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AS OF NOVEMBER 16, 2021

The Carbon Emissions of Bitcoin From an Investor Perspective

The Carbon Emissions of Bitcoin From an Investor Perspective

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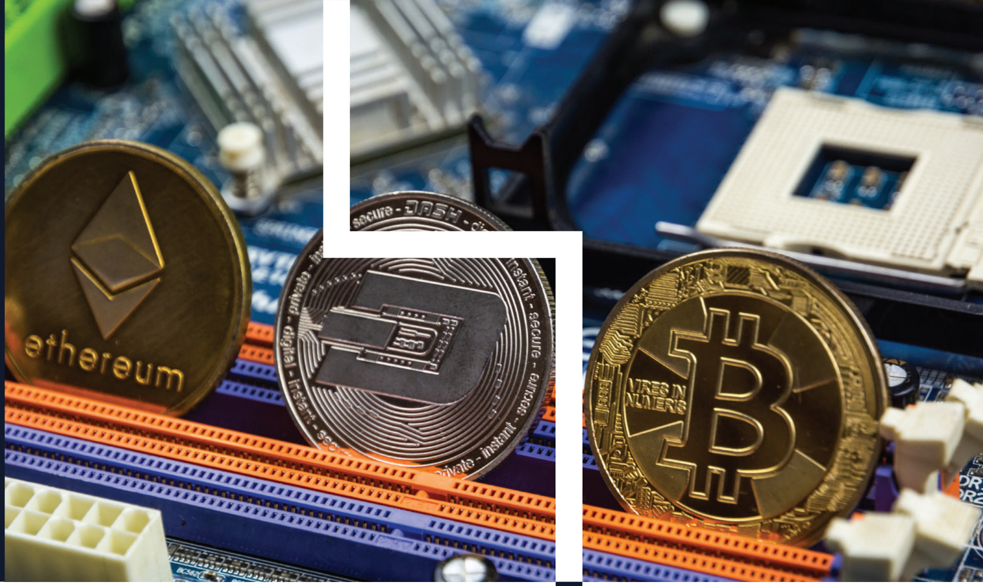
In this study, we address one of the most impactful criticisms of Bitcoin–its electricity consumption. We propose an approach to determine the individual carbon footprint inside the Bitcoin network from an investor perspective. Therefore, we first calculate the worldwide Bitcoin network carbon emissions over the period of one year from September 1, 2020, to August 31, 2021. Second, we outline a two-pronged flexible carbon compensation model, in line with Greenhouse Gas Protocol Scope 3 emissions, for investors, asset managers, crypto exchanges, and custodians. Our model allows the calculation focusing on either the number of Bitcoins held or on the proportional network usage in relation to the Bitcoin blockchain growth during a specific period of time. With our approach, interested parties can adjust their carbon offset strategy over time according to their corresponding business model. Furthermore, our approach allows all actors to anticipate and comply with regulatory requirements concerning ESG criteria at an early stage. In the future, our numbers will be updated continuously.



Executive Summary

Exemplary results refer to the analyzed period from September 1, 2020, to August 31, 2021. For an accurate calculation of the carbon footprint of an investor, the situation must be considered individually depending on the business approach of the company (i.e., simple investing, asset management, crypto exchanges, or custodians).

1. Bitcoin network electricity consumption: The maintenance of the worldwide Bitcoin network required 90.86 TWh and 37.97 $MtCO_2eq$ within the specified period. Electricity consumption should be viewed from a neutral perspective. What matters is the source of the electricity that is consumed. It is key to distinguish between renewable sources of electricity and fossil fuels. We do this by taking into account the total electricity mix of each country to convert Bitcoin's electricity consumption into its carbon footprint.

2. For comparison, the most recent estimate of the total yearly carbon footprint of the world is 45,873.85 $MtCO_2eq$. This leaves Bitcoin with a total footprint of 0.08% of worldwide CO_2eq.

3. For the calculation of the carbon footprint from an investor perspective, we propose a two-pronged model. Depending on the business model or data availability, companies can either focus on the proportional network usage in bytes in relation to the Bitcoin blockchain growth during a specific time frame (transaction-based network usage) or on the number of Bitcoins held for a specific period (ownership-based network usage).

4. An average Bitcoin transaction has a size of 670 bytes on the Bitcoin blockchain, representing an estimated carbon footprint of 369.49 $kgCO_2eq$. Given a price of USD 50 per metric tonne of CO_2eq, the compensation of one average Bitcoin transaction costs USD 18.47. We do not want this figure to be misinterpreted: One transaction can transfer single US dollars or hundreds of millions of US dollars. Also, companies such as crypto exchanges aggregate tens of thousands of users on a few Bitcoin wallets and only a small subset of transactions to the network may be conducted (e.g., daily net inflows or outflows). Evaluating the carbon footprint of Bitcoin transactions needs to be done in a very cautious way.

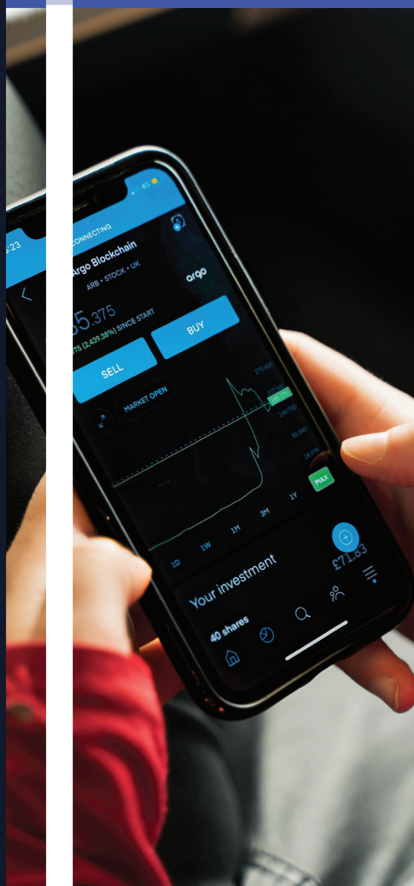
5. Holding 1 Bitcoin over the analyzed period of one year equals a carbon footprint of 2.04 tCO_2eq. Given a price of USD 50 per metric tonne of CO_2eq, the compensation of holding 1 Bitcoin over one year costs USD 102.20.

6. Companies could apply the above-mentioned approaches for transactions and owning Bitcoins to compute their carbon footprint they then should offset. As mentioned above, the specific business model needs to be considered for such computations. In the future, it can be expected that the results of such computations will need to be verified and audited by specialized service providers.

1. Motivation

Making Bitcoin a more sustainable investment.

Although it has only existed for less than 13 years, Bitcoin has had an eventful history. By now, it has become clear that the first crypto asset will play an important role in the future of finance. At the same time, however, climate change continues to become an ever-increasingly urgent issue. The CO_2eq emissions[1] associated with Bitcoin's consensus mechanism, namely proof-of-work (PoW), have been one of the most significant criticisms of Bitcoin in recent years (Independent, 2017). Reconciling Bitcoin's shortcomings and strengthening its role presents a significant opportunity to make Bitcoin a more sustainable investment. While Bitcoin itself could hypothetically be mined with 100% renewable, carbon-neutral energy, this is not the case today as miners are incentivized purely to optimize their profitability by keeping their cost as low as possible. In the area of crypto assets, incentives play an integral role. Externalities, such as sustainability, or lack thereof, outside of the core system are not taken into account with these incentives. Hence, the currently perceived sustainability problem of Bitcoin cannot be taken care of in a decentralized manner. In a recent study, the share of sustainable electricity (i.e., hydro, wind, solar, nuclear, geothermal, and carbon-based generation with net carbon credits) for Bitcoin mining is estimated at 56.0%. higher than, for example, the share of sustainable electricity in Germany (48.9%) (Bitcoin Mining Council, 2021). By comparison, 56% of electricity in Germany in 2020 was also generated from low-carbon energy sources (hydro, wind, solar, nuclear, biofuels).[2]



