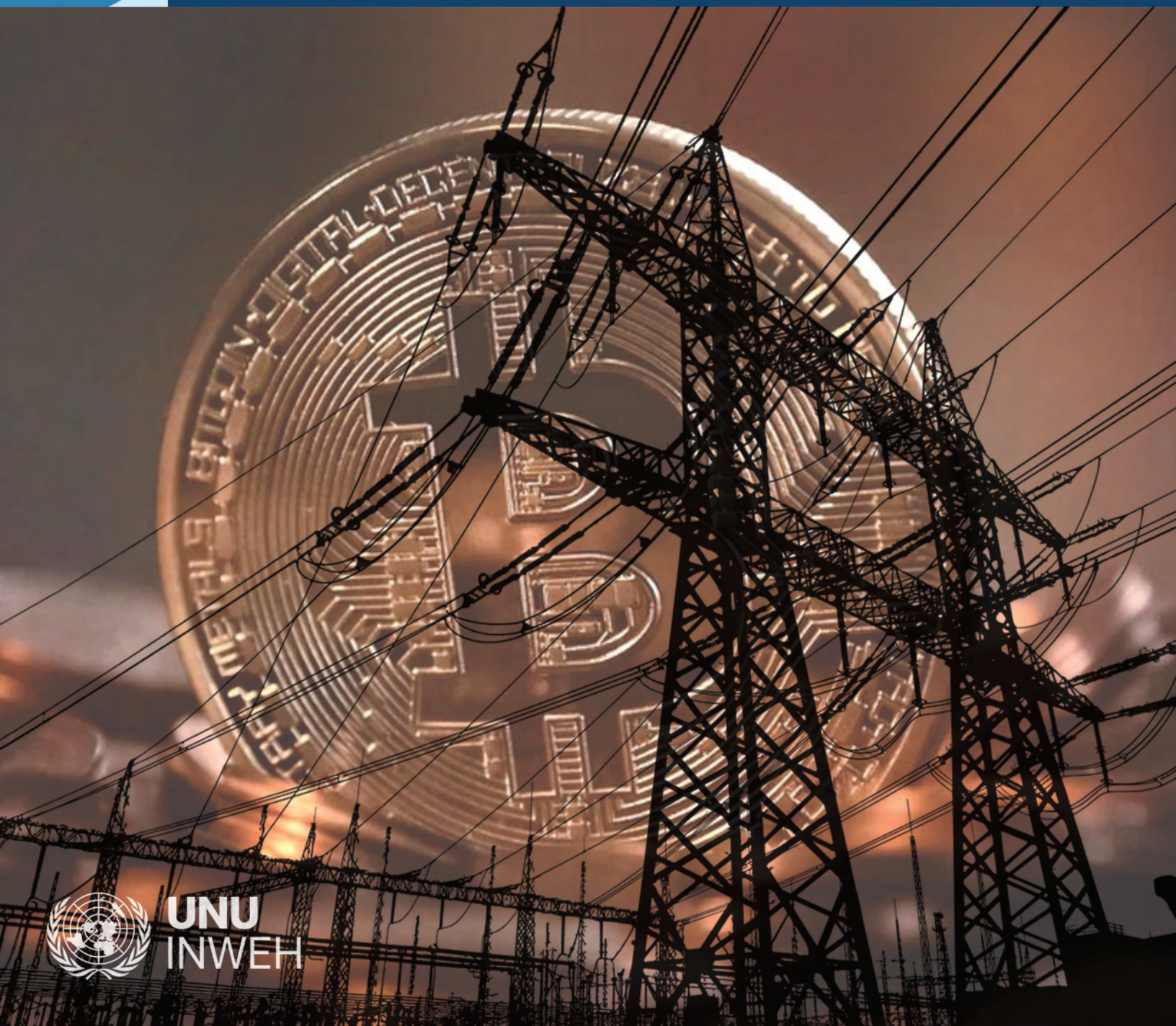
United Nations University
Institute for Water, Environment and Health

The Hidden Environmental Cost of Cryptocurrency

How Bitcoin Mining Impacts Climate, Water and Land



A shorter version of this report will be simultaneously released by the American Geophysical Union (AGU) on October 24th, 2023 as a Commentary:

Chamanara S. Madani K. (2023). The Environmental Footprint of Bitcoin Mining Across the Globe: Call for Urgent Action.

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The Hidden Environmental Cost of Cryptocurrency: How Bitcoin Mining Impacts Climate, Water and Land

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United Nations University Institute for Water, Environment, and Health (UNU-INWEH)

2023

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Back cover image: El Salvador is the first country to build a Bitcoin city using volcanic energy.
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UNU-INWEH is an integral part of the United Nations University (UNU) - an academic arm of the UN, which includes 13 institutes and programmes located in 12 countries around the world, and dealing with various issues of development. UNU-INWEH was established, as a public service agency and a subsidiary body of the UNU, in 1996. Its operations are secured through long-term host-country and core-funding agreements with the Government of Canada. The Institute is located in Hamilton, Canada, and its facilities are supported by McMaster University.

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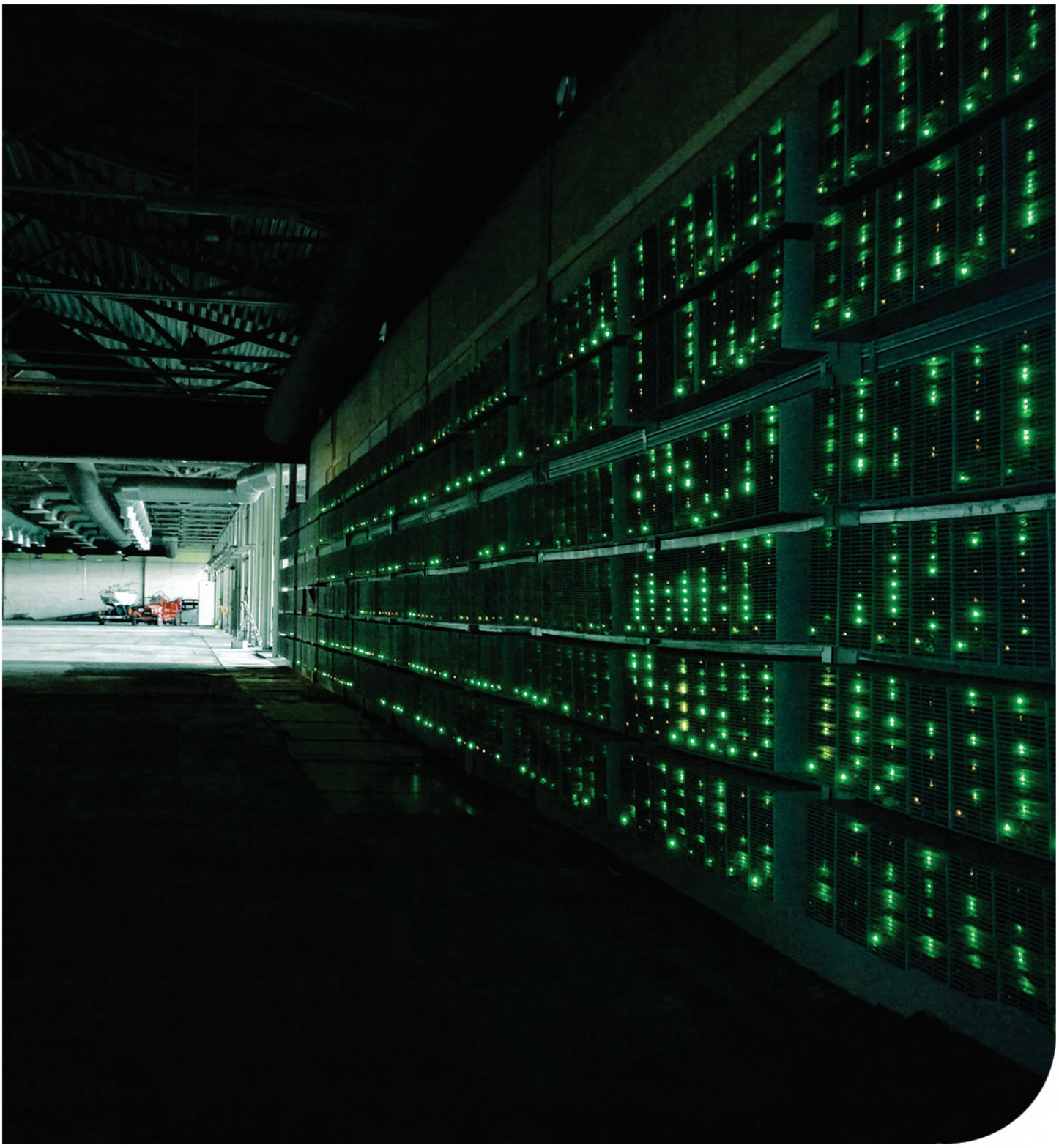
Executive Summary



A Bitcoin mining farm, by Marko Ahtisaari/ flickr (Image is cropped)

Key Findings in Brief:

- The cryptocurrency sector provides valuable opportunities and benefits, but has major, overlooked environmental impacts.
- Bitcoin (BTC) as the most popular form of cryptocurrency has worrying environmental impacts on climate, water, and land.
- A substantial correlation exists between BTC price fluctuations and electricity consumption, with a 140% growth in electricity use as a result of a 400% BTC price increase from 2020 to 2021.
- China, USA, Kazakhstan, Russia, Malaysia, Canada, Germany, Iran, Ireland and Singapore were the world's top BTC miners of the world in 2020-2021.
- 67% of the electricity consumed for BTC mining in 2020-2021 came from fossil energy sources.
- Coal, the main source of energy for BTC mining, provided 45% of the total electricity used by the global BTC mining network in 2020-2021.
- BTC mining emitted about 86 Mt of CO_2eq from 2020 to 2021.
- The greenhouse gas emissions of BTC mining alone could be sufficient to push global warming beyond the Paris Agreement's goal of capping anthropogenic climate warming below 2 degrees Celsius.
- The top ten BTC mining nations are together responsible for 94% of the global carbon footprint of BTC.

The cryptocurrency sector is increasingly integrated into the global financial system. The world's transition to a digital economy, facilitated by major technological breakthroughs, has several benefits. But as the demand for exchanging and investing in digital currencies is rapidly growing, the world must pay careful attention to the hidden and overlooked environmental impacts of this growth. The dramatic increase in the price of some cryptocurrencies over the last decade, especially in recent years, and the resulting global race for cryptocurrency mining is turning the digital currency market into one of the world's leading polluting sectors. Yet, our knowledge about the environmental footprints of mining cryptocurrencies is very limited.

