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Carbon Footprint Comparison of Bitcoin and Conventional Currencies in a Life Cycle Analysis Perspective

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Abstract

Cryptocurrencies are a digital form of money based on the blockchain technology. Their relatively recent raise in popularity and use, together with the energy-intensive nature of some of their algorithms, has raised environmental concerns about growing energy consumption (and associated carbon dioxide emissions). This paper aims at comparing the environmental impact of the most common cryptocurrency (i.e., Bitcoin) and *fiat* currencies (i.e. coins, banknotes, credit and debit card networks). Such comparison is carried out assessing and analyzing the life cycle main phases of each currency in terms of carbon dioxide equivalent emissions. Results show that Bitcoin has a carbon footprint almost 4 to 5 times greater than the sum of all forms of traditional currency together in one year. Furthermore, environmental impact "hotspots" of *fiat* currency including raw material production of coins, transportation of banknotes and electric energy consumption of ATMs are identified. Finally, considering future scenarios and the sensitivity of various parameters on the results, some solutions are proposed to reduce the environmental impact of currencies.

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Keywords: Lifecyle ; Environmental; Energy efficiency

1. Introduction

Currencies are constantly changing over time: their manufacturing may change, their value fluctuates, some currencies are replaced in favour of others (like happened in Europe with the adoption of the Euro) and new currencies appear and compete with traditional ones, like in the case of cryptocurrencies. In the majority of cases, such new form of coinage has a mode of operation that requires energy consumption proportional to the amount of computational power available to generate cash and operate transactions (the so-called "proof of work").

Therefore, a few recent studies have tried to estimate the environmental impact of the observed growing energy consumption caused by cryptocurrencies and their future evolution. Furthermore, in the past decade research has focused on the environmental impact of each traditional (or *fiat*) currency individually but rarely in the form of a comparison. Such studies were not carried out on a global scale and not in a life cycle perspective. Therefore, it remains unclear (among other related questions) if cryptocurrencies are associated with a greater carbon footprint than traditional currencies that might be potentially replaced. The purpose of this study is then to answer this scientific question comparing the carbon dioxide equivalent emissions of the dominant cryptocurrency (i.e., the Bitcoin) to conventional currencies in the form of banknotes, coins and bank cards with associated networks. The relevant model is based on the Life Cycle Assessment (LCA) methodology, and it is used to define possible future scenarios.

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2. Blockchain and Bitcoin mining

To estimate the environmental impact of Bitcoin it is necessary to understand the blockchain technology and the mining activity. Blockchain represents the foundation of almost all cryptocurrencies and follows the steps highlighted in Fig. 1.

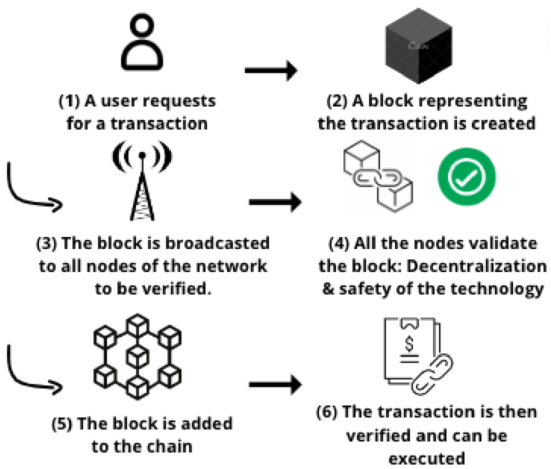

Fig. 1: Functioning of the Blockchain technology: validation of a transaction

To operate transactions, new blocks in the blockchain must be created, and this is done through mining. Miners compete to solve as quickly as possible complex mathematical problems where the solution is a computing hash of the problem associated with the transaction. When the solution is obtained, a block is added to the chain validating the transaction. The miners who found the solution share rewards in the form of newly minted bitcoins and transaction fees proportional to the contribution of the miner (Fig. 2). [1]

The related environmental impact is linked to the fact that the difficulty of the mathematical problem to solve is adjusted to add a new block approximately every 10 minutes [2]. Therefore, the growing interest (towards Bitcoin in particular) attracted a growing amount of computational power by miners that required a sheer increase of complexity of the mathematical problem necessary to add a block with growth of the related electric energy consumption [3].