[1] To account for the emissions from different greenhouse gases, we use carbon dioxide equivalents (CO_2eq) as a metric measure by converting amounts of other gases to the equivalent amount of CO_2eq with the same global-warming potential.
For example, emissions of 1 million tonnes of methane are equivalent to emissions of 25 million tonnes of CO_2eq (Eurostat, 2017)

[2] See *https://lowcarbonpower.org/region/Germany.*

According to the polluter-pays principle, it would seem natural for CO_2eq to be offset by mining companies or mining pools as they purchase generated electricity for their operations (Greenhouse Gas Protocol Scope 2 emissions). However, this assumption would be infeasible to implement and also falls short in fact. First, of the total 21 million Bitcoin that will exist at maximum, around 89% are already in circulation. Therefore, emissions would have to be calculated, allocated, and compensated retrospectively. At present, however, the necessary data and tools are lacking for these calculations, and presumably the willingness of the affected parties to pay for the emissions. Second, mining operators enable users to carry out transactions. They thus provide the infrastructure for transaction settlement in the Bitcoin network. Remember, Bitcoin is a monetary network – but a decentral one. An example here is PayPal: PayPal potentially allows millions of citizens to hold and transact Bitcoin. However, it settles only a few transactions per day into the Bitcoin blockchain by netting out these transactions of many citizens off-chain. Since Bitcoin needs to be seen as a settlement network, rather than a payment network, this clearly shows that many people transact, but only a few transactions will be observed in the Bitcoin blockchain. In fact, assume that in the future primarily large transactions or a subset of the value that is transacted will be recorded on the Bitcoin blockchain, while smaller transactions are likely to be settled off-chain.

The above shows that the maintenance of the network by the miners is elementary for the continued existence of Bitcoin and the basis for Bitcoin's potential positive price development. Therefore, all parties that invest in Bitcoin, whether directly via crypto exchanges or indirectly through financial products such as Exchange Traded Notes (ETNs) or crypto funds, benefit from mining operations and, thus, ultimately from their power consumption.

Based on these explanations, an approach is required which determines the proportional accountability for Bitcoin's CO_2eq footprint based on the utility stakeholders enjoy. Since Bitcoin mining has the function of adding new transactions to the blockchain, a quantifiable method is needed to calculate the CO_2eq emissions of transactions. Therefore, the most accurate approach is determining the share of blockchain space used relative to the total Bitcoin blockchain growth **(transaction-based network usage).**

However, this approach would generally exclude many parties who do not have access to their transaction-related data. Furthermore, as shown above, a significant portion of Bitcoin's utility is derived from its long-term macroeconomic model; the store of value. For this situation, we suggest a calculation model which focuses on the portion of Bitcoins held relative to Bitcoins in circulation for a specific period **(ownership-based network usage).**

Whether an investor applies the approach related to transaction-based network usage or to ownership-based network usage cannot be defined at the outset. This should be the result of individual investors' considerations reflecting the business approach. A comparison can be made to aircrafts: An airplane needs to be built. Once sold, it is in operation for decades. Both processes have a carbon footprint: the building of the airplane and operating it. If people purchase an airplane ticket and travel from A to B, what needs to be compensated? The operations or the building of the aircraft, or both? And by whom? As said, assigning the carbon footprint is inevitably linked to the business model of the company. This is also true for companies in the Bitcoin space: miners, custodians, exchanges, funds - they all have different business models and therefore need to identify whether the approach related to transaction-based network usage or the ownership-based network usage fit in a better way.

In this vein, we see an opportunity for all investors, asset managers, crypto exchanges, and custodians to step in, and take responsibility for their associated carbon footprint in the Bitcoin network. Here, the objective should not be limited to demonstrating corporate social responsibility (CSR) but also in creating added value in making Bitcoin a more sustainable investment regarding its carbon footprint.

Compliance with SFDR regulation.

The European Union's Sustainable Finance Disclosure Regulation (SFDR), which has been in force since March 10, 2021, requires asset managers and financial market participants to disclose ESG-relevant information and categorize their products depending on certain sustainability criteria. In this context, the EU would like to increase transparency with regard to sustainability risks and adverse sustainability impacts in relation to financial products. Statements on the latter will become mandatory for financial market players as of July 2022 (so-called “level 2” disclosures). Consequently, the companies concerned must collect and disclose corresponding data on their products. Financial products that include Bitcoin or other cryptocurrencies, such as ETNs or funds, could potentially come under pressure from a sustainability perspective, as the high power consumption in this area has already been criticized many times. In this regard, this report intends to provide financial market participants with information on their carbon footprint in relation to financial products that include Bitcoin and take appropriate measures to avoid being potentially labeled as non-sustainable. In general, it is also important to consider that other industries and companies are also affected by the stricter regulations on sustainability. Technology companies that operate large data centers or infrastructures with high electricity consumption could also be affected. It should be noted that all financial products of EU market participants are subject to disclosure requirements under the SFDR. For proper evaluation and comparability, the carbon footprint of Bitcoin must therefore be put in the context of, for example, the carbon footprint of gold production (i.e., use of diesel, excavators, and chemicals). Such regulation as happened in the EU can of course also be expected for other countries.

By the way, if we talk about ESG, we should not just keep the electricity consumption in mind. Bitcoin delivers value. This value can also add to ESG objectives. This can be illustrated by the developments in El Salvador: El Salvador introduced Bitcoin as legal tender. Several weeks after the national payment app Chivo was launched, more than 50% of the population has downloaded the app. This way, more than 3 million people in El Salvador are now empowered to use both the US dollar and Bitcoin through this new payment app. Hence, hundreds of thousands of people now suddenly have access to payment services (e.g., storing value, transferring value nationally and internationally) – something they did not have previous to the launch of Chivo. As such, we will be able to observe in the upcoming months whether Bitcoin can promote “financial inclusion” – a very important topic within the discussion around ESG and sustainability. In other words, the positive impact of increasing financial inclusion for thousands of citizens in El Salvador can be expected but is not possible to assess at the time of publication of this study (Sandner, 2021a). Still, it can be assumed that, in the future, this positive impact needs to be viewed in relation to the CO_2eq consumption of Bitcoin as a monetary network.

Addressing investors' concerns about the carbon footprint of Bitcoin.

Bitcoin with a market capitalization of more than USD 1.2 trillion is arguably an important part of many investors' portfolios. It allows for greater diversification, not to mention historically significant annualized returns, and a protection mechanism against inflation in many countries. However, with more and more investors prioritizing ethical investments, Bitcoin may be “inaccessible” to them due to the significant CO_2eq footprint associated with it, putting these investors with admirable intentions at a distinct disadvantage. Considering the social good Bitcoin can do in promoting financial inclusion and equality, this is unfortunate and needs to be evaluated carefully. By offsetting the CO_2eq emissions of the Bitcoin network, and complying with the SFDR, Bitcoin may become “accessible” to environmentally conscious investors. One could argue that this, in turn, adds value to the underlying financial product and justifies charging a reasonable premium when purchasing Bitcoin.

Objective and structure of this paper.

The objective of this paper is to develop a calculation model, which allows every user of the Bitcoin network to compute its carbon footprint based on either their transactions or the amount of Bitcoins held for a specific period of time. Moreover, the model is intended to be applicable for companies that offer financial products on Bitcoin (i.e., ETNs or funds) and thus have to disclose ESG-related information in the future for regulatory reasons (SFDR) or other service providers that enable users to acquire, hold and transfer Bitcoin. Calculating the carbon footprint of a Bitcoin portfolio involves a certain degree of subjectivity and therefore needs to be based on certain assumptions. We aim at assessing the various factors involved in such calculations and present the most accurate figure possible. After providing a concise, yet in-depth, explanation of how the Bitcoin network and the business of mining works, we present our assumptions made, explain our methodology and describe how our model is designed.

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2. Bitcoin Mining

Securing the network – the economics of Bitcoin.

