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Original research article

Life cycle assessment of Bitcoin mining in the top ten miner countries

Rahim Zahedi[1], **Alireza Aslani**[1,*], **Mohammad Ali Nasle Seraji**[2]

[1] *Department of Renewable Energy and Environmental, Faculty of New Science and Technologies, University of Tehran, Tehran 11366, Iran*

[2] *Department of Energy Engineering, Science and Research Branch Islamic Azad University, Tehran 11366, Iran*

*** Corresponding author:** Alireza Aslani, Alireza.aslani@ut.ac.ir

Abstract: An unprecedented emergence has occurred for the cryptocurrencies among enterprises, customers, and investors as a result of the growing number of internet connections worldwide. The most popular cryptocurrency is Bitcoin representing the rise of digital payment systems. Though, harsh criticism has been also created for cryptocurrencies about their environmental sustainability and power consumption, decelerating the acceptance of bitcoin by consumer as a means of payment. The ecological impact or footprint of a process is determined mainly through life-cycle-assessment (LCA) quantifying all material flows' inputs and outputs for a process or product and their effect on the environment. This study provides LCA-based framework to show the environmental impacts of Bitcoin mining from top ten miner countries (China, USA, Kazakhstan, Russia, Iran, Malaysia, Canada, Germany, Ireland, Norway). The results show that with the share of 53.3% of the world's mining, China has the most negative environmental impact specially in marine ecotoxicity with 26.8 kg 1,4-DCB and human health with 0.0043 DALY but with the equal mining ratio Germany and Kazakhstan have the most negative environmental impacts.

Keywords: life cycle assessment; blockchain; environmental sustainability; Bitcoin

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1. Introduction

Recently, environmental issues have been of great concern to the society at large including global warming, depletion of natural resources, loss of biodiversity, and chemical pollution[1]. Increasingly, businesses' actions affect the environmental sustainability. Therefore, reliable tools are required to manage the environmental issues and measure and quantify the business activities' environmental impacts[2]. The fast increment in the crypto-assets' prices at the end of 2017 represented the effects blockchain-technology on the world. Although it has various advantages and several applications, according to the young technology's supporters, its usage has been known as the primary technology for the Bitcoin network. Bitcoin is based on the trust of the people accepting it as a means of payment as any currency. Moreover, it is a difficult task to obtain such trust. This task has become more difficult by emergence of criticism on Bitcoin. This criticism highlights the Bitcoin network's heavy energy consumption the and the system's negative intrinsic incentives. Considering the questions regarding the sustainability in financial sector and banking, Bitcoin users and developers have considered the extent required for mitigating the environmental effect of their financial transactions[3].

With the rising approval of cryptocurrencies, concerns have been raised about the Bitcoin's sustainability since a high amount of electricity is used by the Bitcoin network for mining. Therefore, it may have substantial environmental impacts. Various estimations have been published on energy consumption by Bitcoin, which reflect the uncertainty of these evaluations. For instance, it was claimed that more energy is used for Bitcoin mining than mining gold[4]. This was equal to energy consumption of Switzerland[5] all the world's energy by 2010[6]. It is alone in charge of not reaching the Paris agreement[7]. According to the present studies both in academic and gray literature, the energy consumption of Bitcoin is estimated as 22−67 TWh/yr (mid-March 2018), 43 TWh/yr (October 2018), 45 TWh/yr (November 2018), 62 TWh/yr (average of 2018), 39−83 TWh/yr (mid-November 2018), and 105.82 TWh/yr (29 July 2018)[8].

Processing cryptocurrency transactions requires a computational set up which contributes to the network by solving the cryptographic puzzle. Subsequently, the contributor would receive reward for this proof of work (PoW) operation which is known as mining. These computational units (miners) consume an intense amount of electrical power to operate. As the value of the received financial reward outweighs the costs of contribution, mining cryptocurrencies becomes economically viable, resulting in a significant growth in electricity consumption. According to estimations, there are currently 1 million miners operating around the world[9]. An average BTC miner requires about 1.5 kW of power, equivalent to 36 kWh per 24 hours of operation[10]. This is slightly bigger than the daily electricity use per capita in the US, one of the world's top energy consumers. While miners are becoming more efficient in terms of energy use, the 50% increase of total Hash rate over the past year indicates that more miners are being added into the BTC network. The cumulative power needed to satisfy the annual BTC mining electricity demand of the top ten mining countries is sufficient to provide electricity to more than 10, 31 and 52 million households in the US, Germany and Japan respectively. This is more than 15% of Africa's total electricity consumption with 54 countries and 1.2 billion people.

Regardless of the energy source, producing and transmitting electricity for cryptocurrency mining have numerous environmental impacts. This makes the growing digital currency market a potentially polluting sector with an environmental footprint level more than some conventional methods for digital transactions[11]. For example, each BTC transaction is believed to have an equivalent carbon footprint of more than one million VISA transactions[12]. It is projected that in less than three decades, the BTC usage alone can produce enough greenhouse gas emissions to push global warming beyond the Paris agreement's goal of capping anthropogenic climate warming below 2 degrees Celsius[13]. Despite these alarming expectations, the financial and technological motivations of cryptocurrencies have suppressed the conservation surrounding their environmental costs. Various approaches have been presented to determine the Bitcoin network's actual energy usage. However, the Life-Cycle-Assessment method has not been studied yet. LCA traces the environmental impacts of all stages during a product's life cycle such as disposal and production. For measuring the energy consumption of Bitcoin adequately during mining, first the boundaries and elements of the mining procedure should be determined along with the related factors on the energy consumption.

Although some studies have been recently conducted to analyze cryptocurrency's environmental costs, the uncertainties surrounding the extent of these costs remains considerable[14]. Additionally, past studies have been only focused on the carbon emissions of BTC mining[15], not reflecting its other major environmental impacts such as water and land footprints[16] that contribute greatly to the total environmental footprint of the cryptocurrency sector. Subsequently, global BTC mining is currently emitting more than 69.17 Mt of CO_2 eq per year. To offset this amount, about 3 billion trees should be planted, taking up an area almost equal to the area of the UK or 5% of the Amazon rainforest. Hydropower, an energy source with a higher water footprint due to evaporative losses and a land footprint higher than all renewables except for bioenergy, is the dominant renewable energy source of BTC operations, satisfying more than 17% of the global BTC network's electricity demand. **Figure 1** shows the contributions of different energy sources in supplying electricity to the global BTC mining network, as of 2021[17].

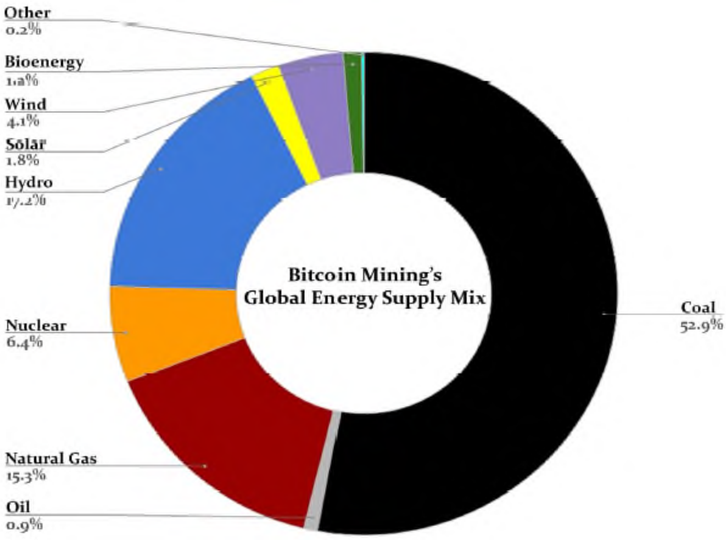


Figure 1. Global energy sources for BTC mining.

