WIRTSCHAFTSUNIVERSITÄT WIEN
Vienna University of Economics and Business

Bachelor Thesis

Title of Bachelor Thesis (english)	Comparative Analysis of the CO2 Footprint of Bitcoin Transactions versus Traditional Financial Transactions using Life-Cycle-Assessment
Title of Bachelor Thesis (german)	Vergleich des CO2 Fußabdrucks von Bitcoin-Transaktionen mit traditionellen Finanztransaktionen anhand einer Lebenszyklusanalyse
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Comparative Analysis of the CO_2 Footprint of Bitcoin Transactions versus Traditional Financial Transactions using Life-Cycle-Assessment

A Basic Approach to a Life-Cycle-Assessment of Bitcoin Transactions

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Bachelor Thesis

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“The question of the dangers of mining and the crypto-sphere for the environment has become so urgent, not only because of the harm to the nature that it carries, but because mankind simply could not imagine in advance what scale Bitcoin mining would reach in a matter of months and, accordingly, couldn’t predict what consequences this may lead to.“[1]

[1] *Stargame* (2018), Green mining: a review of projects, Medium.

Abstract

With changing customer needs and preferences coinciding with technological advance, payment systems have changed rapidly over the past 50 years. With the growing number of internet connections around the world, cryptocurrencies have experienced an unprecedented emergence amongst customers, enterprises and investors. Cryptocurrencies are characterized by the absence of a central counterparty, the blockchain-based distributed-ledger technology and independence of monetary policies carried out by central banks and governments. The popularity of cryptocurrencies is reflected by the number of cryptocurrencies available: at the time of writing, *Coinmarketcap* lists 2068 different cryptocurrencies on their website.[2] *Bitcoin*, as the most popular of cryptocurrencies, represents the rise of digital payment systems. However, cryptocurrencies have also faced harsh criticism regarding their power consumption and environmental sustainability, which slowed down consumer acceptance of bitcoin as a means of payment. One way of determining the ecological impact / footprint of a process is the so-called life-cycle-assessment (LCA), which provides a quantification of all inputs and outputs of material flows of a product or process and their impact on the environment.[3] By determining the system boundaries of a process and the functional unit and examining the resources used to support it, the LCA provides tangible key figures to compare different processes regarding their ecological footprint.[4] In order to obtain valid results, one should follow a usual order of steps:[5]

1. *Definition of Goal and Scope*
2. *Inventory Analysis*
3. *Impact Assessment*
4. *Interpretation*

The point of this paper is to assess one Bitcoin transaction as a functional unit in order to define the relevant factors of the power consumption and environmental impact of one bitcoin transaction and compare it to other forms of cashless payment systems such as bank transactions and credit card payments.

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[2] *Coinmarketcap*, https://coinmarketcap.com/all/views/all/ (accessed 10th December 2018).

[3] ISO 14041:1998; *Schaltegger* et al. (1996), Life-Cycle-Assessment (LCA) - Quo Vadis? 5.

[4] „Life Cycle Assessment - Overview" available here: https://sftool.gov/plan/400/life-cycle-assessment-lca-overview (accessed 25th June 2019).

[5] *Schaltegger* et al. (1996), Life-Cycle-Assessment (LCA) - Quo Vadis? 5.

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Introduction

The quick rise of prices of crypto-assets at the end of 2017 has, if anything, depicted one thing: the range of influence blockchain-technology has on the world. While it does have a variety of advantages and numerous areas of application, as supporters of the young technology enthusiastically point out, it is best known for its use as the underlying technology for the Bitcoin network. As any currency, Bitcoin too depends on the trust of the people accepting it as a means of payment, and to gain that trust is a difficult task. A task that has become more difficult since criticism about Bitcoin has emerged, calling it out on the high energy consumption of the Bitcoin network and the negative incentives that are intrinsic to the system. As questions about sustainability have found their way into banking and the financial sector, Bitcoin users, too, as well as developers, have started to ask themselves to what extent are they required to mitigate the environmental footprint of their financial transactions.

In order to provide the public, i.e. the (potential) users of the Bitcoin network, with the information necessary to decide whether or not they want to use bitcoins to conduct a payment, we need reliable data as to how big the impact of the Bitcoin network on the environment actually is.

While there have been different approaches to determine the actual energy usage of the Bitcoin network, one that, to my knowledge, has not been conducted yet is the Life-Cycle-Assessment method. LCA is designed to track the environmental impact of all steps during the life cycle of a product, including production and disposal. In order to measure Bitcoin's energy consumption adequately when it comes to mining, we first need to examine the elements and boundaries of the mining process and determine the relevant factors regarding energy consumption.

Yes, Bitcoin is energy consuming. Still, to this day, we have yet to establish how much energy exactly one Bitcoin transaction consumes and how it compares to regular financial transactions such as bank transactions, credit card transactions and cash payments. In this context, the LCA is a promising method in order to receive valid key figures of Bitcoin payments and to identify areas in the transaction process in which energy consumption can be reduced. This work aims to provide the reader with an overview of the literature available of Bitcoin's energy consumption, define the parameters necessary to conduct a Life-Cycle-Assessment of a Bitcoin transaction and compare Bitcoin to other means of payment, digital and analogue.

I) **Bitcoin**

To gain a deeper understanding of the environmental impact of Bitcoin mining, it is vital to make oneself familiar with the underlying technology of Bitcoin and how Bitcoin works from an economical point of view. Therefore, before going further into the topic of the environmental impact of Bitcoin mining, I will first give a brief overview of Bitcoin's history and technical background as well as its legal status in Austria and the European Union.

A) Characteristics and Historical Overview

Bitcoin today is the world's best-known cryptocurrency. Bitcoin was introduced in 2008 by its creator *Satoshi Nakamoto*, whose name is known to be a pseudonym. Even though there are a handful of theories about the person or people behind Bitcoin, the creators' true identity remains unknown until today. Nakamoto first published his groundbreaking paper „Bitcoin: A Peer-to-Peer Electronic Cash System" in 2008, and shortly after, in the beginning of 2009, launched the Bitcoin network by mining the so called *genesis block.*[6] The Bitcoin-system is in its entirety explained in Nakamoto's first paper. Bitcoin is best characterized as a digital currency based on the distributed-ledger-technology using a public blockchain, or, as *Nakamoto* calls it, a purely peer-to-peer version of electronic cash.[7]

The Bitcoin blockchain is a public ledger recording transactions between participants of the Bitcoin network, with one bitcoin being "a chain of digital signatures".[8] The blockchain, whose integrity is ensured by cryptographic technology, contains all transactions that have been conducted, allowing the owner of a Bitcoin wallet to determine their account balance.

Transactions between users transfer value from one wallet to another by adding it to the blockchain. For this reason, every Bitcoin wallet comes with two digital keys, one private and one public. While the public key is used like a publicly available address to the wallet and thereby enabling incoming transactions, the private key is used like a signature to confirm outgoing transactions, preventing the transaction from being altered once it has been signed.

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[6] see: https://www.economist.com/the-economist-explains/2015/11/02/who-is-satoshi-nakamoto and https://www.newyorker.com/magazine/2011/10/10/the-crypto-currency

[7] *Nakamoto* (2008), Bitcoin: A Peer-to-Peer Electronic Cash System 1.

[8] *Nakamoto* (2008), Bitcoin: A Peer-to-Peer Electronic Cash System 2.

The founders designed Bitcoin similar to fiat money and, by using the internet, aimed to establish a peer-to-peer payment system, i.e. a system independent of governments[9], central banks and commercial banks working as intermediaries. Without a third party, transactions happen directly between the exchangers. By bypassing the middlemen, the system eliminates any dangers a bank-centered system entails, such as credit-risks and political influence on central banks influencing their monetary policy. The biggest difficulty of leaving out trusted third parties like banks lies in the so-called double-spending problem, i.e. simplified, spending the same amount of money twice. Bitcoin's developers solved it by combining digital signatures with highly sophisticated cryptographic technology ("hashing"), thereby leaving behind the trust-based model and creating a currency free of intermediaries. However, the peer-to-peer system also entails that transactions usually cannot be reversed and that there is no user support through a central counterparty.[10]

B) Technological Background and Mining Process

The mining process of Bitcoin guarantees the functionality of the system. Bitcoin is built on the blockchain technology. Blockchain technology uses highly sophisticated cryptographic algorithms to guarantee the integrity and safety of the transactions that are comprised in the different blocks, which, as a whole, make up the blockchain.

In order to validate a transaction the Bitcoin system sets up cryptographic tasks that must be solved by computing power by one of the participating miners and their hardware, thus, through computing power. This way of confirming a transaction is called Proof-of-Work, which means that work, i.e. computing power, is needed to conduct a transaction. A validated transaction is added to a block, which consists of a list of multiple transactions and a hash at the end of the list, through which it is connected to the previous block. The network timestamps the transactions by „hashing them into an ongoing chain of hash-based Proof-of-Work, forming a record that cannot be changed by redoing the Proof-of-Work"[11], thereby setting a nearly insurmountable obstacle for malicious attacks on the Bitcoin network. Once the block is added to the blockchain its transactions are conducted.

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[9] A clear indicator of the Bitcoin founders critique and aversion towards government controlled monetary systems is the text embedded in the coinbase of the genesis block, which reads as follows: „The Times 03/Jan/2009 Chancellor on brink of second bailout for banks.", see: https://www.newyorker.com/magazine/2011/10/10/the-crypto-currency.

[10] For further information on the technological background of Bitcoin see: *Nakamoto* (2008), Bitcoin: A Peer-to-Peer Electronic Cash System; for a comprehensive overview see: https://bitcoin.org/en/how-it-works.

[11] *Nakamoto* (2008), Bitcoin: A Peer-to-Peer Electronic Cash System 1.

With every block added to the chain, new bitcoins are created as a reward to the miner for providing the system with the necessary computing power. This way, in the absence of a central authority, bitcoins are distributed without a person or group deciding who gets them but as a reward to people for doing the work of verifying new transactions into new blocks through computational work. The so-called "block reward" thereby serves as an incentive for participants to provide the network with computing power, who will continue to do so as long as its profitable for them, i.e. as long as the price of the bitcoins they earn is higher than their expenditures.

