DNB UNRESTRICTED

Analysis

The carbon footprint of bitcoin

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EUROSYSTEEM

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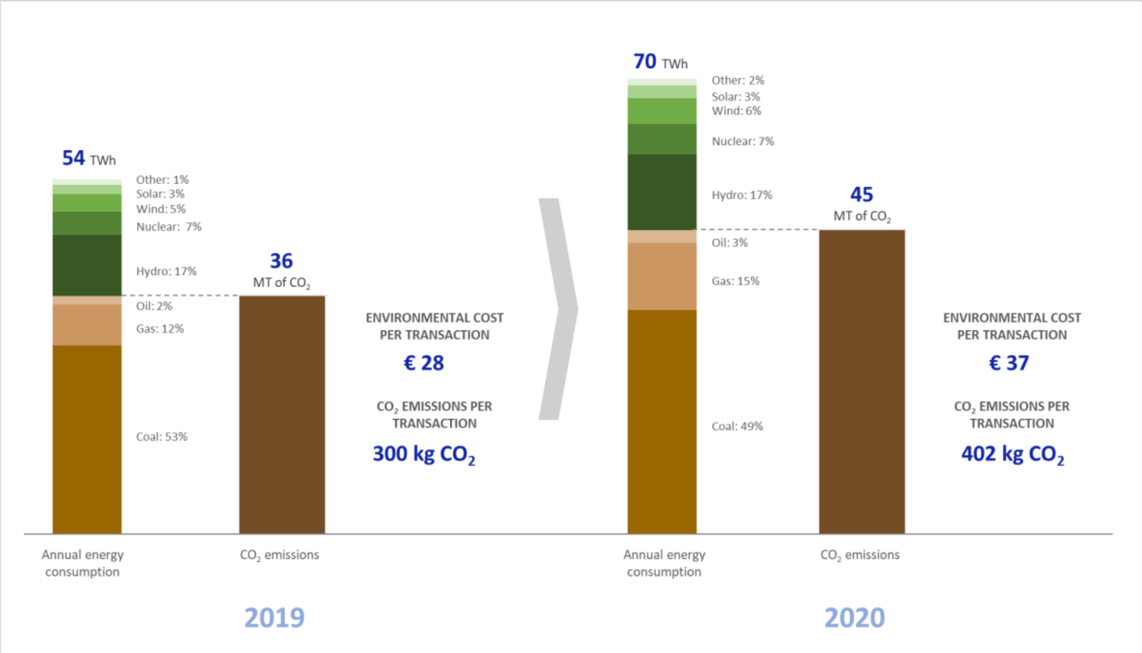
1 The carbon footprint of bitcoin

The total carbon footprint of the bitcoin network has increased by 25% in 2020, while the number of transactions decreased by 6%. The resulting climate impact in 2020 is estimated to be 402 kg of CO_2 per bitcoin transaction. This outcome is based on a new method developed by DNB to measure bitcoin's carbon footprint. The new method has five building blocks, each based on open access data sources. DNB encourages any interested party to adopt the method, suggest improvements and update results when more recent and/or better data becomes available.

1.1 The carbon footprint per bitcoin transaction is increasing

The bitcoin network requires an enormous amount of energy, and thereby contributes to CO_2 emissions. As part of DNB's continuous effort to provide more insight into the climate impact of the financial sector, this study presents the first results of a new methodology to measure bitcoin's carbon footprint. We find that in 2020 the climate impact of a single bitcoin transaction can be estimated to equal about 402 kg of CO_2 emissions. This is comparable to two-thirds of the monthly emissions of an average Dutch household (611 kg CO_2 per month). Figure 1 shows that this is an increase of 34% compared to bitcoin's carbon footprint per transaction in 2019. This increase in climate impact per transaction can be attributed to a sharp increase in the total energy consumption of the bitcoin network. Total CO_2 emissions increased by 25% (from 36 to 45 megatons) in 2020, while the number of transactions decreased by 6% (from 119 to 112 million). With the electricity mix between renewable energy sources and fossil fuels remaining fairly constant, the increase in CO_2 emissions can be almost entirely attributed to the growth in the computing power (i.e. hashrate capacity) of the bitcoin network (which grew 30% in the same period, from 54 to 70 TWh). This growth can be attributed to the higher bitcoin price in 2020 over 2019. Rises in price drive profitability upwards, incentivizing the operation of more energy-hungry mining equipment.