This study brings new insights in evaluating the effects of the Bitcoin mining network by presenting a more complete analysis on the environmental impacts hotspots in the BTC mining and by incrementing the accuracy in the regional electricity mixes modeling. Moreover, this work presents a prospective method by taking into account the possible changes on the electricity generation or the mining network's geography in the future. To achieve these objectives, blockchain is integrated into multiple LCA stages. Adopting LCA as a powerful scientific methodology is the added value of this analysis along with the use of the established databases to assess the environmental impacts, such as the effects of mining equipment in analyzing and presenting a viewpoint on the future impacts. First, midpoint and endpoint environmental impacts of Bitcoin mining for the top ten miner countries with equal mining ratio are analyzed, then the real amount of each environmental impact for these countries according to their mining share in the 2021 is obtained.

2. Background

Life cycle assessment is considered a powerful tool for quantifying the basic inputs and outputs of a product-specific system[18]. It can assess the footprint associated with a particular product for meaningful comparisons[19]. Since the "top-down" principle is used to analyze and design the system, this method solves the global problem first and emphasizes the consideration of specific solutions under the premise of the overall optimization of the system, which indicates its better integrity and strong systematic pertinence[20]. In addition, multiple life cycle stages and contain various types of environmental impact assessment indicators can be covered to avoid the transfer of environmental problems between these types of impacts[21]. It can provide environmental data support for various technical, management or policy decisions in accordance with the unified international standard (ISO14040 series), equivalent to the national standard (GB24040 series)[22].

Blockchain as a distributed ledger is able to efficiently record the transactions between two parties on a verifiable and global basis[23]. Satoshi Nakamoto in 2008 proposed the Blockchain concept[24]. In this technology, a decentralized consensus is facilitated by maintenance of a digital record of events through multiple blocks rooted in programs. The cryptographic hash identifies each block, which is connected with others in terms of the previous block's hash to create a chain of blocks[25]. The negotiated terms are stored by the individual block and the outcome is verified. A system of permanent stamp is adopted by the technology driving a collective responsibility amongst stakeholders for data reliability and safety[26]. Every transaction is authenticated by the system based on the agreement of more than 1/2 of the members contributing to the network[27]. The working mechanism results in a lower risk of censorship, downtime, and data distortion[28]. It is expected that Blockchain would facilitate a higher level of digital transformation with an objectivity level with no full control or absolute power for each member and with various applications in multiple domains[29].

In the initial design of the network, a certain number of bitcoins are defined. These bitcoins are not available and must be withdrawn by individuals with special devices. but how? Simply put, bitcoin comes from solving complex mathematical problems[30]. To do this, miner computing devices test different numbers in a mathematical function called a hash function to predict output. The first person to solve the problem and arrive at the correct function is a certain amount of bitcoin. The title gets a reward, then announces to the rest of the network that the answer has been reached here, so the rest of the people move on to the next issue in the next block. The nature and center of gravity of the bitcoin system is based on what is called the "blockchain" (Advanced Block Chain). Register on the network without the network breaking down due to user interference and losing its integrity. Currently, due to the popularity of Bitcoin, the number of miners has increased a lot and as a result, mining has become more difficult[31]. It is true that the production of bitcoin does not require special costs and physical work, and all work is done by digital devices. But the fact is that these devices consume a lot of electricity and electricity generation is expensive and often requires fossil fuels[32]. A typical bitcoin mining machine equals the power consumption of two refrigerators and a TV at the same time. If this device is turned on all year round, it will consume about 15,000 kW hours of electricity to produce about 40 bitcoins. In Germany, for example, the cost of production per kilowatt-hour is about 30 cents, which imposes a cost of 4,000 euros on the electricity grid. High heat generation due to this huge electricity consumption is one of the harms that climatologists and climate change experts have warned about[33].

Equipment must be purchased to extract digital currency. This equipment also varies depending on the amount of activity to be performed[34]. In the early days of the advent of bitcoin, the first digital currency (mining mainly with processors) (CPU) was made, or ordinary computers at home could be profitable for the miner[35]. You also need the Internet to extract digital currency (mining)[36]. One of the most important items in extraction equipment is electricity. Miners need a lot of electricity[37]. You may know that digital currency extractors are very noisy, they reach high temperatures very quickly, so a cooling device needs to be placed next to the equipment to increase both the efficiency of the device and its longer life[38]. The following requirements are required to extract bitcoins[39]: Extraction or Miner Hardware—Power Cables—Digital Currency Wallet—High Speed Internet or ADSL Extraction Pool. **Table 1** introduces the common market miners and their properties.

Bitcoin was analyzed by Giungato et al. concentrating on three different aspects related to its sustainability including social issues, environmental impacts, and economic aspects[40]. A very detailed study was performed by Hass McCook on the environmental and economic cost of Bitcoin mining[41]. An overview of recent literature about the sustainability of Bitcoin was provided by Vranken concentrating on the economic and environmental aspects[42]. More precisely, four questions are examined by the author including How large is this energy consumption? What factors have role in the bitcoin mining energy consumption? Does this impede sustainability? If yes, are there alternatives for reducing the energy consumption? In 2014, a paper was published by O'Dwyer and Malone on the power consumption of the bitcoin mining procedure[43]. They used the network hash rate as a starting point to estimate the whole Bitcoin network's energy consumption. Alex de Vries started by explaining the Bitcoin network as severely energy-hungry to predict an incrementing power demand for the future[44]. De Vries calculates indicated that the network has to perform 8.7 quintillion hashes at the current mining circumstances for processing one transaction[6]. Obviously, the Bitcoin network's power consumption of the poses a major problem since electricity is the main fuel for the hashing operations.

Table 1. Miner hardware properties.

Miner hardware	Device power (hashes per second)	Power consumption (Watts)
Antminer S9J	14 TH/S	1350 W
Whatsminer M10	33 TH/S	2100 W
Antminer S17	53 TH/S	2800 W
Ebit E11	44 TH/S	2000 W

3. Methodology

As indicated by ISO, the LCA study is generally per-shaped as four phases: (1) goal and scope definition; (2) LCI creation; (3) life cycle influence evaluation; (4) interpretation of results.

3.1. Top ten Bitcoin mining countries

Bitcoin has been focused by the financial market with better investment returns compared to the most traditional assets during the COVID-19 pandemic. Last year, one bitcoin would cost about $6000. Though, it is more than $55,000 today, nine times more than one year ago, even reaching over $61,000 at one point. The largest producer of bitcoin in the worlds is China based on the data from Cambridge Centre for Alternative Finance (CCAF). The USA accounted for 10.55% of the computing power of the world for bitcoin between September 2020 and April 2021. This is even higher than Russia, with only 6.91% over the same period. **Figure 2** shows the Bitcoin mining share for each country from September 2019 to May 2021[45].

