

The water and carbon footprint of cryptocurrencies and conventional currencies

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ARTICLE INFO

Handling Editor: Giorgio Besagni

Keywords:

Cryptocurrency
Conventional currency
Water footprint
Carbon footprint
Spatial analysis

ABSTRACT

When compared to traditional fiat currencies, cryptocurrencies represent a small, but growing, fraction of financial transactions. The rapid growth of cryptocurrencies has raised concerns regarding the environmental impact of this energy-intensive type of currency. In this study, water and carbon footprints associated with cryptocurrencies are assessed. These environmental footprints are then compared to the water and carbon footprints associated with conventional currencies, which is a novelty of this study. A spatially refined, bottom-up analysis of the most energy-intensive aspects of each financial system is used in the comparison of these systems. Specifically, the energy use for printing money, bank branches, automated teller machines (ATM), and cashless transactions is evaluated at the country level and compared to the energy use of crypto mining around the world. Cryptocurrencies' electricity use of 236×10^6 megawatt hours (MWh) in 2021 surpassed that of the conventional transaction system, despite cryptocurrencies representing less than 0.5% of global cashless financial transactions. In terms of its water footprint, cryptocurrencies have an annual water consumption of 3670×10^6 cubic meters (m^3). Cryptocurrencies' water footprint is more than double that of conventional currencies because crypto mining takes place in countries with higher water intensities for electricity. Crypto mining activities are also estimated to result in almost 139×10^6 tonnes carbon dioxide equivalent (CO_2 -eq) of global greenhouse gas emissions. While cryptocurrencies represent a small percentage of financial transactions, their environmental impact is much larger than the conventional financial transaction system. This study shows how regulatory changes, such as the 2021 crypto mining ban in China, and crypto mining location can have implications on the environmental footprint associated with cryptocurrency.

1. Introduction

In the past decade, cryptocurrencies have gone from an esoteric medium of exchange to a mainstream asset. Several major corporations, as well as countries such as the Central African Republic and El Salvador, now accept cryptocurrencies as legal tender. As of July 2022, there were nearly 22,000 listed cryptocurrencies with a total market capitalization of over 1 trillion US dollars. Bitcoin, the first and largest cryptocurrency, constitutes a little under half of the cryptocurrency market capitalization ("Today's Cryptocurrency Prices by Market Cap," 2022). In comparison, the United Nations lists only 152 fiat currencies as legal tender (United Nations, 2022), with the US Dollar (USD) having the largest circulation volume of notes, valuing roughly 2 trillion USD, as of 2021 (US Currency Education Program, 2022). Market uncertainty may shift investments toward sustainable production systems and away from traditional financial markets (Caferra and Falcone, 2022). However, the

volatility of cryptocurrencies currently limits its widespread replacement of fiat currencies although this condition may change in the future (Extance, 2015; Krause and Tolaymat, 2018). Presently, cryptocurrencies constitute a small, but growing, fraction of financial transactions when compared to traditional fiat currencies and cashless transactions.

While over one hundred national governments print paper money and a handful of companies handle the vast majority of cashless financial transactions (e.g., Visa, Mastercard, UnionPay), over one million miners across the globe 'mine' cryptocurrencies (Chamanara et al., 2021). The mining of cryptocurrencies is a computationally intensive process that uses specialized machines to competitively add new transactions, which are stored as digital blocks in a blockchain and maintained by the decentralized community. The increasingly large computational power required to mine cryptocurrencies requires a significant amount of electricity. For example, Krause and Tolaymat (2018) estimated that Bitcoin, Ethereum, Litecoin, and Monero mining consumed an average

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<https://doi.org/10.1016/j.jclepro.2023.137268>

Received 23 November 2022; Received in revised form 12 April 2023; Accepted 20 April 2023

Available online 29 April 2023

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of 17, 7, 7 and 14 megajoules (MJ), respectively, to generate one USD in value for the period of January 1, 2016–June 30, 2018. For comparison, the conventional extraction of gold and platinum consumed 5 and 7 MJ to generate one USD in value, respectively. The mining of Bitcoin alone is estimated to constitute between 0.5 and 0.6% of global electricity use (Chohan, 2022; Kohli et al., 2022). The growing energy demand for cryptocurrency mining has raised concerns about the environmental sustainability of this new form of currency (Krause and Tolaymat, 2018; Mora et al., 2018; Wendl et al., 2023).

A lack of spatially explicit data and analysis has inhibited a consensus on the environmental footprint of cryptocurrency. Estimates of carbon emissions for Bitcoin and other cryptocurrencies vary widely. In 2017, these estimates ranged from 2.9 to 69.0 million tonnes CO₂-eq/yr (Digiconomist, 2022; Foteinis, 2018; Krause and Tolaymat, 2018; McCook, 2018). These values also had a similar range in 2018 (Houy, 2019; Kohler and Pizzol, 2019; Stoll et al., 2019; de Vries and Stoll, 2021). In 2021, the estimates of carbon emissions ranged from 64.18 to 108.92 million tonnes CO₂-eq/yr (de Vries et al., 2022; Kohli et al., 2022; Sarkodie et al., 2022). The variance in carbon footprint estimates reflects a similar range of energy use estimates associated with cryptocurrency mining, which is partly attributable to uncertainty regarding the equipment used by miners and their precise location. Operational locations are typically chosen based on access to high-volume and low-cost electricity as well as stable political and friendly regulatory environments (Rauchs et al., 2018). Equipment and location information would help reveal how much electricity is used and the most likely sources of power, the latter of which can help identify carbon emissions from power plants that can be attributed to cryptocurrencies. Stoll et al. (2019) was the first study to use detailed data on mining hardware, facilities, and pools, along with the pool server, miner, and device IP addresses, to estimate the amount and location of electricity consumption and the carbon footprint associated with Bitcoin in 2018. Though significant uncertainty remains regarding the environmental footprint of cryptocurrencies, there is general agreement that the energy use and carbon emissions of cryptocurrencies have increased over time and that the carbon emissions associated with crypto mining are significant, often comparable to the carbon footprint of small countries. However, other environmental impacts of cryptocurrencies, such as water consumption, are not well understood.