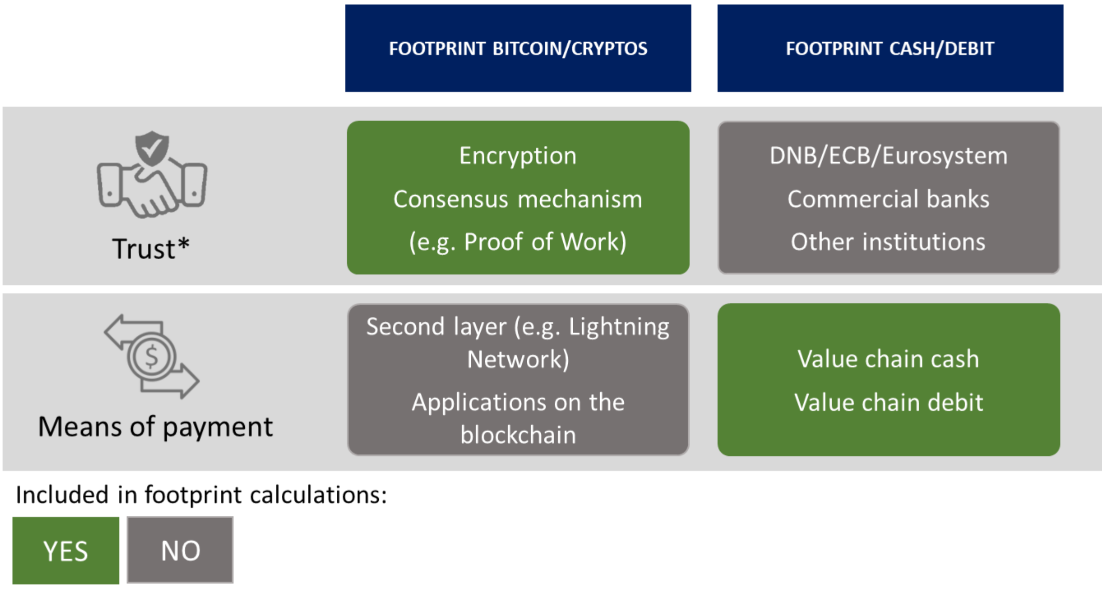
Figure 1. Carbon footprint of bitcoin per transaction 2019-2020, broken down by energy source



1.2 Comparing the footprints of cryptos and conventional payment methods

The Proof-of-Work (PoW) consensus mechanism that add new blocks to the bitcoin blockchain requires enormous amounts of energy. The annual electricity consumption of the bitcoin network (70 TWh in 2020) is now often compared with the annual electricity consumption of a country such as the Netherlands (111 TWh in 2020 based on CBS figures). While this puts total energy consumption into perspective, it does not directly provide insight into the relative energy efficiency of a bitcoin transaction. That is why our new method also provides a carbon footprint per transaction. It is however difficult to make a comparison with other cryptos and conventional payment methods. Previous DNB research on cash and debit card payments provides insight into the climate impact per transaction, but is restricted to the value chain of the payment methods. In other words, all other activities of the central banks of the Eurosystem, the ECB, commercial banks in the euro area and the surrounding institutions, which together result in trust in the monetary system, are not included. For bitcoin, the carbon footprint of the cryptographic calculations and the consensus mechanism, which ensures (a different level of) trust, are included in the calculation of the footprint. Figure 2 shows these differences schematically. The figure is not all-encompassing. For instance, if we look more broadly at cryptos, e-waste, the IT infrastructure of exchanges, bitcoin ATMs, and for instance insurers that cover hot wallet hacks should also be part of the footprint for trust. And for cash/debit, consistent and transparent assumptions are needed to determine the scope of the 'other institutions' to be included and exactly which parts of the value chains of cash and debit transactions need to be included for a fair comparison. Finally, the figure does not imply that the same level of trust is ensured when it is based on liability/accountability or when trust is based on the current consensus/encryption mechanisms. Details on what trust based on liability/accountability (i.e. there being an entity that is liable and/or provides supervision) entails and the extent to which this is (not) comparable to different digital assets can for instance be found in the ECB's digital euro report (see Annex 2 of the report).

