's 15% share would translate into an annual revenue of around $0.5B, with the remainder of the market making up the remaining $0.33B. Canaan sells their Avalon miners in a minimum order quantity of 40 units at a very similar price-point to Bitmain, so it is safe to assume that Canaan services medium-to-large scale miners. Putting the numbers together, it is assumed that Canaan would have shipped over 150,000 Avalon units, with the rest of the market producing 100,000 "equivalent" units. Rounding down, one could draw the conclusion that 1 million S9-equivalent mining units were shipped.

At this hash rate and price per S9i, this model estimates that roughly $115 million is invested in more mining power every difficulty cycle (see CAPEX on page 16), or around $3.25 billion per year (in line with 2017 figures). Drawing on the 80/20 rule again we can put chipfabs somewhere in the ballpark of 20% of direct hash power. That said, with Bitmain administering at least two mining pools (AntPool & BTC.com) [91] providing 40.2% of hash power[62], it is likely that they contribute about half of that power or more. Throw in the other chipfabs in proportion to the sales figures mentioned above, as well as any chipfabs that don't sell to the public, and **we will assume that chipfabs provide at least 35% of direct hash power for this study**.

Due to the laws of perfect competition discussed earlier, it can be assumed that only the most profitable miners are switched on at any given time, and that when a new generation of mining equipment is released, equilibrium is reached very quickly where all miners are operating at a similar cost basis.

	Retail Miner	Chip Fabricator	Weighted Average
Hash Power Share %	65%	35%	
Discount Level	0%	60%	
$/GH	0.047	0.019	**0.037**
W/GH	0.098	0.098	**0.098**
$/W	0.04	0.02	**0.033**

Table 9 - Rationalised Weighted "Network-Average" Miner

Network Hash rate

As at the date of this report, total network hash rate is 42,587,731,568 GH/s. Miners need to successfully forecast hash rate and difficulty increases when planning future capital expenditure and setting strategy and targets.

CAPEX

To better assess the overall impact of the bitcoin mining industry, we should also consider the CO_2 emissions from the manufacture and recycling of mining equipment.

A study using data from 2000[94] suggests that total energy to produce a PC is 895kWh. Although the data is quite dated, it sets a very conservative benchmark, as manufacturing efficiencies consistently improve in line with the laws of competition, alongside Moore & Koomey's laws discussed earlier.

	Direct Fossil (MJ)	Electricity (kWh)	Total Energy (MJ)	Total Energy (kWh)
Semiconductors	298	170	909	252.5
Semiconductor manufacturing equipment	392	29.4	498	138.3
Passive Components	109	10.3	146	40.6
PCB	26.7	7.71	54.5	15.1
Bulk Materials	-	-	770	213.9
Silicon Wafers	0	38.1	137	38.1
Assembly	35.3	51.2	220	61.0
Transport	338	3.5	351	97.4
Packaging	120	4.8	137	38.1
	1319	**315**	**3222**	**895**

Table 10 - Energy Required for ASIC manufacture

As 98% of electronic waste is completely recyclable[95], and an estimated energy saving of 90% on the recovery of metals and silicon[96], we will reduce the "Bulk Materials" energy use by 90%, to result in a total of **703 kWh**. Recycling of ASICs is a fair assumption due to the short life of mining equipment, and the value to be extracted out of quickly obsolete equipment through means of recycling.

OPEX

Environmental Impact from operations is effectively pure energy use. If miners are using cheap hydroelectricity to mine, emissions are insignificant. If miners are using dirty coal with no carbon capture, environmental impact is much higher.

It is assumed that the average miner will use power that emits a weighted average value of CO_2 based on the world's energy mix shown in Table 8.

Calculating the Costs

Economic Costs

The following tables shows the outputs from the economic model, which is based on the assumptions set out in the section on *Economic Cost Inputs / Drivers*. Orange cells are variables / inputs, grey cells are calculation cells.

