Developing a Novel Approach to Calculating the Crypto Asset Carbon Footprint

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Abstract: The calculation of carbon emissions for crypto assets has been explored in various academic and practitioner approaches. However, the analysis of these approaches in this paper reveals that the assumptions and data which are being used are very heterogeneous and thus the results differ enormously. This paper uses an integrated approach that combines a transaction-oriented view, which calculates carbon emissions on single crypto asset transactions and a network-oriented view, which focuses on carbon emissions from a macro level perspective, by introducing a life cycle model which includes crypto asset transactions, holding of crypto assets and other relevant processes. Surprisingly, the results of the analysis show that the network-oriented view shows lower carbon emissions than the transaction-oriented view. Potential reasons for this can be the combination of different data sources from different approaches with different assumptions, fuzzy data, or other reasons. Because of this result, the paper suggests a more comprehensive approach in the form of a meta model based on a life cycle model which includes all relevant aspects.

1. Introduction

Crypto assets are relatively novel instruments in financial markets. They are characterized by the fact that there is usually not a claim on either an issuer or a custodian. However, the users of a crypto asset attach value to it due to different reasons, such as limited supply, low transaction costs, ease of storage or decentralized decision mechanisms on a blockchain to determine who is entitled to sell any of the units in circulation.

One major issue of crypto assets is their high carbon footprint, because of their (digital) consensus mechanisms that replace centralized decision making of institutions, such as financial intermediaries. The consensus mechanisms which underly the transfer of a crypto asset from peer-to-peer or institution-to-institution systems differ for each blockchain. While proof-of-work (PoW) networks like Bitcoin and Ethereum are very energy intensive, proof-of-stake (PoS) networks such as Cardano or Solana are based on lower energy consumption and thus lower carbon footprints. For a particular blockchain, the key idea is that miners and node operators will run the equipment as long as it remains economically profitable including the overall energy consumption.

However, until today, there is no single commonly agreed framework to calculate the exact carbon footprint of crypto assets and crypto asset transactions. The reasons for this are manifold and include the different forms of consensus mechanisms and their required energy consumption, the energy consumers included (e.g., only miners or also other energy consumers), etc. This paper addresses this issue by (1) analyzing the existing relevant literature (section 2), (2) deriving various relevant carbon footprint calculations from each of these approaches and combine them in an integrated approach which considers transaction-oriented and network-oriented approaches (section 3) and (3) proposing a novel, more comprehensive approach which addresses the gaps of the existing literature and data sources (section 4).

2. Literature Analysis

To analyze the existing theory in more detail, a literature analysis was undertaken, comprising five steps (Wolfswinkel et al., 2013): (1) definition of the scope of the analysis, (2) literature search, (3) selection of the final sample, (4) corpus analysis and (5) presentation of the findings.

In the first step, the relevant search terms were delineated and comprised "carbon AND crypto" and "crypto AND environmental impact." In the second step the online databases Web of Science, Scopus and Google Scholar were chosen for the literature analysis. With these three databases, a broad universe of literature can be covered and thus, the existing knowledge be identified. Each publication was downloaded and read through. In the third step, the selection of the final sample was performed.

The final sample comprised a total of 20'818 papers, from which 30 papers were identified as relevant for further analysis after reading through the papers' abstracts and keywords and after deleting doubles (see Table 1). In the next step, all 30 papers were analyzed in more detail. In an additional step, a backward and forward search was taken out. In the fourth step, each paper was classified according to descriptive elements like the title of the paper, author(s), publication outlet (journal or conference name), type of publication outlet (journal or conference), abstract, keyword, theories, methods (empirical), methods (non-empirical) and definitions. In the fifth step, the findings of the analysis are presented.

Sources	Search words	Papers
Web of Science	Carbon & crypto	54 (1)
Web of Science	Crypto & environmental impact	18 (1)
Scopus	Carbon & crypto	34 (2)
Scopus	Crypto & environmental impact	12 (1)
Google scholar	Carbon & crypto OR crypto & environmental impact	20'700 (25)
Total (relevant)		**20'818 (30)**

Table 1: Results of the Literature Analysis

All these 30 papers are presented in more detail in Table 2 which summarizes the results of the literature analysis of the papers that are related to the carbon footprint of crypto assets. The analysis reveals the following differences between the approaches.