The number of bitcoins created per block halves every 210,000 blocks, which is approximately every four years. The first halving took place in 2012 and the second one in 2016. Consequently, starting from 50 bitcoins per block with the genesis block in 2009, we now stand at 12.5 bitcoins mined per block. The next halving will presumably take place in 2020 and the last one around 2140. The reason for the implementation of the halving-concept has an economic background: *Satoshi Nakamoto* wanted to prevent Bitcoin from inflation; he supposed that the availability of an unlimited supply of Bitcoin would necessarily lead to a decline in its price. Thus, Nakamoto sought to tackle the market forces of supply and demand by creating an artificial scarcity, similar to the scarcity of precious metals like gold, thereby keeping inflation under control.

With rising Bitcoin prices, more miners eagerly looking for the block reward are entering the market, making it more difficult, thus, more power consuming for a single miner to make a profit with bitcoin mining. As a consequence of the Proof-of-Work concept, miners compete against each other in who validates transactions quicker. Thus, in order to be rewarded by the system, miners are incentivized to get better hardware in order to validate transactions faster than the other miners do. Higher performing hardware usually is more computing intense and by that more energy consuming. However, miners have to find the right balance when investing in higher performing hardware so the mining remains profitable.[12]

In practice, most of the transactions are not confirmed by single miners but rather so called mining farms and data centers. These institutions have entered the market due to the high interest and fierce competition in Bitcoin mining. Retail customers, who in most cases lack the

[12] *McCook* (2018), The Cost and Sustainability of Bitcoin 6f.

knowledge or funding to compete in the mining market, pay a relatively small financial contribution in exchange for the mining wins of highly sophisticated mining software.[13]

In conclusion: In order to conduct a transaction, the network uses a distributed consensus system called *Mining*. This so-called Proof-of-Work system is designed to prevent the Bitcoin system from malicious attacks on the system (e.g. Distributed Denial of Service (DDoS) attacks) and double-spending. It relies on the computing power of network participants, called miners, who in return for transaction fees and newly mined bitcoins perform highly sophisticated computational tasks using the computational power of their own computing equipment. By solving these tasks, the system aims to reach consensus among the network participants and to keep a synchronized ledger, thereby minimizing the need for trust within the system.[14] However, with their eyes on the block reward and the transaction fees, miners are using vast amounts of natural resources, i.e. energy, in order to perform the computational tasks necessary to keep the system up and running in exchange for digital assets, i.e. bitcoins[15], with, as has been purported by adversaries of cryptocurrencies, considerable consequences for the environment.

C) <u>Acceptance and Legal Status</u>

As any other currency, Bitcoin can only fulfil the purpose intended by its founders, i.e. serving as an efficient and independent payment system, if people accept it. One reason why Bitcoins' acceptance has been stagnating is the uncertainty about its legal status in numerous jurisdictions around the world. With cryptocurrencies becoming ubiquitous in the last decade, we have seen a trend of governments and authorities either enacting specific regulation regarding the handling and status of cryptocurrencies or applying the regulations in force to the rather new phenomenon of digital currencies. However, due to the high number of different cryptocurrencies and other ways of using the blockchain, the legal status of blockchain-based financial instruments and cryptocurrencies such as Bitcoin remains unclear for the bigger part. The European Union recently addressed cryptocurrencies in the fifth Anti-Money Laundering Directive, which entered into force on 9 July 2018.

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13 For an overview about data centers and mining farms see: *Kosik* (2018), Data Centers Used for Bitcoin Mining, *Engineer* (2018).

14 *Bentov* / *Gabizon* / *Mizrahi* (2017), Crypto Currencies without Proof-of-Work 1; *Bendiksen* et al. (2018), The Bitcoin Mining Network 1.

15 *Bentov* / *Gabizon* / *Mizrahi* (2017), Crypto Currencies without Proof-of-Work 1.

Aiming at the prevention of money laundering, the Directive brings custodian wallet providers and virtual currency exchange platforms within the scope of the EU regulations, meaning they will be obligated to establish strict due diligence requirements as regards their customers and users. Additionally, the Directive contains a definition of virtual currencies: Virtual currencies are "a digital representation of value that is neither issued by a central bank or a public authority, nor necessarily attached to a fiat currency, but is accepted by natural or legal persons as a means of payment and can be transferred, stored or traded electronically."[16] Furthermore, in 2018 different financial markets supervisory authorities of the European Union jointly published a consumer warning regarding virtual currencies, putting forward that they are highly risky and unregulated products and not suitable as investment, savings or retirement planning products.[17] However, while imposing heavy obligations and restrictions on the entities dealing with cryptocurrencies through the Anti-Money Laundering Directive and warning customers of the dangers of dealing with cryptocurrencies, the EU also took a first step towards higher legal certainty by legally defining virtual currencies.

Austrian authorities do not regard cryptocurrencies as legal tender or financial instruments, but rather as commodities. In addition, the Austrian national bank supports the prevailing view that Bitcoin does not qualify as a currency due to it not fulfilling basic functions of a currency. However, according to the Austrian Finanzmarktaufsicht (FMA) the mining of cryptocurrencies within the framework of a "mining pool" could fall within the scope of the Alternative Investment Fund Manager Directive (AIFMD, implemented into Austrian national law as AIFMG), which could pose as a major setback for Austria's mining industry.[18] With regulators solely focusing on the financial sector of blockchain applications, until now, there have been no noteworthy attempts to implement regulation targeting the environmental impact or which at least considers the environmental aspects of the blockchain technology.[19]

[16] Directive (EU) 2015/849 of the European Parliament and of the Council, Article 3 (18).

[17] European Supervisory Authorities, WARNING. ESMA, EBA and EIOPA Warn Consumers on the Risks of Virtual Currencies (Feb. 12, 2018), https://www.eba.europa.eu/documents/10180/2139750/Joint+ESAs+Warning+on+Virtual+Currencies.pdf

[18] For a comprehensive overview of the different approaches to cryptocurrency regulation in different jurisdictions around the world, see: The Law Library of Congress, Global Legal Research Center (2018). Regulation of Cryptocurrency Around the World, available here: https://www.loc.gov/law/help/cryptocurrency/cryptocurrency-world-survey.pdf

[19] *Truby* (2018), Decarbonizing Bitcoin: Law and Policy Choices for Reducing the Energy Consumption of Blockchain Technologies and Digital Currencies 403.

II) **Environmental Impact in General**

In order to see the field of crypto-economics in the context of the often-used terms of Environmental Impact, Environmental Footprint or Carbon Footprint we need to examine the meaning and measurement of these concepts and evaluate their relevance. Below, I will give a comprehensive summary of what these terms mean, what methods of measurement are available and why they matter.

A) Definition and Measurement

The above-mentioned terms have become widely popular in science, media and politics - especially with regard to global warming. (E.g. the Paris Agreement[20]).
Yet, there is still a lack of scientific approaches regarding their definition. While plenty of scientific papers and studies address the topics of environmental impact and carbon footprints, barely any of them provide the reader with a clear definition of these terms.[21] In order to reach comparable results, we first need to define what exactly we want to compare.

The OECD defines Environmental Impact as the „direct effect of socio-economic activities and natural events on the components of the environment"[22], others define it as "the change in an environmental parameter, over a specified period and within a defined area, resulting from a particular activity compared with the situation which would have occurred had the activity not been initiated"[23]. Obviously, both of these are very broad definitions, leaving space for innumerable ways of affecting the environment. Many scientific papers addressing the issue of sustainability and environmental impact of the Bitcoin network only examine the energy used to keep the system running.[24] However, this method provides no information about the sources of the energy. While they do shed a light on how much energy is necessary to maintain the Bitcoin network, they leave us in the dark about the actual environmental impact of Bitcoin mining.

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20 UN Treaty Collection, Vol. II Kap. 27; 7d Paris Agreement.

21 *Wiedemann / Minx* (2008), A Definition of ‚Carbon Footprint', ISA Research Report, 07-01, 1.

22 see OECD, Glossary of Statistical Terms, available: https://stats.oecd.org/glossary/detail.asp?ID=827

23 *Wathern* (1988), Environmental Impact Assessment 7.

24 e.g. *Vranken* (2017), Sustainability of Bitcoin and Blockchain; *O'Dwyer / Malone* (2014), Bitcoin Mining and its Energy Footprint; see below under chapter 3.b.

For the purpose of this paper, we need to narrow the range of effects further down to make the Bitcoin system comparable to other ways of payment in terms of precise effects of the network on the environment.

One way of affecting the environment is by emitting greenhouse gases. The amount of greenhouse gases emitted by a process or a product on the environment is commonly known as 'Carbon Footprint'. The common understanding of the term 'Carbon Footprint' is that it stands for 'a certain amount of gaseous emissions that are relevant to climate change and associated with human production or consumption activities'.[25] While this gives us a vague impression of the baseline of the common understanding, it leaves us in the dark with a view to the measurement and quantification of the carbon footprint. Looking at the relevant literature, the reader is confronted with numerous different approaches ranging from 'direct CO2 emissions to full life-cycle greenhouse gas emissions' each considering different system boundaries and claiming to reach a conclusion that represents the carbon footprint. Other questions arise, taking regards to what gases should be considered: just carbon dioxide or other greenhouse gases as well? What about carbon monoxide? Should you only consider the emissions of the product itself or also the emissions occurring during production and disposal? Etc.[26]

While these questions cannot be answered within the scope of this paper, they still serve to put the criticism of Bitcoin's carbon footprint into perspective: not only is there no clear and common definition of a carbon footprint, but also do all of the papers regarding Bitcoin's environmental impact use different methods, different units and reach different conclusions. Especially with a technology as new as the blockchain technology, the methods used should be clearly and transparently defined in order to be able to understand how certain results have been reached and which factors are included in the calculation. Keeping this in mind, a valid comparison to other, more established means of payment is a relatively difficult task that must be met with the highest accuracy regarding not only the figures but also the terms we are using.

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[25] *Wiedemann / Minx* (2008), A Definition of ‚Carbon Footprint' 2.
[26] *Wiedemann / Minx* (2008), A Definition of ‚Carbon Footprint' 2.

B) Relevance

The terms discussed above have become widely popular in science, the media and politics. Nowadays, the issue of sustainability plays a vital role not only for society as a whole but it also found its way into the economy. Amid fears of an environmental breakdown or a climate catastrophe, customers and users display a growing awareness for environmental factors. Consequently, producers and entrepreneurs more and more need to show that their products are not harmful to the environment; otherwise, they will have a hard time surviving in the market.