The Bitcoin network is secured by the PoW consensus mechanism. Transactions are broadcasted to the network, confirmed by miners, and added to the blockchain. Approximately every ten minutes, a miner “finds” a new block and is allowed to add it to the chain.[3] All miners compete to be the first one to find this new block by using computer hardware and the required electricity to compute SHA-256 hash computations. The difficulty of these hash computations is adjusted automatically in accordance with how much computing power is being necessary across the network with the goal of keeping the block time (i.e., the average time it takes to find a block) at ten minutes. At the time of publication, the Bitcoin network operated at 161.97 exa hash operations per second.[4] The difficulty is adjusted every 2016 blocks – roughly every two weeks. For each new block found, the successful miner receives a block reward, currently 6.25 Bitcoins. In addition, miners receive all transaction fees related to the transactions they process through a newly mined block. The block reward is reduced every 210,000 blocks – roughly every four years. The block reward reflects the new Bitcoins being brought into circulation. At the time of writing, 18.87 million Bitcoins have been generated. This way, mining serves two functions in the Bitcoin network: first, verifying transactions and recording them on the blockchain in a secure manner, and second, issuing new coins maintaining the monetary system. The latter function is often compared to the mining of gold. This is reasonable to argue since with gold mines, resources are being invested for finding new gold- not for “maintaining” gold or for “allowing” gold transactions (Sandner, 2021b).

However, at the time of writing this paper, mining new Bitcoins will probably stop around the year 2140, as the maximum number of 21 million Bitcoins will be reached (Kim, 2019). At this point, miners will receive their rewards only in the form of transaction fees. Nevertheless, this situation will not influence the energy consumption of the network per se. Therefore, miners will continue to provide the infrastructure for transaction settlement in the Bitcoin network in the future. Exactly because of this, the consideration of transactions in the Bitcoin network is also a reasonable parameter (**transaction-based network usage approach**). Conversely, it falls short to relate the carbon footprint of the bitcoin network solely in relation to the amount of newly mined bitcoin (**ownership-based network usage approach**).

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[3] The Bitcoin network aims to keep the average block time at ten minutes. In reality, this figure may differ slightly as the process of finding a block is probabilistic. In fact, according to our calculations, the blocktime was 10.12 minutes in the last months.

[4] See *https://www.blockchain.com/charts/hash-rate. Last accessed on November 11, 2021.*

Energy consumption of Bitcoin.

While Bitcoin has received a lot of negative press lately regarding the power consumption of its consensus mechanism, there are no "plans" for Bitcoin to switch to other consensus mechanisms (e.g., proof-of-stake) that could be considered more sustainable. In fact, given the governance of the Bitcoin network, it is basically impossible to change the consensus mechanism. This is a result of the checks and balances built into the governance of the Bitcoin network. As an implication, the PoW consensus mechanism can be expected to be in place for the years and decades to come. The PoW consensus mechanism employs economic incentives to organize and secure a distributed network. By requiring computational hardware, and the associated power to run it, there is a real cost to participating in the consensus mechanism. In short, PoW allows anyone to participate, rewards good actors, and punishes bad actors as they use power but do not receive rewards. To a certain extent, one could say Bitcoin is secured by the electricity it uses. This aspect is highly important: It is the PoW consensus mechanism that protects the Bitcoin network from cyber attacks and is therefore integral for Bitcoin's security architecture. The resulting extremely high level of security is the basis for the survival of Bitcoin. But, recall, electricity consumption should be viewed from a neutral perspective. What matters is the source of the electricity that is consumed. It is key to distinguish between renewable sources of electricity and fossil fuels.

That being said, Bitcoin mining today is mostly organized at an enterprise level. Miners today are profit-seeking data centers looking to maximize their revenue (i.e., hashrate) while keeping their fixed cost (i.e., hardware) and variable cost (i.e., electricity) as low as possible. An example in this respect can be seen by the 20-fold increase in the hashrate of mining equipment based on more energy-efficient chips (Wingen, 2018).

While there is no direct economic incentive to keep emissions low, Bitcoin is far from incompatible with carbon neutrality. As low-carbon power such as hydropower and geothermal energy are becoming the most cost-effective electricity sources, many mining operations are using these sources (U.S. Energy Information Administration, 2021). In turn, it can be expected that this will lead, over the long run, to an increase in the share of renewable energies consumed by Bitcoin. Accordingly, companies that use outdated hardware or pay too high electricity prices can be expected to be forced out of the market by more efficient companies (Sandner et al., 2020).

In Iceland, for example, where about 8% of all Bitcoins have been mined thus far, electricity is almost exclusively generated from geothermal sources (Walter, 2021). On the other hand, the single largest source of electricity globally is still coal, which accounts for the largest share of carbon emissions from electricity generation. As a result, it is often the most economical source of electricity. An interesting middle ground can be found when Bitcoin mining is used to support a transition to green power. Miners can, for example, use excess electricity from fossil fuel power plants that would otherwise be wasted as a backup for renewable power sources (Willms, 2019). In addition, hazardous coal waste can also be disposed of by converting it into electricity for Bitcoin mining, an activity that would not be profitable if that electricity were sold to the network (Helman, 2021).

3. Related Work

The issue of Bitcoin's energy consumption and resulting carbon footprint has been debated in the academic literature for several years. During this time, a number of different approaches have emerged, some of which build on each other. This section will briefly review some of the main approaches used in academia and in the industry and compare them with the approach described in this paper.

"The Carbon Footprint of Bitcoin" by Stoll et al. (2019).

Stoll et al. (2019) outline a method for calculating the carbon footprint of the entire Bitcoin network. They estimate the electricity consumption of Bitcoin based on mining equipment and multiply it with the average CO_2eq emission factor resulting from countries' shares of the total Bitcoin hashrate. However, Stoll et al. (2019) do not take into account carbon emission factors of renewable energy sources, but only consider the CO_2eq intensities of coal, oil, and gas. Consequently, they define a range of carbon emissions from the Bitcoin network between 0 and 51 MtCO_2eq,[5] assuming 100% clean surplus electricity and 100% coal-fired power generation as lower and upper bounds. Also, the data they employ was from 2019 and earlier. At that point in time, the last halving had not occurred yet, such that more Bitcoins per block were generated. Also, the Bitcoin price was significantly lower such that miners invested significantly less energy.

"Carbon Emissions Report of BTCetc" by Gallersdörfer et al. (2021).

This recent report from June 2021, prepared by the Crypto Carbon Ratings Institute (CCRI) for ETC Group, explains the methodology used to measure the carbon footprint of the Bitcoin holdings of BTCetc (Gallersdörfer et al., 2021). As with our methodology, Gallersdörfer et al. (2021) rely on the Cambridge Bitcoin Electricity Consumption Index (CBECI) for electricity consumption. Similar to the CBECI mining map we use, they estimate the regional distribution of mining centers based on IP addresses. The authors of the report follow the approach of Stoll et al. (2019) for converting electricity consumption into carbon emissions. Furthermore, they calculate the carbon footprint across the entire Bitcoin network and allocate the carbon emissions to the Bitcoin holdings of BTC etc.

Digiconomist.

Besides the CBECI, only de Vries (2021) offers another live index, the Bitcoin Energy Consumption Index (BECI), that tracks the power consumption of the Bitcoin network in real-time. De Vries looks at the calculation of Bitcoin power consumption from an economic point of view and argues that the miners' energy consumption is directly linked to the income from mining. The reasoning is that the higher the income, the more machines are turned on to mine Bitcoins. We support the rationale that miners turn on more machines with higher income. We argue that this also points towards an important logic: The total electricity consumption of the Bitcoin network depends on miners' expectations of the future Bitcoin price.

Netpositive.Money.

Netpositive.Money is an online calculator for estimating the carbon footprint of Bitcoin.[6] Similar to our methodology, it is also based on the CBECI. However, instead of considering the actual carbon footprint of each mining region, the calculator multiplies the CBECI data by a constant factor taken from Stoll et al. (2019). Most importantly, this calculator estimates the average CO_2eq impact for all existing coins and does not focus on current mining operations. However, the electricity consumption within a specific time frame should be related to the Bitcoins generated in that timeframe. We argue that using the *current* electricity consumption and distributing it to Bitcoins mined in *previous* periods in time can be criticized.