Cryptocurrency transactions are generally considered to be more energy and carbon intensive than cashless financial transactions, such as Visa, by several orders of magnitude (Kohli et al., 2022). If cryptocurrencies are to become more mainstream and seek to replace traditional financial systems, it is important to understand the broader implications of this transition, particularly as it relates to the environment. First, a baseline of comparison between the two financial systems is needed. At present, little is known about how energy use and the environmental footprint associated with cryptocurrencies compares to the traditional financial transaction system as a whole (i.e., fiat currencies, banking, and cashless transaction systems). Additional studies with diverse methodological approaches can narrow estimates for the water and carbon footprints associated with cryptocurrencies as they change over time and benchmark the environmental footprint of cryptocurrencies against traditional financial systems.

There has previously been no spatially explicit analysis regarding the environmental impact of cryptocurrency and its water consumption is not well understood. Additionally, a comparison between cryptocurrencies and traditional financial systems is necessary to understand the environmental implications of transitioning from traditional to cryptocurrency. Thus, this study estimates the country-level energy use and water and carbon footprints of conventional and crypto financial transaction systems. We use a spatially refined, bottom-up assessment of the water and carbon footprints of cryptocurrencies and conventional currency systems. The water and carbon footprints of cryptocurrencies are compared to conventional fiat currencies and the financial system that enables their use, which is a novel contribution of this study. Using

an operational lifecycle approach, conventional currencies are defined to include the printing/minting of paper notes/coins, the operation of bank branches, automated teller machines (ATMs), as well as the online banking that supports the storage and distribution of fiat currencies. In summary, the following research questions are addressed in this paper: 1) How much and where are energy and water consumed, and greenhouse gases emitted, in support of the global financial transaction system? 2) How does the environmental footprint of digital cryptocurrencies compare to conventional currencies? 3) What are the global implications of mandating or regulating cryptocurrencies at the regional level?

2. Methodology

This study focuses on estimating the operational water and carbon footprints for the global crypto and conventional financial systems. These operational water and carbon footprints include the water consumed and greenhouse gases emitted during daily operations or production, but do not include the water and carbon footprints for things like the construction or manufacturing of bank branches, mining rigs, or ATMs. Instead, the system boundaries of this study focus on the most energy-intensive aspects of each financial system, as shown in Fig. 1, since these components are a good indicator of the overall environmental footprint (de Vries et al., 2022; Kohler and Pizzol, 2019). While necessary due to data limitations, the truncation of system boundaries means that the water and carbon footprints calculated for both the conventional financial system and cryptocurrencies are likely to be underestimated in this study. However, Kohler and Pizzol (2019) determined that the operational stage constitutes over 99% of Bitcoin's carbon footprint; thus, values estimated in this study are likely to be only slightly less than the full lifecycle environmental footprint.

The most spatially detailed data available is used to estimate the energy use, water footprint, and carbon footprint for conventional and crypto financial systems. Table 1 summarizes the data used in this study, including the data type, source, spatial resolution, and the method utilized to fill in missing data records. Data quality, completeness, and coverage vary significantly by location and data type. Representative national or continental averages are used when data for certain countries are not available. In the following subsections, we describe how these data are integrated and incorporated into models to estimate the water and carbon footprints for the different system components.

2.1. Water and carbon intensity for electricity generation by country

Electricity generation is a water intensive sector that consumes water through evaporative cooling (thermoelectric power plants) and open surface evaporation (hydroelectricity). The type, location, and amount of energy used in the operation of both financial systems provides a good indication of the systems overall water and carbon footprints given the large water use and greenhouse gas emissions associated with energy production (Siddik et al., 2020). The amounts of water consumed and greenhouse gases emitted vary widely depending on the fuel type (e.g., natural gas, coal, wind, solar, nuclear, hydropower) and the technology used by the power plant. However, we lack a global dataset that includes regional or local variation in water intensity (m³/MWh) of electricity production for different fuel types.

The generation capacity associated with each fuel source for each country was taken from US EIA (2022). Based on water availability, a power plant facility may select a cooling system, or even a dry cooling system, in water scarce regions. Therefore, the type of cooling system selected has implications in deciding the water intensity of a power plant's electricity generation. For example, coal-based power plants that implement recirculating cooling systems consume almost three times more water per unit generation than coal-based power plants that utilize once-through cooling systems (Spang et al., 2014). It is assumed that the distribution of cooling technologies (e.g., once-through, recirculating,

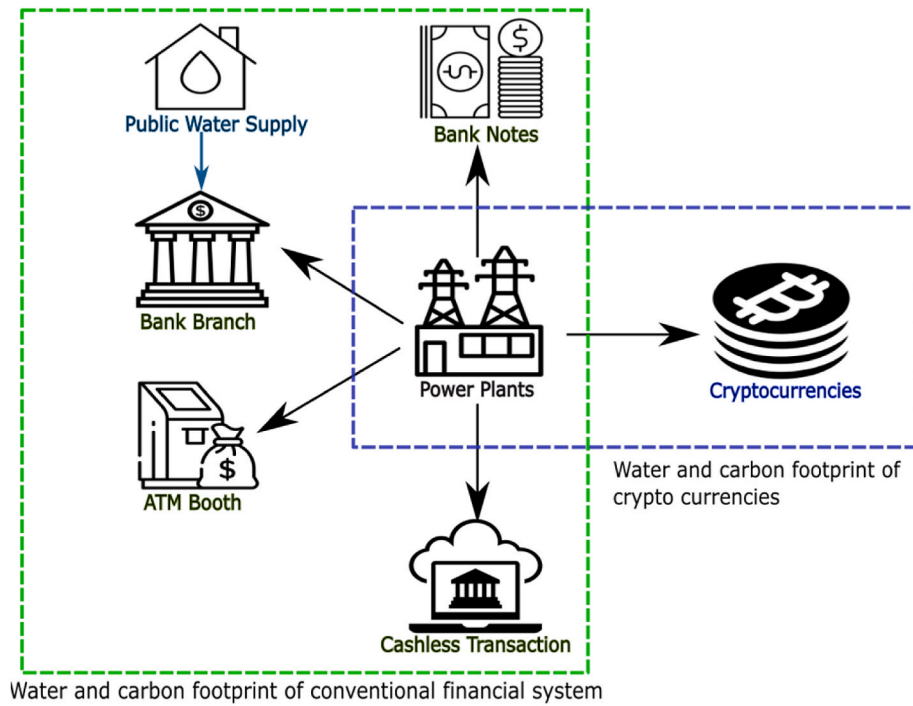


Fig. 1. The system boundary of our study includes the main components of the conventional financial system and cryptocurrencies contributing to their water and carbon footprints. The water and carbon footprint of both systems is largely tied to its energy consumption, though bank branches also consume a non-trivial amount of water directly within their facilities.