Bitcoin still is relatively new to the market and its competitors are government backed fiat currencies and multinational financial institutions - naturally, this is not an easy position to start in. In addition to that, Bitcoin has faced harsh criticism regarding its environmental footprint. This is even more important keeping in mind, that the majority of Bitcoin users are relatively young[27], between 14 and 35 years old, and therefore part of a generation with a higher sensitivity for environmental concerns than others.[28] Seeing that, if Bitcoin should fulfil the purpose that Satoshi Nakamoto sought out for it, namely to replace the whole monetary system as we know it, it is crucial for Bitcoin to gain the trust the users by tackling environmental concerns, as otherwise it would remain in its role of a niche currency.

[27] for Austria see: *Finanzmarktaufsicht* (2019), Fakten, Trends, Strategien 2019 181.

[28] see: *Glass Packaging Institute* (2014), Millennials, A Generation Invested in Health and the Environment, http://www.gpi.org/sites/default/files/GPI-TheMillennials-11%206%2014-FINAL.pdf

III) Current Literature

Bitcoin's sustainability has been discussed in different papers in the last couple of years, using different approaches to render the system's boundaries and measure its energy usage. However, due to the relative recency of the issue (by the time of writing Bitcoin as the oldest of cryptocurrencies has been up and running for only ten years), the number of papers addressing the topic of sustainability in the cryptocurrency eco-system is low with the majority having been published in the last 4 years.[29] Below I will look into the different approaches used by the authors, give an overview of the different outcomes and point out the differences in the respective methods and results.

A) Different Approaches / Different Outcomes

Regarding the current literature of Bitcoin's environmental impacts we are currently faced with two issues: First, most of the authors use different approaches regarding the measurement of Bitcoin's energy consumption and aim to establish different results based on different terms such as sustainability, environmental footprint, carbon footprint, energy usage etc. Second, with most of the authors using different approaches, to this date no well-founded base of literature has been established. Due to this, the high complexity of the subject and, in some parts, the lack of reliable statistical figures, the different outcomes can only serve as estimates, which has been conceded by most of the authors.[30]

B) Overview of the Current Literature

1. Giungato / Rana / Tarabella / Tricase *(Sustainability, Vol. 9, 2017)*: Current Trends in Sustainability of Bitcoins and Related Blockchain Technology:

Giungato et al. analyze Bitcoin focusing on three different aspects, all of which relate to its sustainability: environmental impacts, social issues and economic aspects.
They begin by rendering Bitcoin's sustainability embedded in Bitcoin's digital ecosystem, consisting of different elements of hardware, software and all sorts of data, with bitcoins having economic value due to their scarcity and the computing power needed to create them.

Considering the environmental aspect, the authors first purport that Bitcoin, due to its limited character, can be compared to a natural resource such as crude oil or gold: just like them, the

[29] *Giungato* et al. (2017), Current Trends in Sustainability of Bitcoins and Related Blockchain Technology 2f.
[30] *Gauer* (2017), Bitcoin Miners True Energy Consumption 2.

mining of bitcoins becomes more expensive as the number of bitcoins already in existence approaches the quantitative limit of 21 Million. Consequently, the mining of bitcoin requires better and more efficient hardware. However, the increasing demand for computing power and electricity does not pose a limiting factor to the mining of new bitcoins.
Referring to *McCook*, the authors state that the environmental costs of bitcoin mining are less than paper money, gold and banking systems. However, looking at the possibility of a transition of the traditional money system into the Bitcoin ecosystem, they estimate a huge amount of energy consumption to maintain the entire virtual monetary system. Regarding a Bitcoin Life-Cycle-Assessment (LCA) they -referring to *Loviscach*- suggest, that two main points are to be considered: computer energy consumption and disposal of e-waste.
Regarding the social aspects of Bitcoin sustainability, the authors point out the numerous possibilities to improve processes in different sectors such as health care, agriculture and electricity generation through blockchain technology. On the other hand, they assume that the politically independent nature of Bitcoin favors the most powerful users, eventually turning the distributed network in a monopolistic practice.
From an economic point of view, Bitcoin has attracted the attention of countless enterprises, customers and investors. One of the major obstacles of Bitcoin's track record is the relatively slow rate of transactions.

Putting Bitcoin into perspective of economic, environmental and social aspects, the group of authors from three different Italian universities provide a well-balanced and comprehensive picture of Bitcoin, its economical background and the multiple possibilities to use blockchain technology in society.

2. McCook *(2018)*: The Cost & Sustainability of Bitcoin

Hass McCook's provides the reader with very detailed and meticulously researched work on the economic and environmental cost of Bitcoin mining. McCook intends to illustrate exactly how big the energy expenditure is for the different difficulty cycles of the Bitcoin mining timeline and compares the relative sustainability of the Bitcoin network to the gold industry.
McCook starts by describing Bitcoin mining economics in the context of the micro-economy, macro-economy and global macro-economy surrounding Bitcoin and goes on to explaining the various factors of energy consumption of Bitcoin mining, including, amongst others, the manufacturing, transport and cooling of the hardware components necessary to mine Bitcoin.
He concedes that the Bitcoin Network uses large amounts of energy and, with 63 Mt per year,

emits comparatively high numbers of CO2eq (0,12% of global greenhouse gas emissions). However, he purports, a high usage of energy must not necessarily entail high CO2e emissions; high emissions are due to the composition of the world's energy grid. Consequently, with the focus on renewable energies and the generation of energy steadily becoming greener globally, so will Bitcoin mining. Criticism about Bitcoin having a low transaction volume in relation to the total power being used by the network is countered by McCook, referring to the upcoming of the so-called Lightning Network that has been live since March 2018. Furthermore, with the growing of the Bitcoin network, demand for energy will rise, which will lead to more research being conducted and innovations coming up in the energy sector, resulting in cheaper and more sources of renewable energy being used.

By embedding the environmental impact of Bitcoin mining into the micro- and macro-economic surroundings of the Bitcoin mining industry, McCook gives a comprehensive overview of economic driving factors of bitcoin miners and crucial points regarding environmental sustainability of the mining process.

3. Vranken *(Current opinion in environmental sustainability, Vol. 28, 2017)*: Sustainability of Bitcoin and Blockchain

With his paper, *Vranken* aims to provide the readers with an overview of recent literature regarding the sustainability of Bitcoin, focusing on environmental and economic aspects. More precisely, the author examines four questions: What factors play a role in the energy consumption of bitcoin mining? How large is this energy consumption? Does this impede sustainability? If yes, are there alternatives that can reduce energy consumption?

Vranken begins by setting out the history and the technological progress made in that field, starting from a simple Central Processing Unit (CPU) to the now state of the art Application-Specific Integrated Circuits (ASICs). He then goes on by examining the mining market and rendering economic factors such as USD earned per Gh/s and electricity costs.
He then goes into further detail about current literature regarding energy consumption of the bitcoin mining industry and gives in-depth explanation of mining technicalities. Keeping in mind the total amount of energy consumed worldwide in one year (2.3 TW) and economic factors such as electricity costs, *Vranken* concludes that the daily average energy consumption of the mining industry, depending on the hardware used, lies between 45 MW as the lower boundary value and 400 MW to 2.3 GW as the upper boundary value. Furthermore, applying the current average of 60 USD per MWh as electricity costs he reaches the conclusion that, at

the time of writing, only ASICs-based mining can remain profitable. He then provides an overview of conclusions regarding energy consumption reached in current literature. More precisely, *O'Dwyer* and *Malone* reach 100 MW to 10 GW, *McCook* estimates 120 MW and *Magaki* et al. 300-500 MW. Given these numbers, *Vranken* concludes that using only the latest mining hardware (ASICs), energy consumption for bitcoin mining could be as low as 45 MW. However, looking at the mining tools currently used by miners around the globe, a more realistic estimate of the current energy consumption would be around 100-500 MW.

Since power consumption is dependent on the energy-demanding Proof-of-Work mechanism, *Vranken* gives a brief overview of alternative mechanisms such as proof-of-stake and proof-of-space, which are known to be less power consuming, however, with intrinsic security issues at hand, not safe enough for public blockchains.

Summing up, *Vranken* provides the reader with a comprehensive overview of the bitcoin mining industry and its energy consumption, giving detailed information about the hardware used by miners, current literature, and a well-thought-out estimate of the energy used for bitcoin mining globally.

4. O'Dwyer / Malone *(2014)*: Bitcoin Mining and its Energy Footprint

In 2014, O'Dwyer and Malone were one of the first to publish a paper regarding the power consumption of the bitcoin mining process. Using the network hash rate as a starting point, they developed a model to estimate the energy consumption for the whole Bitcoin network.

After explaining the relevant economic and technological factors of Bitcoin mining, the authors go on by going into further detail into mining hardware. Against the background of technological progress of mining hardware, O'Dwyer and Malone define mining efficiency (E) as the hash rate (R) -measured in Megahash per second (Mhash/s)- divided by the power usage (P) (denoted by Joule); more precisely: $E = R / P$. This easily graspable formula provides a helpful reference number when comparing hardware. The higher (E), the cheaper the mining of bitcoins. Given that in order to reach a high efficiency it is advantageous to have low power usage (P), mining hardware has become much less energy consuming in the last couple of years.

From an economic perspective, Bitcoin mining is profitable as long as the price of one bitcoin is higher than the price of the energy needed to mine it. Thus, energy consumption will naturally be limited by the economics of the market while at the same time new hardware will be developed and introduced into the market in order to mine more efficiently. Using 0,1 USD per

kWh as electricity costs, the authors conclude that using older hardware (Core i7 CPUs, GPUs or FPGAs) mining is not profitable.
Regarding the total energy usage of the Bitcoin network, O'Dwyer and Malone reach the conclusion that Bitcoin mining uses between 0.1 and 10GW electrical energy, which is a number comparable to the usage of the Republic of Ireland.

5. <u>De Vries *(Joule, Vol. 2, 2018)*: Bitcoins growing energy Problem</u>

Alex de Vries starts by describing the Bitcoin network as „extremely energy-hungry“ and predicts an increasing power demand for the future. To support his argument, *de Vries* calculates, that at the current mining situation, in order to process one transaction the network has to perform 8.7 quintillion hashes. Evidently, given that electricity is the „primary fuel“ for the hashing operations, the power consumption of the Bitcoin network poses a major problem.