The cryptocurrency market is dynamic and influenced by factors like market uncertainty and investor expectations. By February 2022, over 10,000 cryptocurrencies were traded globally, each with unique features impacting price stability[1]. Bitcoin (BTC), the most renowned and popular cryptocurrency, saw an astonishing price surge of over 540,000% from 2012 to 2022
around 1 million BTC miners were operational worldwide, and the global cryptocurrency market's capitalization stood at approximately $0.5 trillion in September 2023[3]. BTC alone accounted for a substantial portion, with a market capitalization of about $555 billion as of September 2023[3].

The energy-intensive nature of cryptocurrency transactions and mining methods like Proof of Work (PoW) and hybrid PoW/Proof of Stake (PoS) raise questions about their energy use despite the growing efficiency of mining equipment. To put this into perspective, an average BTC miner requires about 1.5 kW of power, roughly equivalent to the daily electricity consumption per capita in the United States, one of the world's top energy consumers. The concerns about cryptocurrencies extend beyond their massive energy consumption. Energy production has various environmental footprints. Thus, cryptocurrency mining is associated with various environmental costs. The greenhouse gas emissions resulting from cryptocurrency mining, especially in the case of BTC, could potentially undermine global efforts to combat climate change. Projections suggest that BTC emissions alone could push global warming beyond the Paris Agreement's goal of capping temperature increases below 2 degrees Celsius[4].

This report by the United Nations University Institute for Water, Environment and Health (UNU-INWEH) offers the first multi-attribute estimation of the environmental footprint of the global BTC mining network, including its carbon, water, and land footprints. The primary objectives of this assessment include assessing the environmental impact of BTC mining, providing a global perspective by evaluating the mining activities of different nations, and emphasizing the need for immediate policy interventions to monitor, regulate, and mitigate the environmental consequences of digital currencies

which play an undeniable and growing role in the global financial system. The global BTC mining network's electricity consumption is substantial. Price of BTC plays a crucial role in mining profitability, with higher prices driving increased mining activity and energy consumption at the global level. A 400% rise in the BTC price from 2020 to 2021, was followed by a 140% surge in the worldwide BTC network's electricity use. In the 2020-2021 period, the global BTC mining network devoured 173 terawatt-hours (TWh) of electricity, marking a 60% increase from the 2018-2019 period. Projections for 2023 suggest that electricity consumption can exceed 135 TWh. To provide context, if BTC were considered a country, its electricity consumption in July 2023 would rank it 27th globally, outpacing populous nations such as Pakistan.

The BTC network relies heavily on fossil energy sources, with coal constituting 45% of the energy mix. This has led to the emission of more than 85.89 million metric tons of CO_2-equivalent (Mt CO_2eq) from 2020 to 2021. This is equal to the amount of greenhouse gases produced by burning 84 billion pounds of coal, the output of 190 natural gas-fired power plants, or the waste produced by over 25 million tons of landfilled materials.

The water footprint of BTC mining is also significant, amounting to about 1.65 cubic kilometers (km^3) from 2020 to 2021. This is comparable to the volume of water required to fill over 660,000 Olympic-sized swimming pools, enough to satisfy more than 300 million people in rural Sub-Saharan Africa. Furthermore, the land footprint of BTC mining is extensive, affecting more than 1,870 square kilometers of land, 1.4 times the area of Los Angeles.

The landscape of BTC mining is evolving. China is still the world's top BTC miner but has reduced its share from 73% in 2021 to 21% in 2022 through various governmental interventions and bans. The shifting landscape also affected the energy supply mix of BTC mining and hence its environmental footprints. The United States has emerged as a significant player in BTC mining, with variations in regulations across states. Georgia, Kentucky, Texas, and New York are prominent BTC mining hotspots within the U.S. Kazakhstan, the world's third BTC mining nation offers attractive incentives due to its significantly lower electricity costs compared to the U.S., fostering substantial investments in BTC mining. Russia, a neighbor of Kazakhstan is among the world's top BTC miners but consumes slightly less energy than Kazakhstan's for mining BTC. Malaysia, Canada, Germany, Iran, Ireland, and Singapore are the other top BTC miners in the world.

When countries are ranked based on BTC mining's environmental footprints rather than electricity use, their rankings change. These variations are due to

Bitcoin's electricity use (2020-2021) was equivalent to CO_2 emissions avoided by

each country's unique energy mix and the resulting differences in the water, carbon, and land footprints of electricity production. For instance, Canada, ranking 6th in electricity use for BTC mining, is the 9th largest emitter of greenhouse gases due to its lower reliance on coal and higher reliance on nuclear and natural gas, compared to some of the other top BTC mining countries. For example, BTC mining's electricity use in Canada is 20% of that in the United States but the carbon footprint of BTC mining in Canada is less than 7% of that in the United States. BTC mining's water footprint in each country is reflective of its electricity production methods. For example, Iran's high reliance on natural gas for electricity production lowers the water footprint of its mining activities in comparison to countries like Canada and Norway where water-intensive energy sources like hydropower have a more significant role than Iran. Together, the 10 BTC miners in terms of water footprint (China, USA, Canada, Kazakhstan, Russia, Malaysia, Germany, Norway, Iran, and Thailand) contribute to 92.5% of the global water footprint of BTC mining.

The top ten contributors to the total land footprint of BTC mining are countries that rely on land-intensive energy sources, such as bioenergy. These countries are responsible for 93% of BTC's global land footprint. China, known for its coal-intensive BTC mining activities, produced over 41 million metric tons of CO_2 equivalent from January 2020 to December 2021. Addressing this level of emissions would require planting over 2 billion trees or covering an area equivalent to Portugal and Ireland combined, or 45,000 times the size of Central Park in New York City. The top ten BTC carbon emitters are collectively responsible for 94% of the sector's carbon footprint.

Bitcoin's electricity use (2020-2021) was equivalent to CO_2 emissions from

The current environmental footprints of global BTC mining, with heterogeneous impacts across countries, underscore the unaddressed costs of an innovative yet environmentally unsustainable financial solution. Of particular concern is that some of the top BTC mining countries with high electricity use have below-average GDP per capita. The unregulated mining activities leave lasting environmental damages, exacerbating social and economic inequalities. Urgent action is needed through national and global policies, economic tools (e.g., increased electricity prices for mining, cryptocurrency taxes, carbon offset mandates for blockchain tokens, and divestment campaigns), and regulatory measures to mitigate the transboundary and transgenerational costs of digital currencies.

The transition to a sustainable future can benefit from energy-efficient alt-coins and technological innovations, like less energy-intensive validation methods (e.g., proof-of-stake) that reduce the environmental impacts of cryptocurrencies.

Bitcoin's electricity use (2020-2021) was equivalent to carbon sequestered by

Key Findings in Brief:

- To offset BTC mining's 2020 and 2021 CO_2 emissions, about 3.9 billion trees need to be planted.
- Hydropower, an energy resource with major water and environmental impacts, is the main renewable energy source of electricity for BTC, satisfying over 16% of the total electricity demand of the global BTC mining network.
- Nuclear energy provides 9% of the total electricity used for BTC mining globally.
- Only 2% and 5% of the total electricity used for mining BTC came from solar and wind energy sources, respectively.
- The global water footprint of BTC mining (2020-2021) equals 1.65 km^3, exceeding the domestic water use of over 300 million people in rural Sub-Saharan Africa.
- The land footprint of the global BTC mining network (2020-2021) is more than 1,870 square kilometers, 1.4 times the area of Los Angeles.
- China, USA, Kazakhstan, Russia, Canada, Malaysia, Germany, Ireland, Iran, Thailand, Sweden, Norway, Singapore, and the UK are among the top contributors to the carbon, water, and land footprints of the global BTC mining network.
- China's share in BTC mining dropped from 73% (2021) to 21% (2022) due to government's interventions while the shares of the United States and Kazakhstan increased by 34% and 10%, respectively.
- Countries with low electricity prices like Kazakhstan, where electricity price is three times cheaper than that in the U.S., are BTC mining heavens providing major financial incentives for BTC mining that is heavily reliant on non-renewable energy sources.
- Urgent regulatory intervention and technological breakthroughs are needed to mitigate the environmental impacts of the digital currency sector which is rapidly growing.

Bitcoin Mining Across the Globe

Traditional money vs digital money, by edwin chuen/flickr (Image is cropped)

Throughout history, many philosophers have extensively studied the fundamental aspects of money, including its value, form, functions, and circulation within financial markets[5]. The emergence and evolution of money continue to fuel debates on private money. These discussions, particularly since the latter half of the nineteenth century, underline the need for monetary competition and the ability of entrepreneurs to create suitable currencies, even when considered as illicit alternatives[6].

The twentieth century introduced a new element benefiting from the technological breakthroughs of the humans' Fourth Industrial Revolution (Industry 4.0): cryptocurrency. Its classification as private money remains a subject of ongoing debate, with scholars still striving to define its concept and economic nature[5]. From an economic perspective, debates continue regarding BTC's true nature and functions. Some studies view cryptocurrencies as a medium of exchange, while others see it as a speculative investment.

Some analyses consider cryptocurrencies as financial assets[7] with the potential of outperforming traditional currencies in certain aspects, such as durability, divisibility, portability, liquidity, and lower transaction costs[8]. However, critics argue that for cryptocurrencies to have value, they must receive government support[5]. It is argued that cryptocurrencies will not be able to fully replace conventional money because of the lack of a central authority to manage them, fluctuating demand for them, and their inflexible supply[9]. Some scholars also argue asserting that private monetary arrangements, except in special cases, would not be socially optimal and might not address issues more efficiently than government-issued money[10]. Critics also believe that the private arrangement of digital currencies may not achieve a socially efficient allocation[11].

It is true that the cryptocurrency market is highly dynamic, influenced by various factors, including market uncertainty and the investors' expectations[12]. Nonetheless, cryptocurrencies have been successful in winning the trust of a big community of investors, ranging from tech billionaires and big companies to criminals, money launderers, and economic sanction busters. As of February 2022, more than 10,000 types of cryptocurrencies have been traded worldwide[1]. These cryptocurrencies have distinct characteristics that impact their prices and stability, which can fluctuate significantly due to market dynamics and external influences. 65% of cryptocurrency users are bitcoin (BTC) owners[2]. Between 2012 and 2022, the price of this popular cryptocurrency increased by over 540,000%[2].