Table 1

Data type, spatial resolution, and estimation method for missing data and sources. Model variable names are identified in parenthesis for each input variable used in Equations (3)–(6).

Category	Input Variable	Spatial Resolution	Filling Data Method	References
Power plants	Electricity mix and generation	Country	Continental average	US EIA, 2022
	Point of generation water use intensity - thermoelectricity	Global by fuel type	N/A	Spang et al. (2014)
	Point of generation water use intensity - hydroelectricity	Country	Continental average	Mekonnen et al. (2015)
	Point of generation Greenhouse gases (GHG) emission intensity	Country	Continental average	IEA (2022); Chini and Peer (2021)
Bank notes and coins	Number of bank notes	Country	Continental average (per capita)	US BEP (2022); Eurosystem (2021); Trading Economics (2022)
	Point of generation electricity use	Selected countries	Selected countries representative of all other countries within the same continent	Luján-Ornelas et al. (2018); US DOT (2003)
Bank Branches	Number of bank branches	Country	Continental average (per capita)	World Bank (2022a)
	Electricity use bank branches (El_C ; El_H)	Facility-level (Modeled)	N/A	Spyropoulos and Balaras (2011); Borgstein and Lamberts (2014)
	Bank branch floor area (A_B)	Selected countries	Selected countries representative of all other countries within the same continent	Spyropoulos and Balaras (2011); Camanho and Dyson (1999); Aranda et al. (2012); Bancography (2022)
ATM Booths	Heating/cooling Degree Days (HDD_{18} , CDH_{15})	Country	Continental average	KAPSARC (2022)
	Number of ATM booths (N_{ATM})	Country	Continental average (per capita)	World Bank (2022b)
	Electricity use per ATM booth (P_i , H_i , P_D , H_D)	Model	N/A	Roth et al. (2002)
Cashless Transactions	Number of annual cashless transactions	Country	N/A	World Bank (2022c)
	Electricity use per transaction	Model	N/A	Melnichenko (2021)
Cryptocurrency	Energy use for Bitcoin mining	Country	N/A	CBECI (2022)
	Market cap of cryptocurrencies	Cryptocurrency	N/A	CoinMarketCap (2022)

dry) used by thermoelectric power plants in the United States (US EIA 2014) is representative of nations that lack detailed data on plant cooling technology. For hydroelectricity, we utilize the country level water intensity of hydroelectricity estimated by Mekonnen et al. (2015).

Once the electricity mix and the associated water intensity is known,

the water footprint per unit generation of a country can be estimated using the following equation:

$$WI_i = \frac{\sum (G_{i,j,k} \times WI_{j,k})}{G_i} \quad (1)$$

Where, WI_i is the (blue) water intensity of electricity generation (m^3/MWh) for country i , $G_{i,j,k}$ is the electricity generation (MWh) for country i with fuel type j and cooling type k , $WI_{j,k}$ is the associated water intensity for country i with fuel type j and cooling type k , G_i is the annual electricity generation (MWh) for country i .

Generating electricity through the combustion of fossil fuels is a major emitter of greenhouse gases (GHG). The GHG emission intensity, i.e., carbon intensity, CI_i , of electricity generation for each country and fuel type come from the International Energy Agency (IEA, 2022; Chini and Peer, 2021). The GHG emissions and water consumption of an end user of electricity is attributed using the following equation:

$$EF_{E,S,i} = E_{S,i} \times EI_i \quad (2)$$

Where, $EF_{E,S,i}$ is the footprint E (water or carbon) associated with electricity used by financial sector component S (e.g., bank branch) located in country i , $E_{S,i}$ is the total energy used by a sector S in country i (MWh/yr), EI_i is the water intensity (WI_i ; m^3/MWh) or carbon intensity (CI_i ; tonnes $\text{CO}_2\text{-eq}/\text{MWh}$) of electricity for country i .

2.2. Energy use for conventional currency

The energy consumption, water footprint, and carbon footprint are calculated for each country and system component (see Fig. 1) as described below. Values were aggregated across system components to derive the total reported energy use, water footprint, and carbon footprint for the conventional financial system.

2.2.1. Energy and water use for printing money

We relied upon the World Bank database (World Bank, 2022; e.g., number of banks per country), government reporting, and the scientific literature for conventional financial transaction information. A review of existing literature informed operational and infrastructural details about the conventional financial system, such as the average floor area of bank branches in each country (Borgstein et al., 2014; Spyropoulos and Balaras, 2011; Aranda et al., 2012; Camanho and Dyson, 1999; Bancography, 2022). The availability of bank notes in each country is controlled by the central bank of specific countries (Chen, J., 2021). For each calendar year, the Federal Reserve System (US BEP, 2022) and Eurosystem (2021) provide the print order value of USDs and Euros, respectively, as well as the approximate volume of bank notes necessary to attain that value of print order. This analysis uses datasets accumulated by the World Bank and private organizations in estimating the value of currency in circulation and the value of currency printed in USD for the remaining countries. The currency value-volume ratio of USD print orders was used to estimate the volume of bank notes printed in a country to achieve the value of print order (US BEP, 2022).

Estimates of energy use for each country's currency are unavailable. As a result, a study performed by the US Department of Treasury (US DOT) to evaluate the environmental impact of US banknotes serves as the representative energy use for printing a banknote. The electricity used to generate these representative banknotes are distributed among the banknote's lifespan to estimate annual electricity consumption (US DOT, 2003). The currency production process also requires a significant amount of water both for manufacturing and cleaning purposes. However, a negligible portion of this water is consumed during the process, and generated wastewater is discharged to water bodies after treatment.

