achieve the ambitious Paris Climate goals in time, we will need them all.

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AUTHOR CONTRIBUTIONS

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[1]Center for Global Change and Sustainability, University of Natural Resources and Life Sciences, Gregor-Mendel-Straße 33, 1180 Vienna, Austria

[2]Institute for Sustainable Economic Development, University of Natural Resources and Life Sciences, Gregor-Mendel-Straße 33, 1180 Vienna, Austria

[3]Wiener Netze GmbH, Nussbaumallee 21, 1110 Vienna, Austria

*Correspondence: johannes.schmidt@boku.ac.at

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COMMENTARY

Renewable Energy Will Not Solve Bitcoin's Sustainability Problem

Alex de Vries[1,*]

Alex de Vries has been a blockchain specialist at PwC's Experience Center since 2015. He earned his MSc in Economics and Business from the Erasmus University Rotterdam in 2011. In 2014, he founded the blog Digiconomist.net. This blog is a platform that provides in-depth analyses, opinions, and discussions with regard to Bitcoin and other cryptocurrencies. The blog also features the Bitcoin Energy Consumption Index since late 2016, which has played a major role in the global discussion regarding the sustainability of proof-of-work-based blockchains.

INTRODUCTION

Bitcoin was introduced as a ''peer-to-peer version of electronic cash,'' allowing for financial transactions without the need for a financial institution (or trusted third parties in general).[1] Bitcoin's underlying technology, called ''blockchain,'' is a cryptographically secured distributed ledger where these transactions are continuously (and publicly) being recorded. The addition of new (blocks of) transactions happens in a process called ''mining,'' where machines are engaging in a competitive process that involves ''scanning for a value that when hashed, such as with SHA-256, the hash begins with a number of zero bits.''[1] After a node collects new transactions in a block, a nonce in the block is incremented until a value is found that satisfies the required number of zero bits. The finished block is broadcasted to the rest of the network, where other nodes express their acceptance by building the next block on top of it. The creator of a block is rewarded with new coins, as an incentive to support the network.

In the early days of Bitcoin, mining was done using the central processing units (CPUs) of hardware. By the end of Bitcoin's first year (2009), it was realized that mining could also be done using graphic processing units (GPUs). Just like repetitively generating hashes in mining, video processing is a lot of repetitive work. To this purpose, GPUs are equipped with more arithmetic logic units (ALUs) than CPUs. The same ALUs are used in Bitcoin mining to generate SHA-256 hashes. As a result, GPUs mine Bitcoin faster than CPUs. Not long after (2011), miners started to shift to field programmable gate arrays (FPGAs). Then, in 2013, miners started using application-specific integrated circuits (ASICs)