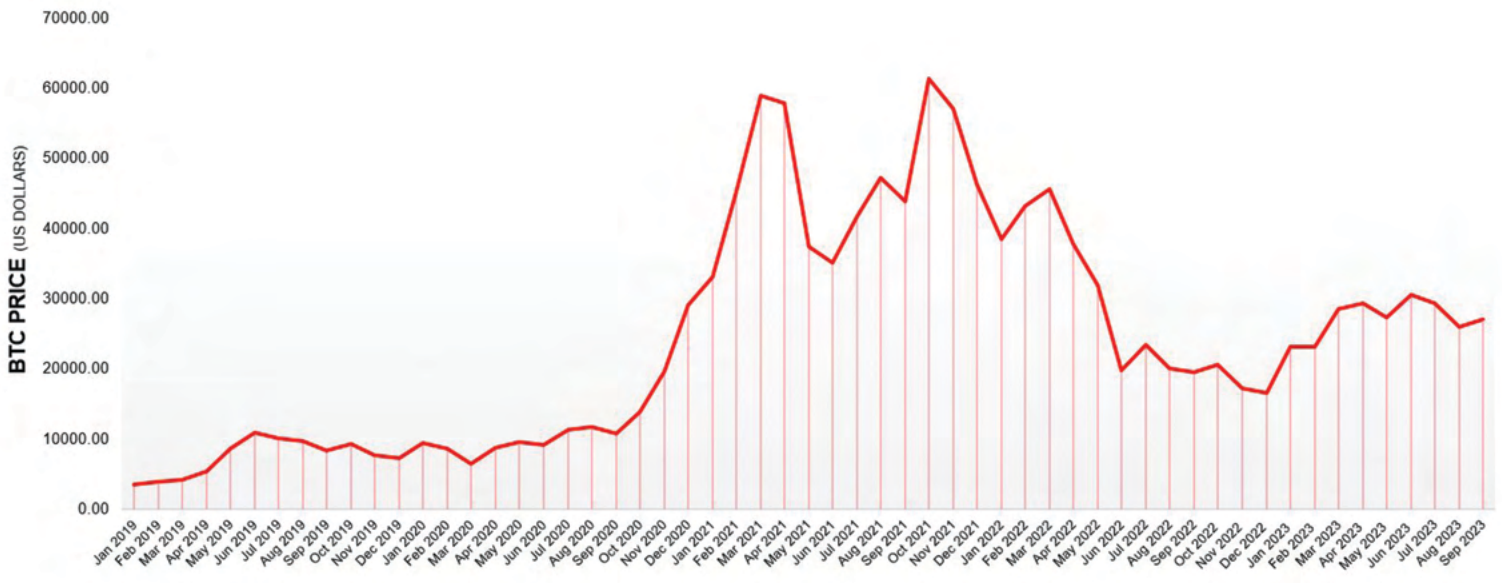


Figure 1. BTC price (2019-2023)
(Data from coinmarketcap.com)

Bitfarms' employees inspecting minning hardwares in Saint Hyacinthe, Quebec, by Christinne Muschi/ Bloomberg

The European Central Bank (2015) views BTC as a digital representation of value that is not issued by a central bank but can function as a substitute for banknotes, coins, demand deposits, and electronic money[13]. A few studies suggest that BTC has the potential to become a universal currency[9] while others propose a dual currency system comprising a government-issued currency and a valueless digital currency[14]. BTC has demonstrated a controlled supply, with a limited number of BTC that can be mined. In the second quarter of 2023, approximately 19.41 million BTCs were in circulation[15]. BTC's increasing popularity has led to its acceptance by various businesses and institutions. Over the years, a growing number of merchants, including major companies like Tesla, Dell, Target, Microsoft, Burger King, AT&T, PayPal, Wikipedia, KFC, Pizza Hut, Overstock, and more, have begun accepting Bitcoin payments. The availability of BTC debit cards issued by Visa or Mastercard has further facilitated its use for transactions. As of September 2023, the global crypto market cap is about $0.5 trillion[3] with BTC being the main shareholder with about $555 billion.

Cryptocurrencies have emerged as a digital alternative to traditional cash, however, their energy demand is a point of concern. Processing cryptocurrency transactions requires a computational setup, which contributes to the network by solving the cryptographic puzzle. BTC mining employs energy-intensive methods, including PoW (Proof of Work) and hybrid PoW/PoS (Proof of Stake) systems 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 significant growth in electricity consumption. It is estimated that around 1 million BTC miners are currently operating around the world[17].

An average BTC miner requires about 1.5 kW of power, equivalent to 36 kWh per 24 hours of operation[18]. This is slightly bigger than the daily electricity use per capita in the United States, one of the world's top energy consumers. While miners are becoming more efficient in terms of energy use, the substantial

increase of total hashrate (the total computing power used by a miner or network of miners for processing transactions on a PoW blockchain) over the past years indicates that more miners are being added into the BTC network.

Estimates of BTC energy consumption vary due to factors such as hardware efficiency and electricity costs[19]. But generally, as more profit-driven individuals enter the industry, energy consumption will continue to rise[20]. In 2017, BTC's energy consumption accounted for about 13% of Turkey's total electricity usage, surpassing many African countries[21]. Estimates suggest that in 2018, BTC mining's global energy demand ranged from 15.47 TWh to 50.24 TWh[22].

There have also been concerns regarding the locations of BTC mining activities and the sources that facilitate mining activities such as the Chinese coal, Icelandic geothermal energy, and Venezuelan subsidies[23]. Intense competition has driven miners to seek locations with low electricity costs, leading to mining centers in regions like the Arctic Circle, where KnCminer, a Swedish company, attempted to capitalize on local hydropower and cooler temperatures for cost-effective mining but ultimately went bankrupt in mid-2016. In 2019, 58% of BTC mining occurred in China, followed by the USA with 16%[21]. China's dominance in this sector is attributed to its cheaper electricity and many Chinese BTC centers rely heavily on coal for energy[24].

Apart from electricity consumption, BTC transactions, have raised concerns about greenhouse gas emissions, potentially undermining global efforts to combat climate change as outlined in the Paris Agreement[25]. Some projections even suggest that Bitcoin emissions alone could push global warming beyond 2 degrees Celsius[4]. BTC mining may leave a carbon footprint, equivalent to the emissions of nations like Jordan and Sri Lanka and on par with the emissions of Kansas City[26]. The disposal of electronic waste generated by obsolete mining equipment poses another environmental challenge. BTC mining hardware typically becomes obsolete in about 1.5 years, leading to significant electronic waste generation, equivalent to the total electronic waste produced by countries like Luxembourg[27]. These concerns have resulted in the emergence of several economic perspectives regarding the sustainability of BTC. Some argue that BTC could become unsustainable due to daily electricity consumption costs exceeding $150,000[28], in 2021. One study estimated that in 2018, every $1 worth of Bitcoin created resulted in $0.49 and $0.37 in health and climate damages in the US and China, respectively[29].

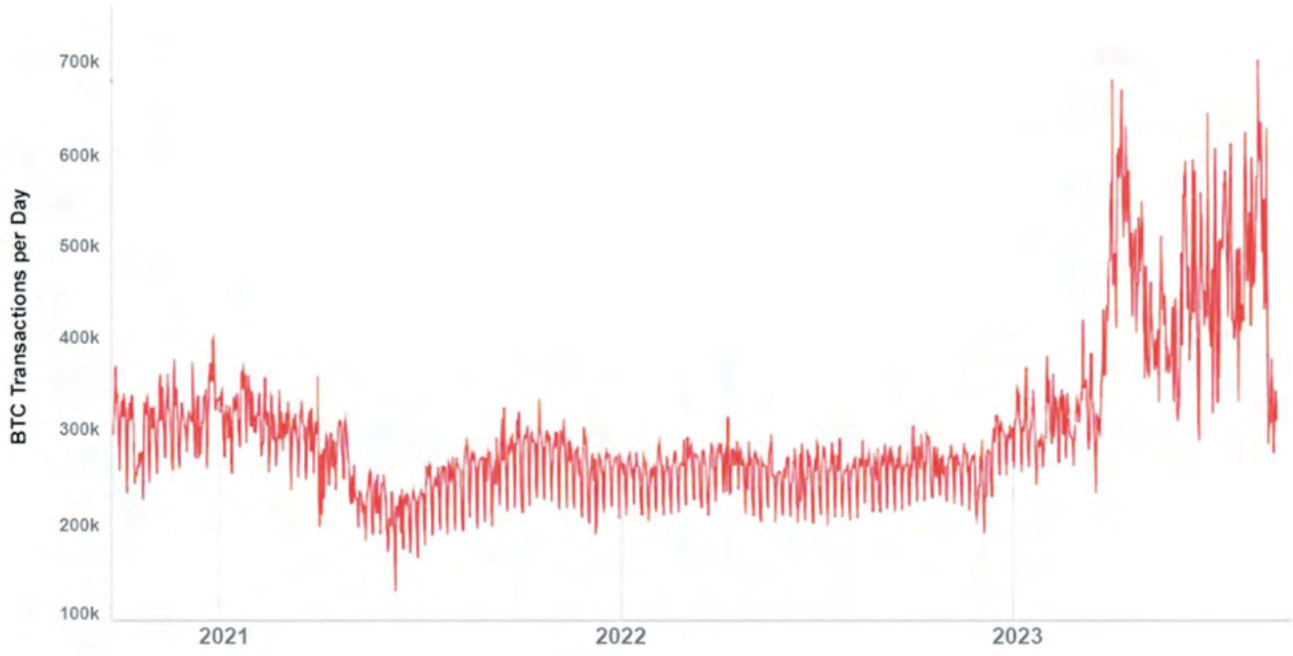


Figure 2. The total number of BTC transactions per day
(Data from blockchain.com)

Despite environmental concerns, some studies argue that BTC remains an economically viable alternative to traditional currencies. Some experts argue that the environmental costs of BTC mining, solely in terms of energy consumption, are lower than the costs associated with issuing paper money, gold mining, and traditional banking systems[30]. However, this comparison overlooks differences in services offered by BTC and traditional banking systems, as BTC requires specific technological conditions, such as an internet connection and compatible devices. Several studies compared BTC's environmental impact to that of traditional payment systems like VISA, but direct comparisons are considered inappropriate because VISA's energy consumption is transaction-specific, while BTC's energy usage encompasses all transactions since 2010[31].

