Bitcoin and Global Climate Change: Emissions Beyond Borders

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Bitcoin is a virtual, decentralized currency based on Blockchain technology. Regardless of where you send Bitcoin, the greenhouse gas emissions stemming from these transactions are distributed around the world. Furthermore, with the increasing public and institutional interest in Bitcoin, the value, complexity of Bitcoin mining, Blockchain networks, as well as the energy required for Bitcoin mining have been rapidly increasing. Here we show the global distribution of greenhouse gas emissions resulting from Bitcoin mining across the globe. We also estimated the carbon footprint of Bitcoin mining per transaction, per country, and per year for the last six years. The carbon footprint estimations of Bitcoin mining are calculated with consideration of the global supply-chain of Bitcoin mining around the world. According to our systematic estimations, carbon emissions are in rapid increase and there is a significant discrepancy between the locations of Bitcoin holders and the locations of emissions. China plays a major role both in emissions due to overall global mining and as a major manufacturer/supplier of Bitcoin mining equipment for all Bitcoin mining countries.

Background: What is Bitcoin?

Bitcoin is an electronic, virtual, decentralized currency based on Blockchain technology which was established by Satoshi Nakamoto in 2009 (pseudonym)¹. The purpose of using Blockchain in the Bitcoin platform was to bypass a central authority and instead use a trusted peer-to-peer network pseudo-anonymously to ensure the use of digital money to purchase services and goods securely. Also, Bitcoin or many other cryptocurrencies are attempts to solve certain perceived problems with governments and banks. According to Satoshi Nakamoto, the root problem with the conventional currency is about trust and efforts to establish this trust to run the system. Trust in government and banking systems was in decline during the 2008 global economic crash and Nakamoto seized this opportunity to shift trust from governments or banks to highly complex Blockchain networks where society at large can involve without borders². This is a fundamental shift in the perception of money as we know it. While Bitcoin has been described by various enthusiastic by “Gold 2.0”³, “the Internet of money”, or “a movement to democratize financial system”², some leaders such as Federal Reserve Chair Jerome Powell stated that Bitcoin is too volatile to replace the dollar⁴. Despite the discussions about whether Bitcoin will be a digital gold or have a real tangible value, Bitcoin and Bitcoin mining have been attracting both public and institutional investors around the world and its market cap value has passed \$1 trillion by February 18, 2021, which is around 10% of the market cap of gold⁵.

Bitcoin and its underlying Blockchain technology are not supervised or controlled by any particular body, such as a centralized authority, or a bank. Bitcoin transactions are conducted by the mining community, which is composed of individual users with mining hardware and computing power. The miners are necessary to validate, verify, and record transactions in the public blockchain. The mining operation focuses on solving complex mathematical puzzles respecting the Proof of work process for validating transactions which results in earning rewards for the miners in form of Bitcoin. Accordingly, there is completion for mining a specific transaction, considering the reward is given to the miner who is the first to solve the puzzle. The number of computer calculations required for recording and verifying transactions is enormous. Moreover, the puzzles are exceptionally complex, and their

complexity is gradually increasing owing to the increasing value and popularity of Bitcoin. Consequently, the demand for high-powered computer processing and electricity is also on the rise. Mining Bitcoin requires more energy than mining gold⁶. With this increasing electricity demand for Bitcoin mining, the carbon emissions resulting from Bitcoin mining has been an important aspect to investigate.

Global Climate Change and Bitcoin Mining

With the increasing energy demand by human activities and rapid industrialization since the mid-20th century, the greenhouse effect around the globe has been increasing by excessive emissions of greenhouse gases (GHG) such as carbon dioxide, methane, and Nitrous oxide. According to the Intergovernmental Panel on Climate Change (IPCC), involving over a thousand scientists around the world, the cost of climate change is likely to be significant and to increase over time. Potential catastrophic impacts of climate change are of paramount interest to humanity as it influences land use, sea-level rise, droughts and heatwaves, changes in precipitation patterns, and global society at large through feedbacks from these natural cycles of earth⁷. In response to increasing concerns about global climate change, 196 parties at COP21 in Paris have reached a consensus to decrease GHG emissions to limit global warming within 2°C. The energy sector is the main source of global manmade GHG emissions with 72% of the total emissions⁸, mainly due to the combustion of fossil fuels to generate electricity.