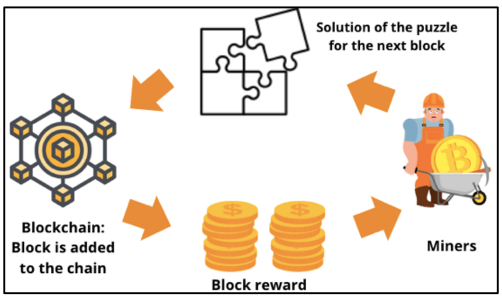

Fig 2: Bitcoin mining steps

It should be clarified that the described computationally intensive approach to process transactions is called "proof-of-work" and, although it is the most mature and common (adopted also by Bitcoin), there is an alternative that reduces drastically such cost. The "proof-of-stake" approach is broadly based on the quantity of holdings in the associated cryptocurrency and, although it looks promising, it has not yet gained significant traction. [4,5]

Therefore, since this work considers Bitcoin as a representative cryptocurrency, it evaluates the "proof-of-work" approach.

2.1. Technical and Economic measures of Bitcoin activity

Almost all methods in existing studies considered the hash rate of miners as the main metric to evaluate the Bitcoin network electric consumption. Such rate is the average number of attempts necessary to find a hash every second. Furthermore, other important parameters affecting the embodied environmental impact of Bitcoin are related to the hardware that miners use and, in particular, their computational power and efficiency as well as and their lifespan. [5]

However, economics considerations related to Bitcoin's price, miner's revenue and mining costs have also a key (although indirect) impact on the environmental impact. Existing literature developed methods around these parameters [6]. Market dynamics measures, like the profitability threshold, has been also used to assess profitability to continue mining while considering equipment costs versus rewards related to the Bitcoin price [3,7]. Consequently, some researchers developed techno-economic approaches, like the Cambridge Bitcoin electricity consumption index [8], to include both technical (e.g., hash rate, equipment) and economic aspects (e.g., revenues, profitability threshold) with potential future scenarios regarding electric energy consumption.

2.2. Mining Operations and geographical distribution

When evaluating the environmental impact associated with electric energy consumption, the geographical distribution of miners has also an influence on Bitcoin's carbon footprint through the local electric power generation mix. Different approaches exist to determine the geographical distribution of mining locations, and they can be based on tracking the nodes of the network, the leading mining pools or checking IP addresses (Device IP, Pool Server IP, Node IP address). Existing studies showed that mining activity is present across 139 countries but with significant spatial concentration. Even if mining pools represent a large proportion of miners (44% of total Bitcoin mining activity in 2021), some isolated miners are likely to hide their activities. Three main factors influence Bitcoin miner location: economic incentives, technological progress and regulatory schemes. [1,9]

Mining operations are another important aspect that influence the environmental impact of Bitcoin: i.e., the type of facilities alongside the equipment used by miners, cooling and the size of the data centers [10].

3. Conventional currencies and their environmental impact

The comparative analysis nature of this work requires to cover a similar study for *fiat* currency.

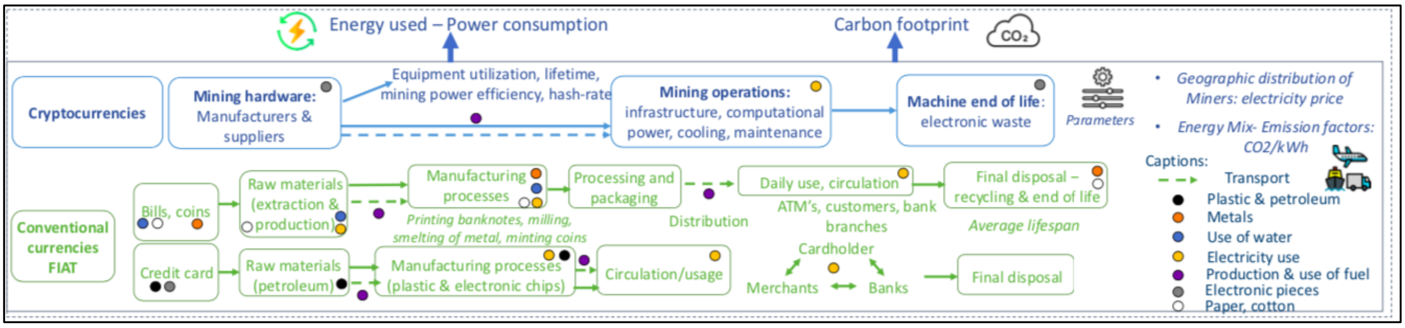

Fig. 3: Framework of the model and parameters considered

In 2020 the Bank of France presented a life cycle analysis of banknotes considering the production pooled at European level [11]. The study shows relevant material and process steps at European level (that might be reasonably generalized): banknotes are manufactured, printed, transported, distributed (via bank branches and ATMs), used to pay merchants, collected, sorted, redistributed, recycled, or disposed of. Furthermore, it is important to distinguish between quantities of banknotes in circulation and manufactured each year. Manufacturing (including also coins) requires a diverse type of resources: including water, pesticides, fertilizers, and metals to be mined. In particular, extraction, mining, milling, and smelting of metals to mint coins could be energy intensive [12,13,14]. Moreover, a publication of the European Central Bank reports data about the typical lifespan of banknotes, the share of currency in each country, the number of coins and the metal composition of coins. [15]