The total power usage of the network can be estimated quite easily: given that the Bitcoin network performs 26 quintillion hashes per second and the most efficient mining hardware (Antminer S9) uses 0.098 Joule per gigahash in terms of mining efficiency, *de Vries* concludes that the lower bound of the power consumption of the Bitcoin network is around 2.55 GW. However, since this formula takes neither other types of mining hardware nor other factors such as cooling into account, the real energy consumption remains unclear. A big part of the total number of mining operations are processed by institutional miners, e.g. mining machines that are clustered together in large mining operations, which, due to the high heat output, have higher cooling costs. Unfortunately, little is known about the exact energy consumption of big mining operations. Judging from different journalist's reports, *de Vries* presumes an electricity usage of *Bitmain*, one of the world's largest mining operations, of around 32 MW. However, *Bitmain* only represents around 1% of the global network hash rate. Therefore, it cannot be ruled out that hash rate is not the decisive factor when it comes to determining the energy consumption of bitcoin mining.

Regarding the expected electricity consumption in the future, *de Vries* uses an economic approach. Referring to *Adam Hayes*, *de Vries* purports that Bitcoin is considered a “virtual commodity with a competitive market of producers“. Following market mechanisms, he expects that miners will continue to mine bitcoins until their marginal costs equal their marginal product. Consequently, the next step is to determine what constitutes the costs of Bitcoin mining: the bigger part of the costs are made up by electricity and cooling costs, while hardware costs usually play a less relevant role, the higher their expected life span is. Using data from

Bitmain for the relevant variables (hardware production cost and lifetime), de Vries finds that electricity costs make up around 60% of the total lifetime costs of an Antminer S9, in an equilibrium the total electricity consumption can be expected to be around 7.67 GW.

In conclusion, de Vries shows that the Bitcoin network currently consumes at least 2.55 GW of electricity, and could reach around 7.67 GW in the future, making it comparable to countries such as Ireland and Austria.

IV) **Bitcoin from an LCA perspective**

Environmental issues are a crucial question of the Bitcoin system as it has been designed in a way resembling the winning of natural resources; the difficulty and thereby costs and efforts (i.e. energy used) rise with the system reaching the ultimate quantitative limit of 21 Million bitcoins.[31] Below I will give an overview of the concept of Life-Cycle-Assessments, describe the terms “functional unit“ and “system boundaries“ and lastly, apply the basic thoughts of the Life-Cycle-Assessment to the mining process of the Bitcoin system.

A) Overview

Life-Cycle-Assessment (LCA) is an internationally standardized (ISO 14040, 14044) method for the analyzation of environmental aspects and impacts of products and processes.[32] The ISO-definition of the LCA goes as follows:

> *“LCA studies the environmental aspects and potential impacts throughout a product’s life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.“*

LCA is a standardized way to examine the ecological impacts of products and processes and was designed to support the environmental management of a product. Its objective is to evaluate and name environmental effects and influences of a product or activity including the quantification of energy and materials used and the waste produced by them. Other than similar analysis concepts (e.g. the product line analysis), LCA focuses mainly on environmental issues and less on economic and social factors. Furthermore, an LCA considers the whole life cycle of a product and not only the environmental impact of production sites.

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[31] *Giungato* et al. (2017), Current Trends in Sustainability of Bitcoins and Related Blockchain Technology 3.
[32] *Klöpffer* / *Grahl* (2014), Life Cycle Assessment (LCA), A Guide to Best Practice 1.

Following the *cradle-to-grave* idea, LCA aim to capture every aspect of a products existence and its implications. In order to meet that general objective, in practice LCA follows a well-established and basic procedure:

1. *Definition of Goal and Scope*
2. *Inventory Analysis*
3. *Impact Assessment*
4. *Interpretation*

The *Definition of Goal and Scope* serves to specify the object, the reason and the target groups of the study and must be the first step in any LCA in order to ensure that it is performed consistently. The definition of the Goal, above all, aims to establish the range of application and the interest of realization; furthermore, it includes the definition of the addressed target groups as well as the public accessibility to the study. The definition of the Scope on the other hand refers to the description of the examined product / process *system,* which includes establishing the *function* of said system and the setting of its boundaries. However, even though the Definition of Goal and Scope systematically is the first step of an LCA, it is still constantly refined and adapted throughout the whole assessment process.[33]

The *Inventory Analysis* is defined in the ISO Standard 14040:2006 as a "*phase of life-cycle-assessment involving the compilation and quantification of inputs and outputs for a product throughout its entire life cycle*"[34]. In other words, the Inventory Analysis aims to analyze materials and energy used and consequently released by a system based on a simplified system analysis. The data won through the Inventory Analysis should be recorded in data sheets, allocated in a detailed inventory table and finally summed up in a comprehensive inventory table including the aggregated data.[35]
The third step, the *Impact Analysis* serves to classify and assess the effects of the environmental impacts identified in the inventory table of phase two of the LCA and consists of three steps itself: classification, characterization and valuation.[36]

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[33] *Klöpffer* / *Grahl* (2014), Life Cycle Assessment (LCA), A Guide to Best Practice 27-31.
[34] ISO (2006a Section 3.3).
[35] *Schaltegger* et al. (1996), Life-Cycle-Assessment (LCA) - Quo Vadis? 5; *Klöpffer* / *Grahl* (2014), Life Cycle Assessment (LCA), A Guide to Best Practice 63ff.
[36] *Schaltegger* et al. (1996), Life-Cycle-Assessment (LCA) - Quo Vadis? 5f.

The fourth and final phase of LCA is the *Interpretation* of the results. In this phase, conclusions are drawn from the Inventory Analysis and the Impact Assessment and recommendations for improvement are made. These recommendations correlate to the objective of the study set out in the *Definition of Goal and Scope* and offer basic approaches to redesign the product or process system in a way less harmful to the environment.[37]

As mentioned in the introduction, a full LCA, i.e. a full assessment (classification, characterization and valuation) of all impacts, would go beyond the scope of this work. Therefore, we will focus on the establishment of a functional unit as part of the *Goal and Scope Definition* and the setting of system boundaries as part of both the *Definition of Goal and Scope* and the *Inventory Analysis* of the Bitcoin system. Both, the functional unit as well as the system boundaries are necessary prerequisites for LCA. While the functional unit determines *what* we examine, the system boundaries determine *how much of it* or to what extent the examination is to be conducted.

B) Definition of Goal and Scope

1. Goal

The goals of a potential LCA study of Bitcoin would most likely be for reasons of comparing its environmental impact to other monetary systems and for the analysis and quantification of the environmental impact of Bitcoin transactions based on the original Bitcoin network as set out in *Nakamoto's* white-paper.

2. Functional Unit

The functional unit provides the reference to which all data relates to and to make different systems providing the same functionality comparable. The functional unit is defined by the *function* a system is supposed to fulfil. As a key element of the LCA, the functional unit has to be precisely outlined.

Every system serves a *function*. For instance, the function of beverage packaging is, primarily, to store and transport liquids i.e. to provide a customer with a certain amount of drinkable liquid.[38] Naturally, a function can be fulfilled in a different ways - to stick with the example, with different kinds of bottles, pouches or cartons. In order to adequately compare the different

[37] *Klöpffer* / *Grahl* (2014), Life Cycle Assessment (LCA), A Guide to Best Practice 329ff.
[38] Example taken from *Klöpffer* / *Grahl* (2014), Life Cycle Assessment (LCA), A Guide to Best Practice 3.

ways (*systems*) that fulfil the same function (i.e. have a specified performance), we first need to define the function. It is important to note, that by comparing *systems* with matching functions, we can also compare tangible goods to services, as long as their performances fulfil the function; thus, both goods and services fall under the definition of *products* in the context of LCA.[39]

For the purpose of this work, we need to define the functional unit about Bitcoin. Even though Bitcoin has probably gained most of its popularity as an investment vehicle, its developers initially intended to create a peer-to-peer currency. Thus, since Bitcoin's main purpose is to serve as a payment method, in the context of LCA Bitcoin's *function* is to conduct payments from one person to another. In order to compare it adequately to other means of payment, such as cash, bank transfers or the use of a credit card, we need to define the functional unit. Thus, it appears reasonable to set the functional unit as one Bitcoin transaction in the Bitcoin network (i.e. not using a trusted third party or an exchange system[40]) regardless of its size.

3. System Boundaries

Once the functional unit has been established, the next step is to set the system boundaries. The system boundaries determine which unit processes are to be included in the LCA. They "define the processes to be analyzed with regard to material and energy flows and emissions"[41], which consequently leads to a limited number of processes under examination as opposed to a „global model".[42] For instance, sticking to the introductory example of beverage packaging, the system boundaries determine, whether or not the production of the machines that produce the cartons are to be included in the examination. Thus, by defining system boundaries, a variety of environmental impacts that are to some extent linked to the process („upstream and downstream steps"[43]) are sorted out and pre-defined rules in the ISO-norm decide how and when processes should be cut off, depending on their overall contribution to the system's impact. This guarantees a manageable assessment process and straightforward and comparable results.

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[39] *Klöpffer* / *Grahl* (2014), Life Cycle Assessment (LCA), A Guide to Best Practice 3; *Wenzel* / *Petersen* / *Hansen* (2004), The Product, Functional Unit and Reference Flows in LCA 29.

[40] More than 80 % of Bitcoin transactions have a trusted third party as a counterparty, see: *de Vries* (2019), Renewable Energy Will Not Solve Bitcoin's Sustainability Problem, Joule 2019, 1.

[41] *Schaltegger* et al. (1996), Life-Cycle-Assessment (LCA) - Quo Vadis? 11.

[42] *Schaltegger* et al. (1996), Life-Cycle-Assessment (LCA) - Quo Vadis? 11.

[43] *Schaltegger* et al. (1996), Life-Cycle-Assessment (LCA) - Quo Vadis? 11.

In literature, three different ways of establishing system boundaries have been worked out, depending on the system under examination[44]:

- LCAs for the evaluation of companies with comparable activities
- LCAs for the evaluation of products having the same function
- LCAs for the evaluation of processes, which produce identical outcomes

In the case of Bitcoin, none of the types set out in literature matches the system perfectly; much rather a mix of these types would be a good match to describe the Bitcoin transaction process: First, we need to recognize that Bitcoin is neither a traditional company nor does it resemble to a product in the traditional sense. There is no board of directors and no owner or shareholders, there is no common object of the enterprise and no hierarchy and, for the environmental aspect, there is no ordinary production site from a traditional point of view. Finally, Bitcoin could be seen as a service instead of a company or product and miners and their hardware could be compared to a production site.

