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Bitcoin's energy consumption is underestimated: A market dynamics approach

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ABSTRACT

As the resource intensity of running Bitcoin has increased over recent years, it has become a serious concern for its potential impact on health and climate. Within this context, there exists a growing need for accurate information. Various organizations need this for multiple purposes like properly assessing the urgency of the problem, implementing the right policy response in the right locations and for setting up mitigation programs.

We propose a market dynamics approach to evaluate the current methods for obtaining information on Bitcoin's energy demand. This allows us to establish that, while historically the Bitcoin mining industry has been growing most of the time, this growth allows market participants to pursue strategies that don't necessarily involve the best devices, device settings, or locations. The bigger the profitability of mining, the more it allows market participants to make decisions that result in suboptimal power efficiency of the Bitcoin network. Specifically, while the profitability of mining peaked during 2019, we find that market participants primarily used older generations of devices with better availability and lower acquisition costs. Common estimation approaches don't only fail to capture this behavior, but also fail to properly capture the market circumstances, like seasonal and geographic variation in electricity prices, that help enable participants to do so in the first place. This combination leaves common approaches prone to providing optimistic estimates during growth cycles. We conservatively estimate the Bitcoin network to consume 87.1 TWh of electrical energy annually per September 30, 2019 (equaling a country like Belgium).

1. Introduction

In 2008 an author, or group of authors, by the pseudonym Satoshi Nakamoto introduced the virtual currency called Bitcoin [1] to the world. The open, peer-to-peer distributed Bitcoin network subsequently started running at the start of 2009. In this network, anyone can join their computer hardware (like central processing units, graphics processing units or specialized application-specific integrated circuits) to help creating new blocks of transactions for Bitcoin's blockchain. The network contains an incentive to join in the form of a reward attached to successfully creating a new block. Network participants are incentivized to behave honestly because the Bitcoin protocol makes the process of creating a block computationally expensive. Participants have to expend resources, such as time and electricity for running their hardware, in order to create blocks that satisfy specific requirements. The whole process of creating new blocks via this proof-of-work system is known as "mining".

In 2017, the rise in the price of Bitcoin caused a significant jump in profitability for those invested in the Bitcoin mining industry. Early 2017 the value of a mined Bitcoin hovered around $1000, and this value peaked at $20,000 by the end of the same year. This growth allowed the industry to expand at a rapid pace. Bitmain, one of the largest manufacturers of specialized Bitcoin mining devices, sold 1.87 million sets of Bitcoin mining hardware during the first two quarters of 2018 alone, as compared to 0.26 million and 1.11 million sets during the full years of 2016 and 2017 respectively [2]. The growth in mining equipment was accompanied by increasing energy consumption [3] and electronic waste generation [4] by the Bitcoin mining network as a whole. While the network had of course been consuming resources since inception, it was this peak in growth that put the topic of the resource intensity of running Bitcoin in the spotlight.

1.1. Current estimates of key Bitcoin metrics

Studies conducted in 2018 estimated that the network's total electrical energy consumption equaled that of entire developed countries like Ireland [3], Hong Kong[1], and possibly even Austria [3]. This led to a spark of debate and interest among academics. The University of

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[1] Hong Kong consumes 46.9 terawatt-hours (TWh) of electricity annually [5], while the Bitcoin network was estimated to consume 45.8 TWh annually [2].

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Cambridge even added a new source, the Cambridge Bitcoin Electricity Consumption Index (CBECI), for daily estimates of the electricity consumption by the Bitcoin network. This presented an alternative to the already existing Bitcoin Energy Consumption Index (BECI). As per September 30, 2019, these two estimated the network was consuming 73.1 [6] to 78.3 [7] terawatt-hours (TWh) of electrical energy annually. For a single Bitcoin transaction this translates to an electrical energy footprint roughly equal to the electrical energy consumption of a British household in two months [8].

These numbers have led to concerns that cryptocurrencies like Bitcoin could "pose a serious threat to the global commitment to mitigate greenhouse gas emissions (GhGs) pursuant to the Paris Agreement" [9], with the most extreme predictions stating that "Bitcoin emissions alone could push global warming above 2 °C" [10]. But even without further growth, Bitcoin mining already has consequences for health and climate. Stoll et al. [2] estimated that the carbon footprint produced by Bitcoin mining "sits between the levels produced by the nations of Jordan and Sri Lanka", and Goodkind et al. [11] concluded that in 2018 "each $1 of Bitcoin value created was responsible for $0.49 in health and climate damages in the US and $0.37 in China".