First, one category of approaches measures the annual carbon footprint, whereas a second category measure the carbon footprint per transaction. Both categories have their legitimacy but also their gaps. For example, with the annual calculation method it remains challenging to estimate single transaction calculations, while the single transaction calculation does not show the overall impact.

Second, another category of approaches quantifies the carbon footprint based on a representative participant node and then extrapolates it from this measurement. Alternative approaches develop a mathematical model that includes core metrics of a DLT system to calculate its energy consumption. Both approaches lack a comprehensive understanding of the total carbon footprint calculation.

Third, the different approaches include different energy consumption elements (in most cases only a limited number of elements), such as the miners, the users, the user devices, the cooling infrastructure etc. For example, in many cases only a representative participant node and its typical infrastructure are used for the calculation, while a more comprehensive calculation method is not applied.

Fourth, the carbon footprint calculation should include the energy mix and the country of origin that is used for the calculation. Most approaches only focus on average energy mixes and do not include more specific data about where (from which country and region) the energy comes from.

Fifth, the carbon footprint differs in a broad range. For example, the range reaches from 369.49 kg per Bitcoin transaction to 4,256 kg per Bitcoin transaction when comparing the different approaches.

Table 2 summarizes the findings of the papers.

Paper	Authors	Crypto assets	Method
Proof-of-work based blockchain technology and anthropocene: an undermined situation?	Christophe Schinckus (Schinckus, 2021)	Bitcoin, Etherum	• Use PoW, electricity and carbon data are from https://digiconomist.net/Bitcoin-energy-consumption. • Effects of mining on atmospheric CO2.
Quantification of energy and carbon costs for mining cryptocurrencies	Max J. Krause, Thabet Tolaymat (Krause and Tolaymat, 2018)	Bitcoin, Ethereum, Litecoin, Monero	• To quantify the power requirement per crypto network, the daily hashrate was multiplied by the energy consumption of a typical mining computer. • To calculate emissions: multiply mass of CO2 emitted per kilowatt hour of energy generated for a country or region on daily energy required to produce a coin.
Bitcoin emissions alone could push	Camilo Mora, Randi L. Rollins, Katie Taladay,	Bitcoin	• a random hardware multiplied the number of hashes required to solve the block by the energy efficiency of the random hardware; this returned

Paper	Authors	Crypto assets	Method
global warming above 2°C	Michael B. Kantar, Mason K. Chock, Mio Shimada Erik C. Franklin (Mora et al., 2018)		the amount of electricity consumed to solve the given block. • For each block mined in 2017, we also collected data on the company claiming the given block, and searched for their country/countries of operation. • For the resulting list of countries, data was collected on the types of fuels used for electricity generation and using average standards of CO2 emissions for the generation of electricity with those types of fuels
The carbon footprint of Bitcoin	Christian Stoll Lena Klaaßen Ulrich Gallersdörfer (Stoll et al., 2019)	Bitcoin	• Calculates Bitcoin's carbon footprint based on its total power consumption and geographic footprint. • To determine the amount of carbon emitted in each country, the power consumption of Bitcoin mining is multiplied by average and marginal emission factors of power generation. • The best guess is based on average emission factors, which represent the carbon intensity of the power generation resource mix, while marginal emission factors account for the carbon intensity of incremental load change.
Renewable energy will not solve Bitcoin's sustainability problem	Alex de Vries (de Vries, 2018)	Bitcoin	• Calculation methods are featured in the Bitcoin Energy Consumption Index available at bitcoinenergyconsumption.com.
Energy footprint of blockchain consensus mechanisms beyond Proof-of-Work	M. Platt, J. Sedlmeir, D. Platt, J. Xu, P. Tasca, N. Vadgama, J.I. Ibanez (Platt et al., 2021)	Etherum, Algorand Cardano, Polkadot Tezos, Hedera	• The method to calculate the energy consumption considers the number of validator nodes, their energy consumption, and the network throughput based on which the energy consumption per transaction is estimated. • Only PoS-based crypto assets are considered and there is no carbon estimate.
Cryptocurrency mining from an economic and environmental perspective - analysis of the most and least sustainable countries	Alonso, J. Jorge-Vázquez, M. Fernández, R. Forradellas (Jorge-Vázquez et al., 2021)	All crypto assets	• Mining cryptocurrencies in a country based on the price per kWh • It is also necessary to know whether that energy is being produced sustainably. To measure this variable, we took each country's data on electricity production from renewable sources. • The next factor taken into account was the average temperature of the country where cryptocurrency mining is intended to be performed as this process gives off a large amount of heat
Sustainability analysis of cryptocurrencies based on projected return on investment	Martynov, O (Martynov, 2020)	Top 30 largest crypto assets by market	• Power usage of cryptocurrency was assessed following De Vries' (2018) in combination with the Li et al.'s (2018) experimental case study of global electricity consumption of Monero cryptocurrency mining.