Figure 2. Schematic representation of current mismatch in footprint calculations



* Different levels of trust are ensured when trust is based on liability/accountability (i.e. there being an entity that is liable and/or provides supervision) vs. trust based on consensus/encryption.

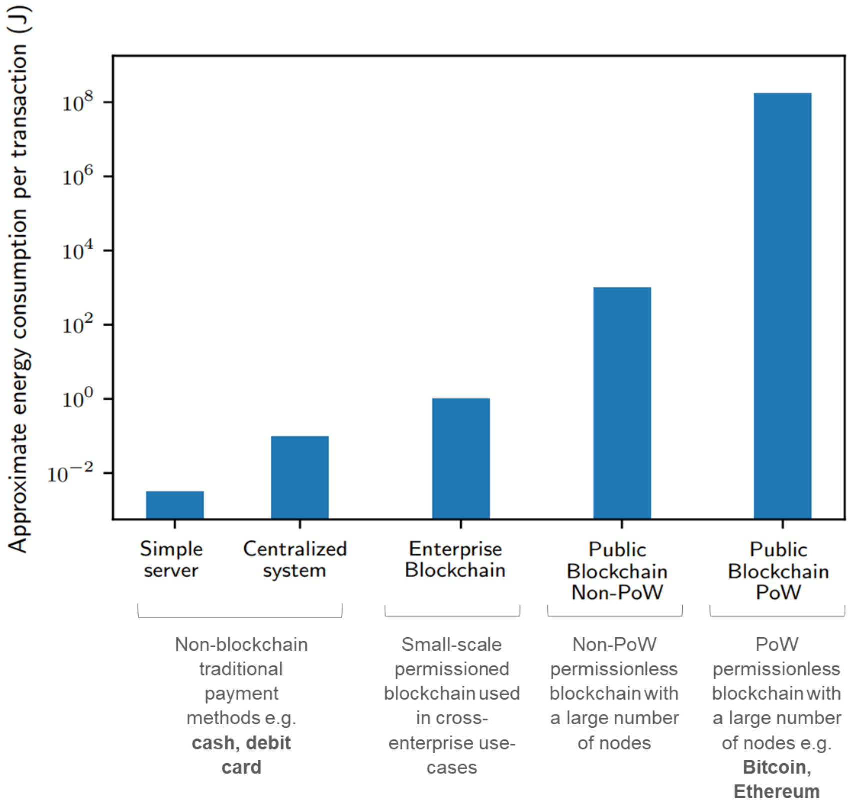
1.3 Cryptos are constantly evolving

The bitcoin network creates trust, but the transactions are relatively slow, the volumes very low and the transaction costs relatively high. A relatively new solution for the low transaction speed and high transaction costs of bitcoin is for example the so-called Lightning Network, a kind of second layer on top of the bitcoin network. Lightning essentially adds a separate type of digital wallet that facilitates fast and cheap transactions, making this second tier more suitable as a means of payment than the underlying bitcoin network (although opening/closing a channel still occurs on the main chain, thus limiting the potential of scaling). The crypto market is constantly evolving. Consensus mechanisms other than the Proof-of-Work (PoW) algorithm that the bitcoin network runs on are emerging and may offer a less energy-intensive alternative.

1.4 The energy consumption of other (crypto) technologies

Not all cryptocurrencies are built on an energy-intensive mining algorithm, as is the case for bitcoin's PoW. There can be significant differences in energy demand, driven primarily by two elements in a cryptocurrency's architecture: the consensus mechanism in use (e.g. algorithms that deliver agreement on which blocks are appended to the blockchain, such as Proof-of-Work, Proof-of-Stake and Proof-of-Authority) and the type of redundant operations (i.e. the algorithms associated with operating transactions). Figure 3 shows that the public blockchain PoW architecture of (among others) bitcoin has the largest energy consumption per transaction when compared to other technologies that are currently available. In any case, energy consumption clearly depends on the design choices that are made, and environmental considerations should clearly not be neglected during the conception of any blockchain-based solution.