Considering that Bitcoin mining is an energy-intensive process and rapidly increasing, concerns about the potential contribution of Bitcoin mining to Global Climate change have been an important topic to investigate in the global scientific community⁹⁻¹¹. For example, Mora et al.¹² estimated that Bitcoin mining alone can increase the atmospheric temperature by 2°C and they estimated annual emission of 69 MtCO₂ in 2017. Houy¹³ estimated a wide interval of GHG emissions for Bitcoin mining with a minimum 2.9 and maximum of 35.1 MtCO₂, depending on the least and most polluting hardware configuration, and their estimation for the year 2017 is 15.5 MtCO₂. Stoll et al.¹⁴ estimated annual Bitcoin mining emissions between 22.0 to 22.9 MtCO₂, which is approximately equivalent to annual emissions produced by countries of Jordan or Sri Lanka in 2018. Köhler and Pizzol¹⁵ conducted a life cycle assessment of Bitcoin mining and estimated 31.29 TWh of annual energy consumption and annual GHG emissions of 17.29 MtCO₂ in 2018. The estimations above mostly focused on single-year data and provided a snapshot analysis. Considering the rapid increase in Bitcoin mining in recent years, the energy requirement for increased complexity in mining as well as emissions due to Bitcoin mining is significantly increasing. Moreover, the decentralized nature of Bitcoin mining has been centralizing in certain locations such as China and thus making it more sensitive to the electricity generation mix of certain countries rather than a diversified source of electricity generation in terms of source and country. Thus, locations of Bitcoin holders/users and mining becoming different, mining has been centralizing in certain locations and making the carbon footprint of mining more centralized in terms of a country location.

The carbon footprint of Bitcoin Mining

With the increasing public and institutional interest in Bitcoin over the last 6 years, the value, complexity of Bitcoin mining, Blockchain networks, as well as the energy required for Bitcoin mining have been rapidly increasing both annually, per hash rate, as well as per transaction. Here, we employed a comprehensive life-cycle assessment approach, conducted an up-to-date estimation of Bitcoin mining for the last 6 years, thus highlighted the rapidly increasing trend (Fig. 1 and Supplementary Figures 5 and 6). The total global annual energy consumption and emissions show a constantly increasing trend since 2015 when the total energy consumption was only 0.152 TWh. However, a striking increase has occurred starting from 2018. To illustrate, the total consumption in 2017 was only 4.97 TWh, and it dramatically increased to 22.462 TWh in 2018, 38.907 TWh in 2019, and 55.57 TWh in 2020. It is expected that this trend will continue in the upcoming years. Similarly, GHG emissions have been increasing rapidly from 0.20 MtCO₂-eq in 2015 to 48.5 MtCO₂-eq in 2020. Furthermore, increased complexity in encryption in Bitcoin Blockchain network boosted emissions and energy requirements per transaction significantly, from 6.09 kWh to 493.77 kWh, and from 4.53 kgCO₂ to 430.92 kgCO₂ per transaction in 6 years. In other words, making a single Bitcoin transaction on average in 2020 means approximately 1,600-2,600 kilometers of travel with moderate size electric or gasoline engine sedan vehicle (per km emission of an electric and gasoline sedan car are 0.17 kgCO₂-eqv. and 0.26 kgCO₂-eqv., respectively)¹⁶.