However, Bitcoin's main competitors are companies, such as banks, credit card companies or internet based companies such as PayPal. Thus, in order to reach comparable results, it makes sense to view Bitcoin in some aspects as a company. For instance regarding miners: They are comparable to employees with the right to profit sharing; Bitcoin's open-source code is similar to a company's articles of association and, of course, the fact that Bitcoin partly fulfils the same *function* as other systems that are considered a company (banks etc.). Regarding the product aspect of Bitcoin, we have to consider that Bitcoin does not offer a real product; much like a state currency does not have a product in the traditional sense. Thus, for the sole reason of LCA, it seems that we will reach the best results by considering Bitcoin under the aspects of a service, more precisely, the process of a Bitcoin transaction („single production process"[45]). However, also taking into consideration its comparability to its competitors, who in the most cases are companies, in order to reach results as complete as possible.[46]
In practice, we now need to figure out what activities, what materials and what energy has to be considered by the LCA. While there are different rules regarding different types of subjects

[44] Referring to other sources: *Schaltegger* et al. (1996), Life-Cycle-Assessment (LCA) - Quo Vadis? 12.
[45] *Schaltegger* et al. (1996), Life-Cycle-Assessment (LCA) - Quo Vadis? 13.
[46] *Schaltegger* et al. (1996), Life-Cycle-Assessment (LCA) - Quo Vadis? 13: "Hence, LCA involves not only the identification of any single operation within a system, but also the analysis of their links and interrelationships. (…) Consequently there is no absolutely correct and perfect data analysis, just more or less completely analysed systems."

of the LCA following individual parameters[47], there are some basic rules applicable to all LCAs. First, we need to consider all the activities that are performed for the special purpose of the system and all the activities that are necessary consequences of the system.

Furthermore, regarding the energy supply we need to consider the whole process, from the winning from the primary energy sources to the final energy supply. The materials and energy consumed must be directly linked to the production process or the activities related to it in order to be within the scope of the analysis.

As we see, the definition of system boundaries is crucial to any LCA. The dilemma of depicting a system as realistically as possible yet not being able to consider all the relevant factors must be met with a well-founded understanding of the underlying system and the cut-off criteria, as to know what factors to sort out and what to consider.[48]

C) Relevant Parameters of a Possible Inventory Analysis

Life-Cycle Inventory Analysis demands the compilation and quantification of all inputs and outputs for a product throughout its entire life-cycle.[49]

Bitcoin transactions are verified through the mining process, which relies on the computing power of miners who, in return, receive transaction fees and newly mined bitcoins (see above). Consequently, we need to take the mining process and all the activities, materials and energy linked to it, into the scope of the system under examination. As the mining process is comprised by multiple elements, we will sort out the non-essential parts of it in order to reach comparable results through LCA.

Following *Loviscach*[50] two fundamental aspects should be considered when assessing the environmental impact of Bitcoin, namely computer energy consumption and the disposal of e-waste. While these are indeed essential factors, we will only use them as a starting point. Instead of the disposal of e-waste we will consider the hardware used in its whole length, from production to disposal. Instead of solely quantifying computer energy consumption, we will also take into account the type of source of primary energy.

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[47] *Schaltegger* et al. (1996), Life-Cycle-Assessment (LCA) - Quo Vadis? 18-20.

[48] *Bousted* (1979), Handbook of Industrial Energy Analysis: "There is no such thing as a absolute or correct value for the energy needed to produce a kg of any commodity. The values obtained depend critically on the system boundaries chosen. However, the purpose of life-cycle-analysis is to provide as complete a description of the burdens of a products as possible and so although there may be no correct system it is certainly true that some systems are more complete than others."

[49] ISO (2006a Section 3.3)

[50] *Loviscach* (2012), The Environmental Cost of Bitcoin.

1. Hardware / Material Flow Analysis

In Bitcoin's early days, miners used the central processing units (CPUs) of regular hardware in order to mine Bitcoin. With rising Bitcoin demand, more miners have entered the market leading to tougher competition. To remain profitable, miners have been looking for more efficient mining hardware - a search that has been matched by developers, providing the market with ever more sophisticated mining instruments. First, in 2009 miners discovered that the graphic processing units (GPU) of their hardware were sufficient and more efficient to mine Bitcoin as GPUs use the same arithmetic logic units to process videos as are used in Bitcoin mining to generate SHA-256 hashes. In 2011, the next generation of hardware used was found: field programmable gate arrays (FPGAs). Starting with 2013, miners began to use application specific integrated circuits (ASICs), which are designed to conduct one kind of calculation only and consequently are more efficient than the hardware to this point: with the introduction of ASICs to the mining business, the hash rate increased from THash/s (10^{12}) to PHash/s (10^{15}) range.[51]

What will be examined?

At the time of writing ASICs are still the most profitable mining machines in the world, which does not mean that there is no one in the network using other sorts of equipment. As the different machines consist of different hardware components and partly serve other reasons than just mining, we first need to separate the analysis by the kind of machine under examination (CPUs, FPGAs, ASICs).

However, since there are different hardware producers in different parts of the world, obviously, the production's impacts differ from producer to producer. In order to keep the LCA as simple as possible yet still reach viable results we should only examine ASICs machines, as these are the most efficient and split up the analysis by producers. We can then compare the different outcomes and establish a range of outcomes which can later be compared to both outdated hardware (CPUs and FPGAs) as well as other means of payment fulfilling the same function (debit card, PayPal and cash transactions).

While this way will not accurately reflect the composition of mining hardware worldwide, it gives a good display of the most efficient - thus dominant - mining hardware and consequently

[51] *de Vries* (2019), Renewable Energy Will Not Solve Bitcoin's Sustainability Problem, Joule 2019, 1; *Wilson* (2018), Bitcoin Mining: A Thermal Perspective, in Electronic Design, available here: https://www.electronicdesign.com/industrial-automation/bitcoin-mining-thermal-perspective

of the future mining market. This is due to the fact that the smaller the block reward and the harder mining difficulty gets, the smaller - because of the hardware's economic inefficiency - the amount of users of lesser efficient hardware.

Can the hardware be used otherwise?

As opposed to CPUs and FPGAs, which serve numerous other uses rather than Bitcoin mining, ASICs, as the name *application specific* integrated circuits imply, serve one reason only. In our case: Bitcoin mining. Consequently, we do not need to take account of other hardware uses that could distort the outcome. This simplification of the LCA is another reason to focus on ASICs only.

Materials / Assembly / Transportation

After determining what hardware will be under examination, we need to look at the materials as well as the different processes and sub-processes necessary to produce and transport the hardware.

First, we consider what kind of materials are used and how they are won and transported to the production site.

Depending on the goal of the LCA (whether the LCA only aims to establish the global warming potential, the carbon footprint or rather the environmental impact), we should take into account whether or not recycled materials are used and how much of them actually get recycled in the end. Even if 95 % of electronic waste is potentially completely recyclable[52], only around 20 % is actually being recycled at the moment. The recycling process itself also has an impact on CO2 emissions and should therefore always be considered, except if it is part of a cut-off process due to the cut-off criteria.

Sophisticated machinery like ASICs consist of semiconductors and printed circuit boards (PCB) as well as different passive components and silicon wafers.[53] The production of these elements itself is highly complex and extensive (especially that of semiconductors). Thus, if there is no respective data easily obtainable, it appears reasonable to set the system's boundaries at the point where the producers already have readymade materials at hand.

52 *McCook* (2018), The Cost and Sustainability of Bitcoin 15.

53 *McCook* (2018), The Cost and Sustainability of Bitcoin 15.

Additionally we must consider the packaging of the products and the materials used to prevent it from damage, spoilage and contamination.

The assembly of the materials to produce the final product requires labor and electricity. As most ASIC machines are built by companies that exclusively build mining hardware, we must not consider other uses (and a consequential allocation of the externalities) of the production site or the workers.

Next, we must consider the transportation of the hardware and its materials respectively. First materials have to be transported to the production site, which, however, we will leave out of consideration. Then, since mining takes place all around the world, the machines must be delivered to either the local distributor or the customers themselves. A good part of the most renowned ASICs manufacturers are situated in China, some in the United States, Great Britain, Japan and Israel.[54] While China has been an attraction pole for miners so far, it now seems that many miners are leaving China for Scandinavia, Russia and the United States, which is due to friendlier regulation, faster internet and cheaper electricity.[55]

Evidently, there are miners as well as manufacturers all over the globe. As miners do not primarily choose their preferred hardware due to the place it was built at, the transportation of mining hardware is also a factor when it comes to the environmental impact of Bitcoin mining and therefore should not be completely left out of consideration. Furthermore, we must keep in mind that longer and more complex transports require more elaborate packaging of the product, especially in the case of highly sensitive materials as in mining hardware.

Finally, we must establish the life span of mining equipment and its consequences. The life span of mining machinery is relatively short due to two reasons. While technical issues do play a role (especially with regards to cooling), the main reason for the hardware's short lifespan is the fact that newer products are entering the market endangering the profitability of older machines.[56] In order to stay profitable it is crucial for miners to operate with the economically most efficient hardware. Consequently, outdated hardware soon becomes obsolete. As most of mining hardware can be recycled, there is value to extract from selling unneeded hardware to

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[54] see: https://www.asicminervalue.com/manufacturers (accessed 24th April 2019).

[55] *Bendiksen* et al. (2018), The Bitcoin Mining Network 4f: However, it is still estimated that the majority of miners (around 60 %) operates from China. Other sources see the proportion of Bitcoin miners located in China at around 48 % (*de Vries* (2019), Renewable Energy Will Not Solve Bitcoin's Sustainability Problem, Joule 2019, 3).

[56] *McCook* (2018), The Cost and Sustainability of Bitcoin 15.

scrap merchants; if not, the miner must consider its disposal. Thus, the lifespan of mining hardware is an essential factor for LCA that, due to its implications for the disposal or recycling of the machinery (and the transport to the respective sites), must be taken into account.

To summarize: When establishing material expenditure of Bitcoin mining, we should consider the following aspects. First, in order to keep the LCA simple yet conclusive and revealing, we should focus on ASICs only, as this is the most dominant type of hardware and is used for Bitcoin mining only. Second, regarding the materials used, we should focus on the ready-made materials used before assembling them as considering the raw material extraction could make the LCA unnecessarily bulky and inconclusive. Third, we have to take into account the location of the production site and the distribution of miners around the world in order to accurately reflect the impact of the transportation of the hardware. Fourth and final we need to consider the average life span and possible reuse of the hardware or its disposal.