CAPEX

Market Composition		NOTES
Retail Miners	65%	
ChipFab Miners	35%	
ChipFab Margin	60%	
Bitmain Antminer S9i		
Hash power (GH/s)	14000	See *Mining Mix – "The Network Average Miner"* on page 13 for details
Energy Usage (W.h)	1372	
W.h/GH (also J/GH)	0.098	
RRP Price	$654.00	
Mkt Avg $/GH	$0.037	
Network Statistics		
Hash rate (GH/s)	42,587,731,568	Network has been rationalised into **S9i equivalents** for easier visualisation as hash rate numbers are so large. No of equivalents is found by dividing the network hash rate by the hash power provided by one S9i.
S9i Equivalents	3041980	
Coins Mined Per Period (BTC)	25200	See *Coins Mined* on page 12 for assumptions on coins mined per period
Avg Difficulty Increase (YTD)	7.20%	
Avg Fees / period (BTC) (YTD)	650	
Cost Assumptions		
Average Period Length (hours)	312	See *Hash Rate Growth* on page 9 for details
Average Price/GH	$0.037	Difficulty Period CAPEX = Avg Difficulty Increase x Average Price/GH x S9i equivalents. See *CAPEX* on page 11 for details
Average W.h/GH	0.098	
Difficulty Period CAPEX	$113,160,226.59	
Per Coin Costs		
CAPEX per coin	$4,337.57	Difficulty Period CAPEX ÷ (Coins Mined Per Period (BTC) + Avg Fees / period (BTC) (YTD))

Table 11 - Bitcoin's Economic Costs - CAPEX

OPEX

OPEX		NOTES
S9i Equivalent Energy Data		
Cooling as a % of total power	20%	See *OPEX* on page 11 for cooling assumptions
S9i kWh/period	428.06	The Hash Rate of an S9i x average difficulty period length
Cooling/S9i kWh/period	107.02	Cooling power as a proportion of total power used
Total kWh/period/S9i	535.08	S9i kWh/period + Cooling/S9i kWh/period
S9i Equivalents	3041980	
Total Network GWh/period	**1627.70**	Total kWh/period/S9i x S9i equivalents

Cost Assumptions		
Large (Discount) Miner $/kWh	$0.02	See *OPEX* on page 11 for electricity price assumptions
Retail Miner $/kWh	$0.04	
Market Avg $/kWh	$0.033	Weighted average based on the Network Average Miner (See *Mining Mix – "The Network Average Miner"* on page 13 for details)
Period Electricity Cost	$53,714,202.32	Total Network GWh/period by Market Avg $/kWh

OPEX per coin	$2,077.92	Difficulty Period OPEX divided by total coins mined / fees earned

Table 12 - Bitcoin's Economic Costs - OPEX

Total Cost of a Bitcoin

Adding the CAPEX figure of **$4,337.57** to the OPEX figure of **$2,077.92** results in a total cost of **$6,455.49.**

Environmental Costs

ENVIRONMENTAL IMPACT		NOTES
GLOBAL DATA		
World avg. Mt/GWh CO_2	0.6	See Table 8
Global Power Generated (TWh/yr.)	160000	See Executive Summary
Global Gt CO_2	53.5	

CAPEX		
Manufacturing Energy per S9i Data		
S9i equivalents added / period	219023	
kWh per S9 manufactured	703.00	See CAPEX on page 15
Manufacture kg CO_2/period	421.80	World avg. Mt/GWh CO_2 x kWh per S9 manufactured
Manufacture MWh/year	19.75	Number of manufacturing cycles per year (*365.25 days x 24 hours per day ÷ average cycle length*) x kWh per S9 manufactured
Manufacture t CO_2/year	11.85	World avg. Mt/GWh CO_2 x kWh per S9 manufactured

OPEX		
S9i Equivalent Energy + Cooling Data		
S9i kg CO_2/period	256.02	S9i kWh/period x World avg. Mt/GWh CO_2
S9i MWh/year	12.03	S9i kWh/period x Periods/year
S9i t CO_2/year	7.22	S9i MWh/year x World avg. Mt/GWh CO_2
Cooling kg CO_2/period	64.00	Cooling kWh/period x World avg. Mt/GWh CO_2
Cooling MWh/year	3.01	Cooling kWh/period x Periods/year
Cooling t CO_2/year	1.80	Cooling MWh/year x World avg. Mt/GWh CO_2

Total Network Energy Data		
S9i Equivalents	3041980	
Network GWh/period	3766.21	(S9i kWh/period + Cooling kWh/period) x S9i Equivalents
Network TWh/year	105.82	Network GWh/period x Periods/year
BTC % of Global Consumption	**0.0661%**	Network TWh/year ÷ Global Power Generated (TWh/yr.)
Network Gt CO_2	0.063	Network TWh/year x World avg. Mt/GWh CO_2
BTC % of Global CO_2 Emissions	**0.12%**	Network Gt CO_2 ÷ Global Gt CO_2

Table 13 - Bitcoin's Energy Use & Emissions

Environmental Impact Factors

It is unfair to only benchmark Bitcoin's environmental impact by CO2 emissions alone, so we will assess a few other environmental impacts to compare with the impact of Gold mining.