Paper	Authors	Crypto assets	Method
and environmental impact		capitaliza-tion	• Digiconomist Bitcoin Energy Consumption Index (Digiconomist) and University of Cambridge (2022) Bitcoin Electricity Consumption Index (CBECI) for ETH, BIT, XRP • Used MIT's methodology of calculating Bitcoin's annual carbon emissions, which determines the geographical footprint of mining activity based on the localization of IP addresses of the mining pools. This geographical footprint analysis is considered as the most accurate estimate of carbon emissions, as it is based on pool server IPs, miners' IP and device IP addresses and regional carbon intensity of electricity consumption
Machine learning the carbon Footprint of Bitcoin mining	Hector Calvo-Pardo Tullio Mancini Jose Olmo (Calvo-Pardo et al., 2020)	Bitcoin	• Use ML to calculate bound of BTC energy consumption. • Then bounds multiplied by carbon emission of energy unit produced to get carbon footprint
Bitcoin's future carbon footprint	Shize Qin, Lena Klaaßen, Ulrich Gallersdörfer, Christian Stoll, Da Zhang (Qin et al., 2020)	Bitcoin	• Electricity consumption estimation comes from interviews with major miners • • Then multiply by the average emissions intensity (weighted by the geographical distribution of hash rates) of the world electricity sector in that year and get total emissions
The carbon emissions of Bitcoin from an investor perspective	Shangrong Jiang, Yuze Li, Quanying Lu, Yongmiao Hong, Dabo Guan, Yu Xiong & Shouyang Wang (Shangrong et al., 2021)	Bitcoin	• The formula develops factors in two approaches: a transaction-based approach and an ownership-based approach.

Table 2: Literature Overview

3. Crypto Asset Carbon Footprint Calculations

As mentioned previously, the approaches in literature have a different focus. Some provide historical data, some are predictive, some calculate the carbon footprint per transaction, some on an annual basis, some don't calculate any carbon emissions and focus on policy considerations. Table 3 summarizes the different approaches with a specific focus on the carbon emission measures in each approach.

Paper	Author(s)	Carbon footprint
Proof-of-work based blockchain technology and anthropocene: an undermined situation?	(Schinckus, 2021)	• Historical view • Per transaction in kg CO_2 • BTC: 809.15 kg
Quantification of energy and carbon costs for mining cryptocurrencies	(Krause and Tolaymat, 2018)	• Historical view • Per transaction in kg CO_2 • BTC: 1074 (2016), 4577 (2017), 23157 (2018) • ETH: 3.36 (2016), 21.9 (2017), 985 (2018) • LTC: 5.45 (2016), 6.11 (2017), 295 (2018) • XMR: 5.47 (2016), 26.5 (2017), 516 (2018)
Bitcoin emissions alone could push global warming above 2°C	(Mora et al., 2018)	• Historical view • Annual carbon emission • BTC: 69 million tons (2017) of CO_2
The carbon footprint of Bitcoin	(Stoll et al., 2019)	• Historical view • Annual carbon emission • BTC: ranges from 22.0 to 22.9 million tons of CO_2
Renewable energy will not solve Bitcoin's sustainability problem	(de Vries, 2018)	• Historical view • Annual carbon emission in million tons CO_2 • Per transaction in kg CO_2 • BTC: ranges from 19.0 to 29.6 million tons of CO_2 • BTC: From 233.4 to 363.5 kg of CO_2 per transaction
Energy footprint of blockchain consensus mechanisms beyond Proof-of-Work	(Platt et al., 2021)	-
Cryptocurrency mining from an economic and environmental perspective - analysis of the most and least sustainable countries	(Jorge-Vázquez et al., 2021)	-
Sustainability analysis of cryptocurrencies based on projected return on investment and environmental impact	(Martynov, 2020)	• Predictive view • Future emissions until 2028 in million tons CO_2 • BTC: ranges from 53 to 63.6 million tons CO_2
Machine learning the carbon Footprint of Bitcoin mining	(Calvo-Pardo et al., 2020)	• Historical view • Annual carbon emission in million tons CO_2 • BTC: 3.8038 (2017), 23.8313 (2018), 19.83472 (2019)
Bitcoin's future carbon footprint	(Qin et al., 2020)	• Historical and predictive view • Future emissions until 2100 in million tons CO_2 • BTC: 24 mega tons (2019), 33 gigatons (2100).