Various perspectives have been developed to make BTC more environmentally sustainable, considering ecological and economic perspectives, although some argue that none of the suggested solutions seem entirely feasible[32]. One study suggested a regulatory approach, proposing fiscal measures such as environmental taxation to limit the environmental impact of blockchain technology
environmental challenges, blockchain technology itself offers opportunities for environmental sustainability[33]. Thus, implementing blockchain technology might have the potential to reduce the ecological footprint of the financial system. One obvious benefit can be achieved by eliminating paper usage in finance[34]. One study estimated that replacing paper money worldwide with cryptocurrencies could save approximately one billion trees from deforestation[35]. Nonetheless, history suggests that increased efficiency and technological advancements do not necessarily result in reduced energy consumption due to increased demand for using the saved resources due to efficiency improvements (rebound effect)[36].

While blockchain technology holds promise for sustainability in various fields, it cannot fully address the environmental concerns stemming from BTC mining. Mining operations have implications for local communities, energy supply, and infrastructure[37]. The concentration of mining operations in regions with cheap electricity has disrupted local electricity grids and raised safety concerns
health and environmental impacts of mining activities also raises major equity and justice concerns. Addressing these issues requires attention from the decision-makers and different stakeholders to find a balanced approach to the future of cryptocurrencies. The first step in finding such an approach is understanding and estimating the environmental impacts of BTC mining around the world, which is the focus of this report.

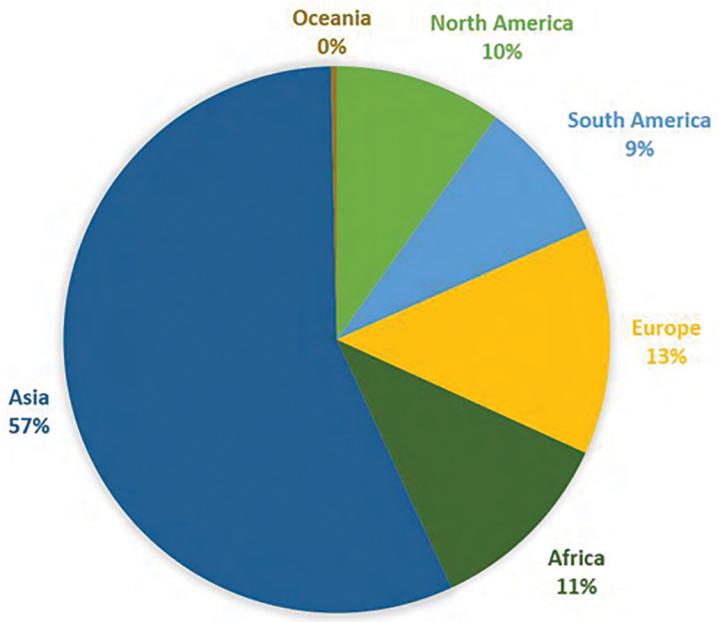


Figure 3. As of September 2023, there are over 300 million cryptocurrency users worldwide

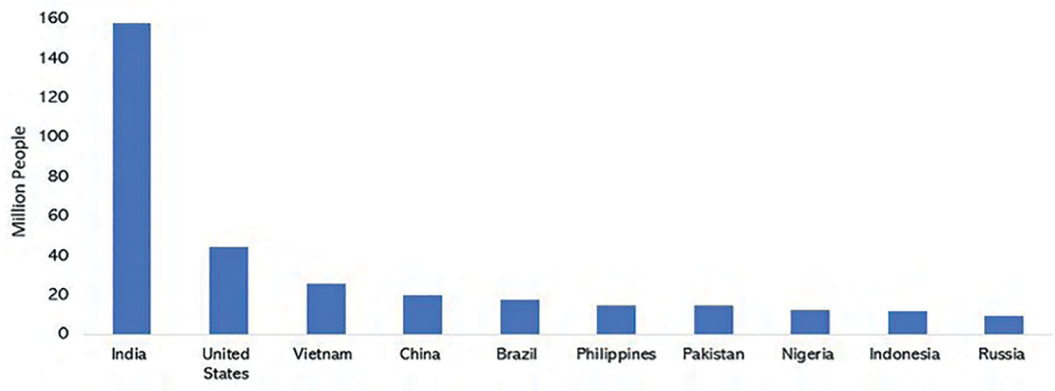


Figure 4. Number of cryptocurrency owners by country, as of September 2023

Environmental Footprint of BTC Mining

Bitcoin image by Dmytro Demidko/ Unsplash (Collaged with power plants and wind turbines images by Pixabay)

Regardless of the energy source, producing and transmitting electricity for cryptocurrency mining has numerous environmental impacts. This makes the growing digital currency market a potentially polluting sector with an environmental footprint level far more than some conventional methods of digital transactions. For example, each BTC transaction is believed to have an equivalent carbon footprint of more than one million VISA transactions[38].

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[4]. Despite these alarming expectations, the financial and technological motivations for mining cryptocurrencies have suppressed the conversation surrounding their potential environmental and social costs.

Evidently, the crypto sector is being increasingly integrated into the global financial system. The world's transition to a digital economy, facilitated by major technological breakthroughs, has several benefits. But as the demand for exchanging and investing in digital currencies is growing faster than ever, the world must pay careful attention to the hidden and overlooked environmental impacts of this growing sector. Although some studies have been recently conducted to analyze cryptocurrency's environmental costs, the uncertainties surrounding the extent of these costs remain considerable[39]. Additionally, past studies heavily focused on the carbon emissions of cryptocurrencies[26], not reflecting their major environmental impacts such as water and land footprints that contribute greatly to the overall environmental footprint of the cryptocurrency sector.