Eutrophication

Eutrophication, measured in tonnes of Phosphorous equivalents, is the introduction of nutrients into groundwater and other fresh water sources, having a drastic impact on water quality, the local ecology in general, and adverse economic impacts[97]. Bitcoin generally has very low externalities, as it relies almost strictly on the electrical grid both to mine and produce hardware. Therefore, to determine the Eutrophication produced by the energy sources that power Bitcoin, based on a weighted world average.

Global Eutrophication stands at 126.6 million tonnes per year[98], from a total 150,000 TWh/yr. of global energy produced[99], therefore, 1TWh produces about 850 tonnes of PO_4^{3-} equivalents. As Bitcoin uses around 105TWh/yr., **89,250 tonnes** are produced.

Acidification

Country [100]	Acidification (g SO_2 eq/kWh)	Energy Mix
Turkey	9.79	43.6% Natural Gas, 28.1% Coal, 24.2% Hydro, 4.1% other (71.7% total fossil fuels)
Portugal	1.22	22% Coal, 22% Gas, 24% Hydro, 22% Wind, 2% Solar, 6% Biowaste, 2% Oil[101] (46% fossil fuels)
Spain	4.93	22% Nuclear, 14% Coal, 20% Gas, 6% Oil, 13% Hydro, 18% Wind, 5% Solar, 2% Biofuel[101] (40% total fossil fuels)
Belgium	1	53% Nuclear, 24% Renewables, 26% Gas, 3% Coal, 0.1% Oil[101] (29.1% total fossil fuels)
Tanzania	4.53	45% Natural Gas, 42% Hydro, 13% Liquid Fuel[102] (58% fossil fuels)
Nigeria	0.22	82.2% Biomass & Waste, 10.6% Oil, 6.8% Natural Gas, 0.4% Hydro[103] (17.4% fossil fuels)
Mexico	6.59	34.45% Natural Gas, 4.89% Coal, 34.83% Oil, 15.75% Gasoline, 7.79% Renewable, 0.78% Nuclear, 1.5% other[104] (89.92% Fossil Fuels)
Average	**4.04**	

Table 14 - Bitcoin's Environmental Impact - Acidification

As can be seen from above, countries that have high percentages of Natural Gas in their energy mix contribute greatly to acidification, while Biomass contributes insignificant amounts. Coal & Oil also have large contributions. Since the global energy mix (Table 6) consists of 81.4% fossil fuels (of which 21.6% is Natural Gas), 9.7% Biowaste, and 8.9% Nuclear & Other Renewables, using the average of around **4 g SO_2 eq/kWh** is appropriate due to the contribution of Biowaste, as well as the above sample countries with high acidification having a disproportionately high use of natural gas compared to the world average. At 78TWh/yr. of energy usage, the Bitcoin Network produces **312,000 tonnes of SO_2 equivalents**

Ecotoxicity, Carcinogenics, Non-Carcinogenics, and Respiratory Inorganics

Global per-capita data on Ecotoxicity, Carcinogenics, Non-Carcinogenics, and Respiratory Inorganics measures[105] are as shown in Table 15. Population statistics[106,107,108,109] are also included. All data is as at 2011.

	North America	Europe	Middle East	Eurasia	Asia & Oceania	Africa	Central & South America
Freshwater Ecotoxicity (CTUe)	2.72E+04	1.79E+04	3.30E+03	1.38E+04	5.42E+03	1.63E+03	1.47E+03
Carcinogenics (CTUh)	2.67E-04	1.48E-04	2.36E-05	1.28E-04	5.20E-05	1.70E-05	9.54E-06
Non-Carcinogenics (CTUh)	1.04E-03	6.69E-04	1.70E-04	5.75E-04	2.40E-04	6.40E-05	4.35E-05
Respiratory Inorganics ($PM_{2,5}$)	2.66	1.26	1.29	2.46	3.72	0.199	0.443
Population (millions)	560	515	145	180	4,100	1,050	480

Table 15 - Ecotoxicity, Carcinogenics, Non-Carcinogenics, & Respiratory Inorganics Data (per-capita)