Paper	Author(s)	Carbon footprint
The carbon emissions of Bitcoin from an investor perspective	(Shangrong et al., 2021)	• Predictive view • Future emissions until 2028 in million tons CO2 (only China) • BTC: 130.5 million tons (2024, only China)
Cryptocurrency mining from an economic and environmental perspective - analysis of the most and least sustainable countries	(Sandner et al., 2021)	• Historical view • Annual carbon emission in million tons CO2 • Per transaction in kg CO2 • BTC: 3. 37.97 million tons of CO2 (2020/2021) • 369.49 kg of CO2 per transaction

Table 3: Carbon Footprint Calculations in Literature

To make the different approaches comparable, this paper compares a BTC per transaction approach which recalculates annual emissions on a per transaction scheme with a network approach which calculates carbon emissions of the entire network. Although these number are not exact, they at least show comparable numbers which is a missing component so far. Figure 1 summarizes this Bitcoin carbon footprint calculation for the transaction-based view. The results show that carbon emission have a range of 369.49 kg CO2 to 4,256 kg CO2 and that there are outliers in the upper and lower area (4,265 and 369.49).

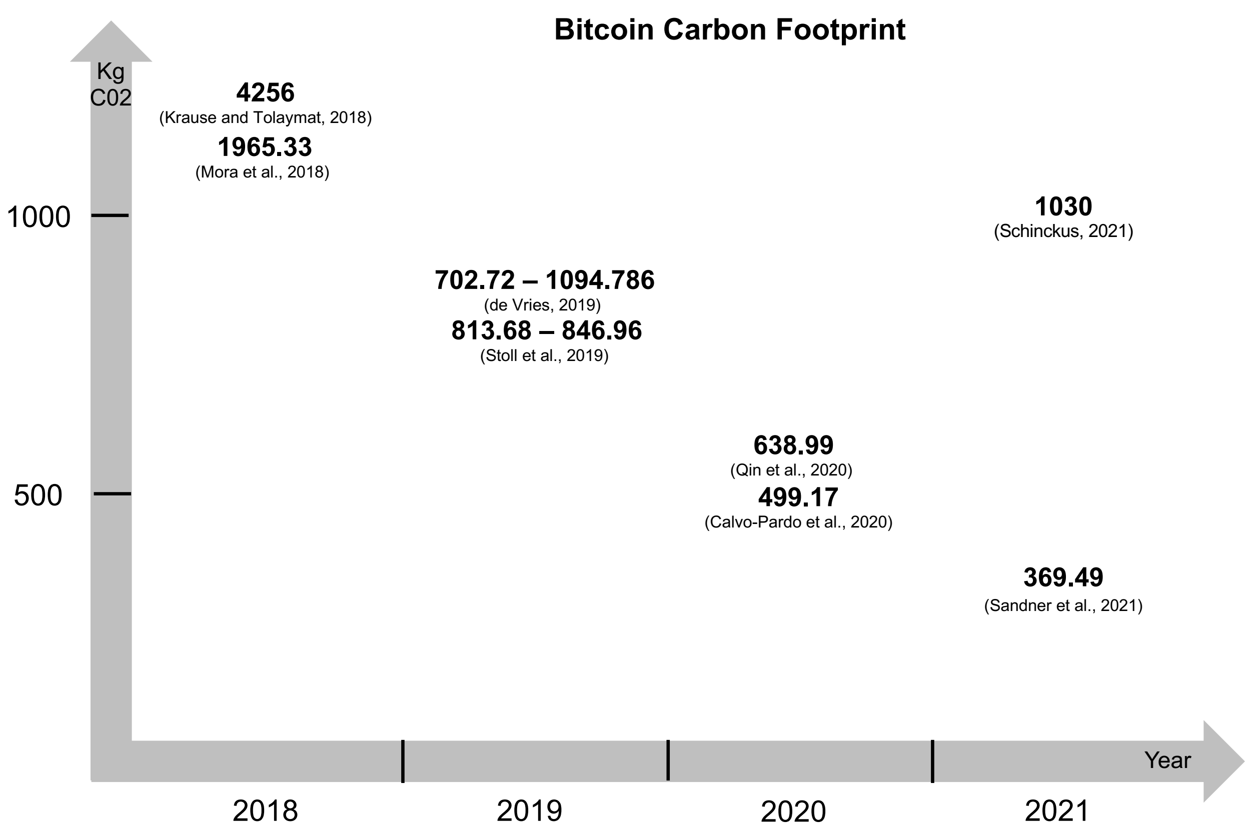


Figure 1: Bitcoin Carbon Footprint per Transaction

To get a meaningful average, the median is often used when a data set is not very uniformly distributed but has some outliers. It determines the value that lies exactly in the middle of the ordered data series. As a result, the median is robust to outliers, i.e., values that deviate greatly from the remaining values. The median of the eight approaches which this paper found as existing approaches can be calculated as 864.79 kg CO2 per Bitcoin transaction.

In contrast to PoW consensus mechanisms like Bitcoin, where at least eight approaches can be identified, this number is much smaller for PoS mechanisms, for which only a small number of calculations could be found for every PoW as of today (see Table 4).

Table 4 distinguishes an optimistic and a pessimistic scenario for each crypto asset, as the numbers vary for each data source. So, for each crypto asset the lowest (optimistic scenario) and the highest number (pessimistic scenario) was chosen. For the calculation of the carbon emissions for each crypto asset, the energy consumption was multiplied with the average carbon emission per kWh. According to the U.S. Energy Information Administration[1], this amounts to 0.85 pounds of CO2 per kWh which is equivalent to 0.39kg CO2 per kWh.