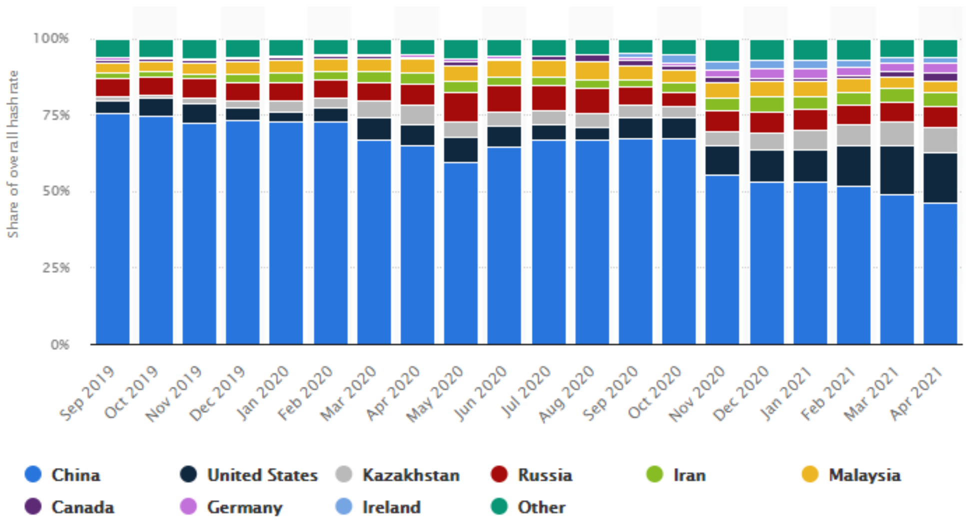


Figure 2. Share of overall hash rate for counties.

3.2. Bitcoin from the perspective of LCA

A Blockchain-based LCA framework is presented in **Figure 3** to integrate Blockchain as well as other smart enabling technologies into multiple LCA stages. Hence, the processes are made more effective and efficient. There are four stages in LCA including inventory analysis, goal and scope definition, interpretation, and impact assessment[46]. In all four steps, smart enabling technologies are used in blockchain-based LCA for achieving operational excellence.

A system architecture of Blockchain-based LCA system was proposed based on the Blockchain-based LCA framework (**Figure 4**). There are four layers infrastructure, Blockchain services, applications, and users in the system. The infrastructure layer is the foundation of the presented system architecture for collecting, transmitting, and recording data. The Blockchain services layer is a bridge, which connects the applications and infrastructure layers through cleaning, processing and analysis of the data. The applications layer visualizes the data and assists in decision making. The system is used by the users via the users layer. Precisely, the functions of these four layers are based on the requirements at the four LCA phases.

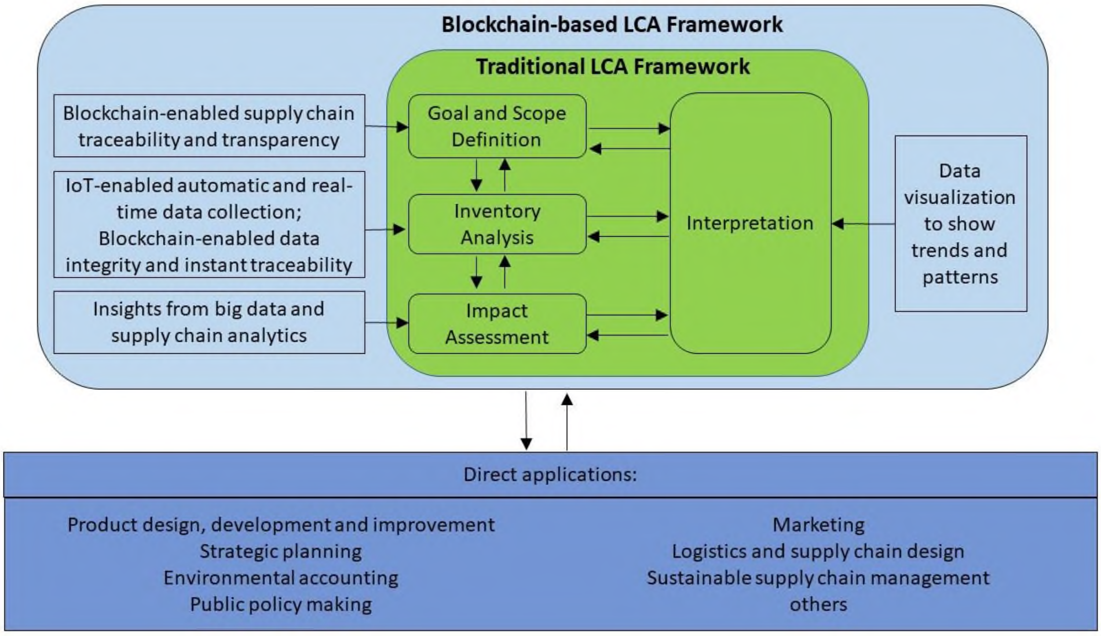


Figure 3. Blockchain-based LCA Framework.