When per capita stats are multiplied by population figures, and the totals then divided by world energy generation (~150,000 TWh/yr.), then multiplying per 78TWh for energy used on the Bitcoin network, the following is found:

	Freshwater Ecotoxicity (CTUe)	Carcinogenics (CTUh)	Non-Carcinogenics (CTUh)	Respiratory Inorganics ($PM_{2,5}$)	Population (Billion)
Total	5.21E+13	4.88E+05	2.13E+06	1.85E+10	7.04
Total/TWh	3.42E+08	3.20	13.96	1.21E+05	
Bitcoin	**2.66E+10**	**249.73**	**1088.97**	**9.45E+03**	

Table 16 - Bitcoin Ecotoxicity, Non-carcinogenics, Carcinogenics & Respiratory Inorganics

A comparison of these 6 indicators versus that of gold mining and recycling is discussed in the section on *Revisiting Gold* on page 22.

Sensitivity Analysis

For the below sensitivity analysis, it is assumed that all aforementioned assumptions in the model are held constant, with one variable being changed at a time to see the impact on overall cost. Four scenarios are demonstrated for each of the 6 variables below, alongside the difference between the modelled cost of $6,455.49.

Mining Mix*	CAPEX	OPEX	TOTAL	Δ
20/80 Chipfab to Retail	$4,876.28	$2,266.82	$7,143.10	10.65%
30/70 Chipfab to Retail	$4,543.81	$2,140.89	$6,684.69	3.55%
40/60 Chipfab to Retail	$4,211.33	$2,014.95	$6,226.29	-3.55%
50/50 Chipfab to Retail	$3,878.86	$1,889.02	$5,767.88	-10.65%

Miner's Margin	CAPEX	OPEX	TOTAL	Δ
30%	$4,959.40	$2,077.92	$7,037.32	9.01%
40%	$4,765.46	$2,077.92	$6,843.38	6.01%
50%	$4,571.51	$2,077.92	$6,649.43	3.00%
70%	$4,183.63	$2,077.92	$6,261.55	-3.00%

Electricity Price	CAPEX	OPEX	TOTAL	Δ
1c/2c Chipfab to Retail	$4,377.57	$1,038.96	**$5,416.53**	**-16.09%**
1c/3c Chipfab to Retail	$4,377.57	$1,448.25	$5,825.82	-9.75%
2c/5c Chipfab to Retail	$4,377.57	$2,487.21	$6,864.78	6.34%
3c/5c Chipfab to Retail	$4,377.57	$2,707.59	$7,085.16	9.75%

Cooling Power %	CAPEX	OPEX	TOTAL	Δ
15%	$4,377.57	$1,955.69	$6,333.26	-1.89%
25%	$4,377.57	$2,216.45	$6,594.02	2.15%
35%	$4,377.57	$2,557.44	$6,935.01	7.43%
40%	$4,377.57	$2,770.56	$7,148.13	10.73%

Transaction Fees	CAPEX	OPEX	TOTAL	Δ
500	$4,403.12	$2,090.05	$6,493.17	0.58%
750	$4,360.70	$2,069.91	$6,430.61	-0.39%
1250	$4,278.27	$2,030.78	$6,309.05	-2.27%
1500	$4,238.21	$2,011.77	$6,249.98	-3.18%

Ave Difficulty Change %	CAPEX	OPEX	TOTAL	Δ
5.50%	$3,343.98	$2,117.88	$5,461.86	**-15.39%**
6.50%	$3,951.97	$2,097.90	$6,049.87	-6.28%
8.50%	$5,167.97	$2,051.28	$7,219.25	11.83%
9.50%	$5,775.96	$2,031.30	$7,807.26	**20.94%**

* - *a 50/50 ratio should be theoretical maximum, as risk of perception of a 51% attack becomes too high for large miners due to potential catastrophic impact on market price.*

Over time, the above sensitivities will allow us to make sense of the model's results when compared to actual market price and tweak the model in line with new evidence.

Comparative Summary

Revisiting Gold

Since this study has considered the manufacture of ASICs in its evaluation of Bitcoin's impact, we must now visit the environmental impact of the manufacture of mining equipment to make a like-for-like comparison. To start, we will revisit the subtotal impact of Gold mining considering current production levels. From there, we will add impacts from machinery production to the original tally. Since the previous iteration of this research in 2014 (using 2013 data), World Gold production has increased 18% from 2770 tonnes, to 3270 tonnes in 2017[110]. We have also witnessed a sharp drop in the amount of recycled gold produced, going from 37% of total annual production in 2011 produced gold coming from recycled down to only 26% at 1160 tonnes in 2017.