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[5] The "Mt" in MtCO_2eq represents one million metric tonnes.

[6] See *https://netpositive.money/calculator.*

4. Calculating Bitcoin Network Carbon Emissions

4.1 Assumptions

Our model is based on certain assumptions, which are discussed as follows. Calculating the CO_2eq emissions of stakeholders in the Bitcoin network is based on three key variables, which are discussed in more detail below, namely the power consumption of the Bitcoin network, the CO_2eq emissions factor, and the proportional network usage.

Electricity consumed

by Bitcoin miners: As outlined in the previous sections, energy is a key ingredient in the Bitcoin mining process. The total Bitcoin network is known to consume a large number of terawatt-hours (TWh) of electricity, putting it on par with entire nations. Estimates of how much energy the Bitcoin network consumes on a yearly basis currently range from 38 to 389 TWh.[7] In our model, the electricity consumption of the Bitcoin network is based on data from the Cambridge Bitcoin Electricity Consumption Index (CBECI).[8] The CBECI provides an estimate of the daily energy consumption of the Bitcoin network. Since it is not possible to precisely calculate the energy consumption based on the network hashrate alone, the CBECI provides a range of values, assuming the most efficient and inefficient equipment used for mining, and a best-guess estimate (see Figure 1). The main reason that the energy consumed cannot be calculated accurately is that miners largely operate pseudonymously and are not subject to any reporting guidelines. Some miners might operate highly efficient equipment, while others run outdated hardware. Our model assumes a theoretical lower and upper bound as well as the best-guess estimate. With upcoming initiatives such as the Bitcoin Mining Council, we can expect a higher degree of transparency regarding the electricity consumption of selected mining facilities in the future, opening up a myriad of interesting research opportunities.

Figure 1: Electricity Consumption of Bitcoin

Carbon footprint

of energy sources: The high power draw of the Bitcoin network is frequently discussed in the media. However, high electricity usage in itself does not necessarily equal high carbon emissions; and by extension negative impact on the environment. Imagine the Bitcoin network were to be fully powered using energy from carbon-neutral sources as opposed to the Bitcoin network being fully powered by electricity from non-renewable sources like coal and gas. Bitcoin's environmental impact very much depends on the energy sources in place. While some miners may be operating completely on renewables, others may operate solely on carbon-intensive sources. There is no exact way to measure this, since most miners do not disclose their energy sources. Some exclusively use electricity from renewable sources. However, this is not necessarily representative of all mining organizations. Our model does not attempt to estimate the share of carbon-neutral energy sources used by miners worldwide, rather it assumes that the electricity consumed by the Bitcoin network is of similar composition as the overall energy mix of their host countries. This is reasonable to assume given the lack of further detailed data from objective sources on the specific energy sources employed in each mining facility. In our model, information on the country's average CO_2eq intensity, based on the country's overall electrical energy mix, is retrieved from www.lowcarbonpower.org. This website compiles a vast amount of energy-related data from sources such as the International Energy Agency (IEA) and the World Bank. In order to determine the average CO_2eq emission per kWh in a given country, the CO_2eq footprint of all renewable and non-renewable energy sources used in a country is combined. The output is CO_2eq intensity per country, measured in gCO_2eq/kWh.[9] The carbon footprint per country is linked to the participation of the respective country in the mining process to obtain a weighted average CO_2eq emission factor based

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[7] These estimates are annualized for October 17, 2021. *See https://cbeci.org/.*

[8] See *https://cbeci.org/.*

[9] The "g" in gCO2eq/kWh represents gram.

on the country's share of the global Bitcoin hashrate. This data is sourced from the CBECI mining map[10] and incorporated into our model.[11] The last values available were from August 2021. This accommodates the short-term impact of the Chinese ban on industrial mining that happened in June. However, the fallout of the Chinese ban and its long-term impact on the electricity sources employed need to be reassessed in future research.

Furthermore, we use a compilation of current data on the average carbon intensity per country resulting from the country's electrical energy mix of renewables and non-renewables.[12] Thus, unlike other studies (e.g., Stoll et al., 2019), we also account for CO_2eq emission factors related to renewable energy sources used for mining. We assume that miners in each country use a similar mix of electrical energy to that used on average in the respective country. By weighting the carbon intensities of each country by their share of the global Bitcoin hashrate, we obtain a global average estimate of 417.88 gCO_2eq/kWh emission factor for Bitcoin mining.

4.2 The Carbon Footprint of the Bitcoin Network

Based on our method explained above, the total amount of electricity consumed for Bitcoin mining from September 1, 2020, to August 31, 2021, was 90.86 TWh. Multiplying this value with the emission factor of the Bitcoin network (417.88 gCO_2eq/kWh) allows us to estimate Bitcoin's total emissions in this period to be **37.97 $MtCO_2eq$.** For comparison, the most recent estimate of the total carbon footprint of the world is 45,873.85 $MtCO_2eq$.[13] This leaves Bitcoin with a total footprint of 0.08% of total CO_2eq. This of course needs to be compared to the resource consumption of gold mines, silver mines, etc. which also consume resources such as electricity, chemicals, and industrial goods. This also needs to be compared to other areas which have a more significant carbon footprint: energy, agriculture, forestry and land use, etc (see Section 5.3).

[10] See *https://cbeci.org/mining_map/methodology.*

[11] An alternative approach would have been to estimate the share of renewables in the Bitcoin network directly. However, prior estimates varied so widely (ranges from 29% up to 73%; see Bendiksen & Gibbons, 2019; Blandin et al., 2020) that the authors decided against this approach. The reason for this wide range is that the exact energy mix is not accurately recorded and therefore needs to be estimated.

[12] See *www.lowcarbonpower.org.*

[13] See *https://data.worldbank.org/indicator/EN.ATM.GHGT.KT.CE?end=2018&start=2009.*

5. Calculating the Carbon Emissions of Bitcoin From an Investor Perspective

When analyzing how carbon-related emissions from the Bitcoin network can be offset, the proportional responsibility of participating actors must first be discussed. However, assigning proportional responsibility to the various stakeholders in the Bitcoin ecosystem is a more subjective task as there is no binary right or wrong approach. According to the polluter pays principle, it would seem natural for CO_2eq to be offset by mining companies or mining pools as they purchase generated electricity for their operations. For the future, this approach would theoretically lead to the most effective way of encountering the issue, for example, by taxing fossil fuel use or subsidizing carbon-neutral electricity. Due to Bitcoin's decentralized nature, such an approach would require enormous levels of international cooperation.

Even at present, the attribution of carbon emissions to miners would be infeasible and in fact, would fall short. First, of the total 21 million Bitcoin that will exist at most, around 89% are already in circulation. Therefore, emissions would have to be calculated, allocated, and compensated retroactively. At present, however, the necessary data and tools are lacking for these calculations (see Section 5.4 Limitations), and presumably the willingness of the affected parties to pay for the emissions. Second, mining operators enable users to carry out transactions. They thus provide the infrastructure for transaction settlement in the Bitcoin network. Their efforts to maintain the network are elementary for the continued existence of Bitcoin and the basis for Bitcoin's potential positive price development. Therefore, all parties that invest in Bitcoin–whether directly via crypto exchanges or indirectly through financial products such as ETNs or funds–benefit from mining operations and, thus, ultimately from their power consumption.

Based on the above explanations, a more realistic approach involves determining proportional accountability for Bitcoin's CO_2eq footprint based on the utility stakeholders enjoy. While calculating the proportionate responsibility for the emissions produced by Bitcoin's miners is a subjective undertaking, we see an opportunity for all investors and asset managers and crypto exchanges and custodians to step in and take responsibility for their associated carbon footprint in the Bitcoin network. However, to achieve this goal, a calculation model is needed that allows all interested parties to attribute responsibility.

Transactions vs. ownership.