2.2.2. Energy use and indirect water consumption at bank branches

Among the building categories reported and analyzed in the US Commercial Buildings Energy Consumption Survey (CBECS), bank branches were found to be one of the most energy intensive offices (Spyropoulos and Balaras, 2011). The electricity use of banks is partly due to the computationally intensive nature of this sector (Siddik et al., 2021; Dayarathna et al., 2015), but mostly due to the installation of HVAC systems needed to maintain the internal temperature of the office

space (Spyropoulos and Balaras, 2011). Therefore, electricity use in a bank branch can be modeled as a function of space characteristics and climatic conditions. The US, Brazil, Greece, and Spain are among very few countries that have reported or estimated the energy intensity of bank branches. This sample size is insufficient for a global normalization as climate, a prominent factor for energy requirement, varies globally.

Modeled values of energy intensity (kWh/m^2) based on cooling degree days and empirical values of energy intensity (kWh/m^2) based on heating degree days for bank branches in each country were estimated following the study of Borgstein and Lamberts (2014) and Spyropoulos and Balaras (2011), respectively. Heating and cooling degree days are the climate factors that impact the operating hours for HVAC systems to maintain a balanced temperature inside the facility. The KAPSARC data portal (2022) published the historical national average degree day's database, allowing this study to estimate the energy use intensity (kWh/m^2) for bank branches globally at the national level. In temperate climates where heating requirements constitute a major portion of the energy use, Spyropoulos and Balaras (2011) provide typical energy intensities based on heating degree days for different areas. The linear regression model developed by Borgstein and Lamberts (2014) reduces the independent variables required to estimate the energy consumption of bank branches in tropical regions where energy use for heating is negligible. The model only requires cooling degree days as an input variable to estimate the average energy use intensity (kWh/m^2) of a bank branch in a tropical region where cooling requirements dominate the energy demand. Other energy uses within a bank branch not strongly influenced by climate, such as internal and external lighting, servers, and electrical equipment are represented by a constant. This linear regression model is defined by the following equation:

$$EI_C = 125.3 + (0.001984 \times CDH_{15}) \quad (3)$$

Where, EI_C is the estimate of annual electricity consumption intensity for bank branches based on cooling days ($\text{kWh}/\text{m}^2/\text{yr}$), CDH_{15} is the cooling degree hours based on 15°C as a reference temperature.

The maximum value between the estimates of bank branch energy intensity is used as the representative energy use intensity (kWh/m^2) for bank branches within a country based on climate factors. The energy intensity was multiplied by the average floor area of bank branches per country (see Table 1) to estimate the total energy consumption at the branch facilities, as shown in the following equation:

$$E_b = \text{argmax}(EI_C; EI_H) \times A_B \quad (4)$$

Where, E_b is the total energy consumption at branch facilities within a country (kWh/yr), EI_C is the annual electricity consumption intensity for bank branches based on cooling days ($\text{kWh}/\text{m}^2/\text{yr}$), EI_H is the annual electricity consumption intensity ($\text{kWh}/\text{m}^2/\text{yr}$) for bank branches based on heating degree days, A_B = surface area in bank branch facilities (m^2).

Automated Teller Machines (ATM) are supplemental on-site or off-site equipment used by the banking sector. Therefore, we followed the study by Roth et al. (2002) to decouple the energy demand of ATMs into idle and dispensing hours. Energy consumption by the bulk of ATMs within a country are estimated using the following equation:

$$E_{ATM} = [(P_I \times H_I) + (P_D \times H_D)] \times 365 \times N_{ATM} \quad (5)$$

Where, E_{ATM} is the total energy consumption of ATMs within a country (MW/yr), P_I is the power draw of idle stage (MW), H_I is the idle hours per day, P_D is the dispensing power demand (MW), H_D is the active hours per day, N_{ATM} is the number of ATMs within a country (World Bank, 2022c).

The sum of E_b and E_{ATM} for each country provides S_i , which is entered into Equation (2) for estimating the water and carbon footprints associated with electricity use by the conventional transaction system.

2.2.3. Direct water consumption at bank branches

The report by CBECS (2012) provides direct water consumption estimates per unit area of office space, which were used to estimate bank on-site water use, as shown in Equation (6). Thus, direct water consumption at bank branches is calculated using the following equation:

$$D_{WB} = DWI_B \times A_B \quad (6)$$

Where, D_{WB} is the direct water consumption at a bank branch (m^3/yr), DWI_B is the direct water consumption intensity ($\text{m}^3/\text{m}^2/\text{yr}$) at a branch, and A_B is the floor area of bank branches (m^2).

2.2.4. Energy and water use for cashless transactions

The electricity use associated with banks' processing customer transactions (online or otherwise) is already included in the electricity use estimates for bank branches above. However, electricity use is also required for initiating cashless transactions by customers. These cashless transactions can be made using debit and credit cards through point-of-sale (POS) terminals or they can be made using online apps. World Bank data provided the number of annual cashless transactions per county (World Bank, 2022c). Estimates of energy use for initiating cashless transactions were taken from the recent study by Melnychenko (2021).

2.3. Energy use of cryptocurrency

2.3.1. Operation phase energy estimates for cryptocurrency miners

The Cambridge University Center for Alternative Finance tracks the monthly share of Bitcoin mining for each country. The US dominates the market, accommodating more than one-third of Bitcoin mining accomplished in 2021 (CBECEI, 2022). This monthly share of Bitcoin mining is used along with the total monthly energy consumption for Bitcoin mining (CBECEI, 2022) to estimate the annual electricity burden on each country associated with Bitcoin mining.

Ignoring the electricity use of thousands of other mineable cryptocurrencies will vastly downplay the environmental impact of these digital tokens. Digiconomist (2022) tracks the electricity use by the two most popular cryptocurrencies, Bitcoin and Ethereum. Ethereum alone was found to consume almost half the amount of Bitcoin's energy demand. As of the end of 2021, these two cryptocurrencies comprised almost 70% of the market cap by the cryptocurrency sector. A recent study by Gallersdorfer et al. (2020) performed a market and energy demand analysis of the top twenty cryptocurrencies, and found a strong correlation between energy use and market cap share. Due to lack of data, we used market cap share (CoinMarketCap, 2022) to estimate the electricity use by all mineable cryptocurrencies, assuming all crypto mining follows the same geographical distribution as the electricity use by Bitcoin. Estimated electricity use by conventional and digital transaction systems are input into Equation (2) to estimate the water and carbon footprints associated with currency circulation.