In a very comprehensive study produced by Dell in November 2017[111] showed some fascinating information on the relative sustainability of gold mining, and gold recycling. Results are shown in Figure 5 and Figure 6. It should be noted that Dell's 15 tonne CO_2/kg figures for gold mining exclude the construction and demobilisation of mine infrastructure, and site remediation. When including those, the original figure of 20 tonne CO_2/kg[1] that we used in 2014 was a very fair estimate. Perhaps the best observation to draw from the Dell data is just how toxic and harmful gold mining is to the planet, even though it produces less than half the amount of CO_2 per kilo.

RESOURCE INPUT	VALUE	UNIT
Electricity	27,696	kWh
Natural gas	12,385,015	Btu
Anion polymer	25	pounds
Borax flux	0.42	pounds
EZ5050 (Nitric Acid)	714	pounds
EZ5050 (Ferric Nitrate)	714	pounds
Ferric Chloride (FeCl3)	423	pounds
Hydrochloric Acid	1,762	pounds
Nitric Acid	564	pounds
Caustic Soda	3,173	pounds
Sulphuric Acid	458	pounds
Sodium Sulfite	105	pounds
Deionized water	5,868	pounds
City water	464	liters
Sodium Hydro Sulphide	21	pounds

Figure 5 - Resource inputs per kilogram of gold recycled

ENVIRONMENTAL IMPACT	UNIT	IMPACT		IMPACT REDUCTION	NET BENEFIT RATIO
		RECYCLED GOLD	MINED GOLD		
Carcinogenics	CTUh	0.00171	0.03208	-95%	x9
Non-Carcinogenics	CTUh	0.01	0.93	-99%	x93
Respiratory Effects	kg PM2.5 equivalence	12	20	-43%	x1.7
Global Warming	kg CO_2 equivalence	37,030	15,032	146%	x2.5
Fossil Fuel Depletion	MJ Surplus	14,903	20,999	-29%	x1.4
Photochemical Smog Formation	kg O_3 equivalence	2,094	3,608	-42%	x1.7
Acidification	kg SO_2 equivalence	180	175	3%	x1.0
Eutrophication	kg N equivalence	150	4,095	-96%	x27
Ecotoxicity	CTUe	154,278	22,139,602	-99%	x144

Figure 6 - Environmental comparison of recycling vs mining 1 kilogram of gold

Now that our original assumptions for gold mining have been validated against an in-depth recent study by Dell, we can take a look at how the numbers stacked up in 2017.

	Greenhouse Emissions (t CO_2/kg Au)	Energy Consumption (MWh/kg Au)
Rate Per kg - Mining	20.00[1]	48.61[1]
Rate Per kg - Recycling	37.00[111]	31.32[111]

	Tonnes Produced[110]	Greenhouse Emissions (Million t CO_2)	Energy Consumption (TWh)
Mined	3268.7	65.374	158.9
Recycled	1160	42.92	36.34

NOTE: All figures have been rationalised into MWh. 1 GJ = 0.27777 MWh. 1 MWh = 3.412 million BTU

Table 17 - Environmental Impact of Gold Mining & Recycling

The next item to assess in the impact of producing mining equipment. To do this, we can look to the world's largest Gold mining company, Barrick Gold, and the fleet and staff data they provide for their Pueblo Viejo[112], Veladero (open-pit)[113], and Barrick Nevada (Cortez[114], and Goldstrike[115] mine operations), which produce 107 tonnes of Gold per year[116], or, about 3.3% of total supply. The aggregate of the fleet lists for the above four mines, alongside data on the weight of machinery from manufacturers are shown in Table 19 and Table 18, below. As can be seen, much less machinery is used in an underground environment as opposed to an open-pit environment. Fleet data does not include the several hundred regular site-vehicles for staff use on the mine site. With an average of 42 staff per tonne of gold produced at the aforementioned mines, it is assumed that 10% of staff have vehicles for use on site, resulting in an extrapolated figure of around 15,000 site vehicles globally. 11 tonnes of CO_2 to produce a vehicle[117] means that **165,000 tonnes of CO_2** are created. Converting this to a kWh equivalent figure, we divide 0.165 million tonne CO_2 by 600 tonnes CO_2/TWh (Table 8), resulting in **0.09 TWh equivalent.** It is assumed site vehicles will last for 10 years (i.e. 0.009 TWh/year).