1.2. Shortcomings in current estimation methods

Despite these numbers not being insignificant, this paper will show that most of the currently used methods to estimate Bitcoin's energy demand are still prone to providing optimistic estimates. This happens because they apply static assumptions in defining both market circumstances (e.g. the price of available electricity) as well as the subsequent behavior of market participants. In reality, market circumstances are dynamic, and this should be expected to affect the preferences of those participating in the Bitcoin mining industry. The various choices market participants make ultimately determines the amount of resources consumed by the Bitcoin network. It will be shown that, when starting to properly consider the previous dynamics, even a conservative estimate of the Bitcoin network's energy consumption per September 30 (2019) would be around 87.1 TWh annually (comparable to a country like Belgium [5]).

1.3. Importance of accurate information

If the Bitcoin network's energy demand is indeed underestimated, this can have a range of consequences for the users of this information. Sources like the BECI and the CBECI have not only received widespread media attention [12,13], but also have been (and are still being) used for multiple purposes by various organizations. The estimate featured on the Bitcoin Energy Consumption Index directly led to a question from the European Parliament to the European Commission on the topic [14]. The Commission subsequently indicated that it would continue to monitor the energy demand of the Bitcoin mining industry, though it wouldn't "put in place any means to track it" [15] (thus implying continued reliance on public sources). The Bitcoin mining industry itself has used this information to (successfully) appeal against a decision by the Canadian power company Hydro-Québec, and the independent Québec Energy Board, to increase electricity rates for cryptocurrency miners to 15 cents per kilowatt-hour (kWh) [16]. The rate hike was implemented after Hydro-Québec claimed to have received requests for up to 18,000 megawatts (MW) of power (exceeding 40 percent of its generating capacity) from the industry. This was more than twice the global estimated energy demand of the Bitcoin mining industry at the time, which allowed Bitcoin mining company Bitfarms to demonstrate that those requests couldn't be taken serious [17]. More recently, we've also seen the appearance of several initiatives using aforementioned sources to calculate carbon offsets for the Bitcoin network. This includes "carbon neutral" Bitcoin trading platforms [18] and rainforest protection projects [19]. Based on the previous examples, it becomes clear that the accuracy of the information is crucial for properly assessing the urgency of the problem, implementing the right policy response[2] in the right locations and for setting up mitigation programs.

2. A market stage framework to cluster and evaluate estimates

The quantification of the resource intensity of the Bitcoin network remains a lot more complicated than one might expect at first glance. It's possible to estimate the total amount of computational power (hashrate) of the network, but this estimate is already surrounded by uncertainty. The network also doesn't provide any information on what hardware is being used exactly. To evaluate the accuracy of the estimates for Bitcoin's energy demand and their respective assumptions, we propose dividing the developments in the Bitcoin mining market in three different stages based on the estimated network hashrate. These stages are growth, stability and decline (highlighted in Fig. 1). The growth stage is identified by observing the increasing amount of computational power (hashrate) in the network. Likewise, stability and decline can be identified by a relatively flat or decreasing amount of hashrate. The growth and decline stages each have their own unique implications with regard to estimation methodology, which will be discussed hereafter.

2.1. Market dynamics during a decline stage

A decline isn't the first phase we observe in Fig. 1, but arguably the most interesting one. It can be argued that market participants behave predictably during this phase, which makes estimating the network's energy consumption relatively easy, hence we will examine this first.

The decline can be observed between the start of November and mid-December 2018 (Fig. 1, phase 3). In less than a month one third is slashed from the network's total computational power. This drop coincides with a rapid drop in miner earnings. As miner earnings go down, the market increasingly punishes the least power-efficient mining devices and those that run under suboptimal conditions (e.g. those running on relatively expensive electricity or those requiring a lot of additional cooling).