2. Operations / Energy Analysis

After establishing the relevant factors regarding materials, manufacturing, packaging and transportation, we look at Bitcoin's presumably biggest problem: the high-energy expenditure necessary to keep up the functionality of the network. By analyzing the use and operation of mining machines during their lifetime, we aim to determine the ongoing environmental impact of the up and running Bitcoin network. Thus, below I will work out relevant factors to keep in mind when examining Bitcoins operational energy expenditure.

Environmental problems are frequently due to disadvantageous energy consumption, i.e. it is either very high or extracted from sources harmful to the environment. Therefore, energy analysis is an essential part of any LCA. The question to be answered in this part of the LCA is how much energy a specific process needs for a certain output. This not only includes the "final energy" bought by the customer, but the whole primary energy expenditure necessary to lead to the predefined outcome. That means, we must also consider factors like the transport and storage of energy, the efficiency of plant and energy conversion as well as grid losses regarding the electricity.[57]

[57] *Klöpffer / Grahl* (2014), Life Cycle Assessment (LCA), A Guide to Best Practice 74ff.

First, we need to consider what machines are used and how much electric energy they consume. All machines mentioned above (CPUs, FPGAs, ASICs) require electricity in order to fulfil the task of generating hashes. The distinction between the different kinds of mining machines is important because unlike ASICs, CPUs are not only used for mining but for other purposes as well, making it harder to distinguish between the proportion of electricity used for mining and the part used for other operations; furthermore, the different kinds of hardware need different maintenance and cooling and emit different amounts of heat (see below). While several authors have conceded that it is impossible to tell exactly how many machines of a kind are used in the network and how much energy is consumed by each, they have created well thought out estimates using, for instance, the total computational power used by the network or the total mining reward available to miners.

According to these models, authors reach results with a total computational power ranging from 40 TWh to 62.3 TWh for 81.4 million transactions processed in 2018.[58] In any case, it should be kept in mind that the most cost efficient machines will lead to the biggest profits. Consequently, Bitcoin's "the winner takes it all" principle simply encourages miners to look for less energy consuming hardware as it will lead to better performance results and the biggest profit.

Second, we have to establish the locations of the miners and look at the respective energy source as Bitcoin's environmental impact is supposedly aggravated by the fact, that most mining facilities are located in regions relying on coal as a primary source of power. As mentioned above, the majority of mining still takes place in China, where renewable sources of energy have become more popular during the last years. However, China is faced with the problem that a good part of the energy generated from renewable sources cannot be used due to a lack of transmission capacity - a problem known as curtailment.[59] The curtailment rate as well as the general energy grid composition differ from region to region, which makes it crucial to precisely pinpoint the miners location, as it is argued that Bitcoin is partly using the otherwise wasted surplus of renewable energy.[60] Thus, even though China is heavily subsidizing the renewable energy sector, we must take into account how much of the energy from green sources is actually used by miners and how much remains unused. Outside of China,

[58] *de Vries* (2019), Renewable Energy Will Not Solve Bitcoin's Sustainability Problem, Joule 2019, 1.

[59] *Stanway* for Reuters, China's renewable power waste falls, but warns of challenges, available here: https://www.reuters.com/article/us-china-renewables-waste/chinas-renewable-power-waste-falls-but-warns-of-challenges-idUSKBN1KL005 (accessed 24th April 2019).

[60] *Bendiksen* et al. (2018), The Bitcoin Mining Network 5ff.

miners focus mainly on the USA, Canada and Scandinavia (including Iceland) as well as Russia and Georgia. With renewables penetration ranging from 17 % in Russia to 100 % in Iceland and parts of the USA and Canada[61], it shows that the energy grid differs from region to region. Besides the energy grid, another reason why location is important is the difference in temperature and consequently the differing requirements for heating and the possibility of reuse of emitted heat (see below). Subsequently, in order to reach accurate results we must establish the local distribution of miners around the world and the respective local energy grid.

Third, we need to consider the cooling of the hardware and the possible reuse of the heat emitted by it. Mining hardware requires appropriate temperature to operate adequately. In order to maintain mining machinery at a steady temperature, different cooling systems are used. While these systems differ depending on the hardware in use, they are based in large part on a concept using chilled water as coolant and all require additional energy to operate. Regarding single ASIC mining rigs with multiple printed circuit boards, thermal requirements are usually met with holistic cooling approaches using forced convection, multiple fans and heatsinks. Bigger scale mining farms, however, require more sophisticated ways of cooling. Due to their high heat emissions they are usually found in cool climate locations (such as Iceland) using the cold-air climate as a basis for their cooling mechanisms. Cold air can be drawn in using vents on the building exterior and distributed across the machinery through exhaustion mechanisms from the roof of the building.[62]

Apart from cooling systems, we have to consider the possible reuse of the heat emitted by the hardware. The vast amount of excess heat emitted by mining hardware has been used in different projects around the world (e.g. Canada[63] and Siberia[64]) to heat homes. Thereby convected thermal energy from the hardware is recycled and reused through a connection of the mining system to the heating system of houses instead of releasing it to the environment. While this reuse does not mitigate the environmental impact of Bitcoin mining, it provides heat

[61] *Bendiksen* et al. (2018), The Bitcoin Mining Network 8.

[62] *Wilson* (2018), Bitcoin Mining: A Thermal Perspective, in Electronic Design, available here: https://www.electronicdesign.com/industrial-automation/bitcoin-mining-thermal-perspective

[63] *Peters* (2018), A Solution to Bitcoins Energy Waste: Use It to Warm Building, available here: https://www.fastcompany.com/90268985/a-solution-to-bitcoins-energy-waste-use-it-to-warm-buildings

[64] *Haig* (2017), Siberians Use Cryptocurrency Miners to Heat Homes, news.bitcoin [online], available here: https://news.bitcoin.com/siberians-use-cryptocurrency-miners-heat-homes/

that otherwise would have had to be generated through different means and thus should be considered in a comprehensive life-cycle analysis.[65]

In recapitulation: to adequately capture the environmental impact when conducting an LCA of one Bitcoin transaction we should consider the following aspects regarding the energy expenditure during the use of the hardware:

First, we should try to establish which machines are used and to what proportion as this helps us to classify on the one hand whether or not energy is solely used for Bitcoin mining or other operations and on the other hand, what cooling mechanisms are necessary.

Second, we should consider the distribution of miners around the globe, as the location gives crucial information about the energy grid and climatic circumstances in the respective area. Third, we need to consider the cooling mechanisms used to keep the hardware at a steady temperature and whether or not excess heat can be reused for different purposes.

D) Interpretation and Improvement

Giungato et al. have shown that costs and efforts rise as Bitcoin reaches its ultimate limit.[66] Thus, we can expect Bitcoin's environmental impact to grow further and further, which leads to the question, what to do about it?

The biggest part of Bitcoin's energy consumption problem is due to the Proof-of-Work (PoW) concept. While there is a negative narrative surrounding it, its supporters point out that out of all currently used consensus algorithms PoW reaches the highest degree of trust minimization.[67]

With rising Bitcoin demand, it becomes harder to fit pending transactions into a block. In order to have their transaction executed first, higher fees are paid, posing as an incentive for miners. With higher fees, more miners are entering the market, which presumably leads to two different effects: first, more energy will be consumed due to the higher number of transactions. Two, due to more miners in the market, the competition becomes tougher. In order to remain profitable, miners will invest in more efficient, i.e. less energy-consuming hardware, leading to an increase in the demand of efficient hardware, which will consequently lead to more

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[65] For a comprehensive overview of cooling and heat recycling regarding Bitcoin mining hardware see: *Nguyen* & *Hoang* (2018), Reusing Waste Heat from Cryptocurrency Mining to Heat a Multi-Family House, available here: https://www.theseus.fi/bitstream/handle/10024/149939/Nguyen_Tri.%20Hoang_Anh.pdf?sequence=1&isAllowed=y

[66] *Giungato* et al. (2017), Current Trends in Sustainability of Bitcoins and Related Blockchain Technology 2.

[67] *Bendiksen* et al. (2018), The Bitcoin Mining Network 1.

innovation in the field of mining hardware and newer, more efficient hardware pushing the older, more power-consuming hardware out of the market.[68]

Finally, while not mitigating Bitcoin's carbon footprint, another way to compensate environmental impacts is by putting blockchain technology to a sustainable use. While it is true that Bitcoin is highly energy consuming, its underlying technology has the potential to offer numerous benefits for all parts of society.[69] Consequentially, we have to find ways to promote the use of the blockchain technology in a way not consuming disproportionate amounts of energy compared to its surroundings. As shown in literature, there are various ways to encourage a more sustainable development of blockchain applications without damaging the blockchain sector itself - one of them is through public policies.

Existing policy measures have until now almost exclusively targeted the financial sector - more precisely, digital currencies - without taking into account environmental aspects. In order to mitigate environmental impacts, regulators need to motivate industry members to shift to less impactful processes. One way would be to focus on the polluter, for instance, by making the polluter pay proportionally to the pollution he produces, in other words, internalize negative externalities. By that, the polluter is held financially responsible for the impact he has on the environment and is thereby incentivized to find processes and blockchain applications less harmful to the environment. Furthermore, revenues are raised that can be spent on environment friendly initiatives. Other options target the developer, the owner or the customer at point-of-sale.[70]

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[68] *Martindale* (2019), Bitcoin mining profits are on the rise. But don't buy your own hardware just yet, Digital Trends, available here: https://www.digitaltrends.com/computing/bitcoin-mining-profits-rise-2019/ (accessed 25th June 2019)

[69] *Truby* (2018), Decarbonizing Bitcoin: Law and Policy Choices for Reducing the Energy Consumption of Blockchain Technologies and Digital Currencies 400.

[70] *Truby* (2018), Decarbonizing Bitcoin: Law and Policy Choices for Reducing the Energy Consumption of Blockchain Technologies and Digital Currencies 401, 403, 408.

V) How do Competitors Compare?

Establishing the environmental footprint of a Bitcoin transaction only makes sense if there is data to compare it to. The data we need for a viable comparison must accurately reflect the environmental impact of Bitcoin's competitors, i.e. processes that fulfil the same function, namely, transferring value from one person to another. There are different ways to conduct a transaction of that sort, provided by different companies using different methods. Below, I will give a brief overview of Bitcoin's most obvious competitors and their environmental impact.