Since Bitcoin mining has the function of adding new transactions to the blockchain, a quantifiable method is needed to calculate the CO_2eq emissions of transactions. The most accurate approach is determining the share of blockchain space used relative to the total Bitcoin blockchain growth (transaction-based network usage).

However, this approach would not be feasible for all investors, as there are various ways to invest in Bitcoin. This category could include, for example, investors who invest indirectly in Bitcoin (i.e., ETNs and funds) and thus do not have any transaction-relevant data. These investors, however, might have a large exposure to Bitcoin and the intention to compensate for it and thus need a suitable approach. Furthermore, a significant portion of Bitcoin's utility is derived from its long-term macroeconomic model, the store of value aspect. For this situation, we suggest a calculation model which focuses on the portion of Bitcoins held relative to Bitcoins in circulation for a specific period (ownership-based network usage). Figure 2 illustrates our two-pronged flexible approach to calculate the carbon emissions of a Bitcoin portfolio.

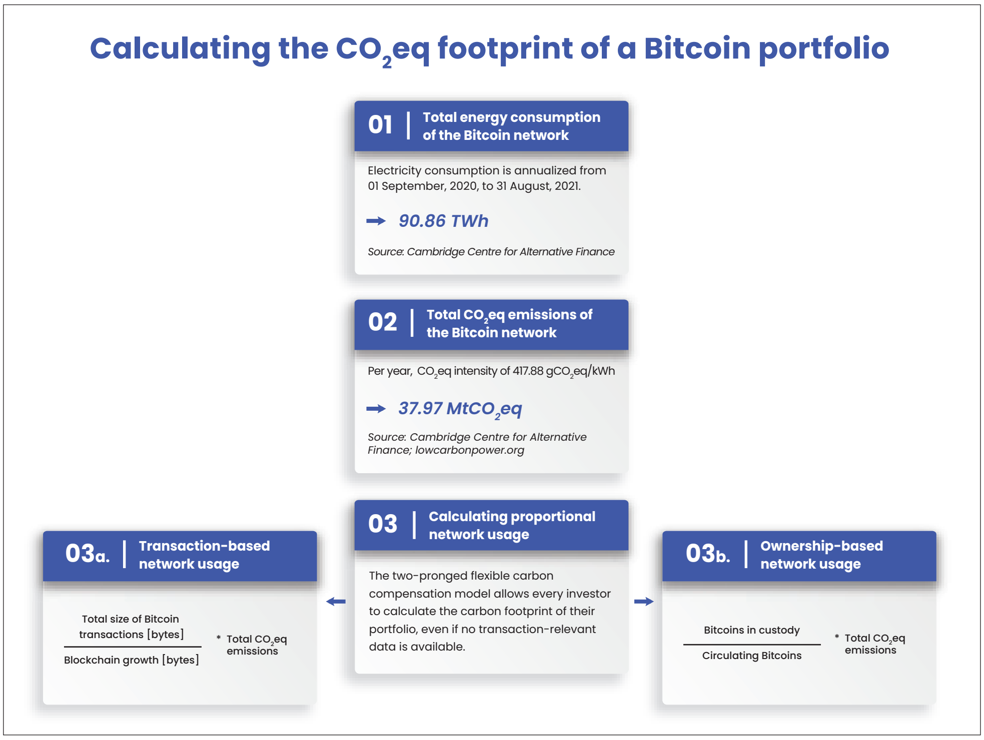

Figure 2: Two-Pronged Flexible Carbon Footprint Calculation Model

5.1 Transaction-Based Network Usage

In order to calculate the relative share of usage of the Bitcoin network by the relevant stakeholder in a certain period, block-size used is contrasted with the total growth the blockchain underwent in the relevant timeframe. For example, to calculate the proportionate usage of the Bitcoin network for any address during a given month, we begin by collecting all transactions sent during that month, adding up their size in bytes, and dividing by the overall change in blockchain size during that month. As a result, we get their proportional usage of the Bitcoin network. When applied to the total CO_2eq footprint of the Bitcoin network (see Section 4.2), we receive the proportional CO_2eq output attributable. The complete formula used is shown in Figure 3 and further described below.

Transaction-based carbon footprint formula

Variables:

CO_2eq= Carbon dioxide equivalent [t]
X_t = Proportional network usage at a specific point in time t
Tx_{size} = Transaction size [bytes]
BS = Blockchain size [bytes]
EC = Electricity consumption [kWh]
EF_{CO2} = CO_2eq Emission factor [t/kWh]

Usage-based carbon footprint

$$CO_2eq(x_t) = x_t * \overline{EC} * EF_{co_2eq}$$

Proportional network usage

$$x_t = \frac{\sum_{i=1}^{t} Tx_{size}}{BS_t - BS_i}$$

Electricty consumption (standardized)

$$\overline{EC} = \frac{1}{t} \sum_{i=1}^{t} EC_i$$

Figure 3: Transaction-Based Carbon Footprint Calculation Model

To calculate the transaction-based portion of network usage during a specific period, we use the following formula (1):

(1)

$$x_t = \frac{\sum_{i=1}^{t} Tx_{size}}{BS_t - BS_i}$$

For example, the proportional network usage of an average transaction, which has a size of 670 bytes, based on the period from September 2020 to August 2021 (blockchain growth of 64.12 GB,[14] 102,754,276 transactions),[15] is 0.000000973195%.[16]

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[14] See *https://www.statista.com/statistics/647523/worldwide-bitcoin-blockchain-size/*. Note that 1 GB represents 1073741824 bytes.

[15] See *https://www.statista.com/statistics/730806/daily-number-of-bitcoin-transactions/#:~:text=The%20number%20of%20Bitcoins%20processed,400%2C000%20in%20early%20January%202021.*

[16] See the appendix for different factors influencing the size of a transaction.

Electricity consumption during this same period is calculated with the following formula (2):

(2)

$$\overline{EC} = \frac{1}{t}\sum_{i=1}^{t} EC_i$$

EC is the electricity consumption in kWh. From September 2020 until August 2021, for example, the total amount of electricity used is estimated at 90.86 TWh. The theoretical lower bound is 36.09 TWh and the theoretical upper bound is 253.05 TWh.

Finally, we substitute these values in the following formula (3) to calculate the total proportional carbon footprint:

(3)

$$CO_2eq(x_t) = x_t * \overline{EC} * EFco_2eq$$

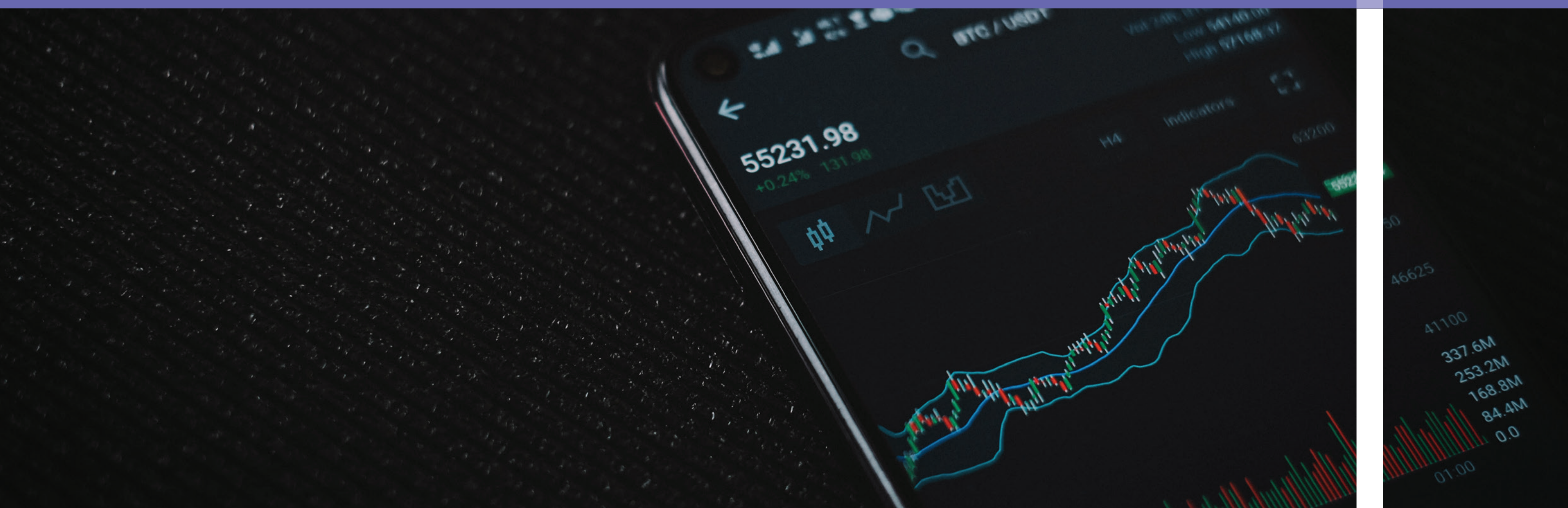
The $EFCO_2eq$ variable is the emission factor, which was calculated to be 417.88 gCO_2eq/kWh in Section 4.1. Hence, for our example, the total CO_2eq footprint is in the range of 146.77 $kgCO_2eq$ to 1029.11 $kgCO_2eq$. Our best guess estimate is **369.49 $kgCO_2eq$.**