2.1.1. Market forces limit participants' choices

As inefficient devices are forced from the market, only the most power-efficient available mining devices running at the cheapest electricity will be able to remain profitable. We assume rational agents will remove themselves from the mining pool entirely once they operate at a loss [3]. Therefore, the harsher the market circumstances, the less choices available to market participants. As profits decrease, market participants are increasingly limited in their choice of possible device types, device settings, and location to run these devices. This goes on until they may have no choice left but to abandon the market (or incur significant losses). The bigger the decline, the closer the network's actual power requirement will get to the network's minimum power requirement (a situation that reflects only the most power-efficient device being used by market participants).

2.1.2. Limited choice simplifies estimation

Stoll et al. specifically estimated the power requirement of the network at 5.23 GW (GW) over November 2018, after performing a detailed analysis of initial public offering (IPO) filings by mining rig manufacturers Bitmain, Canaan and Ebang, and after correcting for power usage effectiveness[3] (PUE) [2]. A back-of-the-envelope

[2] Truby [9] provided an insightful review of law and policy choices within this context, from imposing technical standards on mining devices to taxing or even banning cryptocurrency mining.

[3] PUE is a ratio that captures the total amount of energy used by a data centre to the energy delivered to the computing equipment. The difference may be the

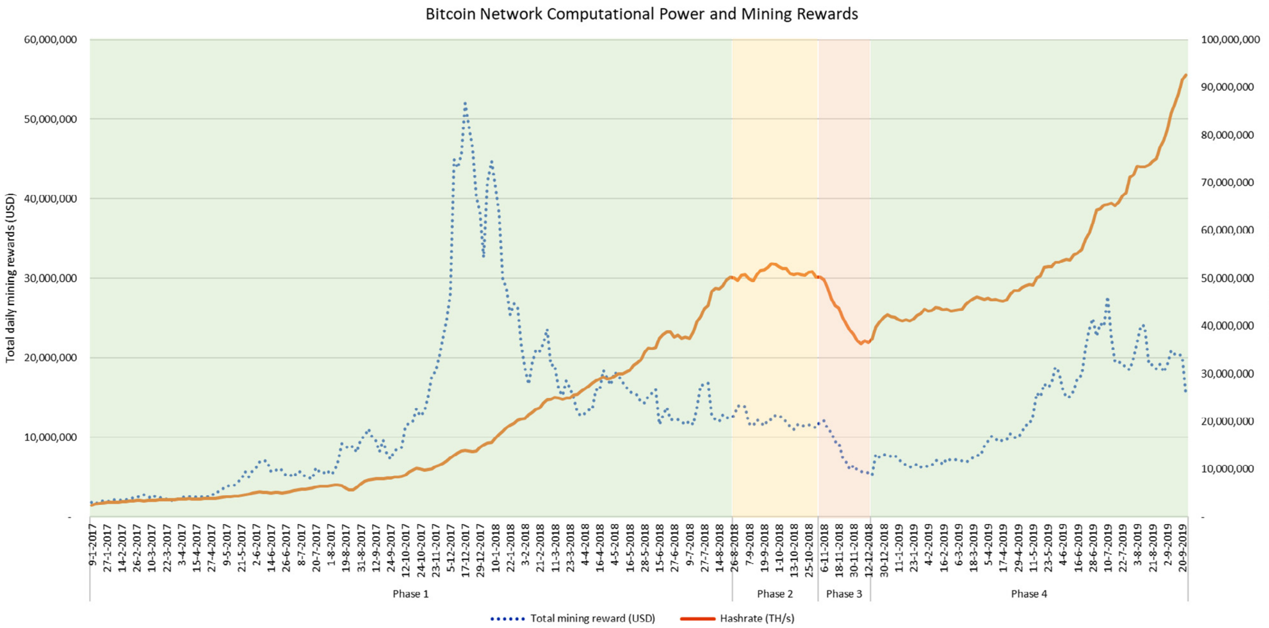

Fig. 1. Bitcoin network computational power (TH/s) and total daily mining rewards (USD) over time, since 2017 up until the end of Q3 2019. The colors in the graph mark different stages in the market cycle. Phase 1 and 4 indicate a growing market, while phase 3 indicates a declining market. The market is relatively stable in the intermediate phase 2. Bitcoin price, fees per day and hashrate (moving average) via blockchain.info.

calculation (hashrate * power efficiency) of the network's power requirement, using only the power efficiency of the most power-efficient device (the Antminer S9) of the most dominant manufacturer (Bitmain with a market share of 78 percent [2]) at the time, would yield 4.36 GW (44.5 exahashes per second [EH/s] * 0.098 J per gigahash [J/GH]).[4]

This shows that in a declining market real-world mining facility efficiency rapidly approaches the theoretic optimum, as suboptimal choices by market participants are increasingly punished. It also shows that during this phase a simple back-of-the-envelope approach (though corrected for market share) can provide a good sense of direction when estimating the electricity consumption of miners.