A) Debit Card / Credit Card Payments

Due to its size, complexity and secrecy, it is quite difficult to obtain valid data regarding the environmental impact of the banking sector or single payments conducted through it. However, debit card or credit card payments are amongst the most popular forms of payment and therefore must be considered in this paper. While there are numbers provided by big financial services providers like *Visa*, who state on their website to use renewable energy only and even provide concrete numbers as to the carbon footprint of their transactions (0.4g of Carbon per transaction in 2014)[71], these numbers should be met with caution[72], as they come from the company itself.[73] However, there are models in literature providing a well thought out estimate of the environmental costs of payments conducted by the traditional financial sector that give a good indicator of how much energy is consumed and how big the environmental impact actually is.

In 2014, McCook worked out an estimate of the energy consumption and carbon footprint of the banking sector and compared it to Bitcoin mining. His assumptions are based on a model that aims to assess the carbon footprint of businesses based on business sectors using the number of people employed in that sector, the number of locations (bank branches and ATMs), the annual revenue and the number of square feet of facilities. Using this model, he reaches the conclusion that bank branches emit 383.1 million tonnes of CO_2 per year and ATMs an

[71] see: https://www.visaeurope.com/about-us/corporate-responsibility/sustainability-the-environment (accessed 25 April 2019).

[72] As an example of inaccurately reflected data: *Visa* provides the number of 680,560 gigajoules (GJ) as their estimated energy use for 2017, only mentioning incidentally that this merely contains energy from Scope 1 and Scope 2 sources, leaving out of consideration energy from Scope 3 sources which amount to around 40 % of the total energy usage in 2017 (see: *Visa*, Corporate Responsibility Report 2017, 14).

[73] Since the IPO of *Visa* in 2008, the company annually examines their environmental footprint which is published in their Corporate Responsibility Report, including data on global energy usage,water usage, waste production, landfill-diversion and greenhouse gas (GHG) emissions. For the 2017 Report see: https://usa.visa.com/dam/VCOM/download/corporate-responsibility/visa-2017-corporate-responsibility-report.pdf; for the more detailed 2016 report see: https://usa.visa.com/dam/VCOM/download/corporate-responsibility/visa-2016-corporate-responsibility-report.pdf

additional 3.2 million tonnes a year, which sums up to a total of 386.3 million tonnes of CO_2 per year for the whole banking sector.[74] While this gives us a good overview of the banking sector's energy expenditure for its ongoing business and the respective carbon footprint, it lacks assumptions and conclusions for the material input necessary to start and keep up the processes and the energy used in the production and assembly processes that would be taken into account in an LCA of the banking sector's key functions.

Following a different approach, *De Nederlandsche Bank* in 2017 conducted an LCA of debit card payments, aiming to evaluate their environmental impact. They define the goal and scope of the analysis as the impact of a debit card payment using the product system for point-of-sale debit card payments in the Netherlands. In order to reach accurate results, they try to include all relevant factors into their system's boundaries. As a result, they split up the debit card payment system into three parts that need to be considered: the debit card used by the customer to initiate a debit card payment, the corresponding terminal used by the businesses to receive payments and data centers processing the payments.[75] The authors start the inventory analysis by thoroughly examining the debit card itself, taking into account the different uses of debit cards besides transactions (e.g. withdrawing cash at ATMs), the material input used for the different parts of the card (debit card body and the chip), the manufacturing and assembly of the card, the different phases of transportation and the disposal of the cards.[76]

Regarding the terminals the authors use a ‚model' payment terminal due to the negligible differences in material and energy use of different terminal models and provide a detailed overview of its components and functionality and the energy necessary to maintain it.[77]
With regard to the physically complex data centers, the authors closely examine the IT equipment as well as the power equipment necessary to process the payments conducted through cards and terminals. As for their power supply, *Lindgreen* et al consider both, the quantity of the energy used as well as its quality, i.e. whether or not it has been extracted from renewable sources.[78]

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[74] *McCook* (2014), An order-of- magnitude estimate of the relative sustainability of the Bitcoin Network 22.
[75] *Lindgreen* et al. (2017), Evaluating the environmental impact of debit card payments, DNB Working Paper No. 574 / October 2017, 4.
[76] *Lindgreen* et al. (2017), Evaluating the environmental impact of debit card payments, DNB Working Paper No. 574 / October 2017, 5ff.
[77] *Lindgreen* et al. (2017), Evaluating the environmental impact of debit card payments, DNB Working Paper No. 574 / October 2017, 8ff.
[78] *Lindgreen* et al. (2017), Evaluating the environmental impact of debit card payments, DNB Working Paper No. 574 / October 2017, 13ff.

Using this methodology, the authors reach the result of 3.78 grams of CO_2-equivalents per transaction or 12.2 million kg of CO_2-equivalents as the environmental impact of all debit card transactions conducted in the Netherlands in 2015.[79] Of all the analyzations of the environmental impact of bank transactions, this one is, in my opinion, one of the most comprehensive and therefore best suited to compare with a diligently conducted LCA of Bitcoin transactions. However, even though its authors consider virtually everything that can be considered in an LCA, some aspects must be kept in mind when comparing it to Bitcoin transactions: First, the authors use data obtained in the Netherlands, which means short transportation distances. Second, the authors leave out of consideration the transportation of raw materials used for the cards and the terminals from South East Asia to the Netherlands as there is no information available. Third, packaging has been left disregarded, which, in the case of Bitcoin mining equipment, should also be considered due to the high sensitivity of the hardware and the complex character of hardware transports. Lastly, we should keep in mind that most of the data used in this paper relies on estimates, which, however, would also be the best option available for an LCA of Bitcoin transactions.

To get back to *Visa*, while their Corporate Responsibility Report consists to a good part of vague promises, it still helps us seeing the differences in energy usage of common financial services providers and Bitcoin, given we view the data provided with the necessary scrutiny.

Visa states that of its total energy usage, 54 % are associated with data centers, 36 % with offices and 10 % with travel.[80] Comparing the *Visa* business model to Bitcoin it becomes obvious, that a good part of the energy consumed by *Visa* is associated with elements of its operations that do not play a role in the Bitcoin network. While data centers can be compared to Bitcoin mining farms or other sorts of mining arrangements, Bitcoin needs neither offices nor traveling to maintain its functionality. Obviously, Bitcoin and Visa do not offer exactly the same services, as Visa is, amongst others, a credit card provider while Bitcoin is merely a payment system. However, looking at Visa from an LCA perspective, we see that the *function* of one transaction can be fulfilled without around 46 % of the total the energy usage going into factors such as traveling and offices. To solve the problem of VISA, which offers more services, one could use an accounting approach. It could be based on physical considerations,

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79 *Lindgreen* et al. (2017), Evaluating the environmental impact of debit card payments, DNB Working Paper No. 574 / October 2017, 17.

80 *Visa*, Corporate Responsibility Report 2017, 14, available here: https://usa.visa.com/dam/VCOM/download/corporate-responsibility/visa-2017-corporate-responsibility-report.pdf (accessed 29th April 2019).

for example if it is known how much computing power is actually needed by the different services. If this information is not available, another option to do that would be via economic accounting – i.e. the total energy consumption of the data center is distributed to the different services according to their share in the overall profit of VISA.

B) PayPal

Besides the different kinds of bank transactions another form of non-cash transactions are e-wallet transactions. The number of e-wallet transactions is growing rapidly around the world, counting 41.8 billion e-wallet payments in 2018, which equals 8.6 % of global non-cash payments in 2018.[81] PayPal, an American company founded in 1998 as *Confinity*, operates a global online payments system that offers e-wallets and real time and cross border e-payments.

On their website, *PayPal* point out their dedication to environmental responsibility and give some insights into their data regarding the environmental impact of their business and their environmental policy. In the "2017 Global Impact Report"[82] they provide the public with a comprehensive collection of data representing their environmental footprint. As always, data publicly disclosed by corporations should be met with caution. First, *PayPal* state that their operations used 325.089 MWh of electrical energy in 2017. They concede that the biggest part of their energy consumption, 215,628 MWh precisely, is associated with their data centers; the lesser part of their energy usage, 109,461 MWh is associated with their offices.

Consequentially, *PayPal* state that their focus is set on increasing the use of renewable energy in the data centers. In the course of this, they purport that they have found different ways to utilize renewable energy, for instance, leasing space that uses 100 % renewable energy and external air temperatures to chill water and support air conditioning. However, while this sounds promising, at the time of writing only 62 % of the energy consumed by the data centers is offset by renewable sources, with the renewable energy share of the total energy consumption of *PayPal* only lying at 45 %.[83] Regarding their carbon footprint, *PayPal* purports a total of

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[81] *Capgemini / BNP Paribas* (2018), World Payments Report 2018, 12, available here: https://worldpaymentsreport.com/wp-content/uploads/sites/5/2018/10/World-Payments-Report-2018.pdf
[82] *PayPal*, 2017 Global Impact Report, available here: https://www.paypalobjects.com/digitalassets/c/website/marketing/global/about/responsible-practices/PYPLGlobalImpactReport2017.pdf (accessed 26th April 2019).
[83] *PayPal*, 2017 Global Impact Report 14.

93,471 tonnes of CO_2e emitted by them in 2017, including the emissions associated with traveling, data centers, offices and other facilities.[84]

In comparison to the Bitcoin network, we can basically draw the same conclusions as we did with *Visa* and the banking system in general with a few specifications: offices and business travels, which are an essential part of *PayPal's* operations, are not necessary to maintain Bitcoin's functionality. However, looking at *PayPal* from an LCA perspective, unlike *Visa* or banks, *PayPal* does not provide its customers with any kinds of cards or maintain bank branches and can therefore be considered efficient in fulfilling the *function* of one transaction.

C) Cash Transactions

Cash transactions are the oldest of the payment methods taken account of in this paper. As opposed to the other methods explained so far, cash transactions do not have a private corporation maintaining its functionality but rather they are based on the legally founded monetary system of the state providing the cash. While cash transactions might seem like the simplest form of payment at first glance, setting the limits of the monetary system of a state or other public entities such as the European Union in order to accurately evaluate their environmental impacts and reach comparable results might in fact be the most complex of all the payment methods laid out in this paper. The multi-facetted system comprises various elements that need to find adequate consideration such as central banks, printing works and coin minters, ATMs and the respective maintenance providers, as well as cash-transport providers and retail banks.