5.2 Ownership-Based Network Usage

Whereas in the transaction-based approach we calculate proportionate carbon footprint as a function of relative network usage, in the ownership-based model it is based on the relative portion of Bitcoins owned during a certain period. Formula (3) used at the end of Section 5.1 holds true, but the variable xt is replaced with the number of Bitcoins held in relation to how many Bitcoins there are in circulation. For example, to calculate the CO_2eq footprint of a wallet that held 1 Bitcoin from September 1, 2020, to August 31, 2021, we divide 1 by 18.58 million[17] and multiply that by the total amount of electricity used during this period, which we calculated to be 90.86 TWh in 5.1. The resulting figure is then multiplied by $EFCO_2eq$, which is 417.88 gCO_2eq/kWh. The carbon footprint for holding one Bitcoin in the period under investigation thus corresponds to an estimated 2.04 tCO_2eq.[18] Using our theoretical lower and upper bounds to repeat this calculation gives us a possible range from 0.81 to 5.69 tCO_2eq.

[17] See *https://www.blockchain.com/charts/total-bitcoins*. We are working on an update to account for changes in the share of Bitcoin holdings on a daily basis.

[18] The "t" in tCO_2eq represents tonnes.



Placing Our Results in Context

As mentioned above in Section 4.2, Bitcoin's carbon footprint needs to be compared to the CO_2eq emissions of other industries, such as gold mines and other areas which have a more significant carbon footprint: energy, agriculture, forestry, and land use, etc. (see Section 5.3). Figure 4 and 5 show the carbon emissions of different industries.

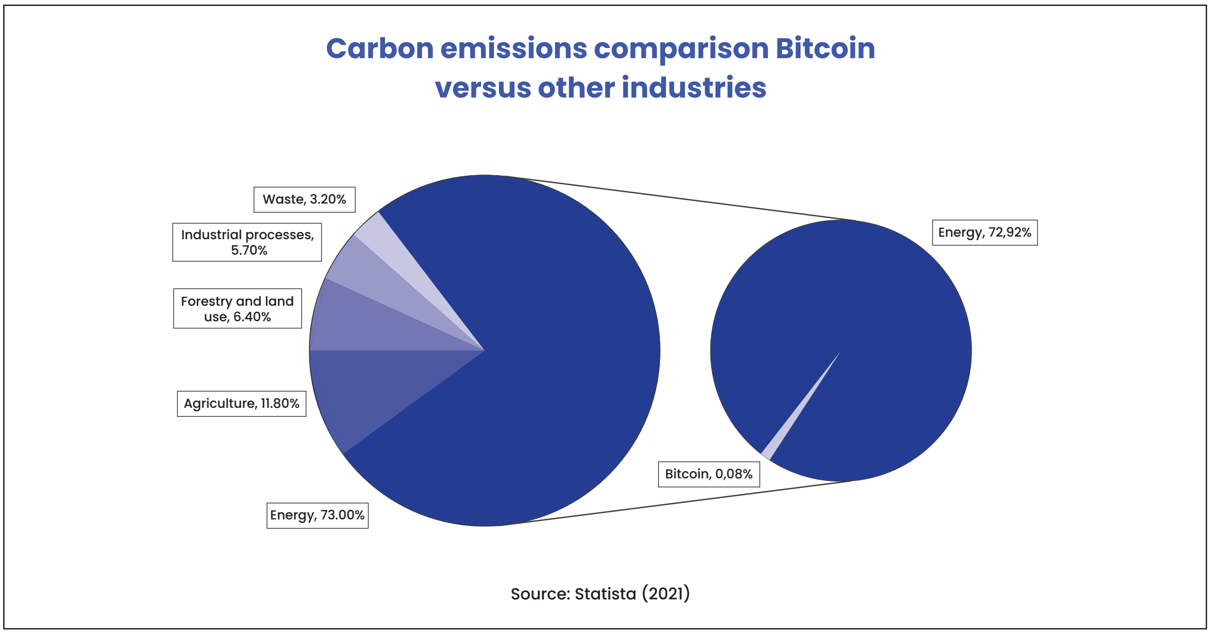


Figure 4: Bitcoin's Carbon Footprint in a Cross-Industry Global Context

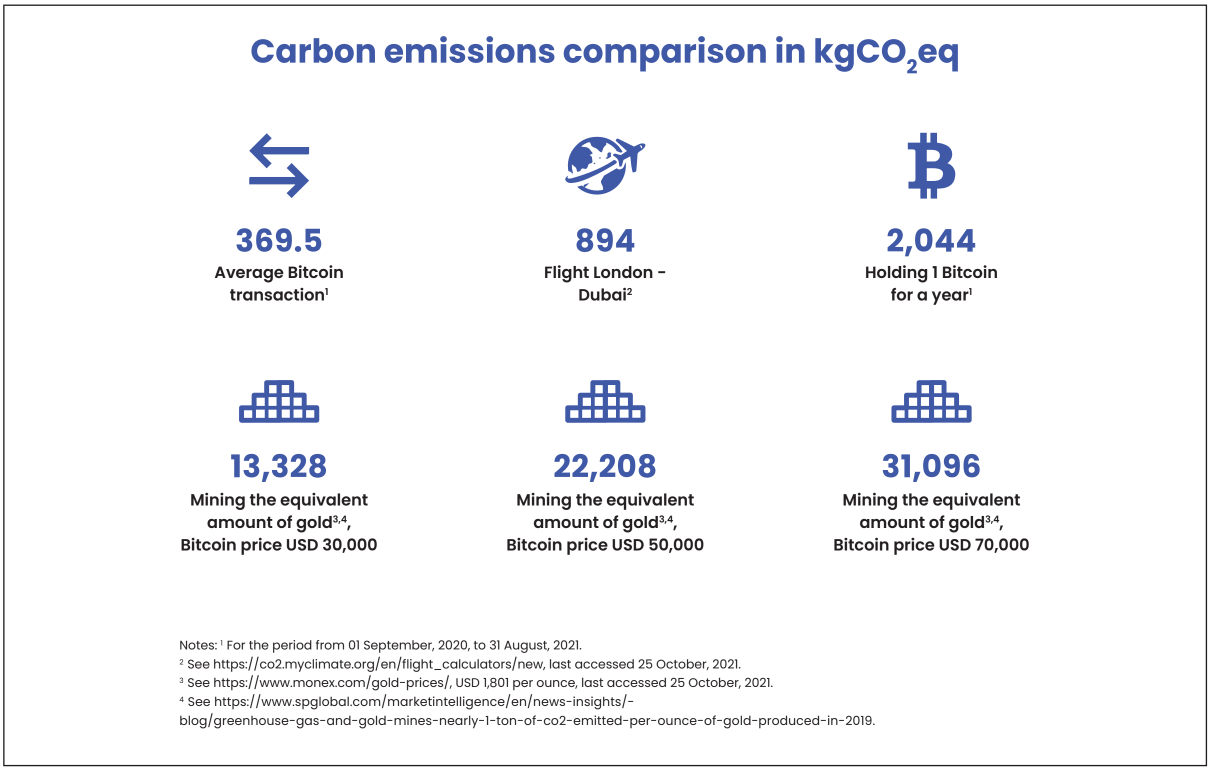
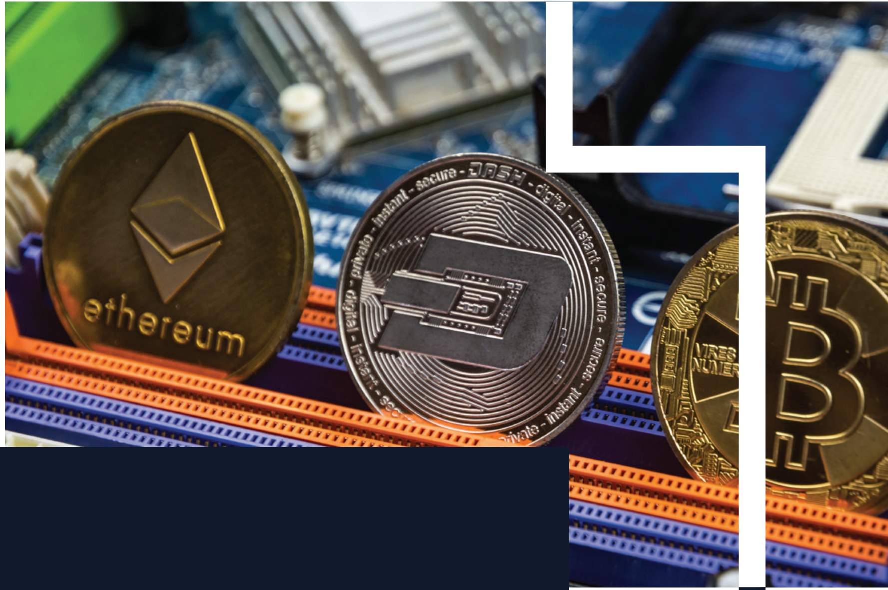