Fig. 1. Carbon Footprint and Energy Consumption of Bitcoin Mining over years

Geographic Distribution of Bitcoin Mining's Carbon Footprint

Regardless of where you send Bitcoin, GHG emissions stemming from these transactions are distributed around the world. Figure 2 shows the global distribution of greenhouse gas emissions resulting from Bitcoin mining across the globe and geographic locations of Bitcoin holders (nodes). Bitcoin nodes reflect the intensity of Bitcoin holders/users in the associated locations. The carbon footprint estimations of Bitcoin mining are calculated with consideration of the global supply-chain of Bitcoin mining around the world. Hence, we were able to capture emissions embedded in the supply chain of Bitcoin mining including manufacturing of mining equipment and electricity generation, as well as further layers of supply chains using Leontief inverse (for more detailed information please see Sections 4.1 through 4.5 in the Supplementary information file available in the journal's website). We estimated that there is a significant discrepancy between the locations of transactions and the locations of emissions.

Figure 2. Geographic distribution of Bitcoin holders/users¹⁷ and Carbon footprint of Bitcoin mining including its supply chain

*The size of the bubbles in the figure shows the magnitude.

When looking globally, the emissions are highly concentrated in China. For example, 81% of the global emissions due to Bitcoin mining occurs in China, which also includes the supply chain of the mining happens in other countries. While top Bitcoin holders are in the western world, mainly in North America and Europe, including United States (22%), Germany (20%), France (7%), and Netherlands (5%), emissions due to Bitcoin mining are predominantly in China followed by the USA by 14% of the total emissions in 2020. The high emission concentration within the regional boundaries of China makes both the environmental impacts of the overall Bitcoin Network and the future value of Bitcoin mining highly dependent on China. Any regulation, potential power outages, taxing, short supply of mining equipment in China could potentially influence the overall performance, value of Bitcoin, as well as carbon

emissions from Bitcoin easily¹⁸. This over-centralization contradicts the philosophy of Bitcoin Network which promotes decentralization over centralization by any means.

Emissions embedded in the global supply chains are contributing to the gap between production emissions and consumption emissions thus, contributing to the carbon leakage between producing and consuming countries. The geographic discrepancy between Bitcoin mining and holding (use), is another emerging case for the rapidly growing gap in production and consumption-based emissions. While the use of production-based national emission inventories to set national emission reduction goals is mostly accepted and utilized way, consumption-based estimations can provide important insights for setting up global goals with a better-shared responsibility to diversify emission mitigation policies^{19,20}.

Figure 3. Percentage distribution of carbon emissions across global supply chains for top Bitcoin mining countries in 2020

According to the comprehensive supply-chain-based carbon footprint analysis, in countries such as China and the USA, the great majority (98.3% and 85.8%, respectively) of the GHG emissions occur within the regional boundaries of these countries. On the other hand, countries such as Iceland (8% inside), Finland (51% inside), and Sweden (45% inside), have their emissions distributed across their global supply chains. However, China plays a very important role in the supply chain of all these mining countries, especially in Iceland, 78% of Iceland's emissions result from China's role in its supply chain, mainly mining equipment imported from China. Also, emissions within the regional boundaries of Iceland account for only 9.3% of its total emissions. This is mainly due to the much lower emission intensity in Iceland's electricity generation sector that heavily relies on geothermal energy. In Finland and Georgia, approximately 40% of the emissions due to Bitcoin mining occurs within the regional boundaries of these countries, while Russia and China play a major contributing role for these countries. Sector breakdown within the national supply chains shows a strong dominance of electricity generation by Coal in GHG emissions. Especially, electricity generation by coal in China is the biggest contributor compared to all other sectors globally. We provided a detailed sectorial breakdown of GHG emission distribution across global supply chains of all major mining countries in Tables 53 till 80 per transaction and per year since 2015, in Supplementary Information File available online in the journal's website. In addition, we provide an interactive data visualization platform for all readers and decision-makers to generate results for their selection of units and per country, globally. To access and generate interactive results please visit the website at the [link](#).