Since global information on cooling technology used by mining operations is not available, we assume free cooling or air cooling, which is more typical in cooler climates and in smaller mining operations (Stoll et al., 2019). Evaporative cooling, which can contribute to crypto mining's direct water footprint, is often used in larger mining operations due to inefficiencies of air cooling at scale (Taylor, 2013; de Vries, 2018). Yet, mining operations in cool climates and with access to low-cost electricity - key criteria in locating crypto mining farms - make it difficult to assume universal use of evaporative cooling (Schinckus, 2021).

3. Results

3.1. Water and carbon footprints of conventional currencies

Globally, it took almost 129×10^6 MWh electricity in 2021 to maintain the conventional financial transaction system, which includes bank notes, bank branch facilities, ATM booths, and cashless

transactions. This electricity consumption resulted in a water footprint of $1590 \times 10^6 \text{ m}^3$ and the global emissions required to support the conventional transaction system was estimated to be 68×10^6 tonnes $\text{CO}_2\text{-eq}$. The direct water use within banking facilities amounted to $191 \times 10^6 \text{ m}^3$. Together, around 85 m^3 of water and 3.25 tonnes $\text{CO}_2\text{-eq}$ of GHG emission were required to produce and distribute the equivalent of one million USD in 2021 within the conventional currency system.

As shown in Figs. 2 and 3, the electricity use, carbon footprint, and water footprint of conventional transaction systems vary widely globally. Countries with larger economies (e.g., US, China, and Russia) also have the largest electricity use supporting conventional financial systems, suggesting that physical infrastructure, like bank branches, is still a major requirement in maintaining financial activity despite the popularity of virtual infrastructure (i.e., online banking, app-based banking) in developed countries (Fig. 3A). The water footprint of the conventional financial system follows a similar trend as electricity use, except that some African and Middle Eastern countries have a relatively large water footprint compared to their small electricity use (Fig. 3C). Almost 60% of GHG emissions of conventional currencies are concentrated in the South and East Asia regions even though these regions supply only 40% of the electricity required for conventional currencies. Most of the electricity, as well as the associated water and carbon footprints, is attributed to bank branch facilities, followed by ATM booths and then online banking. More than 85% of conventional currencies' electricity use supports the operation of bank branches. The water and carbon footprints of conventional currencies follow a similar trend, indicating a similar geographic distribution as the bank branches.

At the continental level, Asia has the highest electricity consumption for maintaining conventional financial transaction systems, followed by Europe and North America. In Asia, the electricity use associated with conventional banking systems is distributed within countries with a lower water intensity for electricity generation. In Africa and South America, the electricity use of conventional currencies is distributed within regions with higher water intensities for electricity generation due to these areas' heavy reliance on hydropower with large evaporative losses. Hydroelectricity has a higher water intensity than other generation sources and South America has the highest share of hydroelectricity in its electricity profile compared to any other region. While the water intensity is much lower in Asia compared to Africa and South America, Asia's overall water footprint is comparable to these other continents (Fig. 2) due to the large electricity usage by Asia's conventional financial system. Asia has the highest carbon footprint associated with its conventional financial system, both in absolute terms (Fig. 2) and in terms of carbon intensity (i.e., GHG emitted per unit of electricity use).

3.2. Water and carbon footprints of cryptocurrencies

Unlike conventional currencies, the environmental footprint of cryptocurrencies is concentrated within only a few countries that constitute most of the mining activities (Fig. 3B, D, F). Although the volume of cryptocurrency transactions are 200 times less than conventional currency transactions, its electricity use has already surpassed the conventional transaction system with an electricity consumption of 236×10^6 MWh in 2021, which is almost double that of the conventional financial system.

In terms of its water footprint, cryptocurrencies have an annual water consumption of $3668 \times 10^6 \text{ m}^3$, which is more than double that of conventional currencies. These results indicate a disproportionate crypto mining in countries with higher water intensity for electricity. High water intensities are largely due to crypto mining in countries where hydroelectricity constitutes a higher ratio of electricity generation, since a significant amount of water evaporates from hydropower reservoirs and can be attributed to the electricity generated by the hydropower facility (Grubert, 2016). The water footprint of cryptocurrencies is highly concentrated in Central and South Asia. Kazakhstan

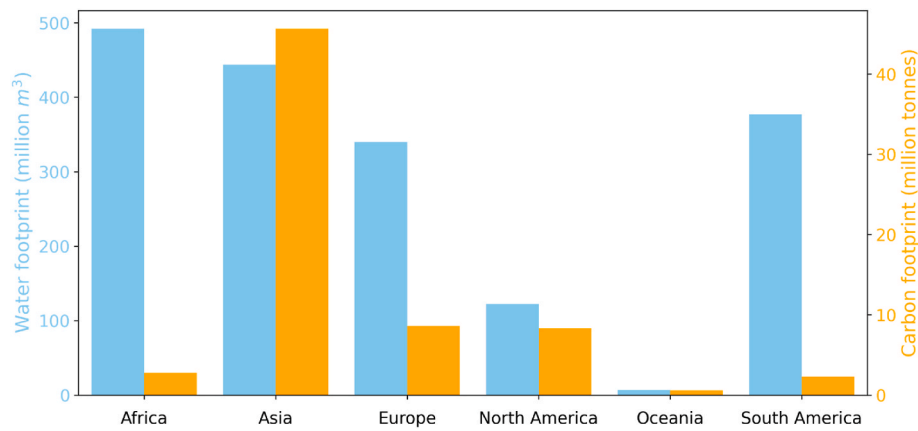


Fig. 2. Continental water footprint (blue) and carbon footprint (orange) comparisons of conventional currencies. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