However, it should be observed that money is increasingly dematerialized in a growing portion of the World, with a significant increase in use of credit or debit cards whose carbon footprint should be included in this analysis. Credit and debit cards are mostly made of plastics (mainly a byproduct of crude oil) and are reported to have a typical lifetime of 8 years, although in many countries they are replaced more often (every 3-4 years) to counteract illegal activities [12]. Main aspects of cards to be included in this study are the manufacturing of the plastic and integrated chip, transport for distribution and electric energy consumption both for payments and servers handling transactions.

4. Framework and input data

As mentioned, the broad goal of the current study is to compare the environmental impact of the currencies in a lifecycle perspective. Although previous studies can be found about the LCA environmental impact of banknotes and cryptocurrencies, to the best knowledge of the authors, no comparative analysis can be found in the scientific literature. As in every lifecycle comparative study, it is of paramount importance to scope the analysis to a reasonable extent to properly compare very different currencies like Bitcoin and *fiat*. [16,17]

To achieve the goal of the study, a comprehensive framework including a number of methods and the generation of models have been developed (Fig. 3). Input data were collected from various sources, paying particular attention to consistency.

4.1. Modelling specifications

Three types of currency are considered:

- bills and coins
- credit and debit cards and related IT networks
- Bitcoin

the first two contribute to the conventional (i.e. *fiat*) currency impact, whereas the Bitcoin is the main representative of cryptocurrencies.

Geographical and chronological scope of the study are set on a global (i.e., World) scale and on a cumulative basis for year 2020. Such choices were made considering the availability of input data and that both greenhouse gas emissions and cryptocurrency mining are present and have an effect globally.

Lifecycle phase boundaries were set in an effort to make a reasonable comparison of the two types of currency. Regarding banknotes, coins and cards (debit and credit), the impact of manufacturing, bank branches as well as offices and server IT infrastructure were included. Similarly, energy consumption for cryptocurrency mining was considered in scope. Impact related to ancillary activities (e.g., dining rooms, restrooms, medical offices, …) and manufacturing of machines and IT equipment were excluded.

The LCA Functional Unit (FU) allows to quantify the performance of a product system and is used to effectively make comparisons. In the context of this study, a good FU should capture the multiple use of *fiat* currency means (banknotes, coins, cards) when manufactured as opposed to Bitcoins that are "manufactured" only once per transaction. Therefore, the chosen FU is the cumulative impact of the currency over one year and the characterization is based on the cumulative energy consumption and carbon dioxide equivalent emissions.

4.2. Model development

4.2.1. Banknotes

Data available for the European area and the United States of America was analyzed and extrapolated globally considering the estimated number of banknotes in circulation worldwide. An equivalent, average banknote composition was considered comprising 0.815 grams of cotton, 0.082 grams of ink, 0.010 grams of thread and 0.049 grams of foil. Storage, packaging of the banknotes (containers, expandable film, plastic strapping), ancillary chemicals in the manufacturing process, manufacturing of the ATMs and bank employee travel are all aspects considered out of scope.

Main parameters extrapolated are: yearly number of new banknotes manufactured, average banknote lifetime and number of banknotes in usage. More specifically, the lifecycle phases evaluated comprised: raw material production and their transportation [18] (cotton, paper, ink, foil and thread production), the manufacturing process [17] (pre-press, printing and finishing), transportation [23] to national central banks and, then, to local branches and ATMs, usage (ATMs electric energy consumption, counting and inspection of banknotes [18]), end-of-life (transportation to incineration, shredding, granulating and compacting, incineration).

Transportation was generalized averaging data available for Europe and the USA including the use of trucks, ships and aircraft. In particular, distribution between central banks and branches with ATMs as well as to retailers, 6-ton armored trucks were considered. The end-of-life phase was estimated using data normalized by mass provided by the European Commission [18]. Finally, the estimated number of banknotes manufactured and in circulation were obtained from data provided by World and European banks [22].