Figure 3. Comparison of energy consumption per transaction for different cryptocurrency and non-blockchain architectures



The Energy Consumption of Blockchain Technology: Beyond Myth (Sedlmeir J., Ulrich Buhl H., Fridgen G., Keller R., 2020)

1.5 The actual energy mix of bitcoin and the impact of seasonality

Our new methodology is based on the assumption that miners consume the exact same energy mix as the country in which they mine. In practice, miners will look for the cheapest energy source in order to maximize profits. The effects on the actual electricity mix can only be known through analysis of granular data of mining sites and their energy contracts, and the composition of primary sources supplying the electric power at each location. This represents a limitation to this model as such data is not yet publicly available. The Cambridge bitcoin Electricity Consumption Index Visualization Map was selected for this method as it is the only source based on real geolocational data, voluntarily supplied by mining pools that account for approximately 35% of the total bitcoin network (in terms of hashrate capacity). This data is reported at the country-level in monthly intervals, and a regional breakdown is available for Chinese provinces.

Observation of the available data, together with public knowledge on the location of major mining hubs, points to one source of low-cost electricity that has attracted large concentrations of miners: hydro-electric power during periods of overproduction. Following natural patterns of seasonality, wet months at hydro-power stations provide excess water that produce an abundance of electricity. When local demand lies below this supply, surplus energy is dispatched at lower prices. This opportunity is then seized by bitcoin miners, which in turn balance the excess electricity from the grid and avoid disruption in supply. The most significant of these cases was Sichuan Province in China where, before the crypto ban was decreed by local authorities, half of the mining power came to be concentrated during the rainy summer months, at a time when China accounted for almost 70% of global hashrate capacity. Similar sites remain in operation albeit at a far smaller scale. The fact that surplus electricity resulting from fluctuations in seasonal and intraday variations is common to other renewable sources (like wind and solar), has sparked arguments that bitcoin could become a driver for renewable energy projects, helping manage oversupplies and supporting more investments. No large scale projects with such characteristics have been identified so far, while initiatives in exploratory phases have recently appeared.

The data currently available does not support the argument that bitcoin's energy mix has a higher share of renewable sources than national country averages. In fact, the data points to factors that may balance out the use of surplus renewable energy with increased usage of fossil fuel sources. First, fossil fuel based electricity is still very competitive compared to cheap renewables. After the crackdown against cryptos in China, miners redistributed globally in search of competitive prices, with the US and Kazakhstan as their two major destinations (Figure 4). These two countries are together currently responsible for roughly 50% of the global hashrate capacity. Kazakhstan's energy mix is made up of over 90% fossil fuel sources, with over 70% sourced from coal. In the US, large mining farms appeared in hydro-powered states like Washington and New York, while others installed their capacity in Texas. While the latter shows an increasing share of electricity sourced from wind, approximately 75% of its mix is still derived from natural gas and coal.

Second, is the behavioral responses to fluctuations in renewable sources. Three scenarios are available for miners when the availability of renewable sources is reduced due to variations in supply: i) maintain mining operations on site and absorb price impacts as long as they allow for a profitable operation, ii) relocate to another site with competitive energy prices, and iii) shut down mining equipment (or a fraction of it). Data on regional mining behavior across Chinese provinces in 2020 points to the second option. Strong mining concentration in the province of Sichuan during the rainy six months of the year and an abundance of hydro power was followed by a large migration of miners to the cost-competitive and coal-sourced provinces of Xinjiang and Inner Mongolia (as shown in Figure 5).

Finally, regulatory pressure on the supply of electricity for mining is increasingly playing a role. Countries are imposing limitations on the electricity supply for power-intensive crypto mining to instead secure the supply of renewable energy to households and industry, and to avoid disruptions of the electricity grid. Cases in which the energy supply is regulated already exist, like the 668 MW energy cap for crypto mining established in the province of Quebec (Canada). Other countries, such as Kazakhstan and Iran, are currently evaluating similar restrictions. Countries with high shares of renewable power increasingly see inefficient cryptos (i.e. based on the PoW algorithm) as a potential threat to achieving national CO_2 reduction targets. The Chinese ban on crypto mining serves as an example of regulatory limitations on the grounds of environmental protection. Recently, Sweden has made a call for a national ban on PoW crypto mining and similar actions to be taken in Europe. Norway is currently considering formally backing the Swedish proposal.