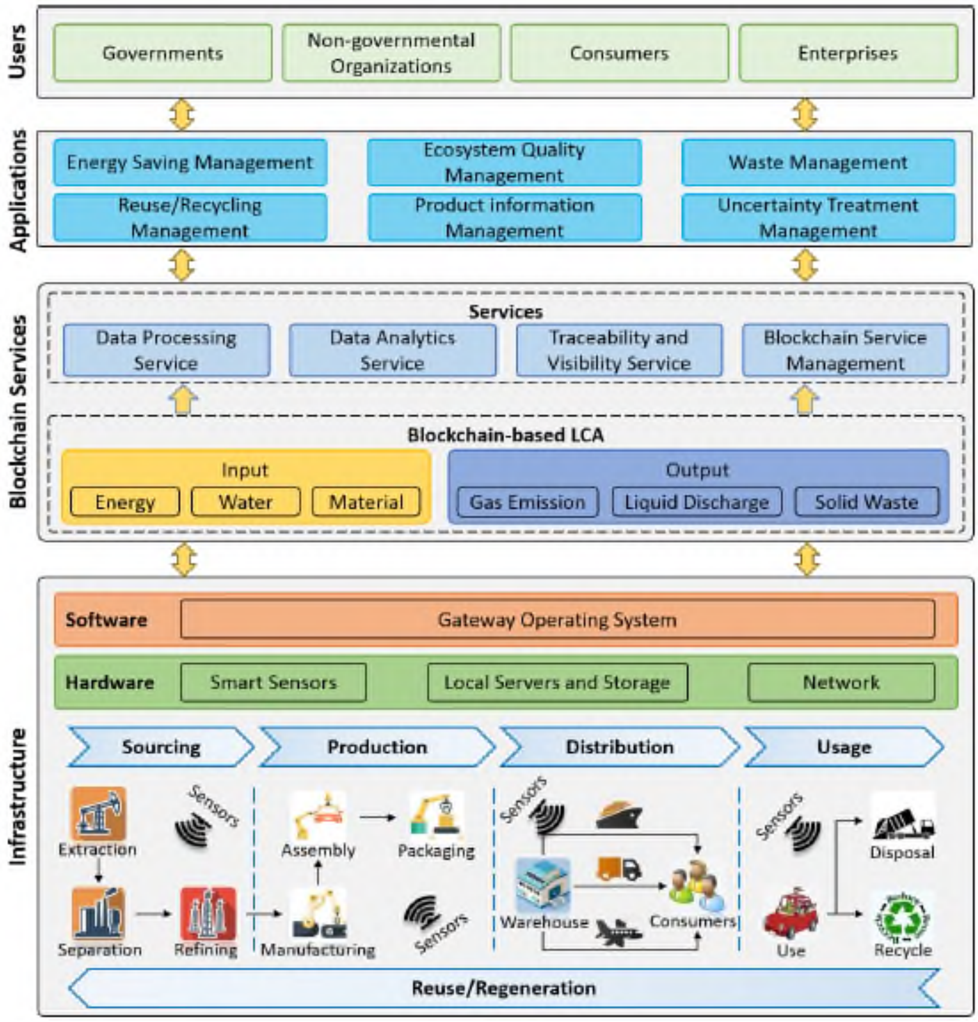


Figure 4. Blockchain-based life cycle assessment system.

3.2.1. Definition of goal and scope

Goal

A potential LCA study of Bitcoin are most likely aimed to compare its environmental impacts to other monetary systems and to analyze and quantify the environmental impacts of Bitcoin transactions in terms of the original Bitcoin network.

Functional unit

By the functional unit, the reference is provided for relating all data and making different systems presenting the same functionality comparable. The supposed function of a system defines the functional unit. The functional unit should be outlined precisely as a key element of the LCA. The attributional model's functional unit was defined as computing 1 tera hashes (TH).

System boundaries

By establishing the functional unit, the system boundaries should be set, which determine the unit processes in the LCA and define the procedures for analyzing based on the materials and energy emissions and flows[47]. Consequently, a limited number of processes are examined against a global model[48]. So in order to perform a simple yet accurate LCA of the Bitcoin, cradle to gate analysis is chosen.

3.2.2. Relevant parameters of a possible inventory analysis

Life-Cycle Inventory Analysis should compilate and quantify all outputs and inputs for a product all over its entire life-cycle[49]. Within the mining process, Bitcoin transactions are verified based on the miners' computing power receiving newly mined bitcoins and transaction fees. Thus, it is essential to examine the mining procedure and all the activities, and linked energy and materials. Multiple elements are included in the mining process, thus, its non-essential parts will be sorted out here to reach comparable findings through LCA.

It is vital to consider two fundamental aspects following giungato[40] to assess the environmental impact of Bitcoin, i.e., computer energy consumption and the e-waste disposal. In fact, these are indeed essential factors, however, they are utilized as a starting point. We will take into account the hardware used in its whole length rather than the disposal of e-waste, from production to assembly and transportation. We will consider the type of source of primary energy rather than merely quantifying computer energy consumptions.

Hardware/Material flow analysis

Various hardware producers exist worldwide and the impacts of production vary from producer to producer obviously. To make the LCA simple as possible with viable results, ASICs machines should be only examined as a result of efficiency and splitting up the analysis by producers. The different outcomes should be compared then to establish various outcomes. Then, they are compared with the both outdated hardware (FPGAs and CPUs) and other payment means with the same function (PayPal, debit card, and cash transactions).

Materials/Assembly/Transportation

Once the hardware to examine is determined, the materials should be considered along with the different sub-processes and processes for producing and transporting the hardware. Sophisticated machinery such as ASICs includes printed circuit boards (PCB), semiconductors, and various silicon wafers and passive components. Electricity and labor are required for the materials assembly and produce the final product. The ASIC machines are mainly built by companies with completely build mining hardware. Thus, other uses (and a consequential assignment of the externalities) of the production site or the workers must not be considered.

Then, it is essential to take into account the transportation of the hardware and its substances respectively. Materials should be transported to the production site first. Nevertheless, they are not considered here. Then, the machines must be delivered to either the local distributor or the customers themselves since mining takes place worldwide. To establish Bitcoin mining material expenditure, the following aspects should be considered. First, ASICs should be only focused to keep the LCA simple yet revealing and conclusive since it is the most leading type of hardware and utilized for Bitcoin mining only. Second, the used ready-made materials should be focused before assembling since taking into account the raw material extraction could cause the unnecessarily inconclusive and bulky LCA. Third, the location of the production site and the distribution of miners around the world should be considered for reflecting the impacts of the hardware transportation accurately.

Operation/Energy analysis

Once the appropriate factors about materials, manufacturing, transportation, and packaging are established, Bitcoin's presumably biggest problem should be considered, which is the high-energy expenditure essential for keeping up the networks. Examining the usage and operation of mining machines over their lifetime, we should define the enduring environmental impacts of the up and running Bitcoin network. First, the machines and their range of electric energy consumption should be considered. Electricity is required by all above-mentioned machines (FPGAs, CPUs, ASICs) to fulfil the generating hashes task. These models were processed in studies[50], and the results were obtained with a total computational power within the range of 40-62.3 TWh for 81.4 million transactions in 2018. We should also establish the miners' locations and consider at the respective energy source as the environmental impacts of Bitcoin supposing that most mining facilities are placed in areas based on using coal as the main power source. The energy grids are different in every area. Moreover, the difference in temperature and consequently the differing requirements for heating and the possibility of reuse of emitted heat is another reason for the importance of location.

The cooling of the hardware and the possible reuse of the emitted heat should be also considered. Proper temperature is required by mining hardware for adequate operation. Various cooling systems should be used to maintain mining machinery at a steady temperature. These systems are different based on the hardware in use. They are mainly oriented by chilled water as coolant and all need extra energy to operate. Holistic cooling methods mainly meet the thermal necessities utilizing forced convection, multiple fans, and heatsinks about single ASIC mining rigs with multiple printed circuit boards. So to capture the environmental impacts adequately during an LCA of one Bitcoin transaction, the following aspects should be considered about the energy expenditure while using the hardware:

First, the machines are selected based on the proportion for classifying the energy consumption for Bitcoin mining or other operations. The cooling mechanisms are also necessarily considered. The distribution of miners around the world are also taken into account, since the location presents critical information about the climatic circumstances and energy grid in the respective area. Considering the cooling mechanisms for keep the hardware at a steady temperature is also essential for reusing the heat can be reused for various objectives.

3.2.3. Attributional baseline model

Bitcoin network

There is scarce and inaccurate information presently available on the Bitcoin miners' location. Though, this information is vital to estimate the Bitcoin network's environmental impacts. This is highly based on the geographical locations' electricity mix for mining. In this study, a geographical distribution of the Bitcoin mining network was developed in terms of the existing information[51] on mining pools.

Mining activities

Bitcoin network is also based on the equipment utilized for mining since it defines the mining efficiency known as the electricity consumption per computed TH. The types of equipment used for the model were based on Martynov's study[52]. Among the miners modeled, 79.9% are Antminer S9, 6.7% Ebang E10, 7.6% Avalon 841. The remaining 5.8% are modeled as other machines.