Crypto asset	**Electricity consumption per transaction (kWh)**		**Total carbon emissions per transaction (kg)**	
	Optimistic scenario	**Pessimistic scenario**	**Optimistic scenario**	**Pessimistic scenario**
Cardano	0.01239[2]	0.5479[3]	0.01239 x 0.39 = **0.0048321**	0.5479 x 0.39 = **0.213681**
Ehtereum 2.0[4] (high through-put projection)	0.000009[2]	0.00286[2]	0.000009 x 0.39 = **0.00000351**	0.00286 x 0.39 = **0.0011154**
Ehtereum 2.0 (low through-put projection)	0.01823[2]	0.55713[2]	0.01823 x 0.39 = **0.0071097**	0.55713 x 0.39 = **0.2172807**
Polkadot	0.00378[2]	0.11556[2]	0.00378 x 0.39 = **0.0014742**	0.11556 x 0.39 = **0.0450684**
Solana	0.00017[5]	0.0005[6]	0.00017 x 0.39 = **0.0000663**	0.0005 x 0.39 = **0.000195**
Tezos	0.00036[7]	0.04[7]	0.00036 x 0.39 = **0.0001404**	0.04 x 0.39 = **0.0156**

Table 4: Energy and Carbon Emission Calculations for selected PoS Approaches

In addition to the transaction-oriented view, the network-oriented view calculates the energy consumption for an entire crypto asset network using a bottom up approach.

[1] https://www.eia.gov/tools/faqs/faq.php?id=74&t=11#:~:text=In%202020%2C%20total%20U.S.%20electricity, CO2%20emissions%20per%20kWh.
[2] http://blockchain.cs.ucl.ac.uk/wp-content/uploads/2021/11/UCL_CBT_DPS_Q32021_updated-2.pdf
[3] https://adan.eu/en/article/blockchain-protocol-energy-footprint#sol
[4] The numbers for Ethereum 2.0 are only estimates from the authors, as Ethereum 2.0 is still under development. There is no annual view on the total carbon emissions of the entire network per year.
[5] https://www.eia.gov/tools/faqs/faq.php?id=74&t=11#:~:text=In%202020%2C%20total%20U.S.%20electricity, CO2%20emissions%20per%20kWh
[6] https://solana.com/news/solana-energy-usage-report-november-2021
[7] https://www.carbon-ratings.com

Error! Reference source not found. Table 4 summarizes the total carbon emissions of the entire network for each crypto asset. Bitcoin, for example is estimated to produce 99.542 bn kg CO2, while Cardano is estimated to produce 1.09 mn kg CO. The table also calculates the offset price in the relation to the total market capitalization for each network. Interestingly, the two PoW networks show similar calculations as do the PoS.