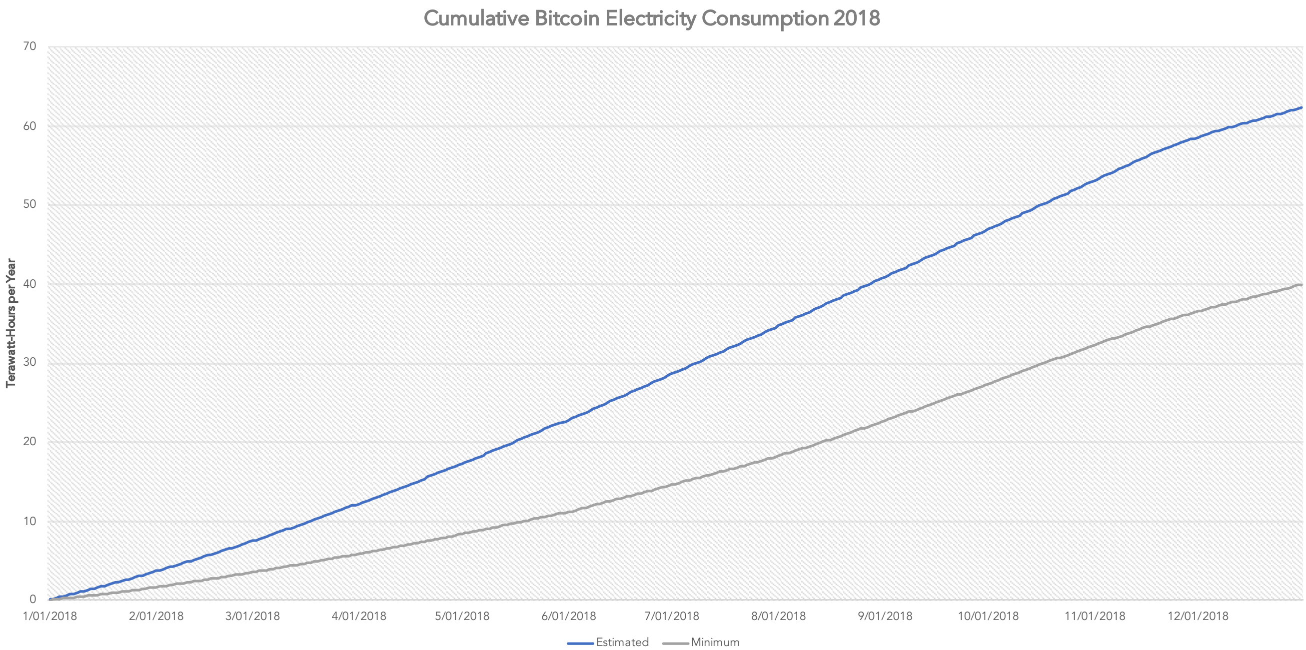

Figure 1. Cumulative Minimum and Estimated Bitcoin Mining Network Electricity Consumption in 2018 Based on the Bitcoin Energy Consumption Index (bitcoinenergyconsumption.com)

for mining Bitcoins. As implied by the name, ASIC chips are hardwired to perform one type of calculation only (unlike FPGAs, which can be reprogrammed to mine anything). This ensures that all resources are optimized for the task of generating hashes.

ENERGY EXPENSES

All of these types of machines require the expense of electricity for the task of generating hashes. We cannot estimate exactly how much electricity is used for Bitcoin mining, as it is not possible to establish how many (or which) mining machines are active in the network. It is, however, possible to create an estimate based off the total computational power in the network, or the total mining reward available to miners.[2] Both methods are featured in the Bitcoin Energy Consumption Index available at bitcoinenergyconsumption.com. The latter shows that the full Bitcoin mining network consumed at least 40.0 TWh, and possibly as much as 62.3 TWh, of electrical energy over the full year of 2018 (Figure 1). This is comparable to the amount of electricity consumed by countries like Hungary (40.3 TWh) and Switzerland (62.1 TWh).[3]

Of course, Bitcoin is not a country, and a better perspective of Bitcoin's energy requirement can therefore be obtained by comparing it to that of the traditional financial institutions. McCook estimated that the entire banking sector could be consuming as much as 650 TWh of energy per year.[4] Critically, this number includes not just the data centers that process transactions but also branches and ATMs. At the same time, we are only considering the energy use by Bitcoin mining while the digital currency (contrary to the original purpose of Bitcoin) has spurred the development of Bitcoin ATMs and a new range of trusted third parties. This includes exchanges, wallets, and payment solution providers. More than 80% of transactions occurring on the network now have a counter-party that is a third-party service.[5]

Focusing purely on data centers, it can be found that all of the world's data centers were estimated to consume 194 TWh of electricity in 2014, with an expected growth of only 3% to 200 TWh in 2020 (iea.org/digital/). It is unknown what share is used by the financial sector, but we can establish that the facilities used for Bitcoin mining already require at least 20% of this amount (40 TWh/200 TWh). On top of this, the financial sector is significantly bigger than the Bitcoin network. Bitcoin processed only 81.4 million transactions in 2018 (retrieved from blockchair.com). This means the average electricity footprint per unique transaction ranges from 491.4 kWh (40 TWh/81.4 M) to 765.4 kWh (62.3 TWh/81.4 M). The global banking industry, by contrast, is processing 482.6 billion non-cash transactions per year.[6] The average electricity footprint for processing these transactions can only be 0.4 kWh (200 TWh/482.6 B) at most.

ENVIRONMENTAL IMPACT

Even though the Bitcoin network can thus be considered extremely energy hungry, we also need to consider the environmental impact this causes. According to the Bitcoin Energy Consumption Index,