Fig. 4 shows the annual emissions per country for the last 6 years. Since 2017, the annual emissions stemming from China (including the global supply chains of other countries, mining equipment manufacturing) increased 8 times, from approximately 5 MtCO₂ to 40 MtCO₂ annually. With the outbreak of COVID19 pandemics, the value of Bitcoin and Bitcoin mining has increased significantly since March 2020. We observed that the percentage of mining that occurs in the USA also rapidly increased with the increased value of Bitcoin. Since 2018, the USA's share in the percentage of total global mining has almost doubled. While in India, Bitcoin mining was banned, in Sweden, the majority of the miners stopped mining due to profitability concerns. However, we included the results of these counties in the Supplementary information file.

Figure 4. Annual Bitcoin emissions per country between 2015-2020.

Conclusions and Future Work

The climate change impacts of Bitcoin mining are global but the mining and the source of emissions are predominantly centralized in China, while users/holders are mainly from the developed world. As the value of Bitcoin rises and its Blockchain network gets more complicated, GHG emissions due to mining have been increasing rapidly. While proof-of-work-based cryptocurrencies, requiring an intensive amount of energy, there are various alternative ways to conduct mining (consensus mechanisms in the blockchain) such as Proof-of-Stake (PoS), Delegated Proof of Stake (DPoS), Proof of Elapsed Time (PoET), etc. There are also eco-friendly cryptocurrency projects such as SolarCoin that are incentivizing real-world environmental activities such as verifiably produced solar energy and BitGreen aiming to incentivize carpooling, purchasing sustainable coffee, volunteering etc²¹. Although more efficient algorithms currently exist and are in use in various cryptocurrency projects, their environmental impacts at a larger scale, when there is much more widespread adoption, have not been investigated. Potential carbon emissions of alternative consensus mechanisms in Blockchain should be further investigated for widespread adoption cases. Furthermore, ways to implement carbon tax should be investigated as a potential way to minimize the rising Bitcoin mining emissions. While the decentralized unregulated nature of cryptocurrencies is challenging to regulate, there can be solutions within the crypto-space where Blockchain technology can be used to minimize carbon emissions from mining.

Methodology

To estimate the carbon footprint of Bitcoin, we conducted the analysis in six main steps as shown in Figure 5. The first step is to extract all the data related to the mined Bitcoin transaction publicly available on the Bitcoin website. Next, the energy consumed per total hashes in each transaction is calculated. As a result, the output of the second step is the energy consumption of Bitcoin per country per year. In the third step, the global EXIOBASE 3.4 database²² is used to develop a multi-regional input-output (MRIO) based carbon footprint analysis and to calculate the carbon footprint of electricity generation by energy source (sector). In the fourth step, we calculated the carbon footprint of electricity generation by country. Next, the carbon footprint of manufacturing mining equipment is calculated using the developed environmentally extended MRIO model. Finally, the two main sources of carbon emissions are merged and analyzed per country, per transaction for the last 6 years. In this step, we also analyzed the global supply chains of bitcoin mining by country per year. The functional unit of the analysis is per transaction, as arguably, the service provided by the Bitcoin use case is the transaction. While the utility of Bitcoin can also be considered as “an asset which holds value (such as gold)”, the functional unit, in such case, would be significantly fluctuating (e.g. per \$ value holding or per gram gold equivalent). Hence, per transaction would provide more a meaningful analysis. However, we also provide estimations on annual basis per country, per transaction, and country. To see the complete set of results please see the supplementary information file that is available on the journal's website and the website at the [link](#). for interactive result generation. A full detailed step-by-step explanation in the supplementary information file, data source files, and scripts, as well as a presentation explaining each step, are provided for researchers to reproduce the results. All these resources are available at [the link](#).

Figure 5. Step-by-step workflow of the analysis

Author Contributions

Nuri C. Onat designed and supervised the research, wrote the main manuscript, revised and edited the Supplementary information file. Rateb Jabbar conducted the analysis, documented all the analysis steps, wrote the supplementary information file. Murat Kucukvar assisted the development MRIO model and life cycle inventory. Noora Fetais contributed to the data visualization and internal funding for the research.

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Supplementary Files

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