Crypto asset	Number of transactions per 2021 (Mio.)	Total carbon emissions per year (kg)[4]
Bitcoin	94.42[8]	94.42 mn x 1054.25[9] kgCO2 = **99.542 bn kg CO2**
Cardano	11.9[2]	11.9 mn x (0.02+0.214+0.0047+0.148) kgCO2 / 4 = 11.9 mn x 0.10 = **1.09mn kg CO2**
Ethereum 1.0	461[10]	461mn x 125.89 kgCO2 = **58.035 bn kg CO2**
Ethereum 2.0 (high)	n.a. [11]	n.a.
Ethereum 2.0 (lows	n.a.[11]	n.a.
Polkadot	4[2]	4 mn x (0.008+0.0016+0.045) kgCO2 / 3 = **72'800 kg CO2**
Solana	11,800[2]	11.8b n x (0.00007+0.000195) kgCO2 / 2 = 1**.564 mio kg CO2**
Tezos	2.5[2]	2.5 mn x (0.016+0.0025+0.00014+0.0043) kg CO2 / 4 = **14'338 kg CO2**

Table 5: Total Carbon Emissions by Transactions per Year

In addition to the transaction-oriented view, the total network energy consumption view shows a different picture (see **Error! Reference source not found.**).

Crypto asset	Network energy consumption (Mio. kWh)	Total carbon emissions per year (Mio. kg)
Bitcoin	**89,000'000 – 138,440,000**[12]	89,000,0000 / 138,440,000 x 0.39 = **34.71 – 53,99**
Cardano	**6**[13]	6 x0.39 = **2.34**
Ethereum 1.0	**74,600,000 - 111'570'000**[9]	74,600,000 / 111'570'000 x 0.39 = **29.09 - 43,51**
Ethereum 2.0 (high)	**n.a.** [11]	n.a.
Ethereum 2.0 (low)	**n.a.** [11]	n.a.
Polkadot	**0.8**[14]	0.8 x 0.39 = **0.31**
Solana	**11.05**[15]	11.05 x 0.39 = **4.31**

[8] https://data.nasdaq.com/data/BCHAIN/NTRAN-bitcoin-number-of-transactions
[9] https://adan.eu/en/article/blockchain-protocol-energy-footprint
[10] https://etherscan.io/chart/tx
[11] The numbers for Ethereum 2.0 are not available yet, as Ethereum 2.0 is still under development.
[12] https://adan.eu/en/article/blockchain-protocol-energy-footprint ; https://coinshares.com/research/bitcoin-mining-network-2022; https://ccaf.io/cbeci/index
[13] https://adan.eu/en/article/blockchain-protocol-energy-footprint
[14] https://adan.eu/en/article/blockchain-protocol-energy-footprint
[15] https://solana.com/news/solana-energy-usage-report-november-2021

Tezos	**0.06**[16]	0.06 xs0.39 = **0.02**

Table 6: Total Carbon Emissions by Network per Year

4. Discussion

The numbers show that there is a gap between the transaction-based view which calculates the energy consumption of a single transaction and the total energy consumption of the entire network in some of the crypto assets (e.g., Cardano, Ethereum 1.0, Polkadot, Solana). The difference is smaller for Bitcoin and Tezos.

The reason for these differences is that the data sources vary, and the approaches take different assumptions into account (see section 3 for a detailed overview of the different approaches). Importantly, the hypothesis that the transaction-oriented perspective would lead to a lower carbon emission number cannot be verified, as the higher numbers in Table 5 shows. The network-oriented view covers the whole life cycle of crypto assets which can be defined along the four phases "buy" (buy a crypto asset on an exchange by transferring fiat money and converting it into crypto assets), "hold" (hold a crypto asset in the owner's digital wallet), "use" (e.g. purchase goods and services or transfer it to another user, etc.) and "sell" (sell the crypto asset on an exchange and convert it to another crypto asset or fiat money) (see Figure 2). In addition, several analyses point to the fact that a certain share of bitcoins might not be accessible anymore, but the estimates of that share are relatively wide.[17]