4.2.2. Coins

In the case of coins again an averaged, representative composition was considered: 2.312 grams of copper, 1.775 grams of steel, 0.086 grams of aluminium, 0.184 grams of zinc, 0.017 grams of tin and 0.126 grams of nickel. Packaging and storage were considered out of scope of the current analysis. Main input parameters comprise the average lifetime, average composition and weight, number of coins in circulation and the number of coins manufactured per year.

Main processes considered are raw material production (metal mining, extraction and coin blank production), transportation, the manufacturing process, transportation to the national central banks, distribution to branches and retailers through armored trucks, usage (circulation, counting and inspection) and the end-of-life (transport to melting company and melting). Thanks to the long lifespan of coins, a relatively small number of them need to be destroyed each year.

The same extrapolation principle considered for the banknotes has been followed also in this case [18,22].

4.2.3. Payment cards

The composition of payment cards was simplified to 90% PVC and 10% electronic chip by mass, whereas assumptions regarding the impact of transport were similar to those made for banknotes and coins with the exception that no armoured trucks were considered in this case. The manufacturing of the servers building the IT networking infrastructure, ATMs and card terminals, paper and electronic receipts, storage and packaging as well as quality control processes were all aspects excluded from the analysis. Main input parameters considered were the card composition, its lifespan, the number of cards in circulation and manufactured yearly and the number of card payments per year.

Lifecycle phases analyzed comprise raw material production [24,25] (electronic components, plastic), transport [24,25], the manufacturing process [24,25] (deposition of PVC layers, recording and printing security and customer information, manufacturing and insertion of the electronic module), transportation and distribution to the consumers, usage (server infrastructure, ATMs and card terminals) and end-of-life [26] (destruction of credit card, incineration). Output data of the representative unit was then scaled appropriately to the volume of credit, debit and prepaid cards estimated worldwide.

4.2.4. Bitcoin

Considering the input data available, output estimates were obtained in the form of lower, upper limit and a best guess [10]. The manufacturing and transport of the mining equipment were consistently considered out of scope for this analysis. The presented literature survey suggested key parameters to be used.

- Mining hardware: World total hash rate, energy efficiency of mining equipment in 2020, equipment lifetime and equipment utilization, share of mining equipment.
- Mining operations: data center energy efficiency and infrastructure overhead power (cooling, IT components).
- Economics: price of Bitcoin, block reward, transaction fee, electricity price.
- Geographical distribution of miners and relevant electric energy generation mix.

Equations from a previous study [10] were used with data available about 2020, including an updated electric grid carbon intensity factor and more specific inputs inspired by another paper [1] i.e., electric energy prices of each country, the share of mining equipment and a more precise average of the hash rate. The amount of carbon dioxide equivalent emitted was obtained for each country multiplying the energy consumption of Bitcoin mining by the grid carbon intensity factor and considering the share of each country in the Bitcoin mining activities (geographic distribution).

Input data were obtained from different sources when concerning the mining hardware [27], the economic parameters [28], the end-of-life [6], the emissions factors [10,19] and share of each region in the mining activities [1,13,29].

5. Results

5.1. Comparison of the currencies carbon footprint

Using the models described allowed to estimate the relevant carbon dioxide equivalent emissions (Table 1) that appear significantly higher for Bitcoin when compared to traditional currencies. Table 1 shows results for 2020 but Bitcoin is expected to have continued to increase in terms of impact and is estimated to emit globally about 60 $MtCO_2eq$ in mid-2022. By considering buildings of institutions, the carbon footprint impact of banknotes is increasing by almost 25%, their share is not negligible. The carbon footprint equivalent of Bitcoin in 2020 has been almost 10 times the one of any form of *fiat* currency and far greater than the sum of all conventional alternatives combined. Looking at the contribution of buildings of financial institutions, it can be seen that their carbon dioxide emissions are significant.

Table 1. Carbon footprint results of all currencies

Currency	Bills	Financial institutions	Coins	Credit card	Bitcoin (Best guess)	Bitcoin (lower limit)	Bitcoin (upper limit)
Carbon footprint ($MtCO_2eq$)	2.98	3.80	2.09	1.96	35.72	31.67	43.40

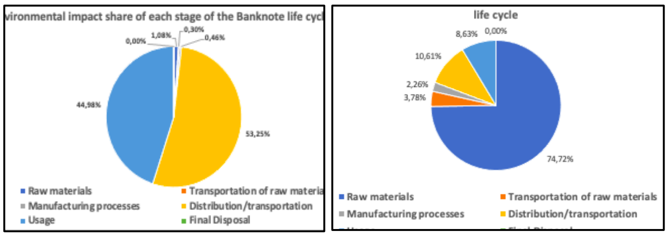

Fig. 4. Carbon footprint share of lifecycle phases of (a) banknotes and (b) coins

Considering the breakdown of emissions for banknotes and coins (Fig. 4), it can be seen that the safe transport of banknotes by armored trucks has a significant carbon footprint as well as the electric energy consumption of ATMs. Coins carbon footprint, instead, is dominated by the impact of the extraction and refinement of metals. It should be noted that most of the carbon footprint related to payment cards is traceable to electric energy consumption necessary to run the servers of their network.