Mining equipment

Two main activities are considered in using mining equipment including electricity production and consumption. The use of electricity for mining is the main contributor to electricity consumption, which is determined based on each machine's product specifications. Additional energy may be required in large facilities, particularly in warmer climates for cooling as well as other inefficiency. An additional electricity use of 5% was presumed in the model[53]. The electricity consumption was modeled utilizing the electricity mix from the ecoinvent v3.5 APOS database of each country, in which the miners are placed[8].

For the production of mining equipment, the ecoinvent v3.5 process was chosen for "market of desktop computer without screen". Such a dataset represents a computer with a weight of 11.3 kg and much lighter mining equipment (e.g., 4.2 kg for an Antminer S9). Thus, the amount of input was modified considering the weight difference (e.g., 4.2/11.3 kg desktop computer for the Antminer S9).

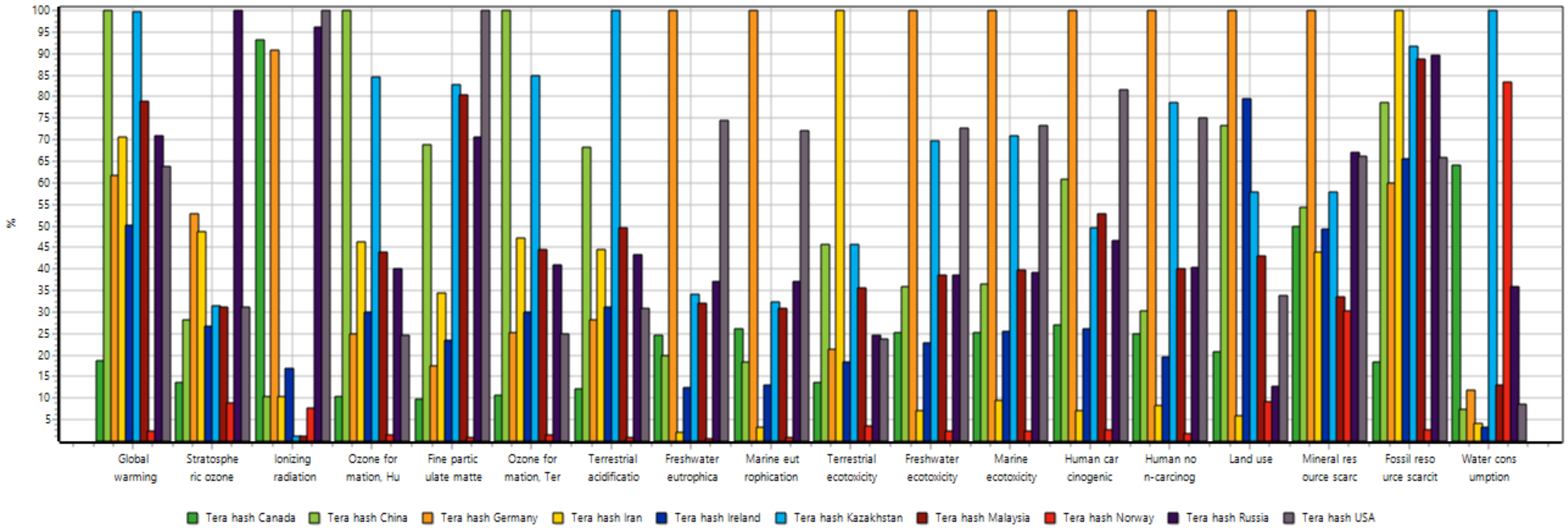
4. Results and discussion

4.1. Environmental impacts for 1 tera hash

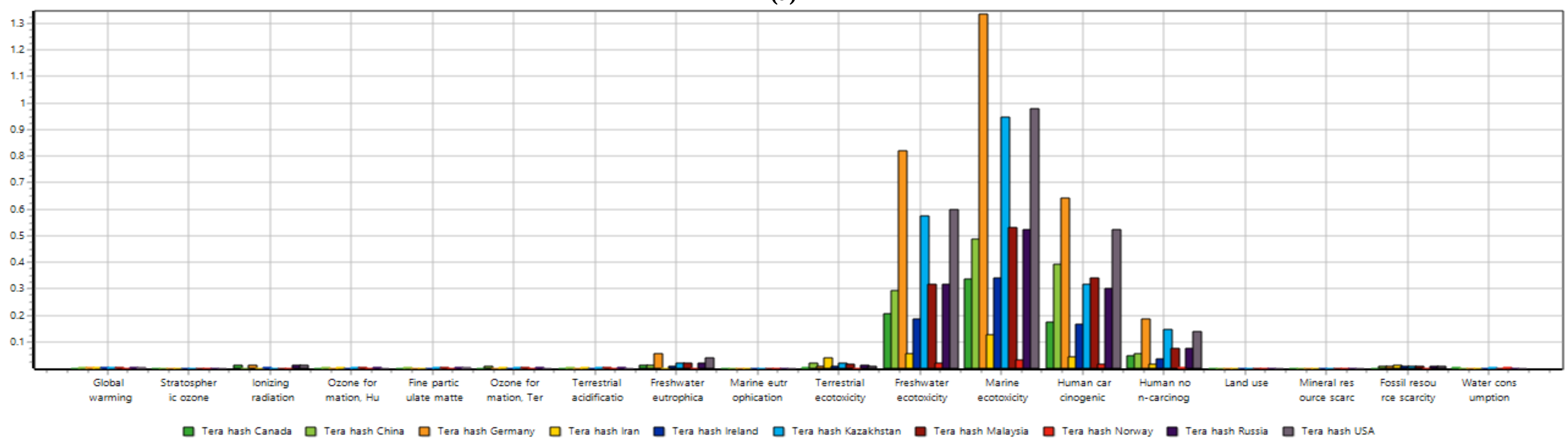
The 18 midpoint environmental effects for mining 1 TH for the top ten mining countries compared with each other is shown in **Figure 5a**. As can be seen in **Figure 5a**, China has the most negative impact on ozone formation human health, global warming, and ozone formation terrestrial ecotoxicity with 39.6 kg CO_2 eq, 0.13 kg and 0.11 kg NO_x eq respectively. Germany has the most negative impact on marine eutrophication, freshwater eutrophication, marine ecotoxicity, freshwater ecotoxicity, human carcinogenic toxicity, human non carcinogenic toxicity, land use and mineral resource scarcity with 0.0362 kg P eq, 0.00246 kg N eq, 1.01 kg, 1.38 kg, 1.78 kg, 27.6 kg 1,4-DCB, 0.64 m^2 a crop eq and 0.0205 kg Cu eq respectively. Iran has the most negative impact on terrestrial ecotoxicity with 42.8 kg 1,4-DCB and fossil resource scarcity with 9.84 kg oil eq. Kazakhstan has the most negative impact on terrestrial acidification with 0.198 kg SO_2 eq and water consumption with 1.28 m^3. Russia has the most negative impact on stratospheric ozone depletion with 3E-5 kg CFC eq. United States of America has the most negative impact on ionizing radiation with 5.91 kBq Co eq.

Figure 5b shows the normalized 18 midpoint environmental effects of each country for 1 TH mining. This figure shows that the most severe environmental impact of Bitcoin mining is on marine ecotoxicity which is mostly in Germany, USA and Kazakhstan with 1.38 kg, 1.01 kg and 0.977 kg 1,4-DCB.