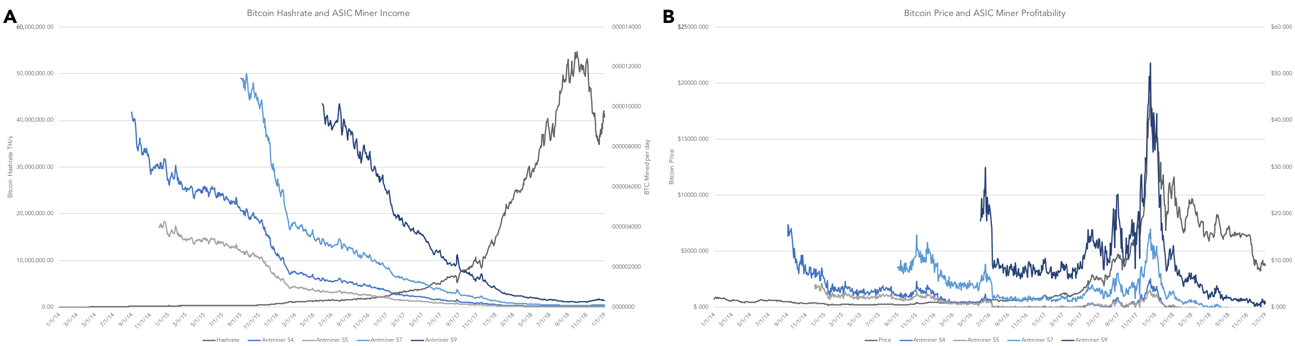

Figure 2. Time Series of Bitcoin ASIC Miner Income and Profitability Per Day of the Antminer S4, S5, S7, and S9 Mining Machines Since Their Release

Antminer machines are produced by Bitmain, the biggest manufacturer of Bitcoin ASIC miners.

(A) Bitcoin's total computational power (hashrate) in TH/s versus the amount of BTC that can be mined per day for a single unit of a specific ASIC miner. The Antminer S4, S5, S7, and S9 have advertised hashrates of 2, 1.155, 4.73, and 14 TH/s, respectively.

(B) Profitability per day for a single unit of a specific ASIC miner. To determine profitability in USD, the average daily rewards in BTC are multiplied with the USD exchange rate for that day. The cost of power is assumed to be 5 cents per kWh. The Antminer S4, S5, S7, and S9 have an advertised power requirement of 1,380, 590, 1,293, and 1,372 W, respectively. Source: https://www.blockchain.com/explorer and Bitmain.

Bitcoin's energy use in 2018 translates to a carbon footprint of 19.0 to 29.6 million metric tons of CO_2 (475 g CO_2 / kWh). The average carbon footprint per transaction would then range from 233.4 to 363.5 kg of CO_2. By comparison, the average carbon footprint for a VISA transaction equates to 0.4 g of CO_2, while a Google search is the equivalent of 0.8 g.[7] However, proponents of the digital currency argue that the ultimate environmental impact is limited. Their primary argument is that the majority of Bitcoin mining is mainly powered by what would otherwise be a wasted surplus of renewable energy.[8] Although miners may indeed be able to take advantage of cheap quantities of hydropower, limited environmental impact is not a foregone conclusion. To understand why it is not, let us first consider the economics of Bitcoin mining and its consequences for energy demand.

ECONOMICS OF MINING

Within the Bitcoin network, all of the participating mining machines are competing with each other for the reward of generating a new block for Bitcoin's underlying blockchain. At the current time, this reward consists of 12.5 Bitcoins per block plus any fees that were included in the processed transactions. Regardless of the total computational power in the network, new blocks are generated non-stop and every 10 min on average. The network self-adjusts the difficulty of generating a block after every 2,016 blocks, ensuring a steady production.

Adding new computational power to the network therefore does not increase the total size of the rewards, but primarily changes the distribution. As the chance of creating a new block for the blockchain is proportional to one's share of the total computational power, each newly added mining unit marginally dilutes the expected income of all others. This effect can be clearly observed when we look at the performance over time of several ASIC mining machines since their release (Figure 2A). As the total network computational power increases, the number of Bitcoins a single one of these machines is expected to mine per day tends to decline rapidly.

In such an environment, miners can only compete in terms of cost efficiency. Since mining machines require energy for the task of generating hashes, the efficiency of this hardware is determined by the amount of electricity required to complete a certain amount of computations. The more computations per unit of energy, the more profitable a machine can be. This has caused a rat race to develop more efficient mining hardware and explains why Bitcoin mining is now done with ASICs rather than CPUs. As "market forces drive the industry toward an equilibrium whereby firms will earn zero economic profit,"[2] we expect that only the most cost-efficient machines can remain economically viable for mining. A rational agent will shut down a less efficient machine once its energy costs exceed the value of the Bitcoin generated with it. Before this point is reached, time is of the essence and machines will have to run non-stop to generate the maximum profit (and to have the best odds of earning back the money invested in the machines in the first place). This also means that mining machines will have a constant energy demand at every time of the day throughout the year, increasing the baseload demand on a grid.