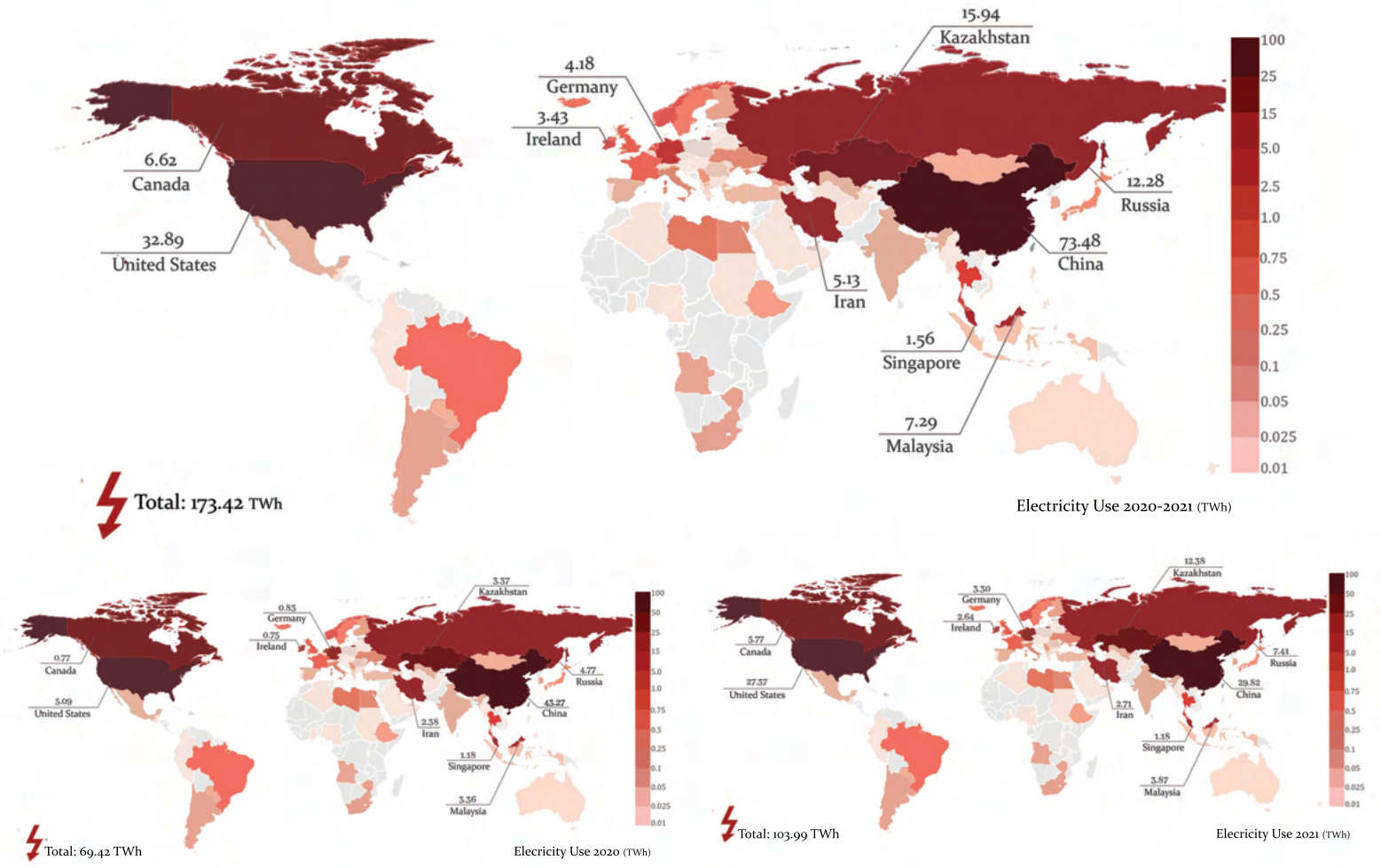


Figure 5. Electricity use of BTC mining across the world

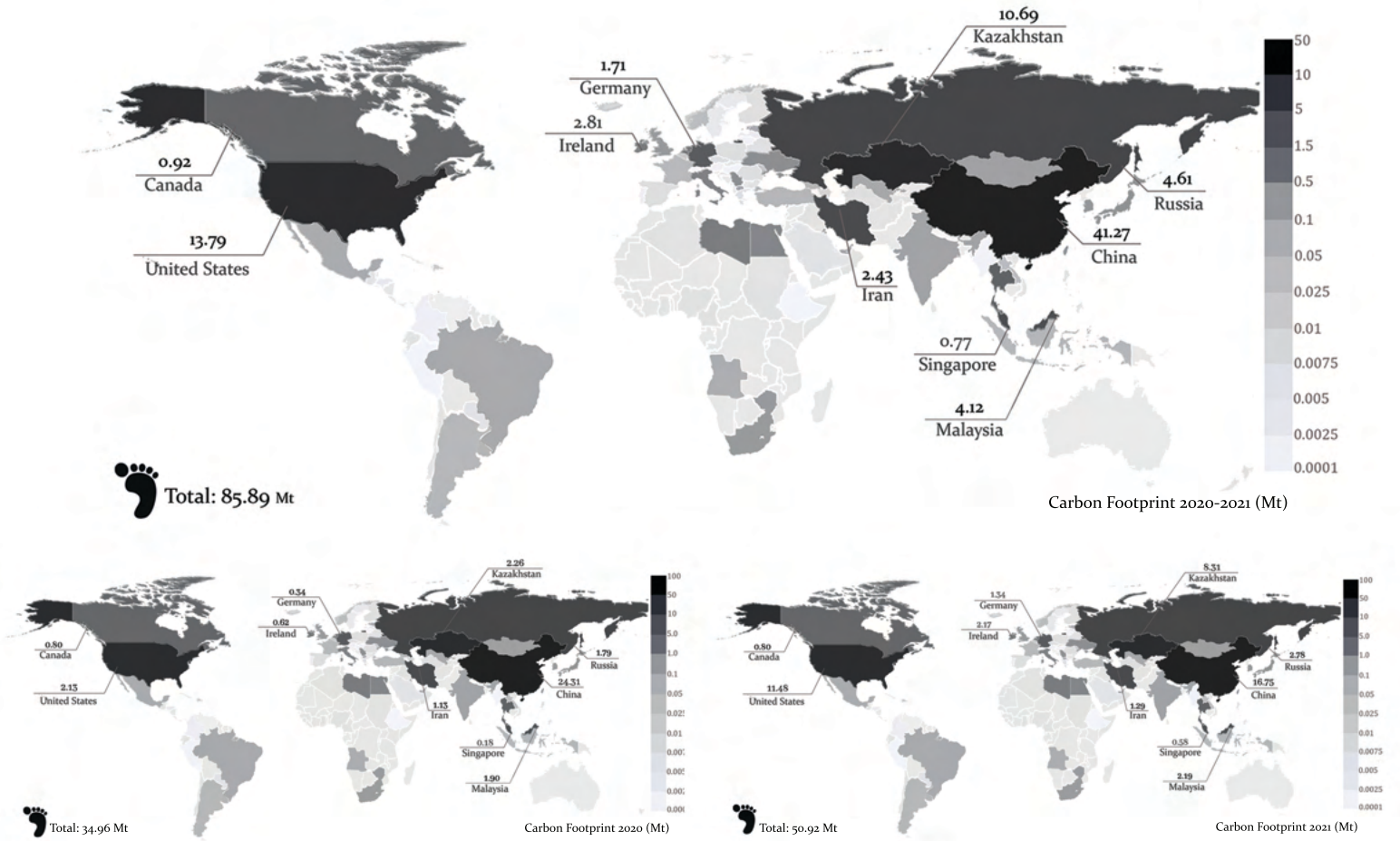


Figure 6. Carbon Footprint of BTC mining across the world

To highlight the need for taking serious regulatory action to monitor and mitigate the environmental impacts of digital currencies, one can evaluate the environmental footprints of BTC as the most well-known form of digital currency. This study used the 2-year Cambridge Bitcoin Electricity Consumption Index (CBECI) values[40] to provide the first global estimate of the carbon, water, and land footprints of BTC mining with respect to the variations in energy supply mixes around the world. First, the monthly electricity use for BTC mining in the 76 BTC mining nations monitored by CBECI between January 2020 to December 2021 was roughly estimated using the average monthly hashrate share of each country and the total monthly electricity use of the global BTC mining network. Then the average carbon, water, and land footprint of electricity generation in each BTC mining nation were estimated[41, 42] based on its energy supply mix data as reported by the International Energy Agency (IEA) and the environmental footprints of electricity generation from different sources using the scientific literature data on footprint valuesy[41, 42] .

Multiplying the BTC electricity use in each country by its footprint values provided the carbon, water, and land footprint estimated of BTC mining for that country. The significance of the estimated environmental footprints explains why the world should be concerned about the overlooked environmental footprints of the global BTC network. In the 2020-2021 period, the worldwide BTC mining network used 173 TWh of electricity, 60% more than its electricity use in during the 2018-2019 period. Based on CBECI values, in 2021 and 2022, the annual electricity consumption for BTC mining across the globe exceeded 100 TWh per year. Currently (as of July 2023) the global electricity consumption for BTC mining in 2023 is expected to be above 135 TWh[40]. So, if BTC were a country, its energy consumption would have ranked it 27th in the world, ahead of a country like Pakistan with a population of over 230 million people.

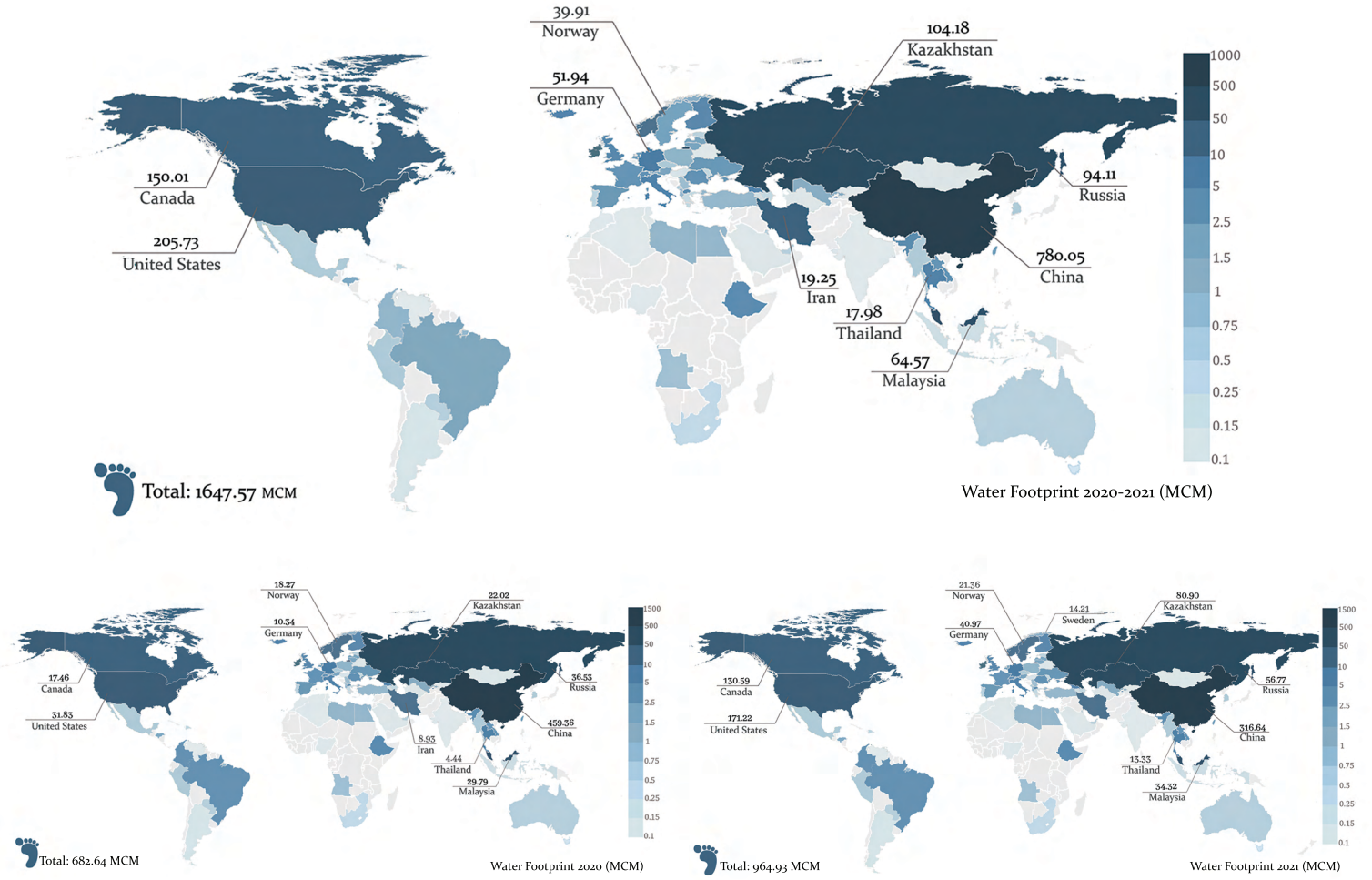
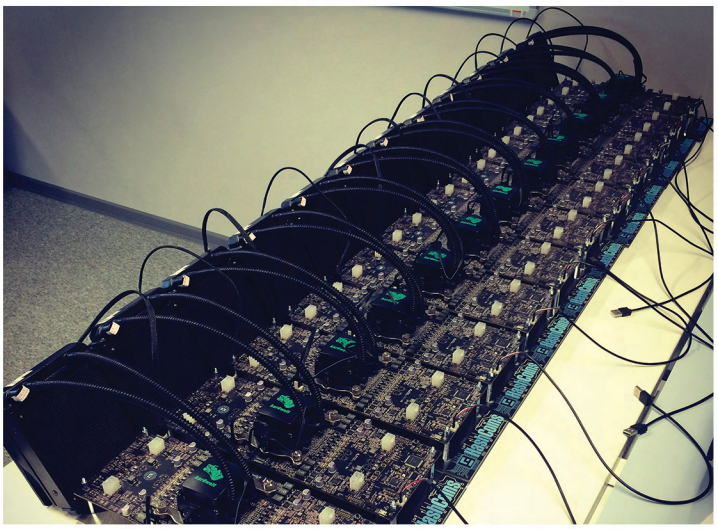


Figure 7. Water Footprint of BTC mining across the world

The BTC network is highly dependent on fossil energies, constituting 67% of the BTC's global energy supply mix, with coal having a 45% share in this mix. Subsequently, global BTC mining emitted more than 85.89 Mt of CO_2eq from 2020 to 2021, equivalent to carbon emissions from 84 billion pounds of coal burned, 190 natural gas-fired power plants, or over 25 million tons of landfilled waste. To offset the CO emissions of BTC mining in 2020 and 2021 about 3.9 billion trees should be planted, taking up an area almost equal to the area of countries like the Netherlands, Switzerland, or Denmark or 7% of the Amazon rainforest. Hydropower, an energy source with a high 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 16% of the global BTC network's electricity demand.

In the 2020-2021 period, the global water footprint of BTC mining was about 1.65 km^3, equivalent to filling over 660,000 Olympic size swimming pools, and more than the current domestic water use of over 300 million people in rural Sub-Saharan Africa. BTC is also intensive in terms of land footprint. The overall land footprint of the BTC mining network around the world in the 2020-2021 period was more than 1,870 square kilometers, 1.4 times the area of Los Angeles.