Figure 6a shows the 3 endpoint environmental impacts of Bitcoin mining for the top ten miner countries. As can be seen from **Figure 6a** for human health, Kazakhstan has the most negative impact with 9.32E-5 DALY, for ecosystems, also Kazakhstan has the most negative impact with 1.94E-7 species.yr and for resources, Iran has the most negative impact with 3.82 USD. **Figure 6b** shows the normalized of the 3 endpoint environmental impacts in which it can be concluded that Bitcoin mining has the most severe impacts on human health compared to ecotoxicity and resources.

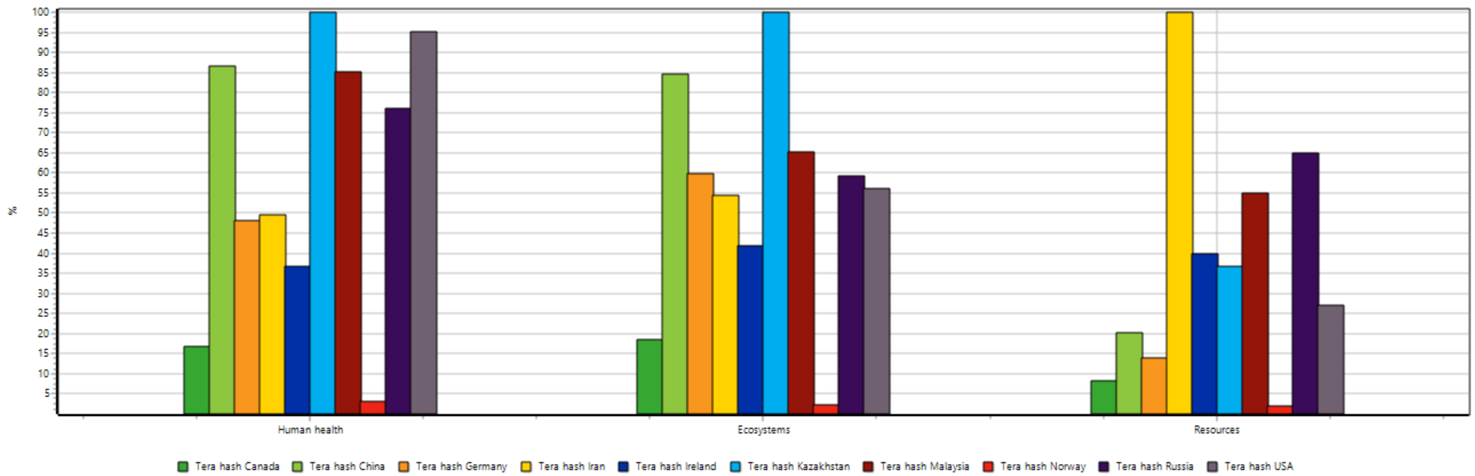


(a)



(b)

Figure 5. (a) the comparison of the 18-tuple environmental effects of each country for 1 TH mining; **(b)** the normalized comparison of the 18-tuple environmental effects of each country for 1 TH mining.



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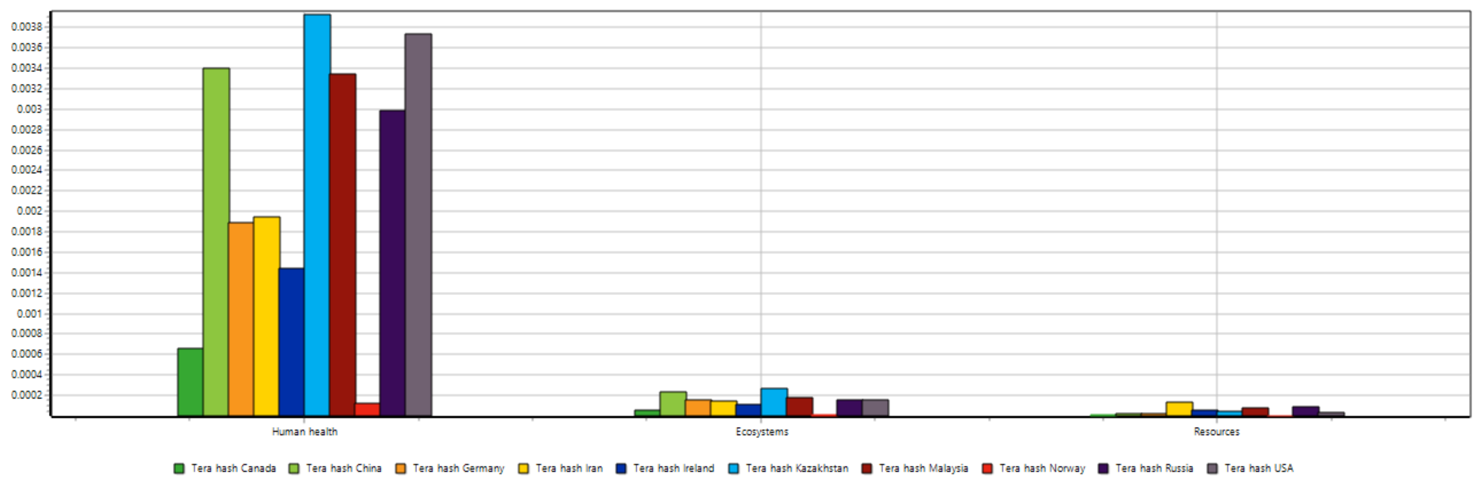


(b)

Figure 6. (a) the comparison of the main 3 environmental impacts for 1 TH mining; **(b)** the comparison of the normalized 3 main environmental impacts for 1 TH mining.

The hashrate reflects the size of the Bitcoin network, of how many miners are trying to gain the right to add the next block. However, the hashrate does not reflect the market price or the amount of transaction throughput meaning it can in the short term, increase or decrease independently of both the market price and the transaction throughput. **Table 2** displays the results for computing 1 TH for all the midpoint impact categories considered in this study.