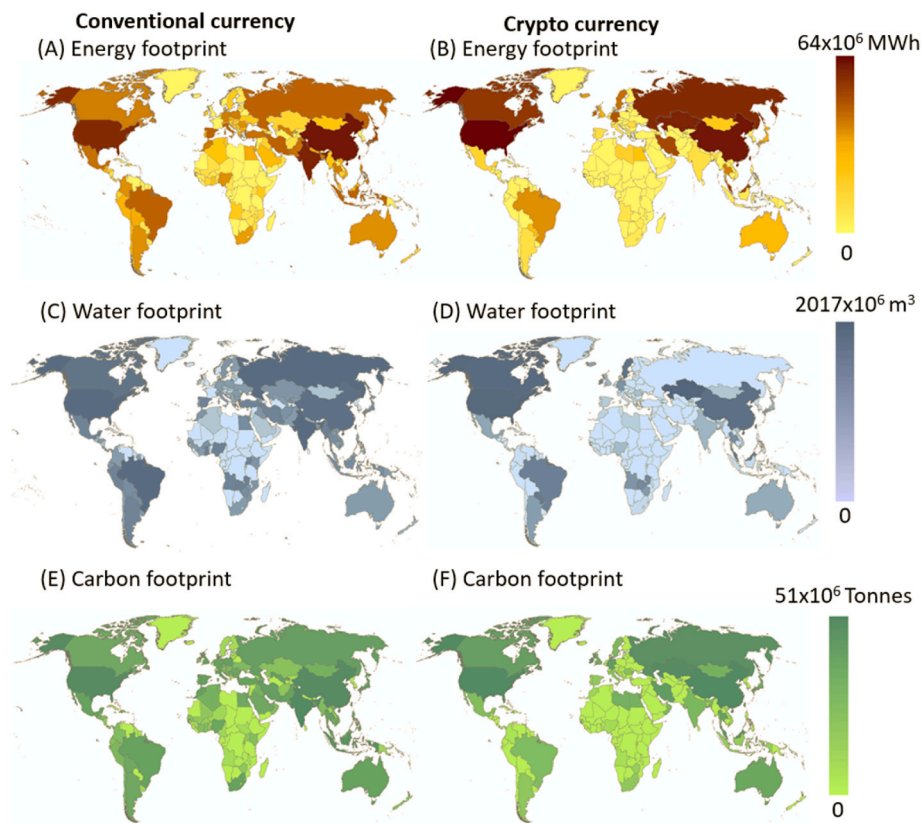


Fig. 3. Comparison of electricity use, water footprint, and carbon footprint of conventional transaction systems and cryptocurrencies at the country level. The six panels show the (A) electricity use of conventional currencies, (B) electricity use of cryptocurrencies, (C) water footprint of conventional currencies, (D) water footprint of cryptocurrencies, (E) carbon footprint of conventional currencies, and (F) carbon footprint of cryptocurrencies.

has the largest water footprint associated with cryptocurrencies because it has a high water intensity for electricity generation and contains roughly one-sixth of global crypto mining operations.

Crypto mining activities are estimated to be responsible for emissions of 139×10^6 tonnes CO₂-eq, about 0.4% of the 2021 global energy-related carbon emissions (IEA, 2022a). The magnitude of the carbon footprint, when normalized by electricity consumption, does not vary as drastically between countries as water (Fig. 4) since emissions are driven by fossil fuel-fired power plants, which are ubiquitous globally and constitute three-fourths of the global generation. Table 2 shows the electricity use, as well as the water and carbon footprints, for both conventional and cryptocurrencies.

3.3. Tradeoffs between electricity use, water footprints, and carbon footprints

Globally, the conventional currency system emits about one-tenth less GHG and water per MWh of electricity consumed than cryptocurrencies (see Table 2). While water and carbon intensities between the two currency types are similar, the total energy use of cryptocurrencies is 83% greater than the conventional financial system. The higher electricity use of cryptocurrencies means that the total carbon footprint (+105%) and water footprint (+106%) of cryptocurrencies is also much larger than the conventional currency system. The contrast between fiat and crypto currencies' environmental footprint is starker when

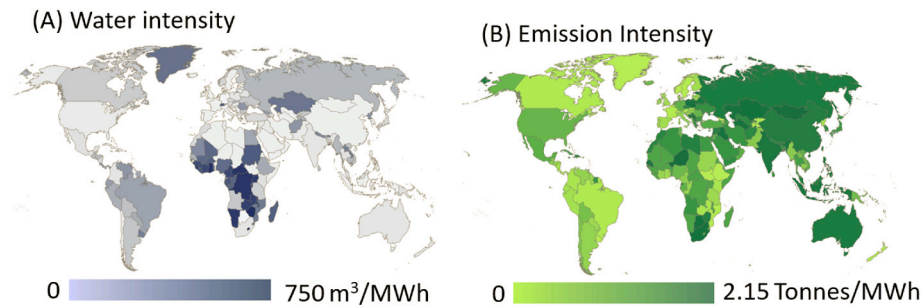


Fig. 4. Comparison of (A) water intensity and (B) carbon intensity of cryptocurrency mining between countries.

Table 2

Electricity use, water footprint, and carbon footprint of financial transaction system components.

Components	Electricity use (MWh) [% value]	Water footprint (m ³) [% value]	Carbon footprint (tonnes CO ₂ -eq) [% value]	Water intensity (m ³ /MWh)	Carbon intensity (tonnes CO ₂ -eq/MWh)
Bank notes	2.02×10^6 [1.56]	13.8×10^6 [0.77]	1.1×10^6 [1.56]	6.84	0.52
Bank branch	115.4×10^6 [89.55]	1639.5×10^6 [92.04]	60.9×10^6 [89.59]	14.22	0.53
ATM	11.0×10^6 [8.53]	122.5×10^6 [6.87]	5.8×10^6 [8.56]	11.14	0.53
Cashless transactions	0.45×10^6 [0.35]	5.6×10^6 [0.31]	0.19×10^6 [0.28]	12.46	0.43
Total/Average: Conventional	128.8×10^6	1781.2×10^6	67.9×10^6	13.83	0.53
Bitcoin	101.2×10^6 [0.42]	1572.3×10^6 [0.42]	59.7×10^6 [0.42]	15.53	0.59
Other cryptocurrencies	134.3×10^6 [0.58]	2096.3×10^6 [0.58]	79.6×10^6 [0.58]	15.53 ^a	0.59 ^a
Total/Average: Cryptocurrency	236.1×10^6	3668.6×10^6	139.1×10^6	15.53^a	0.59^a

^a The water and carbon intensities of other cryptocurrencies match that of Bitcoin due to our assumption that the spatial distribution of other cryptocurrencies is similar to Bitcoin.

normalized by value (USD) and when comparing just the production of each currency (i.e., mining of crypto vs. printing/minting money). In 2021, crypto mining required 299 times more electricity, 679 times more water, and emitted 336 times more GHG compared to printing an equivalent amount of USD.