Unfortunately, we have to establish that most of the time the situation is a lot more complicated, as a declining market only occurs once (and only briefly) over a period of 33 months in total.

2.2. Market dynamics during a growth stage

Since 2017, we can see that the Bitcoin mining industry is actually experiencing growth most of the time. This state is only seriously interrupted by the last quarter of 2018. Both before and after this period we can observe a strong increase in the network's total computational power (Fig. 1). Here we can immediately notice that the link with miner earnings is not as obvious as for a declining market. In fact, the Bitcoin mining industry is booming for nine months after the crash of Bitcoin miner earnings early 2018 (also confirmed by record device production during the entire first half of 2018 [2]). The simplest explanation for this is that, while cutting losses in a declining market merely involves switching off devices, taking advantage of growth opportunities typically requires the acquisition of new devices. This takes time, and even more so if devices are only available in limited quantities due to production constraints. For this reason, the decision to add more units of computational power to the network can remain profitable far beyond a jump in miner earnings. This was illustrated early 2018 by De Vries [3], who predicted further network growth during the rest of the year. This prediction used estimated device production levels along with an assessment of Bitcoin mining profitability.

2.2.1. Bigger profitability creates more opportunities

In general, having the previous constraints allows power inefficiencies to creep into a growing market. These inefficiencies could take shape in the form of suboptimal performance (such as older or overclocked devices) or suboptimal conditions (like higher electricity rates or additional cooling requirements). Crucially, these inefficiencies don't imply irrational behavior by market participants, but merely that rational market participants can pursue a profitable strategy that doesn't necessarily involve the best devices or location. The bigger the profitability of mining, the more viable choices available to market participants. Market participants may make decisions like choosing to acquire older (cheaper but less power-efficient) mining hardware, or moving to an area with relatively expensive electricity prices (e.g. because of the risk of a local government cracking down on cryptocurrency mining [20]), under these circumstances.

2.2.2. The market forces that shaped the Bitcoin network in 2019

2019 provides an interesting case study on how this can shape a market in unexpected ways. This year marks the release of a new generation of Bitcoin mining devices based on chip supplier Taiwan Semiconductor Manufacturing Company's (TSMC) and Samsung's 7 nm & 8 nm process. These devices can achieve around double the amount of computations per joule of energy as compared to the previous generation. For example, Bitmain's Antminer S17 (TSMC's 7 nm process) runs on just 0.04 J/GH, where its previous flagship model, the Antminer S9 (TSMC's 16 nm process), required more than double (0.098 J/GH). Production of the chips required to produce these devices proved to be a major bottleneck for all manufacturers of Bitcoin mining devices up until the third quarter of 2019. MicroBT CEO Yang Zuoxing confirmed this by the end of September, stating that cryptocurrency mining manufacturers had received low priority from chip suppliers, and that chip supply therefore remained "very tight" [21].

(footnote continued)
result of cooling and other supporting IT equipment.

[4] The formula for calculating this lower limit can be written as $P_{LL} = H * e_{ef}$ with: P_{LL} = power consumption (lower limit) [W]; H = hash rate [H/s] and e_{ef} = energy efficiency of most efficient hardware [J/H] as defined by Stoll et al. [2].

The shortage of chips left manufacturers ill-prepared for the Chinese rain season that starts in April-May and ends in September-October. China is estimated to house a significant majority (75.62 percent per September 2019 [22]) of the Bitcoin network's computational power, and during this rain season market participants in the region may be able to obtain relatively cheap electricity (at a rate of less than 1 cent USD per kWh [23]) compared to the rest of the year. The latter opportunity arises as the rain season leads to excesses of hydroelectricity in China's southern provinces Yunnan and Sichuan [4]. The University of Cambridge has revealed that a substantial part of the Bitcoin network does indeed make use of this opportunity. Whereas the combined estimated share of the network's total computational power in these two provinces adds up to 47.63 percent (62.99 percent of the estimated total computational power within China) in September 2019, it only adds up to 15.38 percent (22.87 percent of the estimated total computational power within China) in March 2020 [22]. On top of these annual migration patterns, the Bitcoin price spiked once again during the summer of 2019, causing a sharp increase in total Bitcoin miner earnings (Fig. 1). Amidst these growing revenues and falling costs, investors turned to older generations with better availability and lower acquisition costs.