Bitcoin mine hardware, by Alexander Gromov/ Wikimedia Commons

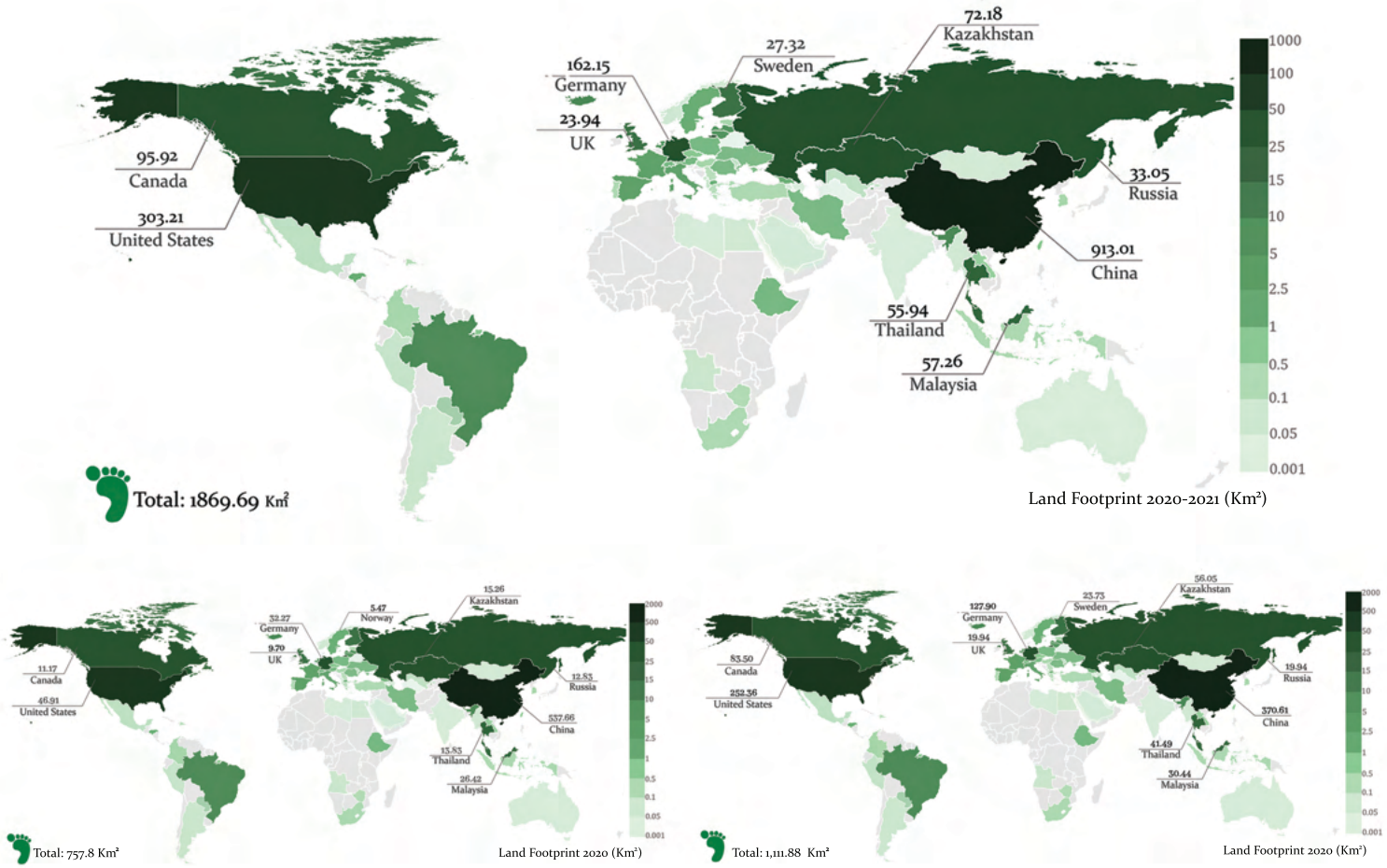


Figure 8. Land Footprint of BTC mining across the world

A mining farm located in Iceland, by Marco Krohn/ Wikimedia Commons

The World's Top 10 BTC Miners

Bitcoin image by Edwin.images/ Wikimedia Commons (Collaged with mining image by Pixabay)

The landscape of BTC mining is very dynamic. For years, China, by a large margin, has been the biggest BTC mining nation. Nevertheless, its share has dropped from 73% in 2021 to 21% in 2022. This can be attributed to the different government bans and actions against BTC mining[43]. Some media reports suggest that China has been transferring some of its load to countries such as Kazakhstan and the United States[44] to reduce its carbon footprint and overcome the challenges of tracking fraud and illegal financial activities[44]. This has resulted in an increase in the shares of the United States and Kazakhstan by 34% and 10% respectively based on the reported CBECI values in 2023. The reduction of China's BTC mining interest has resulted in a shift in the energy supply mix of BTC mining network. In 2020, 52% of the global BTC network's energy supply came from coal.This number was reduced in 2021 and 2022. However, the global BTC mining network is still very dependent on fossil fuels. In fact, the share of the natural gas has increased from 2020 to 2022. This increase is mainly due to the high dependency of electricity generation

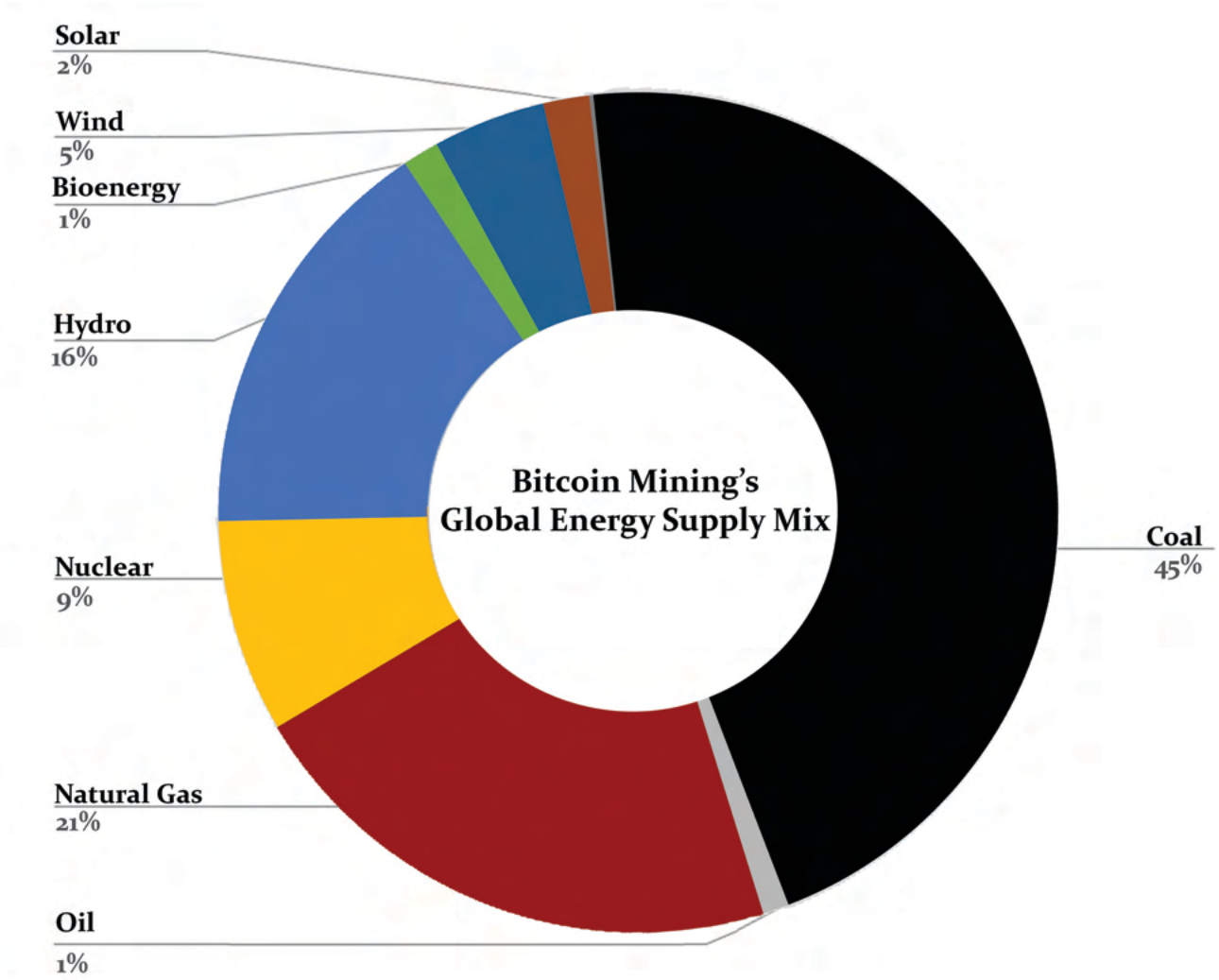


Figure 9. Contributions of different energy sources in supplying electricity to the global BTC mining network (2020-2021)

in some of the top BTC mining countries on natural gas. Currently, there are no federal laws prohibiting BTC mining in the second top BTC mining nation of the world, the United States. BTC mining regulations vary across the states in this country. Georgia, Kentucky, Texas, and New York are the top four hotspots for mining BTC, respectively responsible for 31%, 11%, 10.9%, and 9.8% of BTC mining in the U.S. [40].

Electricity cost in the fossil energy-dependent Kazakhstan—the third top BTC miner in the world—is three times cheaper than the U.S., motivating heavy investments in BTC mining in this country. BTC mining is also popular in Kazakhstan's neighbor, Russia, where electricity consumption for BTC mining is slightly less than Kazakhstan. The BTC mining's electricity use in Russia is 37% and 17% of electricity consumption for BTC mining in the U.S. and China, respectively. Malaysia, Canada, Iran, Germany, Ireland, and Singapore are the other six members of the world's top BTC miners list.