This life cycle includes all energy-related activities including mining, holding crypto assets in a digital wallet, updating the chains etc. This is important as there is also a gap in the number of wallets installed and the number of wallet users who regularly buy and sell crypto assets. One analysis, for example identified 200 million wallets but only 53 million active wallet users and only 270,000 daily users[18]. This means that only around a quarter of all wallets are actively managed at all, while only less than 1 percent of all wallet owners use it daily. Another analysis identified that most Bitcoins (i.e., the largest part of the value) lie in the hand of only a very small number of users. This means that participation in digital assets is still very skewed toward a few users: "only 1,000 clusters control three million Bitcoins and the top 10,000 own more than five million Bitcoins which is about a quarter of all outstanding Bitcoins." (Makarov and Schoar, 2021, 29). However, as could be shown in Table 5 and Table 6, the crypto assets have higher numbers for the transaction-oriented view compared to the entire network view.

All these effects demonstrate that the current data sources do not seem to cover all aspects and it is therefore important to have a more comprehensive view of the entire network with all relevant variables which is currently not yet available. Section 4 therefore suggests developing such a more comprehensive framework to solve these issues.

[16] https://adan.eu/en/article/blockchain-protocol-energy-footprint

[17] E.g.: an analysis by Chainalysis identified that between 2.78 and 3.79 million Bitcoins are not accessible anymore which would be between 13.24 and 18.05 percent of all Bitcoins (https://www.bankrate.com/investing/how-to-recover-lost-bitcoins-and-other-crypto:); another analysis identified that around a fifth of all Bitcoins are not accessible (https://www.wsj.com/articles/a-fifth-of-all-bitcoin-is-missing-these-crypto-hunters-can-help-1530798731).