This was most clearly reflected by data provided in the IPO filing by mining rig manufacturer Canaan at the end of October 2019 [24]. The company reported that it had sold 252,862 units of its older A8 and A9 series (running on 0.10 J/GH and 0.09 J/GH respectively) in the first half of 2019, as compared to 292,826 units in the second half of 2018. These sales (representing 22 percent of all computational power sold in the first half of 2019) reflect a steady demand for older device types in 2019, despite the introduction of newer models like Bitmain's Antminer S17 mentioned before, or Canaan's own A10 series (introduced in the second quarter of 2019 with a power requirement of 0.0625 J/GH). With an average selling price of 7038 RMB per unit (compared to 1008 RMB and 1526 RMB for the A8 and A9 series respectively) the latter device type was sold only 490 times during the first half of 2019.

The turning point for the older generation didn't come until the end of the third quarter, around the end of the Chinese rain season, when MicroBT CEO Yang Zuoxing reported that the company had delivered 200,000 units (with a combined computational power of around 10 EH/s) of its latest generation of devices since July [21]. With MicroBT estimated to take a dominant position (with a potential market share of 50 percent [25]) among the latest generation of high-powered devices, we can only expect this generation to make up for a minority of the network per the end of the third quarter. In fact, when combining confirmed sales in 2019 with a sales analysis of prior years (Stoll et al. [2]), along with several independent market share estimates and observations, we can conclude that Bitmain's Antminer S9 family (first introduced in 2016) must still be the dominant force (though declining [26]) in the mining market per the end of September 2019 (Supplementary Data Sheet 1).

From the total increase in the Bitcoin network hashrate of around 30 EH/s during the third quarter of 2019 (Fig. 1), about 25 EH/s can be attributed to the sale of newly produced devices (Supplementary Data Sheet 1). During the first half of 2019 we observe an increase of around 20 EH/s in the total network hashrate, of which almost 18 EH/s can be attributed to the total computational power sold during this period. That means that, out of the average estimated network hashrate of 92.5 EH/s per September 30 (+/− 4 days), at least 49.5 EH/s of computational power must be generated by devices produced prior to 2019. The continued dominance of the Antminer S9 family (with a market share of 78 percent in 2018 [2]) should thus hardly come as a surprise (especially given continued sales of this device type in 2019).

2.2.3. Dealing with increased complexity

To-date, however, many techniques for estimating the network's energy consumption fall short in dealing with the complex dynamics that led to the previous situation. There is only a broad consensus that there's a need to include economic variables when estimating the network's energy consumption. Most methods like the ones by Bevand [27], Krause and Tolaymat [28] and Vranken [29] all include an assumption on the electricity cost of mining to determine hardware profitability, and subsequently eliminate (presumed to be) unprofitable devices from their estimates. While this may be a step in the right direction, there's two obvious limitations to this approach. The first is there's little consideration of how seasonal and geographic variation in electricity prices, as observed in China [4], should be handled. The second is that it requires another assumption on how the network hashrate should be attributed to the remaining devices.

The widely cited CBECI solves this by assuming that "all miners use an equally-weighted basket of hardware types that are profitable in electricity terms" for its best guess estimate [7]. The sales analysis performed in this article shows that this is too optimistic for two reasons. The first one is that the older mining devices have simply been on sale for much longer than the newer (most power-efficient) devices, so the distribution is already skewed as a result of different production periods. This is then further amplified by the observation that market participants continue to invest in older device types as newer ones become available, motivated by a general shortage of chips needed to produce the latest generation of miners (during a period of growing revenue and falling costs), as well as lower acquisition costs for the older generation of miners. The CBECI neither takes acquisition costs nor seasonal and geographic variation in electricity rates into account, but instead only assumes a constant USD 5 cents per kWh (which also ignores potential structural changes [23] in the average cost of electricity). As a result, it may not only attribute the wrong weights to devices, but also limit its scope too much in favor of the most power-efficient device types (something that affects both the "best guess" and "upper bound" estimates).