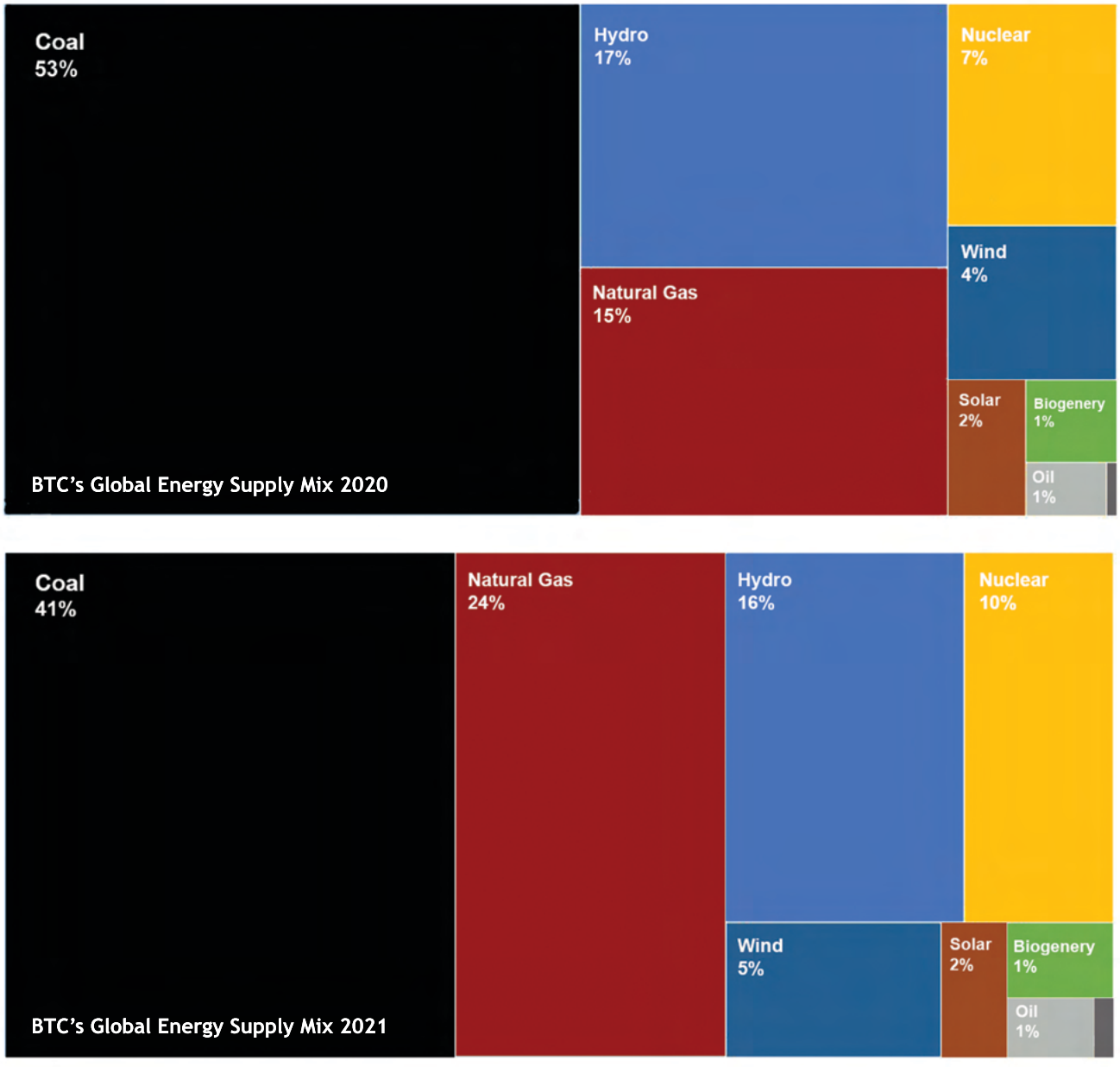


Figure 10. Contributions of different energy sources in supplying electricity to the global BTC mining network

BTC mining in China and the U.S. also have the highest environmental footprint in the world, but the top BTC miners' ranking slightly changes when countries are ordered based on their BTC mining's carbon footprint, water footprint, and land footprint instead of their BTC mining's electricity use. This is because each country uses a unique mix of energy sources to produce electricity, having different water, carbon, and land footprints, making the relationship between BTC's electricity use and environmental footprints non-linear. For example, Ireland ranks ninth in terms of electricity use for BTC mining. But the BTC mining sector in this country has the sixth highest carbon footprint globally due to its high dependency on fossil sources of energy for electricity production. In addition to some ranking changes, one can notice that the differences (in terms of percentage) between the performance values of each country (electricity use, carbon footprint, water footprint, and land footprint) are not of the same magnitude.

For example, Canada is the sixth BTC miner of the world in terms of electricity use but the ninth emitter of greenhouse gases for BTC mining thanks to the smaller role of coal and higher role of nuclear and natural gas in its energy supply portfolio in comparison to some other countries in the top BTC miners list. As a result, BTC mining's electricity use in Canada is 20% of that in the U.S. but the carbon footprint of BTC mining in Canada is less than 7% of that in the U.S. These values are 9% and 2%, respectively, when Canada is compared with the world's top BTC mining nation. China's coal-intensive BTC mining produced more than 41 Mt CO_2eq from January 2020 to December 2021. To offset this level of emissions, over 2 billion trees should be planted which take up an area equivalent to the sum of Portugal and Ireland or 45,000 times the area of Central Park in New York City. Together, the top ten BTC carbon emitters are responsible for 94% of the carbon footprint of the BTC sector.

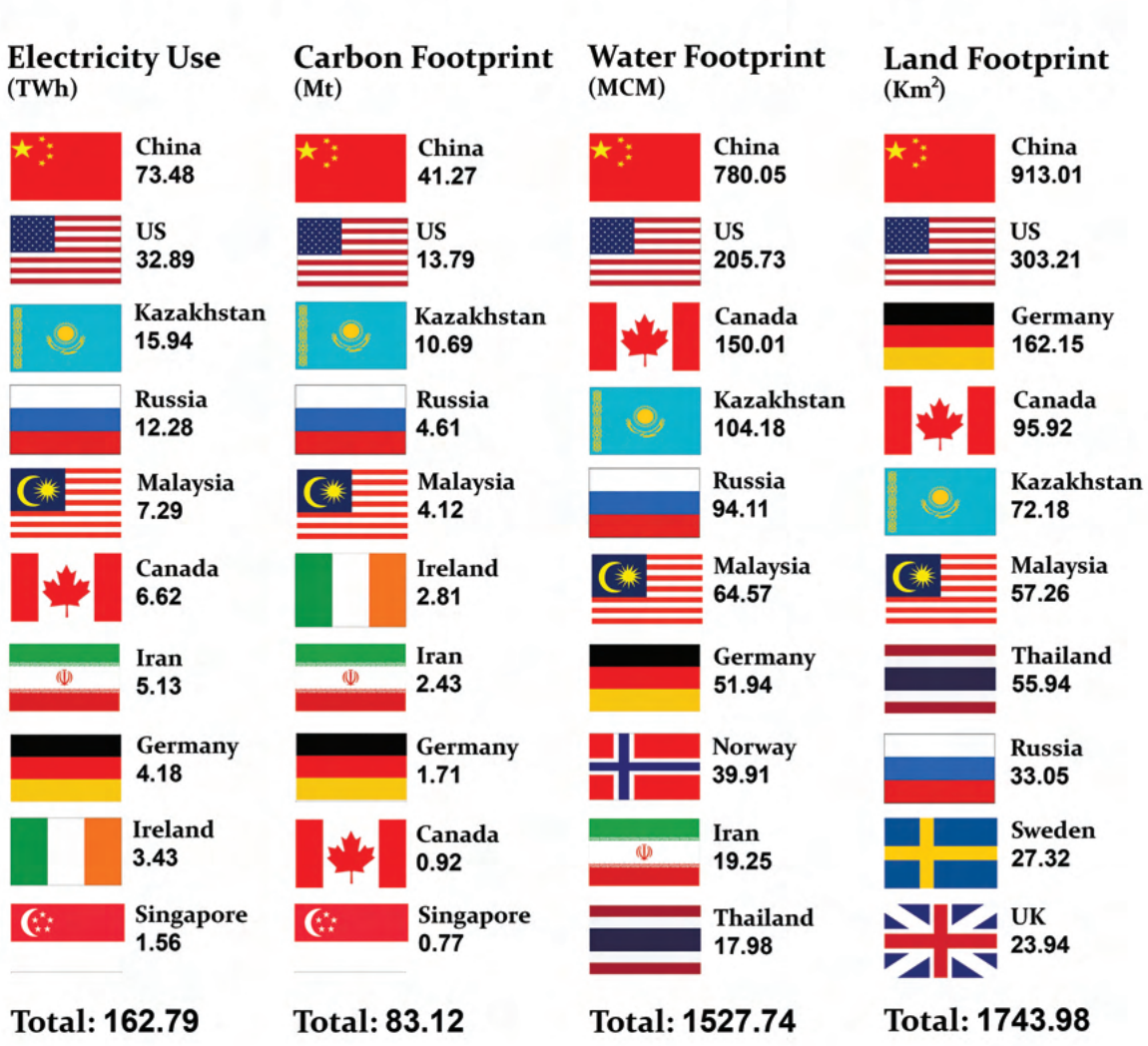


Figure 11. The world's top ten BTC miners in terms of electricity consumption, carbon footprint, water footprint and land footprint (2020-2021)

The ranking based on the water footprint of BTC mining is reflective of the water intensity of electricity production in each country. Iran, a country that is already dealing with "water bankruptcy" [45], is among the top ten countries contributing to the global water footprint of BTC. Nonetheless, the high dependence of Iran's electricity generation on natural gas makes its BTC mining less water-intensive (but more carbon intensive) than countries like Canada and Norway that produce significant amounts of electricity from water-intensive renewable energies. Canada with about 60% dependency on hydroelectricity ranks third globally with respect to the impact of its BTC mining activities on water resources. Thailand with a high dependency on water-intensive bioenergy sources is another country that makes it to the list of top BTC mining nations in terms of water footprint. Together, the ten countries in this list contribute to 92.5% of the global water footprint of BTC mining.

Thailand, Sweden, and UK are not in the list of top ten BTC miners in terms of electricity use. But they are among the top ten major contributors to the total land footprint of BTC mining due to the high contribution of land-intensive energy sources (e.g., bioenergy) to their electricity sector. The ten countries with the most land-intensive BTC operations are responsible for 93% of BTC's global land footprint.

Due to its nature, cryptocurrency mining activities are hard to track, creating barriers to the regulation of the crypto market and its imposed load on the power grid. In February 2021, German officials investigated a case of an individual who mined more than 1,700 BTC - worth $34 million at $20,000/BTC exchange rate - through others' computers without their awareness[46]. The price of BTC is one of the important driving factors to determine BTC mining profitability[47, 48, 49]. Higher prices mean higher profitability, which motivates more BTC mining and therefore higher electricity consumption
BTC price rose 400% compared to the previous year, the worldwide BTC network saw a 140% spike in electricity use.

This price spike and the increased interest in BTC mining had social and political implications in different countries. For example, the Government of Iran blamed its major blackouts in 2021 on hidden BTC mining farms and "illegal" mining activities. Evidently, the growth of the BTC market is not purely motivated by financial incentives, this makes it difficult to explore the causal relationship between the average BTC price and energy consumption on a daily basis. Nonetheless, we see a 77% correlation between these two variables over the January 2020-December 2021.