[18] https://www.buybitcoinworldwide.com/how-many-bitcoin-users/

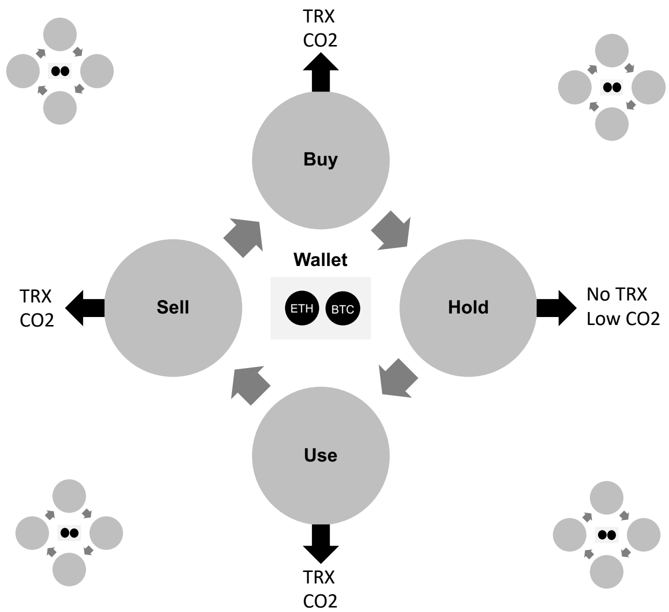


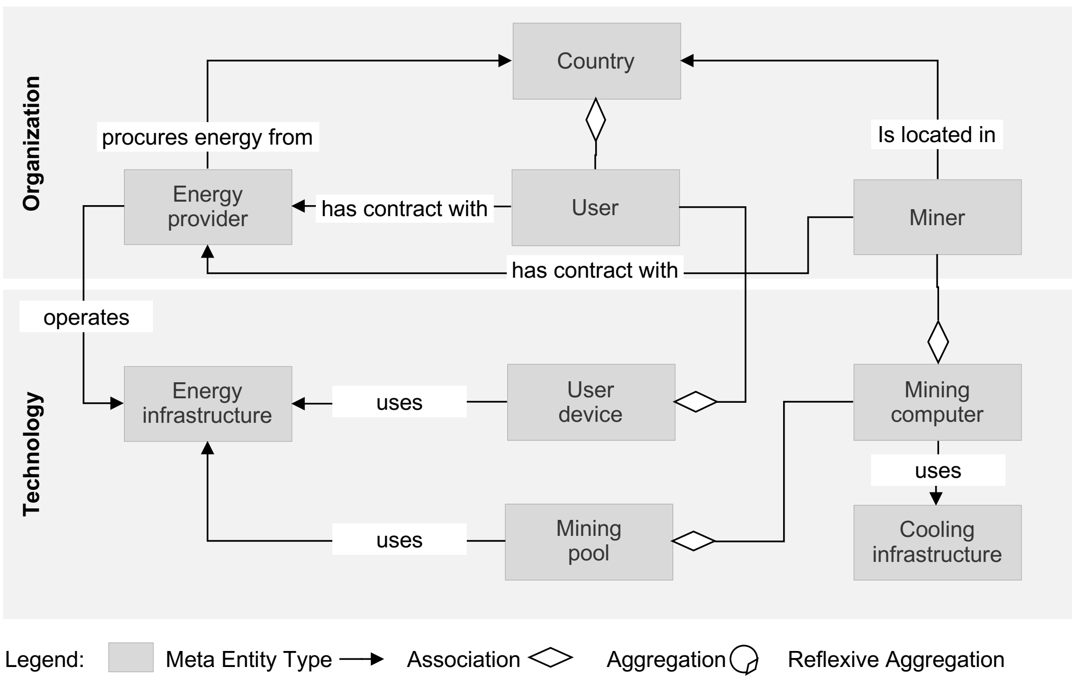
Figure 2: Life Cycle of Crypto Assets

5. Summary and Outlook: Developing a Comprehensive Reference Model for Measuring the Carbon Footprint

The analysis of the existing approaches revealed that the current available approaches do not comprehensively analyze the carbon footprint of crypto assets and rely on different assumptions. The reasons include different calculation mechanisms which are based on annual calculations vs. transaction calculations, mathematical models vs. extrapolations, the use of only a few and different energy consumption elements and often unspecific data about the energy mix and countries of origin. The existing models therefore only reflect approximate values and cannot be understood as exact calculations.

A more comprehensive approach therefore has to consider these mentioned aspects and has to combine them in a holistic model. Figure 3 summarizes these elements in a first design of a meta model which can be derived from the elements of the literature analysis in sections 2 and 3. Following general model theory, models represent an abstract representation of reality and focus on specific characteristics, while abstracting from others (Stachowiak, 1973, 132). Basically, three features are characteristic for modeling (Stachowiak, 1973, 131ff): the mapping feature determines the descriptive area of reality, the reduction feature the modeled attributes, and the pragmatic feature the purpose of a model. The process of modeling describes the process of model construction which is termed reference modeling.

Reference modeling has been established as an instrument for content and methodological design of systems, so that the modeling process is based on proven and / or accepted experiences and demarcations. They are defined as "(...) models that are developed with the goal of being reused for different, but similar purposes. Furthermore, reference models are used as a starting point for the construction of project-specific models" (Becker et al., 2007, 27). Based on the term "reference" (lat.: "referre"), which means "carry back", "deliver", "report", it aims at creating generalized valid models for more than one purpose. The defined design rules as well as the adaptation and reuse mechanisms are also part of the characterizing elements, just as the reusability in a specific application. Model developers define these elements during the design process, while adapting it to a company or application context which is then part of the model's application process (Becker et al., 2007, 30f).



Important data elements:
- Energy provider: Energy mix produced in a specific country and / or procured from other countries
- Country: Carbon emissions per country where mining pools are operated
- User: Total number of Bitcoin transactions per device and country
- Miner: Miners per country
- Mining computer: Average number of mining computers per mining pool
- Mining pool: Total number of mining pools per country
- User device: Number and type of user devices and average energy consumption per Bitcoin transaction per user device
- Cooling infrastructure: energy per mining pool / mining computer
- Energy infrastructure: Energy mix and average carbon emission per energy type

Figure 3: Meta Model for Carbon Footprint Measurement

The interaction of single reference model elements defines meta models. These provide an overall view of all the elements and their inter-relationships. Relationships describe the logical links between the elements, such as the miner who has a contract with an energy provider. Simplified entity relationship models visualize the elements (nodes) and relationships (interfaces). The interfaces' arrows symbolize the reading direction. Lozenges indicate that an element is a part of another element, in which the relationship may be reflexive.

The validation of this model is not part of this analysis of the existing approaches but will be part of further analysis and research.

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