By analyzing sales and market shares data instead, we conclude a conservative weighted average power efficiency of all mining units in the network amounts to 0.0917 J/GH per September 30, 2019 (assuming only the most power-efficient devices produced prior to 2019 are still active). This translates to an annual power consumption 85.8 TWh after performance[5] and PUE corrections (Supplementary Data Sheet 1).[6] This number increases to 87.1 TWh annually (Fig. 2) if we consider a small delay (of one week) before delivered mining machines become active, as this primarily affects the most efficient devices being considered during the third quarter of 2019. The reason for considering such an adjustment is that, even though sales revenue is typically not recognized until the customer obtains control over the sold device(s), a delivered product may still take some time to become operational. For a large mining facility, installing thousands of devices certainly cannot be done in a single day. For example, Argo Blockchain PLC announced on January 2, 2020, that it expected to take more than a week (up to January 10, 2020) to get 3616 delivered Antminer S17 devices fully operational [30]. The amount of days this would take is highly relevant,

[5] Calculations like the ones in this paper and the ones used by Stoll et al. [2] and CBECI [7] make use of the advertised power efficiencies provided by mining rig manufacturers for their devices. These typically represent the minimum power efficiency under the device's default settings and ideal operating temperatures. In reality performance varies, and a correction should be made to represent the device's actual efficiency.

[6] This calculation follows the approach of the lower limit, including corrections for performance and PUE, and using a market share adjusted power efficiency rather than the energy efficiency of most efficient hardware. The formula for this calculation could thus be written as $P_{estimated} = H * e_N * PA_N * PUE_N$ with: $P_{estimated}$ = estimated power consumption $[W]$; H = hash rate $[H/s]$; e_N = weighted (by market share) energy efficiency of the network (using the advertised energy efficiency of the hardware in operation) $[J/H]$; PA_N = losses from variation in device performance [%] and PUE_N = losses from cooling and IT equipment [%]. The outcome is annualized over 365 days.