Figure 5: Comparing Carbon Emissions of Bitcoin, Gold Mining and Flights



6. Discussion

6.1 Choosing the Calculation Method

As the exemplary results for the transaction-based and ownership-based approach show, different outcomes will arise for a Bitcoin portfolio depending on the chosen methodology. The intended purpose of the calculation models presented here is not to minimize the carbon emissions of a portfolio. Instead, the overarching goal of presenting two different methods is enabling every investor to calculate the carbon footprint of their portfolio, even if no transaction - relevant data is available.

From an investor's perspective, it is a question of how the responsibility for CO_2eq emissions is understood within the Bitcoin network. Each company should undertake an evaluation of its own investment strategy in order to determine the most appropriate calculation method. This ensures that the approach chosen best reflects the company's strategy, e.g., position trading or buy and hold. As said, this depends on the business approach of the company (i.e., simple investing, asset management, crypto exchanges, or custodians).

For example, an investor could initiate one average transaction, which corresponds in our best guess estimate to 369.49 kgCO_2eq, and hold 100 Bitcoin for one year equally to 204.36 tonnes CO_2eq in our model. In this case, the investor could decide on the ownership-based approach, as this method might reflect their strategy more accurately than the transaction-based approach. If we turn the example and assume an investor performs 100 average transactions (39.65 tonnes CO_2eq) while holding one Bitcoin for one year (2.04 tonnes CO_2eq), the choice could fall on the transaction-based model.

6.2 Limitations

This section will explain the limitations associated with the various assumptions made in this paper. First, the specific limitations and uncertainties underlying the electricity usage and CO_2eq intensity used are discussed, followed by practical complexities and potential fundamental limitations.[19]

The estimated electricity consumption of the Bitcoin network used in this paper is a best-guess estimate based on the current hashrate and available mining equipment. Miners may use, on average, far less or far more efficient hardware. Specifically, the range from theoretical lower bound to the theoretical upper bound of electricity consumption is quite large. Currently, the theoretical lower-bound estimate is 38.5 TWh annualized while the theoretical upper-bound estimate is 276.9 TWh. For comparison, the best-guess estimate currently sits at 103.2 TWh annualized. This is a rather large range, and unless miners begin reporting what hardware they are using, it cannot be narrowed further. Under these circumstances, this paper assumes the best-guess estimate to be accurate.

Similar to the lack of specific information on mining hardware, the same holds true on energy sources used by miners. While there are some reports from mining farms that they exclusively used carbon-neutral energy sources, there is not enough information to say this is accurate for the majority of miners. Hence, this paper uses the overall national energy mix for electricity instead, proportional to a country's mining hashrate contributions. This again introduces some uncertainties. Firstly, it assumes that the location of most miners can accurately be determined based on their IP address. Of course, this would not be the case if the majority of miners are, for example, using VPNs. Secondly, this overall energy mix changes over time as miners change location as the Chinese mining ban showcased earlier this year, and hence needs to be recalculated periodically to maintain relevance.

As mentioned previously, assigning responsibility for carbon emissions of the Bitcoin network to the various stakeholders is a subjective undertaking. While the data is there, the question of who actually is responsible can be approached in many different ways. One possible issue is that the methods mentioned in this paper all account for 100% of Bitcoins emissions. Hence, they cannot be combined without the possibility of overestimation of stakeholder responsibility.

Finally, it needs to be considered that Bitcoin mining is used in many cases as a way to use up excess power that would otherwise be wasted. In such cases, it can get very questionable to what extent stakeholders in the Bitcoin network should be held responsible for associated emissions as responsibility may lay outside the Bitcoin network.

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[19] From a mathematical perspective, comparing the CO_2eq impact of one transaction per year with holding 100 Bitcoins over a year shows that the ownership-based approach results in a higher CO_2eq offset than the transaction-based approach. This result is to be expected for the following reasons: The size of one transaction is comparatively small compared to the network growth in one month (bytes compared to gigabytes). In contrast, the relative share of holding 100 Bitcoins out of the approximately 18 million Bitcoins currently in circulation is high compared to the transaction-based approach.

7. Conclusion and Outlook

Trends.

Over time, the variables used in our calculations will change. Some will slowly change, such as where miners locate their operations. Others will fluctuate more rapidly, such as the total network hashrate, which depends to some degree on the current price of Bitcoin or miners' expectation of the future Bitcoin price. However, since we use an annual average for electricity consumption, this should be easy to account for. Other trends in the macro-environment will be more interesting. For example, the most significant long-term change that can be observed right now is the shift of hashrate from China, which banned "industrial mining" only a few months ago, to other countries (Shen & Galbraith, 2021). Based on the latest available figures from the CBECI mining map as of August 2021, the United States now dominates global mining operations with 42.7%, followed by Kazakhstan with 21.9% and Russia with 13.6%. Overall, there appears to be a trend for miners moving to countries with a higher proportion of renewable energy sources in their energy mix (Helman, 2021).

Carbon offsetting for Bitcoin as service offering.

From an economic point of view, platform operators such as crypto exchanges or crypto custodians would have the power and the possibility to allocate the compensation of carbon emissions proportionally to their users. A look at other industries shows such methods in practice. Lufthansa, for example, enables its customers to offset the carbon footprint of their flights. In line with this analogy, crypto exchanges, for example, allow customers to offset the carbon footprint of their transactions by supporting sustainable projects before submitting a transaction to the blockchain.

Price scenario for sustainably mined Bitcoins.