Figure 4. Change in absolute hashrate between May and August 2021

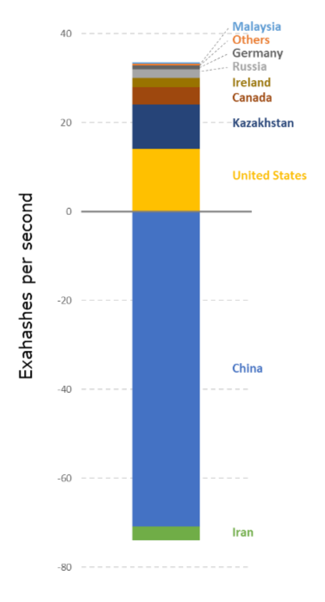
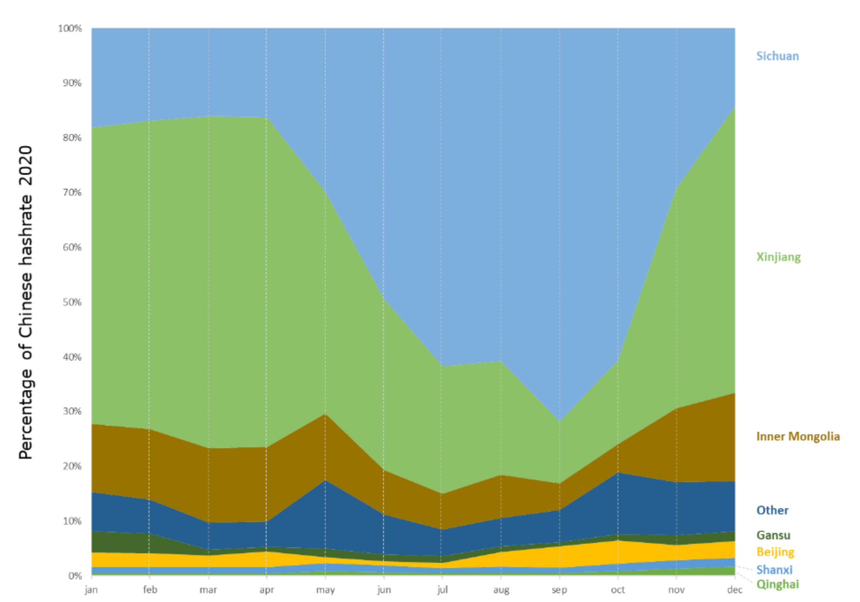