Machine	Make	Qty	Weight (t)	Total Weight (t)
R-2000 RoadHeader	Alpine	1	60.00	60
3.5 yd3 Loader	AtlasCopco	5	17.27	86
Boltec M Bolter	AtlasCopco	16	21.60	346
120 Grader	Caterpillar	7	16.88	118
414E loader	Caterpillar	19	6.82	130
966 Loader	Caterpillar	4	16.74	67
AD30 Truck	Caterpillar	11	30.00	330
D4 Dozer	Caterpillar	12	4.93	54
R1600G loader	Caterpillar	14	29.80	268
DT-20N truck	DUX	2	19.40	39
DT-26N truck	DUX	13	25.00	325
A64-C/LT/SL Vehicles	Getman	21	12.50	75
Mule Pro-DXT Utility Vehicle	Kawasaki	62	0.84	52
MHT Telehandler	Manitou	4	24.00	96
Rough-Terrain Forklifts (various)	Manitou	23	5.00	115
Ultimec MF500 Shotcreter	Normet	7	12.00	84
DT721 Tunnelling Jumbo	Sandvik	11	24.50	270
Tamrock 1400 Hauler	Sandvik	8	33.70	270
		Total Weight		**2784**

Table 18 - Underground Fleet Register for Barrick's Nevada Mines (Cortex & Goldstrike)

Machine	Make	Weight (t)	Qty	Total Weight (t)
L2350 loader	Komatsu	72.57	2	145
Haul Truck, 730E	Komatsu	146.69	19	2787
Face Shovel, PC4000	Komatsu	362.00	2	724
Wheel Loader, WA1200	Komatsu	216.40	3	649
Track Dozer, D375A	Komatsu	56.29	6	338
Track Dozer, D85-EX	Komatsu	28.10	1	28
Motor Grader, GD825A	Komatsu	29.68	3	89
Backhoe, PC300LC	Komatsu	33.80	1	34
Backhoe, WB140	Komatsu	7.30	1	7
Wheel Dozer, WD500	Komatsu	26.90	1	27
Wheel Dozer, WD600	Komatsu	41.08	2	82
Water Truck, 330M	Komatsu	24.04	2	48
930E Truck (290t)	Komatsu	210.19	24	5044
HM400 Water Truck	Komatsu	30.30	3	91
605 Truck (water)	Komatsu	46.20	6	277
930E Water Truck	Komatsu	505.75	3	1517
Face Shovel, PC5500	Komatsu	490.00	2	980
Backhoe, PC2000	Komatsu	204.12	1	204
P&H 4100 XPB shovel	Komatsu	1512.00	7	10584
P&H 2800 XPB shovel	Komatsu	1084.00	4	4336
Liebherr T282B trucks	Liebherr	252.00	25	6300
Face Shovel, 996	Liebherr	676.00	3	2028
Drill, SKS 12	Reedrill	95.58	2	191
DrillTech D55SP	Sandvik	79.33	12	952
DrillTech D75K	Sandvik	64.86	11	714
Drill (Blasthole), D90K	Sandvik	140.33	5	702
Sandvik D45KS Drill	Sandvik	47.73	2	95
Sandvik DX780 Drill	Sandvik	14.80	2	30
Drill, Ranger 700	Sandvik	15.20	1	15
DP 1500	Sandvik	19.20	2	38
Schramm T450GT Drill	Schramm	21.75	1	22