CHALLENGES IN UNITING RENEWABLE ENERGY WITH BITCOIN MINING

As the most cost-efficient machines will generate the biggest profits, agents are incentivized not just to use the most efficient hardware but also to seek out the cheapest electricity. According to Coinshares, one popular area for such cheap electricity is the province of Sichuan in China. It is suggested that 48% of the global mining capcity is now situated here.[8]

The southwest of China is capable of producing large amounts of hydropower while local demand is substantially lower. Unfortunately, "China's grid infrastructure is currently a bottleneck for renewable power generation."[9] Because of insufficient grid penetration and a lack of high-quality grid infrastructure, the power export capacity of the region is also limited. This leaves the Sichuan and Yunnan provinces with an abundance of hydropower, which lures in energy-hungry and polluting industries trying to take advantage of the low rates. Bitcoin mining is one these industries.

Unlike the power demand of Bitcoin mining machines, which is consistent all year long, the production of hydropower is subject to seasonality. In an extensive report, China Water Risk (CWR) explains that "hydroelectricity cannot be generated year-round" because of "variations in water availability through rain/floods/droughts."[9] Production of hydropower is high in the wet season during the summer months and low in the dry season during the winter months. As a result, seasonal variability in hydropower is already higher than 30% and expected to increase further because of climate change.

In Sichuan, specifically, "the average power generation capacity during the wet season is three times that of the dry season."[9] These fluctuations in hydroelectricity generation need to be balanced out with other types of electricity. CWR adds that this "is usually coal," and as a consequence, this renewable option is "not technically 100% green." It should thus be no surprise that the carbon emission factor of purchased electricity in Sichuan ranges from 265 to 579 g CO_2/kWh, depending on the chosen method.[10] This is more comparable to the GHG emissions of generating electricity from natural gas (469 g CO_2/kWh) than it is to the GHG emissions of generating hydropower (4 g CO_2/kWh).[11]

The former reveals the challenges in uniting "green" renewable energy with Bitcoin mining. Miners may indeed be able to take advantage of (temporary) excesses of hydroelectricity, but they effectively increase the baseload demand on a grid throughout the year. This demand has to be met with energy from alternative sources, when seasonality causes production of this renewable energy to fall. In the worst-case scenario, it presents an incentive for the construction of new coal-fired power stations to fulfil this purpose.

Environmental Impact beyond Energy Use

The previously described challenge is not the only challenge in trying to address Bitcoin's sustainability problem with renewable energy. One thing that renewable energy cannot solve at all for Bitcoin's environmental footprint is what happens to the mining machines once they reach the end of their economic lifetime. For ASIC mining machines, there is no purpose beyond the singular task they were created to do, meaning they immediately become electronic waste (e-waste) afterward. To estimate the total e-waste potential of the Bitcoin network, we need to determine first the quantity of mining equipment in the network and, second, the rate at which this equipment becomes obsolete.

As mentioned before, there is no way to determine the exact composition of the Bitcoin network. Since we can estimate the total computational power in the network, we can use this to derive a quantitative estimate of the total mining equipment. We can observe that at its peak (in October 2018), the Bitcoin network was estimated to process around 54.7 exahashes per second (Figure 1). We can subsequently establish that it would require at least 3.91 million Antminer S9 machines, with an advertised output of 14 terahashes per second, to produce that amount of computational power. The combined weight of these machines would amount to 16,442 metric tons. This number represents the minimal quantity of mining equipment in the network, as the Antminer S9 had the least amount of weight per unit of computational power at this time (Table 1).

With the release of the new (more cost efficient) Antminer S15 in December 2018, we can expect all of this equipment to become obsolete in the very near future. The recent drop in total network computational power (Figure 2A), following a decreasing Bitcoin price and mining machine profitability (Figure 2B), suggests that this process is well underway. From October to December 2018, the total computational power in the network decreased by 19.9 exahashes per second, meaning at least 5,973 metric tons of mining equipment were removed from the network. Although this does not mean they were immediately disposed.

In general, we can expect mining equipment to become obsolete in roughly 1.5 years, which would follow from Koomey's law and the observation that only the most cost-efficient machines can remain economically viable for mining. Koomey et al. observed that "the electrical efficiency of computing (the number of computations that can be completed per kilowatt-hour of electricity)" has "doubled about every 1.5 years" over a period of 65 years.[12] The developments in Bitcoin ASIC mining equipment have easily kept up with this pace (Table 1).