The intensity of GHG emissions and water consumption vary regionally for electricity generation across the globe. The location of crypto mining can have significant implications on its environmental footprint since the water and carbon footprints of cryptocurrency are largely driven by their electricity consumption. Several regions, such as South America and sub-Saharan Africa, have low GHG emissions per unit of electricity generation, but electricity generation in these regions is also relatively water intensive. In contrast, electricity generation in China and Indonesia is relatively water efficient but it is also very emission intensive. However, electricity generation in some large countries, such as Russia and Kazakhstan, is both emission and water intensive, which would make these areas unsuitable for crypto mining from an environmental perspective. There are a few island countries in the Caribbean Sea, such as Aruba, Guyana, and Barbados, whose electricity supply is among the least water and carbon intensive, making

them ideal locations for crypto mining when only considering the environmental footprint. However, these small countries might not be able to absorb the significant electricity demands of large-scale crypto mining operations. Fig. 5 provides more information on the regional distribution of emission and water intensities throughout the world.

In general, the mining of cryptocurrencies is skewed toward regions with higher water and carbon intensities compared to the conventional financial system. Fig. 6 shows the continental breakdown of electricity usage, water footprint, and carbon footprint dedicated to cryptocurrencies versus conventional currencies. In general, North America and Europe have higher electricity use, water footprints, and carbon footprints for cryptocurrencies when compared to conventional currencies. Asia's electricity use, water footprint, and carbon footprint are more evenly split between conventional currencies and cryptocurrencies. The environmental footprint in the remaining regions is still dominated by conventional currencies. Asia has a higher fraction of its water footprint attributed to conventional currencies compared to its electricity consumption and carbon footprint. This divergence is due to differences in the type of electricity generation fuel/technology used where each of these currencies are primarily produced within the

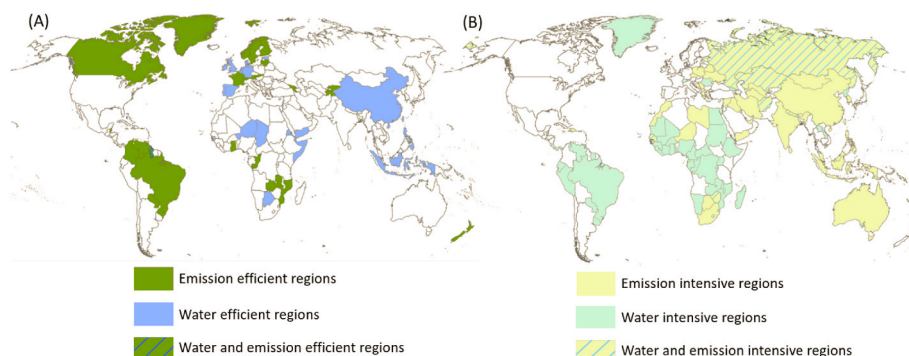


Fig. 5. Countries with (A) 25th percentile water intensity and 25th percentile GHG emission intensity for electricity generation, (B) more than 75th percentile water intensity and more than 75th percentile GHG emission intensity for electricity generation. Countries in the 25th percentile or better produce electricity while emitting relatively little GHG emissions (green), consuming relatively little water (blue), or both (hatched). Countries in the 75th percentile or worse produce electricity that emits a relatively large amount of GHG emissions (yellow), consumes a relatively large amount of water (green), or both (hatched). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

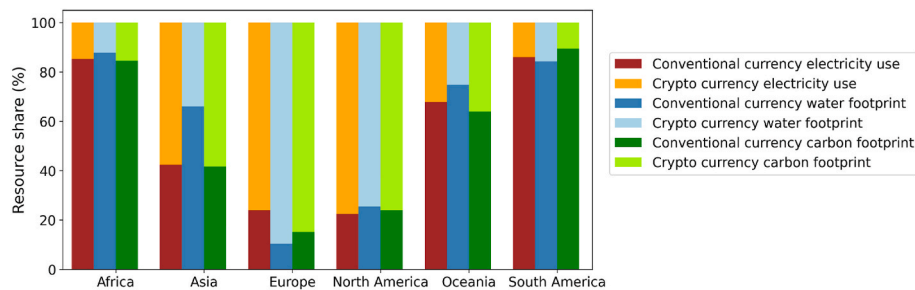


Fig. 6. Fraction of electricity use, water footprint, and carbon footprint of conventional and cryptocurrencies by region.

continent.

3.4. Global implications of regulating cryptocurrencies at a regional level

China had the largest share of crypto mining, with more than half of the hashrates, before a ban on crypto mining in 2021 (China resumed mining operations in September 2022). China's ban caused a sudden drop in the electricity use for crypto mining, but global crypto mining hashrates, as well as its electricity usage, recovered to previous levels within a few months after mining operations relocated. The crypto mining share previously occupied by China was redistributed to other countries, especially the United States and Kazakhstan (see Fig. 7). This redistribution had implications on both the water footprint and carbon footprint of global crypto mining. Almost 80% of crypto mining electricity usage displaced by China's ban went to regions with a higher water intensity (i.e., crypto mining requires more water per coin). However, around 60% of crypto mining electricity usage displaced by China's ban went to regions with a lower carbon intensity (i.e., crypto mining emits less carbon per coin). The redistribution of China's crypto mining operations increased global water consumption associated with crypto mining by 73%, but led to a 10% decrease in GHG emissions.