Figure 5. Seasonal adjustments in China in 2020



Source: Cambridge bitcoin Electricity Consumption Index visualization map

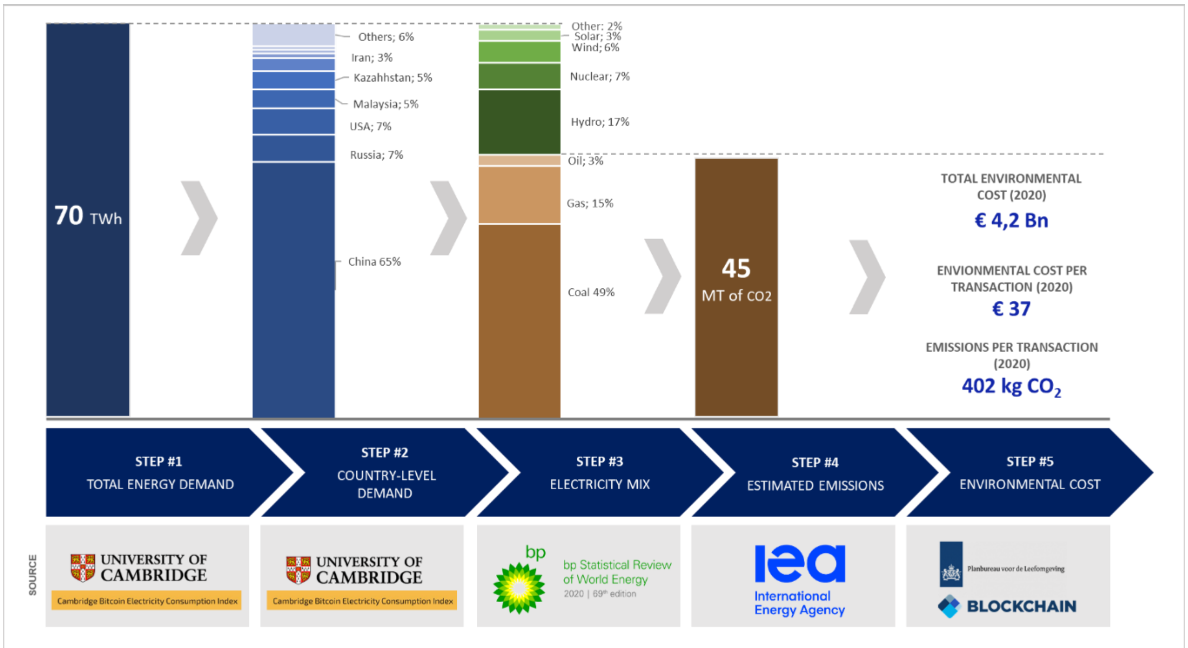
1.6 More research and data is needed for consistent footprint calculations

For cryptos as well as for conventional payment methods, the wide variety of possible design choices can result in major differences in the total footprint per transaction. It is therefore important to make the methods behind these calculations more consistent and transparent. This will provide better insight into the climate impact and will contribute to a sustainable and future-proof payment system. In order to be able to better compare the total environmental impact in the future, more research is needed for both cryptos and conventional payment methods. In particular, the gray areas in Figure 2 will require more data in the future. To this end, it is important that central banks and commercial banks, among others, report consistently on the footprint of their business operations. DNB is one of the first central banks to publish the carbon footprint of its own operations annually.

1.7 From global energy consumption to carbon footprint per transaction

The methodology that is used to calculate the carbon footprint per transaction consists of 5 building blocks: 1. bitcoin's total annual electricity demand; 2. Country-level electricity consumption; 3. The electricity mix per primary source or fuel; 4. Conversion of electricity produced from fossil fuels into (metric) tonne of CO_2 emitted; and 5. Conversion to the environmental cost and carbon footprint (as a total and per transaction). Figure 6 summarizes the methodology and the open access data sources that are used to calculate each building block.

Figure 6. The five open source building blocks to determine the carbon footprint of bitcoin per transaction



Step 1 provides an estimation of the annual demand of electric power required by the bitcoin network. In recent years, various methodologies have been published producing estimates of this figure. For this study, the Cambridge bitcoin Electricity Consumption Index (CBECI) was selected which, through a bottom-up methodology, produces live information on bitcoin's electricity consumption. Table 1.1 describes the methodology and assumptions considered in this estimation.

Table 1.1 Total energy demand

Method	Assumptions	Source
▪ Calculation of the average annual value of electrical power consumption from the bitcoin network (TWh/year) reported in the CBECI	▪ Calculations based upon CBECI "Best guess" scenario of "Annualized consumption" ▪ "Best guess" scenario assumes mix of mining hardware reflecting market share of equipment manufacturers and default hardware efficiencies (Joules/Gigahash) ▪ "Annualized consumption" is an estimation of total electricity used over the period of one year, reported as a 7-day moving average	UNIVERSITY OF CAMBRIDGE Cambridge Bitcoin Electricity Consumption Index

Digiconomist was identified as an alternative source of data providing similar live estimations reported as the bitcoin Energy Consumption Index (BECI). Differences in results between CBECI and BECI are driven by their methodologies. The Digiconomist index relies on developments in miner income along with an assumption on the speed of mining device production. The Cambridge index on the other hand, relies on the hashrate capacity and assumptions on the mix of mining devices used as well as their performance (optimal performance under default settings).