It still remains challenging to determine to what extent BTC price changes can affect energy consumption[50]. While the BTC price has an impact on the interest in BTC mining, the growth of the markets of BTC and other cryptocurrencies involves a range of financial, political, security, and even criminal incentives, that can motivate states along with large corporations and investors to invest in these markets. Undeniably, the digital currency sector is growing while its environmental impacts remain overlooked.

A Bitcoin mining farm, by Marko Ahtisaari/ flickr

Figure 12. The world's top ten BTC miners in terms of electricity consumption, responsible for 96% (2020) and 94% (2021) of total electricity use of the global BTC mining network in 2020 and 2021, respectively

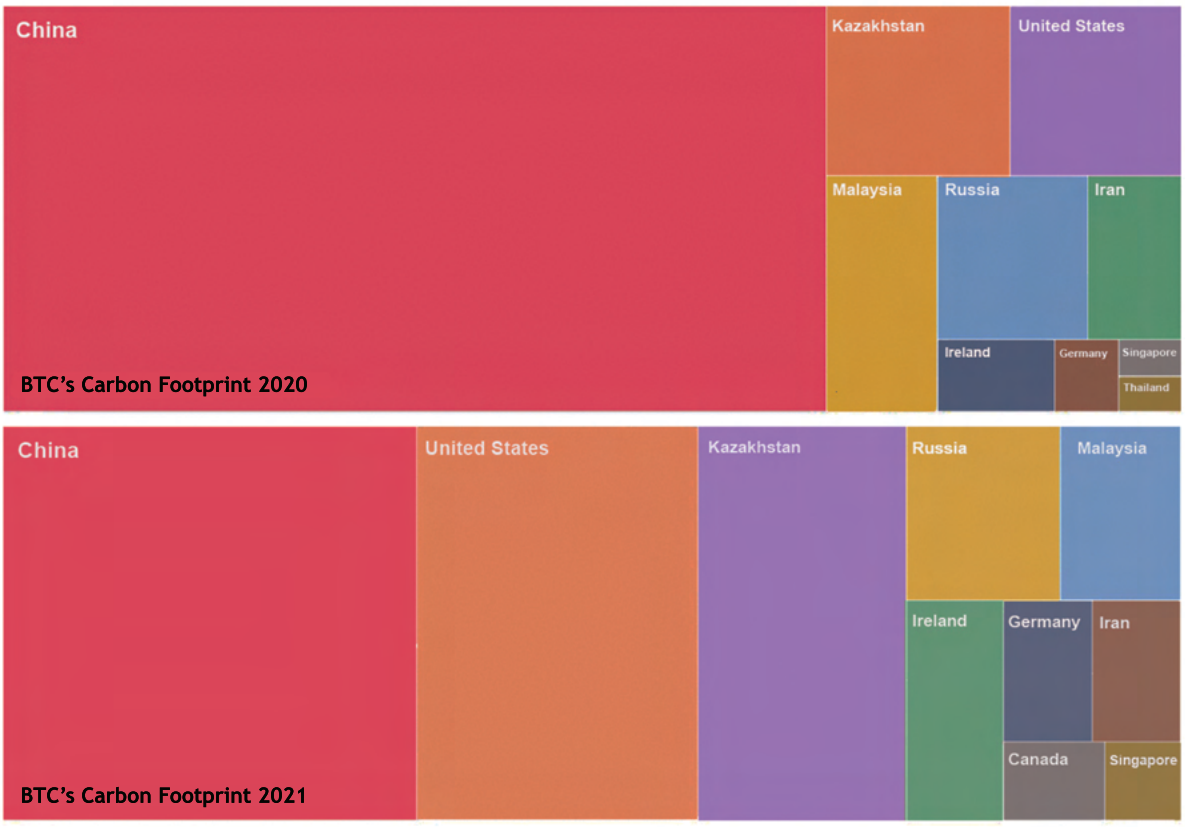


Figure 13. The world's top ten BTC miners in terms of carbon footprint, responsible for 97% (2020) and 96% (2021) of total carbon footprint of the global BTC mining network in 2020 and 2021, respectively

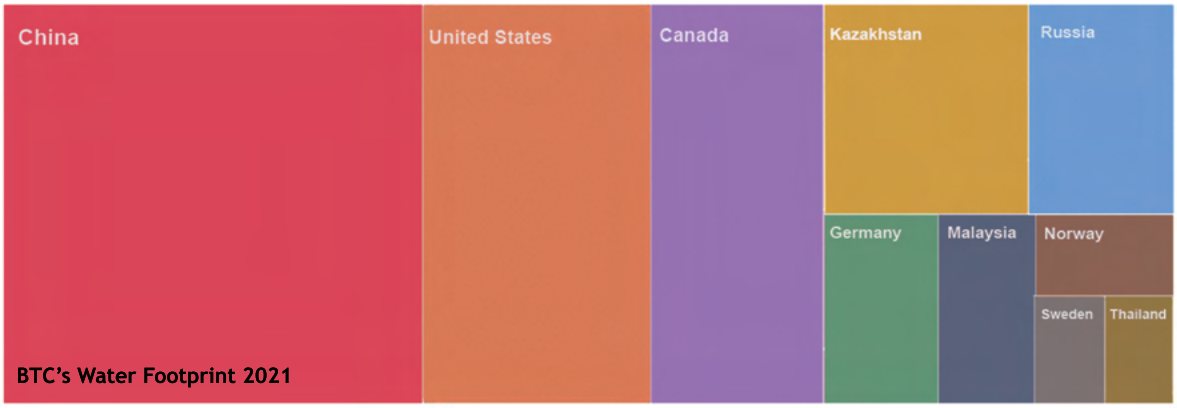


Figure 14. The world's top ten BTC miners in terms of water footprint, responsible for 95% (2020) and 92% (2021) of total water footprint of the global BTC mining network in 2020 and 2021, respectively

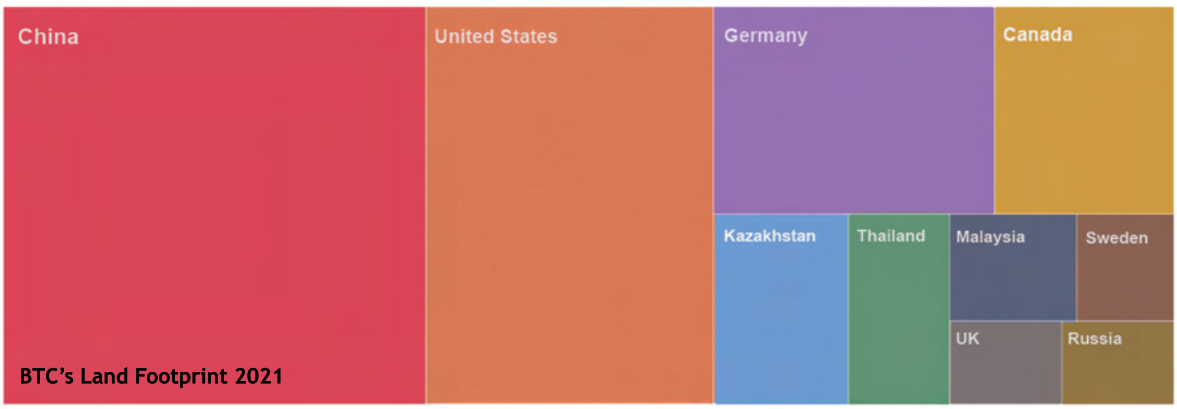


Figure 15. The world's top ten BTC miners in terms of land footprint, responsible for 95% (2020) and 93% (2021) of total land footprint of the global BTC mining network in 2020 and 2021, respectively

Policy Recommendations

Bitcoin image by Brian Wangenheim/Unsplash (collaged with images by Pixabay)

The estimated environmental footprints of global BTC mining and its heterogeneous environmental impacts across the world unpack the concerning costs of the unchecked growth of an innovative but "ungreen" economy. This is especially concerning as some of the countries in the top ten countries on the BTC miners in terms of electricity use have a GDP per capita of less than the global average and are already struggling with social and economic justice measures. Unregulated and untaxed mining activities exacerbate the inequality in these areas and have lasting environmental impacts. Thus, we advocate for immediate policy, technologic, and scientific interventions to mitigate these transboundary and transgenerational costs with major environmental injustice implications.

Policies must be enacted at the national and global levels to increase the transparency of cryptocurrency mining. These policies can be accompanied by a suite of economic and regulatory tools (e.g., increased cryptocurrency mining electricity price, taxes on cryptocurrency revenues and transactions, carbon offset mandates for blockchain tokens, ban on unclean energy-based cryptocurrency and digital-currency mining, and environment-unfriendly digital currency divestment campaigns) to limit and compensate for the environmental costs of cryptocurrency market and reducing its reliance on "ungreen" energies, i.e. those non-renewable and renewable energies that have high RAFs (Relative Aggregate Footprint is an index that normalizes the overall environmental footprint of energies according to local resource availability conditions[42, 51].

Transition to a sustainable future requires taking advantage of different Industry 4.0 products without overlooking the need for a careful examination of their economic, environmental, and social trade-offs at the local and global levels.

A Bitcoin mining hardware, by Wikimedia Commons

Different Bitcoin and cryptocurrencies ATM, by John Paul Cuvinar/ Unsplash

The overall footprint of BTC and all other 'alt-coins' networks depends both on the mining hardware and the blockchain validation protocol. Creating energy-efficient alt-coins and technological innovations that reduce the life-cycle impacts of all contributing elements of the crypto network are essential to reducing the environmental impacts of this global network. For example, developing and implementing blockchain validation protocols that are safe, but not as energy-consumptive as the PoW, such as the proof-of-stake (PoS) validation method, can reduce the cryptocurrencies' energy use per transaction and consequently slow down the global cryptocurrency energy demand growth.

Finally, more research is needed on the comprehensive evaluation of the transition to digital currency and its associated environmental impacts and various trade-offs. Future studies must go beyond carbon and BTC, as carbon footprint is not the only negative environmental impact of cryptocurrency mining and BTC is not the only popular, energy-consumptive cryptocurrency. High-resolution estimates of cryptocurrency mining footprints and future growth projections are required to enable a sustainable digital crypto market. The availability and knowledge of such estimates are vital for: 1) policymakers to enact change, and 2) individuals and companies to minimize the environmental footprints of their investments and protect their reputation and financial assets against transition risks, resulting from market, legal, and policy changes as the world is fighting climate change, and physical risks, resulting from resource availability issues (e.g., water or energy shortage).

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