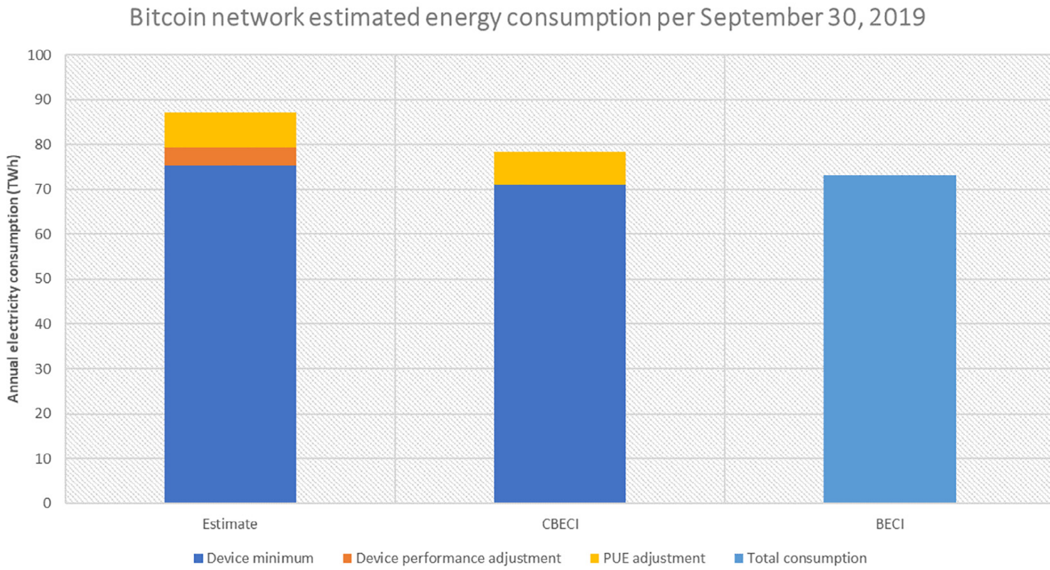

Fig. 2. Estimated electrical energy consumption by the Bitcoin network per September 30, 2019. The applied power efficiency is 0.0930 J/GH and reflects the weighted average power efficiency of devices estimated to be in the market per this date. The "device performance adjustment" reflects that devices typically perform at a power efficiency that is higher than the advertised efficiency, even under optimal operating environment circumstances, and amounts to 5 percent. The PUE adjustment adds another factor 1.1 on top of the previous, in line with the PUE adjustment used by the Cambridge Bitcoin Electricity Consumption Index (CBECI). The Bitcoin Energy Consumption Index directly estimates total electricity consumption, hence a further breakdown is unavailable.

as the network's average estimated hashrate increases to 97.3 EH/s (October 7, 2019, +/− 4 days) just a week after September 30 (when the hashrate is at 92.5 EH/s), and exceeds 100 EH/s less than three weeks later (on October 19).

3. Limitations and next steps for future research

The latter shows that sales analysis as a validation tool is far from perfect. The discrepancy between delivery and getting devices operational leaves it inherently optimistic without further adjustments. Connecting such an adjustment to the network hashrate makes sense in the absence of weekly sales figures, but remains highly uncertain as it involves hashrate estimates on two different dates. Consider September 30, 2019; on that day alone, we find that a 95% confidence interval on the estimated network hashrate (92.5 EH/s) amounts to 5.4 EH/s. This is a generic problem that affects estimates that leverage the total network hashrate (like the analysis in this article and CBECI), and might result in a bigger or smaller difference with the BECI that avoids using hashrate. CBECI specifically presents live (daily) estimates only using the hashrate estimate over the week prior to it, whereas ideally an estimate should include observations around a certain date like in this article to avoid creating a lagging indicator. Moreover, a certain portion of all devices sold may be undergoing repairs, or be broken down beyond repair. More data should be collected to determine how this affects sales analysis. Though, it is to be expected that this primarily affects older devices. As such, this would most likely raise the estimate produced in this article as only the most power-efficient devices produced prior to 2019 (all assumed to be in a working condition) have been taken into account.

Additionally, while the analysis in this article leverages market shares at a manufacturer level, it could further benefit from knowing the market shares of individual device types. Historically this level of detail has only been provided once for Canaan's IPO filing in 2018 [2], hence requiring some assumptions on how these market shares should be attributed to devices is unavoidable (for the analysis in this article these mostly follow the approach set forth by Stoll et al. [2] and Cambridge [7] and are available in the notes of Supplementary Data Sheet 1).

Lastly, this article has primarily focused on the question what mining devices should be in scope (and to what extent) under different market circumstances, but how investors subsequently use their devices is an entirely different matter. Investors may choose to overclock their devices to take advantage of very high profitability in a growing market, or underclock their devices to increase survivability during a declining market. This would be a logical extension of the content presented in this article, but to-date very little is known about the extent to which agents manipulate their devices. Hence this remains a subject for future research.

4. Conclusion

When estimating the Bitcoin network's energy consumption, one should take great care in considering the market circumstances surrounding an estimate. Common approaches apply static assumptions in defining both market circumstances, as well as the subsequent behavior of market participants. But market circumstances are dynamic, and this will affect the choices made by those participating in the Bitcoin mining industry. These choices ultimately determine the amount of resources consumed by the Bitcoin network. Historically the Bitcoin mining industry has been growing rapidly most of the time, but this growth allows market participants to pursue strategies that don't necessarily involve the best devices, device settings, or locations. The bigger the profitability of mining, the more it allows market participants to make decisions that result in suboptimal power efficiency of the Bitcoin network. Market inefficiencies that may occur during these growth cycles leave common approaches prone to providing optimistic estimates.

Based on a Bitcoin miner sales analysis we can conservatively estimate the Bitcoin network to consume 87.1 TWh electrical energy annually per September 30, 2019, exceeding commonly cited estimates of the Bitcoin's network electricity consumption at this time (73.1 to 78.3 TWh annually). Moreover, it is almost double the network's estimated electricity consumption near the end of 2018 (45 TWh) [2]. To put this number into perspective, it represents close to half of the current global data centre electricity use (200 TWh [31]), while equaling the electricity use a country like Belgium (87.9 TWh) [5].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2020.101721.

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