Step 2 breaks down the annual electricity consumption to the country-level according to countries' hashrate share. This information is taken from the CBECI, which produces a country-level map from data voluntarily provided by bitcoin mining pools, providing geolocational data based on IP addresses of the mining facility operators. Mining pools providing the data account for 32%-37% of the network's total hashrate capacity (i.e. the relative weight of mining pools may bias results towards regions where they are located). These inputs are assumed here to be representative of the entire mining population. Table 1.2 describes this step in more detail.

Table 1.2 Country-level demand

Method	Assumptions	Source
▪ Calculation of yearly average of hash rate share per country reported ▪ Breakdown of average annual electricity consumption into country-level (TWh–Country/year)	▪ Sample data is assumed to be representative of the entire mining network	UNIVERSITY OF CAMBRIDGE Cambridge Bitcoin Electricity Consumption Index

Step 3 converts the electricity consumption per country into the electricity produced per primary source or fuel. This breakdown is done in accordance with countries' electricity mix which describes the combination of the various fuels and sources that make up the national electricity supply. As mentioned above, using national totals represents a limitation to the model given that mining operations have shown seasonal concentrations within specific territories and provinces, in which the local electricity mix differs from the national average. Such is the case for the coal-concentrated provinces of Xinjiang and Inner Mongolia, and the hydropower-concentrated province of Sichuan in China.

This step is conducted through data provided by the private party data source British Petroleum. This source was selected instead of other potential public sources as it provided the highest level of data granularity, which is necessary for this analysis. Primary sources and fuels are classified into "Green", including low-emitting sources (solar, wind, hydro, nuclear and other renewables), and "Brown" (carbon, natural gas and oil). Table 1.3 describes this step in more detail.

Table 1.3 Electricity mix

Method	Assumptions	Source
▪ Breakdown of total electricity consumption per country into primary sources or fuels used for electricity generation (TWh-Country-Fuel/year) ▪ Annual electricity mix reported at country-level by BP Statistical Review of World Energy	▪ Electricity consumed by the mining network per country is assumed to resemble the country's national electricity mix	bp bp Statistical Review of World Energy 2020 | 69th edition

Step 4 converts the electricity consumed from *brown* sources into estimated CO_2 emissions, using the country's average CO_2 emissions coefficient from International Energy Agency (IEA). Emissions produced from combustion of biomass or biofuels are not accounted for in this step, given that global data on this specific energy source is still limited and currently represents a very small percentage of the total electricity mix (contained in "Other Renewables"). Table 1.4 describes this in more detail.

Table 1.4 Estimated emissions

Method	Assumptions	Source
▪ Conversion of electricity consumption per fuel into country's annual CO_2 emissions through the country's electricity emissions coefficient (Mt CO_2/TWh) ▪ Country's electricity emissions coefficient calculated per primary source or fuel with data provided by International Energy Agency at regional level: Electricity production per fuel type, and Total CO_2	▪ bitcoin's network electricity emissions are comparable to the country's average emissions ▪ Biomass emissions are not included due to data limitations	iea International Energy Agency

emissions from electricity production per fuel		

Finally, step 5 converts the estimated CO_2 emissions into an environmental cost using a Social Cost of Carbon (SCC) price. For the purpose of this study, we use the SCC reported by the Netherlands Environmental Assessment Agency (PBL) which equals €93/tonne CO_2. Results are reported in total global cost and on a unitary basis (per transaction). The latter is calculated by dividing total global cost by the total number of bitcoin transactions reported by Blockchain.com. Table 1.5 provides more details on this last step of the methodology. The code to run this methodology is available upon request.

Table 1.5 Environmental cost

Method	Assumptions	Source
▪ Conversion of total CO_2 emissions to total environmental cost, using average Social Cost of Carbon (SCC) ▪ The carbon footprint and environmental cost per transaction are calculated by dividing the total CO_2 emissions with the total bitcoin transactions reported by Blockchain.com	▪ SSC reported by Planbureau voor de Leefomgeving at €93/tonne CO_2 published by Drissen and Vollebergh (2018)	Planbureau voor de Leefomgeving BLOCKCHAIN

For more information on cryptos see:
Everything you should know about cryptos (dnb.nl)

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