Machine	Make	Weight (t)	Qty	Total Weight (t)
PV271 drill	AtlasCopco	84.00	8	672
Flexirock D65 drill	AtlasCopco	24.00	3	72
MD6420 drill	Caterpillar	95.00	1	95
795F trucks (345 st)	Caterpillar	202.27	30	6068
16H grader	Caterpillar	24.70	16	395
24H grader1	Caterpillar	73.34	7	513
994F Front-End Loader	Caterpillar	243.11	7	1702
D10T Track Dozer	Caterpillar	70.17	20	1403
D9T Track Dozer	Caterpillar	48.99	3	147
834H Wheel Dozer	Caterpillar	47.11	7	330
854K Wheel Dozer	Caterpillar	98.49	7	689
777F Haul Truck	Caterpillar	80.00	13	1040
C322 Hydraulic Excavator	Caterpillar	24.83	1	25
C336 Hydraulic Excavator	Caterpillar	30.50	3	91
349D Hydraulic Excavator	Caterpillar	45.83	1	46
962 Support Loader	Caterpillar	19.37	2	39
938 Support Loader	Caterpillar	13.18	1	13
785C Haul Truck	Caterpillar	102.15	6	613
6040 Trackhoe	Caterpillar	397.40	1	397
992 Loader	Caterpillar	94.93	5	475
793 Haul Truck	Caterpillar	122.30	46	5626
385 Backhoe	Caterpillar	84.13	1	84
345 Backhoe	Caterpillar	45.38	1	45
988 Wheel Loader	Caterpillar	43.37	4	173
789C / 789D Haul Truck	Caterpillar	99.12	34	3370
EX-5500 excavator	HItachi	518.00	4	2072
EX3600 Hydraulic Shovel	Hitachi	362.00	2	724
X1200 Hydraulic Excavator	Hitachi	112.00	1	112
Drill, DMM2	Ingersoll Rand	5.40	3	16

Total Weight (tonnes): 66128

Table 19 - Open-pit Fleet Register for Barrick's Nevada, Pueblo Viejo and Veladero Mines

Having precise data on the machinery required to produce 3.3% of the world's Gold, we will extrapolate the total weights found above (66128 + 2784 = 68,912 tonnes) out to the other 96.7% of the market. This results in almost **2.1 million tonnes of mining equipment**, which we will conservatively assume is mostly steel for the next part of the analysis (since the energy needed to extract steel is typically lower than other materials used in vehicles, such as aluminium)[118].

1.95 tonnes of CO_2 are emitted in the extraction and production of one tonne of steel[119]. Data on vehicle manufacturing shows that the manufacture and transport stages of the vehicles life can vary anywhere from 5 to 20% of the energy required to extract raw materials[118]. Therefore, we will say that for each tonne of manufactured and delivered construction machinery there is 2.2 tonnes of CO_2 emitted (i.e. 1.95 tonnes + 10%). Multiplying this by 2.1 million tonnes of global Gold mining equipment results in **4.62 million tonnes of CO_2**. We will also conservatively say that well maintained mining machinery will last for 10 years if operated 24 hours per day, 365 days per week, resulting in a yearly average emission of **0.462 million tonnes of CO_2,** or **0.77 TWh equivalent.**, towards the manufacture of new machinery.

This 210,000-tonne heap of equipment also needs to be packaged and transported each year. While there is no data on emissions from packaging an excavator, estimations can be made regarding transportation emissions. As most mines are remote, equipment must be transported using several modes – by sea to move equipment continentally and then by road. A 3000-kilometre journey is not something unusual and would even be considered very conservative considering where the major equipment manufacturers are based, and how remote these mines truly are. We will assume that 75% of the journey happens via sea freight, and 25% of the journey via truck transport. This results in 4.725 billion tonne-km by sea, and 1.575 billion tonne-km by road. With sea travel on a large container barge producing 19.6 g/CO_2 per tonne-kilometre, and 62 grams for road travel[120], this results in 190,000 tonnes of CO_2, or **0.114 TWh equivalent.**

Therefore, the total amount of energy needed to manufacture and deliver machinery to the mines is 0.77 TWh for manufacture of machinery, 0.009 TWh for site vehicles, 0.0114 TWh for transport, which equals **0.7904 TWh**, or, **0.474 million tonnes of CO_2**. Adding this to mining and recycling totals shown in Table 17, we have the following:

	Tonnes Produced[110]	Greenhouse Emissions (Million t CO_2)	Energy Consumption (TWh)
Mined	3,268.7	65.374	158.9
Recycled	1,160	42.92	36.34
Equipment	2,100,000	0.474	0.7904
Total		**108.768**	**196.09**

Table 20 - Gold's Environmental Impact - Energy Use & Emissions

Comparison of Yearly Energy Use

Looking at the table below, it appears that Bitcoin uses a substantial amount of energy – now closing in on the entire Gold industry, and due to its reliance on the electrical grid, CO_2 emissions are high. As the electric grid moves towards renewable energy sources, Bitcoin's figures for CO_2 emissions will continue to improve, however there will be little improvement in the gold mining industry. That said, Bitcoin's energy use will continue to grow in line with the Network's computing power growth, and will most likely eclipse the Gold Industry within this decade.