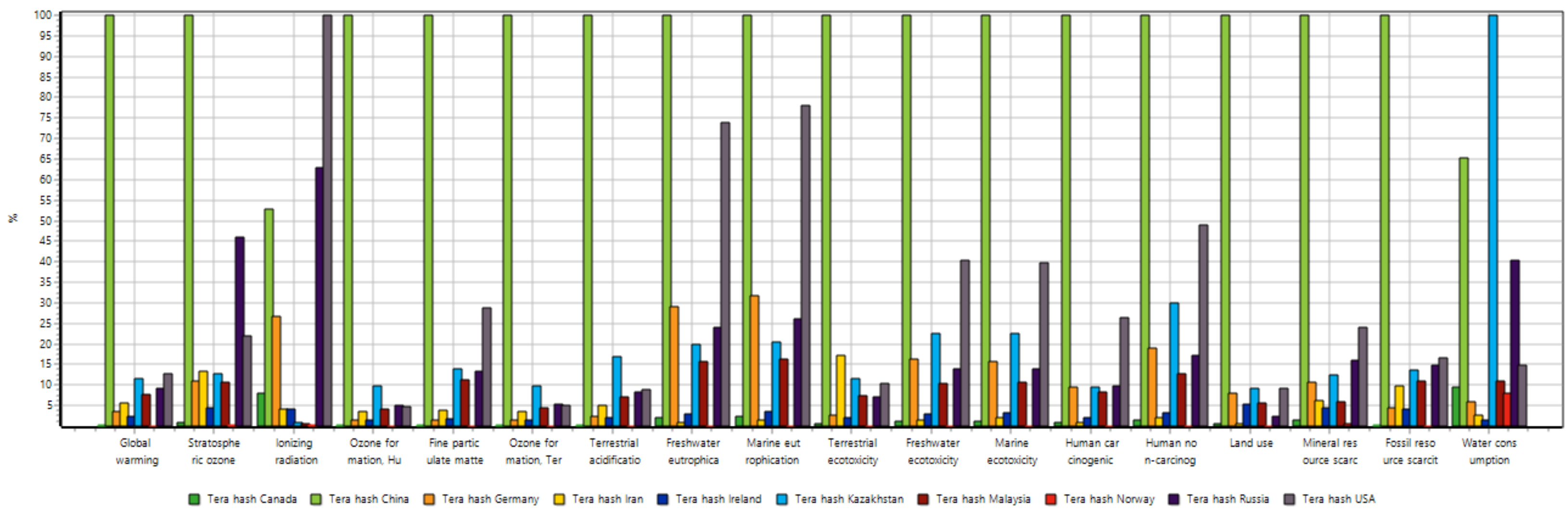
Table 2. Environmental impact of 1 TH according to the IPCC and the ReCiPe methods.

Impact category	**Midpoint impact of 1 TH**
Climate change GWP (mg CO_2-eq), IPCC	14
Climate change GWP (mg CO_2-eq), ReCiPe	13.7
Fossil depletion FDP (MJ)	3.72×10^{-6}
Metal depletion MDP (kg)	6.5×10^{-7}
Human toxicity HTP (kg 1,4-DCB-eq)	5.61×10^{-6}
Terrestrial acidification (kg SO_2-eq)	3.2×10^{-8}
Freshwater eutrophication (kg P-eq)	4.63×10^{-9}
Photochemical oxidation formation POFP (kg ethylene-eq)	3.47×10^{-8}
Ozone depletion ODP (kg CFC-11-eq)	4.88×10^{-13}
Terrestrial ecotoxicity (kg 1,4-DCB-eq)	9.81×10^{-10}
Marine ecotoxicity (kg 1,4-DCB-eq)	5.01×10^{-7}
Freshwater ecotoxicity (kg 1,4-DCB-eq)	5.72×10^{-7}

4.2. Environmental impacts for top ten miner countries in 2021

With the share of 53.3% by China, 10.55% by United States of America, 6.91% by Russia, 6.17% by Kazakhstan, 5.18% by Malaysia, 4.15% by Iran, 3.09% by Germany, 2.59% by Ireland, 0.9% by Canada and 0.6% by Norway of the total 100% of the Hash mining in 2021 the real environmental impacts of these countries can be achieved. As can be expected from the high percentage of China, except for ionizing radiation in which USA has the most negative impact with 62.3 kBq CO eq and for water consumption in which Kazakhstan has the most negative impact with 7.93 m^3, in all other 16 midpoint environmental impacts, China has the most negative impacts in which marine ecotoxicity is the most severe one with 26.8 kg 1,4-DCB. Also, China had 2.11×10^3 kg CO_2 eq impact on global warming in 2021. **Figure 7a** shows the 18-midpoint real environmental impacts of the top ten Bitcoin miner countries in 2021 and **Figure 7b** shows the normalized diagrams of the **Figure 7a**.

With the high 53.3% share of Bitcoin mining in China, this country has the most negative environmental impact in all 3 endpoint human health, ecosystems and resources environmental indicators with 0.0043 DALY, 8.78×10^{-6} species.yr and 41 USD respectively. Also the most severe impact of Bitcoin mining in 2021 was on human health in which China, USA and Kazakhstan has the most share of it. The 3 endpoint environmental impacts and their normalized diagram for Bitcoin mining in 2021 are shown in **Figure 8a,b**.



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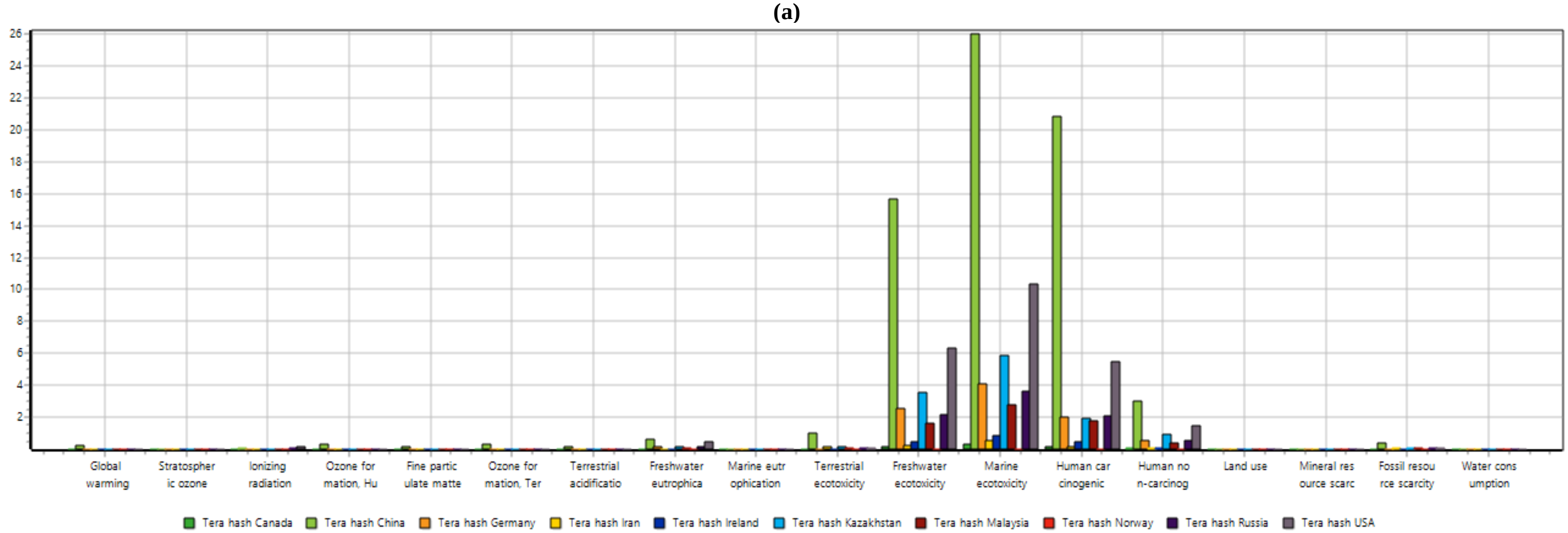
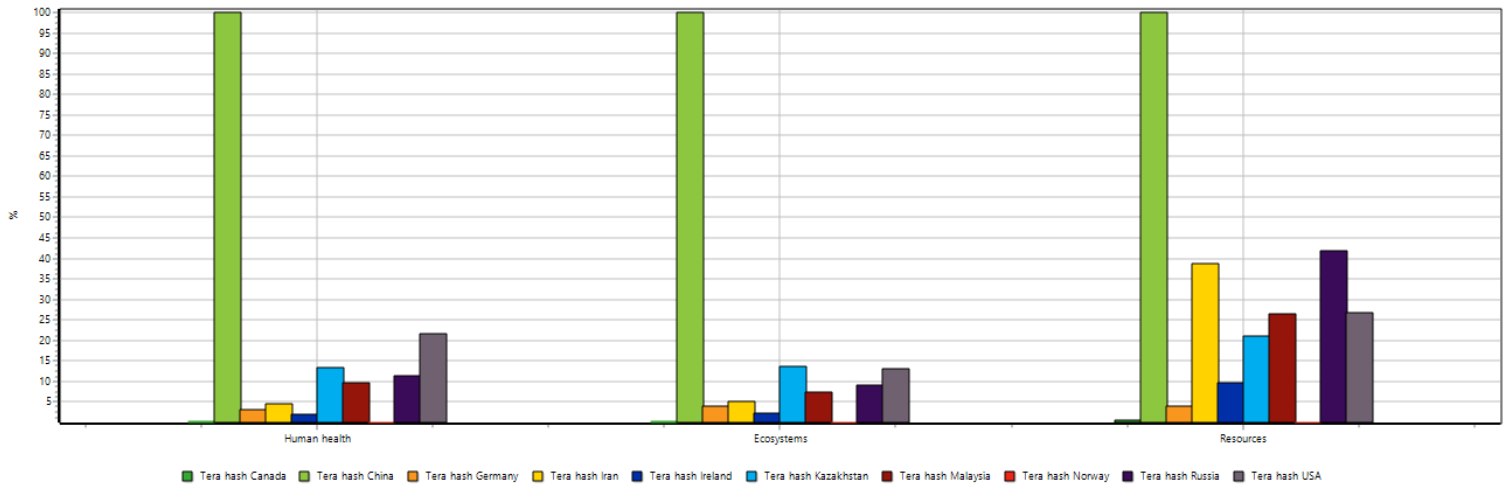