4. Discussion and conclusions

We estimate the electricity and water consumption and GHG emissions of conventional and crypto financial systems to compare their global and regional environmental footprints. When viewed together with previous studies, our results show that the electricity use and environmental footprint associated with cryptocurrencies are increasing rapidly (Corbet et al., 2021; Wendl et al., 2023). The electricity use and water and carbon footprints of cryptocurrencies have already surpassed that of conventional financial transaction systems, despite being a fraction of the size. This study further adds to previous studies by showing the impact of relocating mining activities. While the crypto mining ban in China did not impact the long-term electricity use or hashrate, it significantly increased the overall water footprint, while

leading to a slight decrease in the carbon footprint associated with global crypto mining. We demonstrate that both the scale and the location of crypto mining is important when considering the environmental footprint of this nascent form of financial transaction. We also acknowledge that the environmental burden of financial transaction systems' energy use extends beyond water and carbon footprints, especially when considering the life cycle analysis of the supporting equipment and infrastructure. Despite the recent movement to minimize GHG emissions associated with electricity generation, fossil fuels remain the source of almost two-thirds of global electricity generation (IEA, 2022a). Although this study only focuses on water consumption and GHG embedded within electricity use of different financial systems, electricity generation also consumes several other natural resources (e.g., 92% of the total coal mined in the United States is used for electricity generation; US EIA, 2023). Other environmental impacts could be explored in future research, such as the ecological footprint, which assesses the assimilative burden of a system to preserve the ecosystem's sustainability (Vance et al., 2015). These broader environmental impacts warrant a separate study that considers the uniqueness of the system boundaries for an ecological footprint, compared to water and carbon footprints.

This study is among the first to provide a comparison of conventional currencies' and cryptocurrencies' environmental footprints and builds on several other studies that have estimated the carbon footprint of cryptocurrencies at different time periods (de Vries et al., 2022). It has proven difficult to reach a consensus on the environmental footprint of cryptocurrency due to a lack of spatially explicit data and analysis. While this study makes methodological advances that improve the spatial detail relative to many other studies, it still rests on several assumptions, most notably related to incomplete data records for some countries. Incomplete data required us to impute missing values based on data or empirical equations derived from other geographic regions. Specifically, we assumed that the geographic distribution of lesser used cryptocurrencies mirrored that of Bitcoin. Where data was only available for a limited number of countries for components of the conventional financial system (e.g., printing money, bank branch floor area,

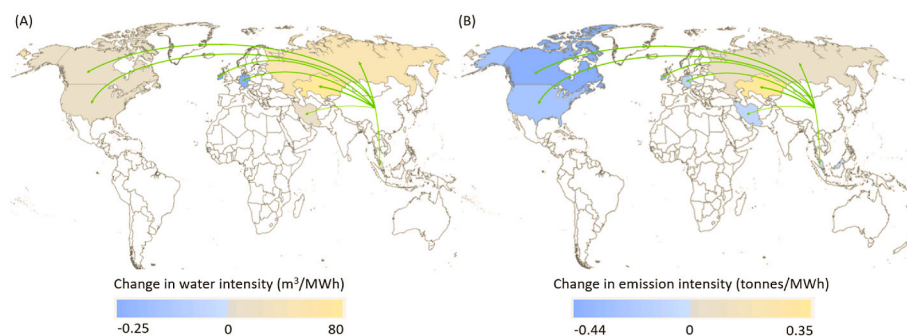


Fig. 7. Impact of 2021 crypto mining ban in China on the water footprint (A) and carbon footprint (B) of cryptocurrencies. Green arrows leaving China lead to countries where an increase in crypto mining electricity use occurred after the China ban on crypto mining. The thickness of the arrow represents the change in the hashrate in the receiving country, ranging from 0.4 to 15 EH/S. Countries shaded blue represent areas with a lower water (A) or carbon (B) intensity (i.e., crypto mining requires less water/carbon) than China. Countries shaded brown represent areas with a higher water (A) or carbon (B) intensity (i.e., crypto mining requires more water/carbon) than China. Note that the positive and negative sides of the legend are not at the same scale. (For interpretation of the references to colour in this figure legend, the

reader is referred to the Web version of this article.)

direct water consumption at bank branches, etc.), equations and data for countries that had data were assumed to be representative. There is not an agreed upon method to attribute electricity demand to electricity sources (Siddik et al., 2020), meaning our approach of assuming all electricity demands within a country are met in proportion to the electricity generated by each power plant within the same country may produce different results from alternative attribution methods. For instance, some crypto miners may directly connect to and utilize their own energy supply instead of connecting to the electricity grid, as we assume all miners do in our study. There is no evidence that a significant fraction of miners maintains their own electricity supply, and if they did, that the water and carbon intensities of these electricity supplies differ substantially from the electricity grid. Nonetheless, the lack of data detailing instances where miners utilize alternative electricity sources is a shortcoming of this study and others like it (Corbet et al., 2021; Lobo, A., 2022). Lastly, we do not account for potential differences in cooling technologies used in mining operations. We assume all mining operations use free cooling or air cooling, though some facilities likely use evaporative cooling, particularly larger mining farms in warmer regions (de Vries, 2018). Direct water use for evaporative cooling can be significant in large mining farms, meaning our water footprint estimates of cryptocurrencies are likely conservative. If we were to assume that evaporative cooling was used for all crypto mining operations, the total water footprint of cryptocurrencies would be approximately 10% larger. Future research could leverage new and improved data on crypto mining or environmental footprints if it were to become available.

As cryptocurrency's acceptability and market capitalization grows, energy efficient mining algorithms and an environmentally sustainable energy supply need to be further developed to minimize the environmental footprint of crypto mining. Moving from proof of work to less energy intensive proof of stake to validate transactions has been suggested as one way to reduce cryptocurrencies' electricity use and associated environmental footprint (Vranken, 2017). Technological advances, the volatility of the crypto market, and the positive correlation between mining activities, electricity usage, and coin price, make it difficult to predict how the industry will evolve moving forward. It is likely, however, that the energy-intensive nature and economies of scale of crypto mining will lead to greater industry consolidation, likely in places with reliable and cheap electricity. As we have shown is already the case, many of the places where crypto mining is occurring have higher environmental footprints. One of the touted benefits of cryptocurrencies is that they are not controlled by a central government and, in that way, they are 'borderless'. This study demonstrates that the global nature of cryptocurrencies could be leveraged by mining it in locations around the world where the environmental footprint is lowest.

Credit author statement

L.T.M.: conceived the study, designed the study, Formal analysis and preparation of findings, wrote and edited the manuscript, **M.A.B.S.:** designed the study, performed the data processing and modeling, Formal analysis and preparation of findings, wrote and edited the manuscript, **M.A.:** Formal analysis and preparation of findings, wrote and edited the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data has been provided as a supplement to this paper.

Acknowledgements

L.T.M. acknowledges support from the National Science Foundation Grant No. CBET- 2144169 ("CAREER: Advancing Water Sustainability and Economic Resilience through Research and Education: An Integrated Systems Approach"). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2023.137268>.

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