Another interesting statistic is that more energy goes into building Bitcoin hardware than goes to producing the world's gold mining equipment. But since a large part of ASIC manufacture is tied to the electrical grid (Table 10), Bitcoin's emissions proportional to its energy use will reduce

	Energy Used (kWh)	Tonnes CO_2 Produced	Emission-Per-Unit Trend
Gold Mining + Equipment	159.69 million	65.85 million	Increasing
Gold Recycling	36.34 million	42.92 million	Decreasing
Bitcoin Mining	105.82 million	63 million	Decreasing

Table 21 - Bitcoin vs. Gold - Emissions & Energy Use

Comparison of Other Environmental Indicators

As can be seen below, Bitcoin is dramatically less harmful than Gold on all indicators aside from Carcinogenics, where the Global Electric Grid, i.e., the sole unified entity powering the Bitcoin network, spews more than double that of the Gold industry. As the electric grid moves towards renewable energy sources, Bitcoin's figures will continue to improve quite dramatically, however there will be little improvement in the gold mining industry.

	Gold Mining	Gold Recycling	Total Gold (tonnes)	Bitcoin	Δ
kg Produced	3268700	1160000	4428.7		
Acidification (kg SO2 /kg)	175	180	780823	423265	**-45.8%**
Eutrophication (kg PO43- /kg)	4095	175	13588327	89944	**-99.3%**
Freshwater Ecotoxicity (CTUe/kg)	22139602	154278	7.25E+10	3.61E+10	**-50.2%**
Carcinogenics (CTUh/kg Au)	0.03208	0.00171	107	339	**217.1%**
Non-Carcinogenics (CTUh/kg)	0.93	0.01	3051	1477	**-51.6%**
Respiratory Inorganics (PM2,5/kg)	20	12	79294	12817	**-83.8%**

Table 22 - Bitcoin vs. Gold - Broad Environmental Impact

Discussion & Conclusion

There is no doubt that the Bitcoin Network uses large amounts of energy (yes, it uses more power than the country of Ireland[121]), however, as alluded to in the Foreword, this energy is necessarily required to effectively turn electricity or power into "money". While emissions are high, this is due to the composition of the world's energy grid, and over time, emissions will continue to reduce proportionately to the amount of power that has been used.

Some critics have labelled Bitcoin as an environmental disaster[121], however it has been demonstrated that Bitcoin is dramatically less harmful to the environment than the gold mining industry when other key environmental indicators are assessed. Others have made the very fair criticism that costs per transaction are unruly[122], especially when volume of transactions (about 7 per second[123]) is considered in the context of the total power being used by the network. This criticism is only temporarily fair, as the Lightning Network[124], which has been live and growing since March 2018, will significantly increase transaction capacity without increasing energy consumption. The Lightning Network, as of July 31, 2018, has over 2700 nodes, 7700 channels, and a network capacity of about 93 BTC[125] (note, this is growth of almost 10% in node count, almost 30% in channel count, and over 30% in BTC capacity a period of only two weeks). In fortnight before that (July 1 to July 14), node-count increased over 10%, channel count by 30%, and network capacity more than tripling. It may not be unrealistic to expect a Bitcoin / Lightning Network that can process several hundred near-feeless transactions per second by the end of 2019, and potentially several thousand by the end of 2020. This would effectively allow Bitcoin to scale its transactional capacity by several orders of magnitude ahead of the next price hype-cycle.

As Bitcoin's market capitalisation grows, let's say two orders of magnitude to bring it in line with Gold's $7 trillion-dollar market cap, the Bitcoin mining industry will start to drive innovation in the world's electrical generation market due to the sheer amount of energy that the network will demand. Judging by current profits that mining hardware manufacturers currently make, mining companies may even become large enough to vertically integrate and acquire energy companies, and to remain competitive, the energy will need to be very cheap which means a high likelihood of migrating to hydroelectricity, and other renewables that get cheaper by the kWh every year.

We have also presented some broad assumptions about the composition of the Bitcoin mining market, and the dynamics at play that affect the cost to mine a coin. As the industry grows by a magnitude or two and becomes more competitive, the market price of a bitcoin will start becoming more correlated with the cost to mine, just as is the case for traditional commodity producers.

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