5.2. Sensitivity analysis

Scenarios have been developed to assess the sensitivity of results to some input parameters.

Regarding the Bitcoin carbon footprint, an important variable is the energy mix used to mine Bitcoin. Therefore, a worst-case scenario with a coal-based electric energy generation mix and a best-case with gas or renewable energy were designed yielding carbon footprint results in the range between 71.36 $MtCO_2eq$ and 35.17 $MtCO_2eq$. Another important parameter is the hash rate of the network and how it could evolve in the future: a 10% change in the input, leads to a proportional (i.e., about 10%) variation in Bitcoin carbon equivalent footprint.

Regarding the traditional currencies, polymer banknotes are being adopted by more and more countries (e.g., Canada, Australian Mexico) and represent a new alternative material. According to various banks institutions, they could reduce by 30% the carbon footprint when compared to cotton-paper based banknotes. Moreover, polymer-based notes are reportedly more secure, more easily recyclable, cleaner (with a shorter survivability of viruses and bacteria) and more durable. Another parameter could be reduced (based on observed trends) is the number of ATMs. A reduction in the number of ATMs by 25% shows a reduction in the carbon footprint by almost 10% (from 2.98 $MtCO_2eq$ to 2.65 $MtCO_2eq$).

6. Discussion

Findings of this study clearly show that the carbon footprint of Bitcoin is very significant and it can be traced back to the concept of "proof-of-work" that increases automatically the computational power required by the miners with the increase of their available means. Such principle dictates an increase of electric energy consumption when more resources are available with the growth of the cryptocurrency. On the other hand, all forms of *fiat* currency appear less impactful on the environment. Although physical resources are required to produce them, they can be reused several times, amortizing their manufacturing environmental impact. Payment cards appear even more appealing because they de-materialize significantly monetary transactions without being subjected to the described problems stemming from the "proof-of-work" mechanism.

Results raise questions about the future of currencies. Changes could take place in the coming years with the growth of online payments worldwide with *fiat* currency and the shift towards a cashless society (that is already a reality in some countries). For nations slower to transition or opposed to de-materialized cash, polymer-based banknotes seem to be promising to reduce the relevant carbon footprint and appear to be getting more and more ubiquitous. Future wide adoption of Bitcoin could create a significant environmental problem if the basic mechanism linked to the blockchain "proof-of-work" is not corrected or substituted by a "proof-of-stake" approach.

It should also be considered that the models presented have some limitations caused by the lack of available data (due to confidentiality for *fiat* currencies and lack of reliable and recent data sources for the Bitcoin). Furthermore, the very dynamic nature of Bitcoin make difficult to obtain accurate data of a timespan of one year like in this study. In addition, the system and infrastructure of the two types of currencies (in the many forms) are quite different and it is not straightforward to develop a useful and representative comparison. To this end, although the selected FU worked very well, another potential FU that could have been used with profit is the environmental impact per transaction. Notwithstanding approximations and assumptions, models capture a clear and sensible comparison where the results leave no doubt about the answer to the scientific question and allow also a more fine-grained analysis of "hotspots" in the LCA.

7. Conclusion

This study developed a framework to compare the yearly carbon dioxide emissions over the entire life cycle of the major cryptocurrency (Bitcoin) with conventional forms of coinage in the form of banknotes, physical coins and payment cards. Results show that Bitcoin has a carbon equivalent footprint 10 times larger than banknotes or coins and about 4 times larger than the sum of all traditional currency forms.

Future improvements in the environmental impact of currencies can be directed in two main directions.

• Improving the carbon footprint of traditional currencies with a transition towards polymer-based banknotes and (more significantly) de-materialization.

• Adopt a "proof-of-stake" protocol for cryptocurrencies.

Further considerations (that are beyond the scope of this work) can be made in favor or against cryptocurrencies for its independence from the traditional financial system and central banks. Furthermore, also the dilemma between "proof-of-work" and "proof-of-stake" approach touches quite wider aspects well beyond the mere environmental impact in terms of carbon footprint.

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