The pressure within the investment industry with regard to sustainable investments will continue to intensify in the wake of the SFDR. It is conceivable that large crypto asset portfolios in the future will also take into account at what point in time a Bitcoin was created as the associated power consumption varies significantly over time. Furthermore, scenarios are also possible in which funds, for example, acquire Bitcoins from miners that rely entirely on renewable energy in order to avoid a mandatory carbon emissions offset at a later date. In this scenario, companies would potentially buy Bitcoins for amounts above the current market price. On the other hand, mining pools that rely on a non-renewable energy mix could be penalized by receiving less than the current market value for a Bitcoin they create. Based on our results for the specified period from September 2020 to August 2021, this scenario seems likely in the context of the SFDR for financial products within the EU as the following results show

1. For the transaction-based network usage, given a price of USD 50[20] per metric tonne of CO_2eq, the compensation of one average Bitcoin transaction costs **USD 18.47.**

2. Accordingly, for the ownership-based network usage, the compensation of holding 1 Bitcoin over one year costs **USD 102.20.**

Future research. Considering the above trends, we recommend that the variables used in this paper be updated quarterly or twice a year for best results. As mentioned previously, our method of calculating CO_2eq emissions of the Bitcoin network involves assumptions, as miners do not provide accurate data on a fine-grained level. Collaborating directly with mining farm operators to gather precise numbers on what hardware and energy sources they use is a promising opportunity to develop the model further. Also, our model needs to be updated frequently due to the dynamics in the population of Bitcoin mining companies and due to the dynamics of the network (e.g., halving events). Eventually, a live tracker that automatically applies daily or weekly updated variables to our models would be a promising endeavor. Most important, as the metrics of the Bitcoin network and the characteristics of the population of miners change over time, the CO_2eq emissions of the Bitcoin network change accordingly. Therefore, to compensate for the carbon footprint of a Bitcoin portfolio, it would ultimately be required to analyze the age of every single Bitcoin and its related carbon footprint.

[20] See *https://www.statista.com/statistics/1241719/carbon-trading-prices-worldwide-by-select-country/.*

Appendix: Factors Influencing the Transaction Size

Each transaction broadcast to the Bitcoin network differs in terms of data volume written on the blockchain. While the size of each block in Bitcoin's blockchain has been limited to a theoretical size limit of 4MB, practically the average block-size is currently between 1-1.3 MB. The essential factors for the size of a Bitcoin transaction are the transaction type and the number of inputs and outputs underlying Bitcoin's unspent transaction output (UTXO) model. Figure 6 will serve as a simplified illustration.

A Bitcoin transaction contains several data fields. The more data these fields contain, the larger the transaction will be in terms of bytes written to the Bitcoin blockchain. The transaction type and the number of inputs and outputs are essential for this, but also, for example, the number of signatures (private keys) required for a transaction.
Some professional or institutional investors use multi-signature transactions to reduce the risk of a compromised wallet significantly.

Nevertheless, all transactions are written and recorded in bytes on the Bitcoin blockchain. For the calculation of the transaction-based network usage, we examine how much the blockchain has grown in total and the relative size attributable to a party's transactions during a specified period.

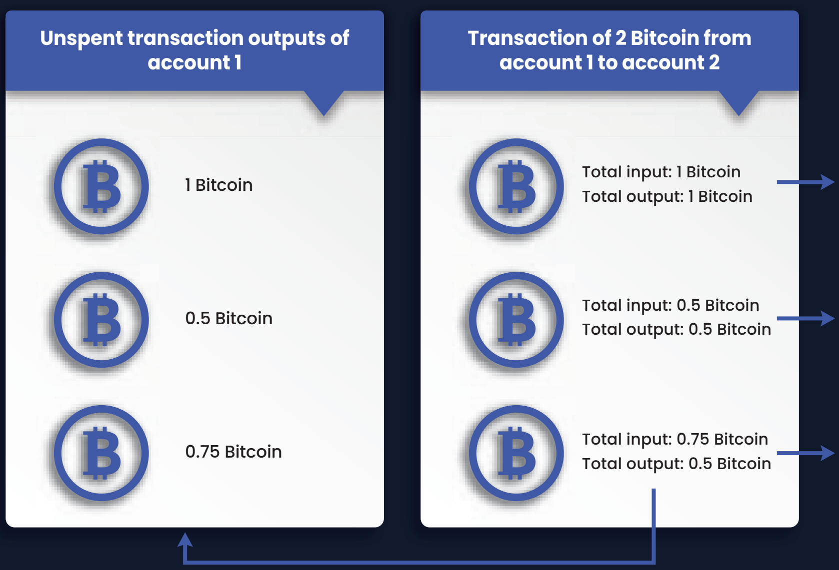
Transaction size.

Transactions on the Bitcoin blockchain typically range between 200 and 2,000 bytes. The size of individual transactions is influenced by a variety of factors, such as the number of inputs and outputs as well as the type of transaction.

Inputs and outputs.

Inputs and outputs are the numbers of UTXOs involved in the transaction. UTXO stands for unspent transaction output. Consider you want to buy an item for $5 in the physical world, but you only have a $10 bill. Instead of cutting the bill in half, you pay $10 and receive $5 in change.

Example of Bitcoin's UTXO model



Unspent output of 0.25 Bitcoin

Figure 6: Breakdown of a Bitcoin Transaction in UTXOs

With Bitcoin, it works much the same way. Consider you have a 1 Bitcoin UTXO and send 0.5 to Bob. In this process, your 1 Bitcoin UTXO is fully consumed and replaced with two 0.5 Bitcoin UTXOs, one of which you keep while the other is transferred to Bob. The UTXO going into a transaction is the input, while the UTXOs resulting from the transaction are the outputs. The number of inputs and outputs has a significant impact on the size of the transaction in bytes. For example, the transaction size of sending 1 Bitcoin made up of one UTXO will be much smaller than sending 1 Bitcoin that is made up of 10 0.1 Bitcoin UTXOs (see Figure 6).

The other major factor influencing transaction size is the type of transaction.

Pay-to-Public-Key-Hash (P2PKH).

Currently the most common script type. The Bitcoin inputs are locked to the hash of a public key. A P2PKH transaction is convenient because the hashed public key reduces the number of characters of the public key. Furthermore, it improves privacy, as the underlying public key is not revealed until the obtained input is spent.

Pay-to-Public-Key (P2PK).

Similar to P2PKH, with the main difference being that the public key is not concealed through a hashing function. Sending funds using this method will publicly display the sender's public key in the transaction details.

Pay-to-Script-Hash (P2SH).

P2PH is a flexible script type that allows multi-signature transactions and transactions after the soft-fork upgrade SegWit to Bitcoin. When using a P2SH script, the sender only uses the hash of the script created by the receiver. In order to unlock the received Bitcoin, the script corresponding to the hash is required again. P2PH is used for multi-signature transactions in which two or more parties have to sign a transaction with their private key to be valid. Some professional or institutional investors use multi-signature as it significantly reduces the risk of a compromised wallet.
For reference, an average basic (P2PKH) Bitcoin transaction with 1 input and 2 outputs is 226 bytes. On the other hand, a P2SH transaction with 4 inputs and 2 outputs will be above 1200 bytes in size.[21] The number of inputs and outputs depends on the UTXO's included in a transaction. Comparatively, the Bitcoin blockchain processed an estimated 4,380 blocks in 2020 and grew by an average of 5.2 GB per month during that time period. Allowing us to calculate an average block size of 1.2 MB for that time period.

Stakeholders can minimize their block-size footprint in several ways: minimizing the size of individual transactions with regards to the factors mentioned above, combining several transactions into one (batching), consolidating UTXOs when fees are low, as well using basic transactions.

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[21] See *https://bitcoinops.org/en/tools/calc-size/*.

About the Frankfurt School Blockchain Center

The Frankfurt School Blockchain Center is a think tank and research center which investigates implications of the blockchain technology, crypto assets and distributed ledger technology (DLT) for companies and their business models. Besides the development of prototypes, it serves as a platform for managers, startups, technology and industry experts to share knowledge and best practices. The Blockchain Center also provides new research impulses and develops trainings for students and executives. It focuses on banking, finance, mobility and, "Industrie 4.0".

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