In 2018, *De Nederlandsche Bank* conducted an LCA of cash payments in the Euro area[85] using data from the Netherlands to quantify the impact of an average cash payment on the environment and climate and identify areas for improvement. In order to reach telling results, the authors set two functional units: the first functional unit is the entire cash payment system in the Netherlands in 2015, the second is one average cash payment in the Netherlands in 2015. In their study the authors consider the different life cycles of bank notes and coins and therefor split up the cash system into five subsystems: the production of banknotes, the production of coins, the operation phase of banknotes and coins in which they are distributed to ATMs, bank branches and retailers in the cash payment system, the end-of-life phase of banknotes and the

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[84] *PayPal*, 2017 Global Impact Report 15.
[85] *Hanegraaf* et al. (2018), Life Cycle Assessment of Cash Payments, DNB Working Paper 610/2018.

end-of-life phase of coins.[86] Sticking to this structure, the authors then go on to the *Inventory Analysis,* thoroughly dissecting the European / Dutch monetary system to set out the different materials and processes necessary to conduct one cash payment and keep up the entire cash payment system. Using the ReCiPe method, they conclude that one cash transaction has an environmental impact of 637 µPt with a GWP of 4.6 grams CO_2e while the Dutch cash payment system as a whole amounts to 2.35 million Pt and 17 million kg CO2e which corresponds to 0.009% of the total GWP of the Dutch economy in 2015.[87] These results also show that the average cash payment's environmental impact is 36 % higher and its GWP 21 % higher than that of the average debit card transaction.[88] Furthermore, the authors find that the biggest share in the total environmental impact is associated with the "operation phase", which starts after the production of the coins and notes and ends when they are deemed unfit for payment and includes different kinds of processes and factors such as transports, ATMs, cash handling (counting and inspection of coins and notes), and the end-of-life phase. The second biggest share is associated with coin production, the third biggest with banknote production.[89]

In conclusion, the working paper of *De Nederlandsche Bank* gives a highly detailed and well thought out LCA of cash payments in the Netherlands, which enables us to draw a few comparisons to the Bitcoin network. There are some obvious points of critique to the cash payment system, such as the fact that the production of a product as outdated as coins makes up the second biggest part of the total environmental impact or the inefficient necessity to count the money at the POS, which I will not look into deeper. I will, however, point out that the authors did not consider the central banking system backing fiat currencies within the system boundaries of their LCA; central banks play a crucial role in any fiat currency system, as they are responsible for the management of the money supply. Bitcoin, on the other hand, does not need a central authority regulating the amount of Bitcoin in circulation as this has been predetermined in the original Bitcoin code. As this is one of the essential characteristics of Bitcoin, in order to adequately compare the two systems, the LCA of the cash payment system should consider the environmental impact of central banks in the system boundaries of the LCA.

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[86] *Hanegraaf* et al. (2018), Life Cycle Assessment of Cash Payments, DNB Working Paper 610/2018, 4.
[87] *Hanegraaf* et al. (2018), Life Cycle Assessment of Cash Payments, DNB Working Paper 610/2018, 24.
[88] *Hanegraaf* et al. (2018), Life Cycle Assessment of Cash Payments, DNB Working Paper 610/2018, 22.
[89] *Hanegraaf* et al. (2018), Life Cycle Assessment of Cash Payments, DNB Working Paper 610/2018, 15ff.

VI) Conclusion

Bitcoin is the world's leading cryptocurrency and a precursor for the distributed ledger technology in general. This paper aimed to approach Bitcoin and its environmental impact from the LCA perspective. In order to reach viable results, LCA follows a strict set of rules. If one applies these rules to evaluate a system like the Bitcoin network, one needs to take into account the specifics of Bitcoin, particularly, the Proof-of-Work system.

Following the four steps of LCA, we first determined the *Goal* as the analyzation and quantification of the environmental impact of Bitcoin transactions and, as for the *Scope*, we defined the *functional unit* as one Bitcoin transaction in the Bitcoin network. Regarding the *System Boundaries*, we concluded that it seems reasonable to look at Bitcoin as a process and take into account all the energy, materials and activities that are directly linked to the process.

The crucial part of this paper lies in the *Inventory Analysis* and the evaluation of the relevant parameters of a Bitcoin transaction for LCA, which we split up in the evaluation of hardware and energy expenditure.

Regarding the hardware we concluded the following: In order for the LCA not to result in a project too bulky to conduct, we should focus, first, on ASICs only, and second, only take into account readymade materials before the assembly; in order to get telling results we need to consider, third, the location of the production site of the hardware and fourth and last, its average life-span.

As for the energy, we first need to determine what kind of machines are used to mine bitcoins and at what percentage in order to assess whether or not they simultaneously fulfil other functions and what cooling mechanisms are necessary. Second, we need to consider the location of the miners (or rather: mining farms) in order to determine what local energy grid they draw their energy from and assess the respective local climate. Third and last, we need to evaluate the different cooling systems used to keep the hardware at a steady temperature.

In the fourth and last step of an LCA, we look at the interpretation and room for improvement. As this is not a full LCA of Bitcoin but rather an approach and evaluation of the relevant parameters of a possible Bitcoin LCA, the suggestions for improvement are kept very general, with a focus on the sustainable use of the blockchain technology and a greener regulation of the digital currency sector.

After setting out the basic points of a Bitcoin LCA, we compared Bitcoin to its competitors, more precisely, we compared the evaluation of Bitcoin through LCA with the assessments of similar processes and companies. We concluded that most of the different methods used, lack some kind of parameter that we consider important to a Bitcoin LCA. Thus, while there are a lot of numbers going around regarding the energy-consumption or the environmental impact of traditional payment methods, it is important to diligently examine the method applied by the respective authors in order to reach their results and compare it to the relevant parameters of a system as peculiar yet innovative as the Bitcoin network.

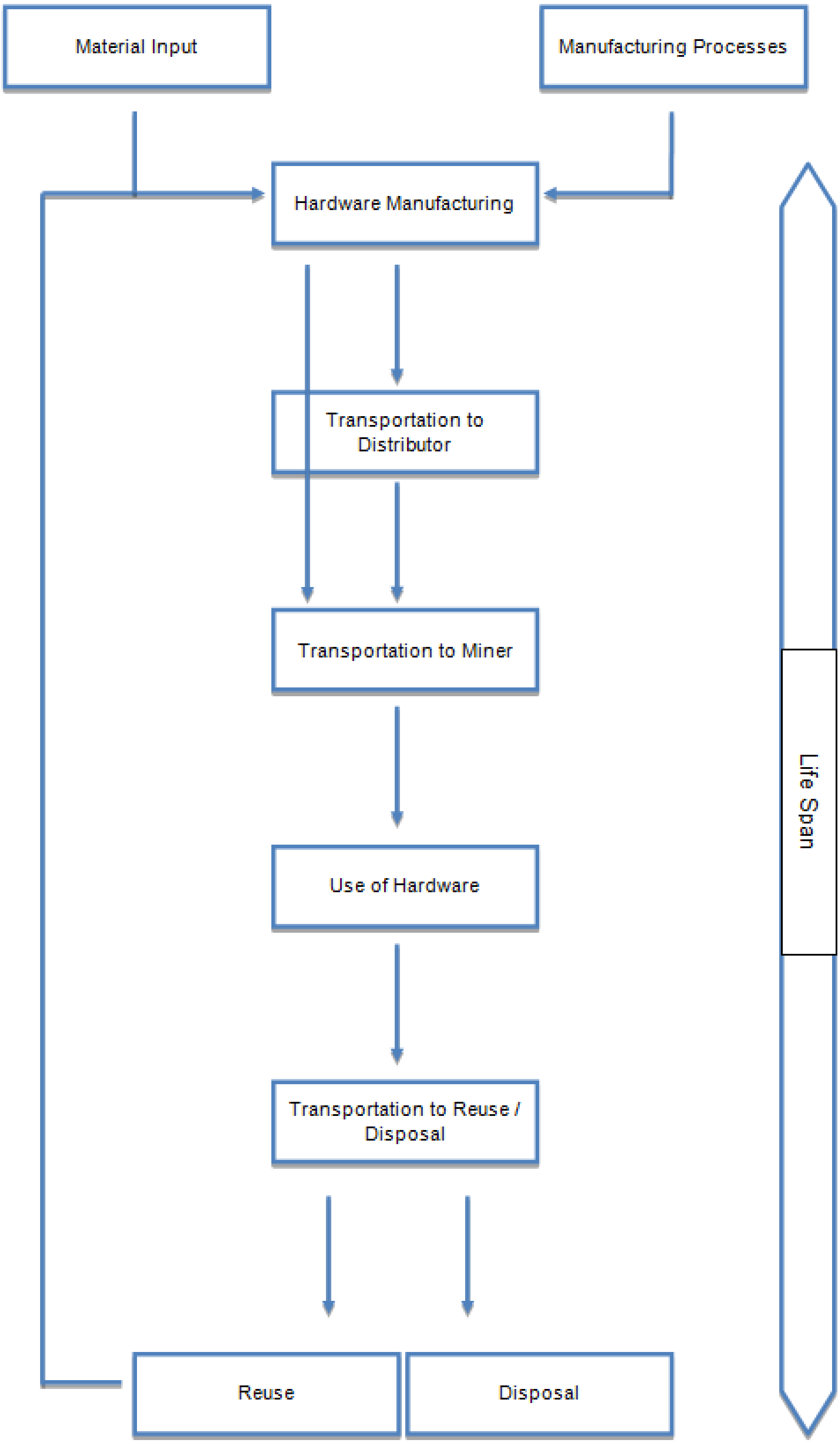

Figure 1: Schematic overview of the Bitcoin mining system

Figure 1 – A short explanation:

Mining hardware is created by combining material input with manufacturing processes and can be compared to a traditional production process of any electronic device. When the production process is finished, the hardware will find its way to the customer, either directly from the production site or through a distributor. Once the customer is in possession of the hardware, he/she will use it until it is not efficient anymore to generate a positive revenue or broken. If, in addition, the customer does not wish to use the hardware anymore, this will lead to the next step of "Transportation to Reuse / Disposal". After this, the final step then consists of sorting out the components of the outdated or broken hardware for Reuse or Disposal. For the materials that are reused the life cycle starts again from the beginning, everything else becomes waste. This figure should be an example that shows the Life Span of Bitcoin mining hardware.

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