Table 1. Examples of Bitcoin ASIC Miner Machine Types

Machine	Producer	Hashrate (TH/s)	Power Efficiency (J/TH)	Net Weight (kg)	Weight/Hashrate (kg/TH/s)	Released
Antminer S15	Bitmain	28	57	7	0.25	December 2018
Antminer S9	Bitmain	14	98	4.2	0.30	June 2016
Antminer T9	Bitmain	12.5	126	4.2	0.34	January 2017
Antminer T9+	Bitmain	10.5	127	4.2	0.40	January 2018
Antminer S7	Bitmain	4.73	273	4.5	0.95	September 2015
Antminer S5	Bitmain	1.155	510	2.5	2.16	December 2014
Antminer S4	Bitmain	2	690	7.3	3.65	September 2014
AvalonMiner 821	Canaan	11	109	4.7	0.43	February 2018
AvalonMiner 761	Canaan	8.8	150	5.8	0.66	July 2017
AvalonMiner 741	Canaan	7.3	160	4.3	0.59	April 2017
Bitfury B8	Bitfury	47	130	37	0.79	December 2017

Source: Bitmain, Bitfury, and Canaan.

If Bitcoin cycles through 16,442 metric tons of mining equipment every 1.5 years, the annualized e-waste generation would amount to 10,948 metric tons. This amount of e-waste is comparable to the total e-waste generated by a country like Luxembourg (12 kt).[13] Moreover, it amounts to a staggering average footprint of 134.5 g per transaction processed on the Bitcoin network in 2018 (81.4 million). This is as heavy as two "C" size batteries (130 g) or four standard 60 W light bulbs (136 g).

We do not know the amount of e-waste generated by the banking sector, but we can find that a financial institution like VISA has a significantly lower e-waste output. VISA does not disclose its exact e-waste production but provides that it has two data centers for processing its transactions.[7] The largest one consists of seven independent physical pods, containing "376 servers, 277 switches, 85 routers, and 42 firewalls" each.[14] We can assume that the total equipment in each of these pods weighs around 40 metric tons (putting the weight of a single server over 100 kg). The combined weight for all pods would then amount to 280 metric tons. Even though the second data center is only half the size of the first one, we assume an equal amount of equipment. This brings the total equipment estimate for both of VISA's data centers to 560 metric tons. If we then assume this equipment would be replaced in full every year, the average e-waste footprint per processed transaction (124.3 billion in total for 2018[15]) would still only amount to 0.0045 g.

It is important to note that even though price movements may lengthen or shorten the economic lifetime of a specific ASIC miner machine type (the effects of price movements on machine profitability can be observed in Figure 2B), Bitcoin's e-waste generation would still continue even under a stable price because of continuous hardware efficiency improvements. The latter ensures that older hardware will inevitably be disposed on a regular basis.

LIMITATIONS

The discussed method with regard to Bitcoin's e-waste generation only considers the e-waste output resulting from mining equipment being disposed. Other equipment present in mining facilities, like cooling, has not been taken into consideration.

Another potential limitation is that there exist other types of transactions, which are not directly recorded on the Bitcoin blockchain. As the amount of transactions processed this way is not known, these could not be accounted for. Off-chain transactions include transactions that are processed internally by trusted third parties in the Bitcoin ecosystem. The very existence of this type of transaction within the Bitcoin ecosystem is counter-intuitive, as Bitcoin was created to "allow online payments to be sent directly from one party to another without going through a financial institution."[1] The Bitcoin community is therefore developing second-layer protocols like the so-called Lightning Network, which would allow for off-chain transactions without the need for a trusted intermediary. This could reduce the environmental footprint per transaction.

CONCLUSION

Given the fundamental challenges in uniting Bitcoin mining with renewable energy, along with the fact that energy use is not the only way in which Bitcoin impacts the environment, we should conclude that renewable energy is not the answer to Bitcoin's sustainability problem. Alternatives to Bitcoin's mining mechanism, such as Proof-of-Stake, are already available and used by an array of alternative cryptocurrencies (e.g., Dash and NXT). In these systems, participating machines do not have to use their computing power. This prevents both extreme energy use as well as the incentive to develop specialized (singular purpose) hardware and showcases that blockchain technology does not necessarily have a significant environmental impact. What is left is for Bitcoin to follow the example set by others.

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[1]Experience Center of PwC, Amsterdam, The Netherlands

*Correspondence: alex.de.vries@pwc.com

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