(b)

Figure 7. (a) the comparison of the 18-tuple environmental effects of each country in 2021; **(b)** the normalized comparison of the 18-tuple environmental effects of each country in 2021.



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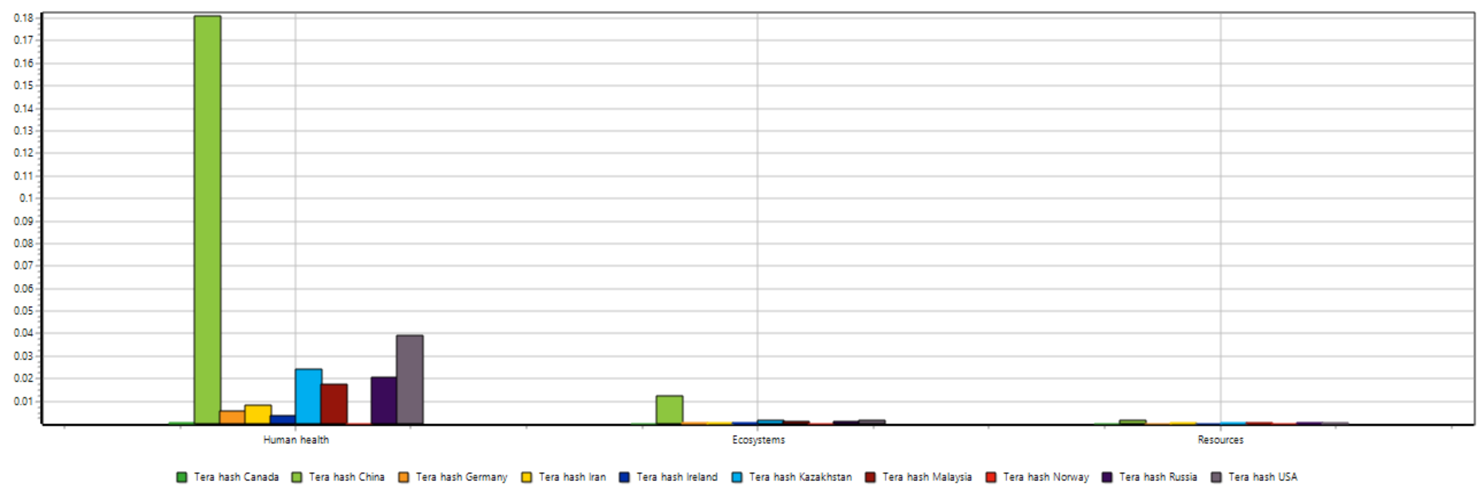

(b)

Figure 8. (a) the comparison of the main 3 environmental impacts in 2021; **(b)** the comparison of the normalized 3 main environmental impacts in 2021.

5. Conclusion

The environmental impact of mining Bitcoin was estimated in the present study, as the most well-known blockchain-based cryptocurrency. It also discussed the supposedly large energy consumption of the technology. This assessment has mainly the obstacle of lack of a strong methodological framework and accurate data on key factors determining the effect of Bitcoin. The well-established Life Cycle Assessment methodology was used in this study to an in-depth analysis of drivers of the Bitcoin mining network's past and future environmental impacts. It was found that the Bitcoin network consumed 62.58 TWh in 2021. Moreover, the main drivers of this impact was the geographical distribution of miners and the mining equipment efficiency. Contrary to the previous studies, it was found that the production, service life, and end-of-life of such equipment slightly contributed to the total impact. Although the overall hashrate is expected to increment, the environmental footprint and energy consumption per TH mined are expected to reduce.

The LCA determines a process's system boundaries and the functional unit and examines the resources utilized for supporting. Thus, it presents the tangible key figures for comparing various processes about their ecological footprint. The following steps should be considered to achieve valid results:

- Defining goal and scope
- Inventory analysis
- Impact evaluation
- Interpretation

Here, one tera hash mining is assessed as a functional unit to determine the related factors of the environmental impact and for power consumption the top ten Bitcoin miner countries. It was found that for 1 TH mining, Germany has the most negative environmental impacts on marine eutrophication, freshwater eutrophication, marine ecotoxicity, freshwater ecotoxicity, human non carcinogenic toxicity, human carcinogenic toxicity, and land use. The reason of the water related impacts, human toxicities and land use should be the energy basket of Germany in which 8.8% energy production from offshore and 53.2% from solar energy is responsible for those impacts respectively. For the most important environmental impact which is global warming, China has the most negative impact with 39.6 kg CO_2 eq. The reason of this is also the China energy basket in which coal has the 57% and crude oil has the 20% of the total energy generation system of China. Canada, Ireland, Malaysia and Norway have less negative environmental impacts which is inferred from their more-green energy basket and high efficiency mining equipment. It should be noted that for real environmental impacts in 2021 with the share of 53.3%, China has the most severe impacts specially in human health with 0.0043 DALY.

Author contributions

Conceptualization, AA and RZ; methodology, MANS; software, RZ; validation, AA, RZ and MANS; formal analysis, MANS; investigation, RZ; resources, AA; data curation, AA; writing—original draft preparation, RZ; writing—review and editing, RZ; visualization, MANS; supervision, AA; project administration, MANS; funding acquisition, AA.

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Conflict of interest

The authors declare no conflict of interest.

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