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Quantification of energy and carbon costs for mining cryptocurrencies

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There are now hundreds of cryptocurrencies in existence and the technological backbone of many of these currencies is blockchain—a digital ledger of transactions. The competitive process of adding blocks to the chain is computation-intensive and requires large energy input. Here we demonstrate a methodology for calculating the minimum power requirements of several cryptocurrency networks and the energy consumed to produce one US dollar's (US$) worth of digital assets. From 1 January 2016 to 30 June 2018, we estimate that mining Bitcoin, Ethereum, Litecoin and Monero consumed an average of 17, 7, 7 and 14 MJ to generate one US$, respectively. Comparatively, conventional mining of aluminium, copper, gold, platinum and rare earth oxides consumed 122, 4, 5, 7 and 9 MJ to generate one US$, respectively, indicating that (with the exception of aluminium) cryptomining consumed more energy than mineral mining to produce an equivalent market value. While the market prices of the coins are quite volatile, the network hashrates for three of the four cryptocurrencies have trended consistently upward, suggesting that energy requirements will continue to increase. During this period, we estimate mining for all 4 cryptocurrencies was responsible for 3–15 million tonnes of CO_2 emissions.

Decentralized cryptocurrencies represent a potentially revolutionary new technology for securely transferring money or information from one entity to another[1–4]. Many cryptocurrencies utilize blockchain, a public ledger, to accurately and continuously record transactions among many decentralized nodes[5]. A process of consensus, or agreement, is performed by 'miners' through repetitive calculations using specialized computer hardware. The first miner to determine the correct 'answer' adds a new block to the chain and is rewarded for this energy-intense calculation with several newly generated coins[6]. The primary purpose of this competitive mining is to maintain the integrity of the decentralized blockchain by facilitating the many millions of transactions occurring across the cryptonetwork[7].

Although cryptocurrencies, by their name, are developed and represented as currencies equivalent in purpose to the US$, euro or yen, they are generally treated as assets or stores of wealth, similar to gold[8]. Many individuals or entities simply purchase the coins on exchanges and store them in the hopes of higher future prices. Thus, there is high demand and limited supply, creating a strong incentive to participate either actively (that is, mining) or passively (that is, holding). As the nascent industry matures, volatility is expected to decline and their widespread use as a substitute for centralized, fiat currency is more promising[1,2]. However, this is not currently the case.

As shown in Table 1, the blockchain networks of Bitcoin, Ethereum, Monero and Litecoin all utilize a proof-of-work time-stamping scheme (that is, tracking changes to the blockchain in time); so-called because the correct answer is proof of work done by the miner[9,10]. This means two or more miners (that is, thousands) will compete to arrive at the correct answer the fastest, and thereby be rewarded with coins. Thus, the cryptonetworks require competition by multiple parties to function[7]. This competition contributes to the total energy required to produce a new block, which in turn produces new coins (via the reward system)[11]. The Bitcoin network has been estimated to consume as much energy per year as Ireland (26 TWh yr^{-1} in 2014[12] and 22 TWh yr^{-1} in 2018[11]) or Hong Kong (44 TWh yr^{-1} in 2017)[13], but significantly lower estimates also exist (4–5 TWh yr^{-1} in 2017)[14]. All of these estimates indicate that cryptocurrencies already consume a non-negligible fraction of the world's energy production.

With Bitcoin energy demand now estimated to be equivalent to some countries, new questions arise. Do all cryptocurrencies require a similar energy supply to function? In the context of energy invested and value extracted, what conventional processes or services would cryptomining compare to (for example, mining a physical material such as gold[15–17])? And what environmental impact might this energy consumption cause? Here we use the publicly available data and mining hardware characteristics to determine the power requirements for four cryptocurrency networks: Bitcoin, Ethereum, Litecoin and Monero. We then use market prices to calculate the energy consumed for each asset per US$ created and examine the environmental costs by applying country-specific CO_2 emission factors to the energy demands of the networks. The four cryptocurrencies analysed here were selected from the top 20 by market capitalization[18] on the basis of the availability and completeness of data and the applicability to our methodology. Some cryptocurrencies, such as IOTA, do not employ blockchain technology, and cannot be assessed in the methodology provided here[19]. Alternately, Ripple is a centralized blockchain platform and their currency is not mineable, again meaning we could not make an equivalent assessment[20].

Energy requirements of mining cryptocurrencies

Bitcoin, like a mineral in the Earth's crust, is finite and extractable and, like conventional mining, cryptomining can be energy-intensive[11]. The energy required to mine cryptocurrencies in a proof-of-work scheme is measurable in the hashrates of the network. Hashrates are the number of calculations (hash functions) performed on the network in seconds. As of August 2018, there are approximately 50 quintillion hashes performed on the Bitcoin network every second of every day[21]. The amount of energy required and the rate at which these calculations can be executed are dependent

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Table 1 | A selection of coins and network characteristics

Cryptocurrency	Symbol	Organizational model	Time-stamping scheme	Year launched	Market capitalization (billion US$)[18]
Bitcoin	BTC	Blockchain	Proof of work	2009	106
Ethereu	ETH	Blockchain	Proof of work	2015	43.8
Litecoin	LTC	Blockchain	Proof of work	2011	4.52
Monero	XMR	Blockchain	Proof of work	2014	2.05

These cryptocurrencies were selected from the top 20 cryptocurrencies (by market capitalization) on the basis of the availability and completeness of data and the applicability to our methodology. Market capitalization is reported from CoinMarketCap (https://coinmarketcap.com/)[18] on 30 June 2018. Not all cryptocurrencies are mineable and not all rely on blockchain technology.

on the type of computer hardware that is used[11]. As in conventional mining, some equipment may not be profitable or effective and certain tools are useful for one mineral but not another.

Blockchain hashrates and coin exchange prices in US$ for Bitcoin, Ethereum, Litecoin and Monero are shown in Fig. 1a–d. The daily hashrates of Bitcoin[22] (exahashes s^{-1}) are several orders of magnitude larger than those of Ethereum[23] (terahashes s^{-1}), Litecoin (terahashes s^{-1})[21], and Monero (megahashes s^{-1})[24]. This reflects the higher quantity of calculations being performed and, consequently, a greater amount of energy being consumed by the network. The increasing hashrates are caused by both increasing participation of miners and increasing difficulty of the calculations[12]. However, comparisons of hashrates across networks might not be meaningful because the mining rigs used to perform these calculations may be different depending on the type of currency being mined. Effective mining of Bitcoin requires the use of specialized computer hardware known as application-specific integrated circuits (ASICs)[1]. Monero is ASIC-resistant and is primarily mined with graphical processing units[24]. The number of calculations that can be performed by an ASIC is much higher than can be performed by a graphical processing unit and the ASIC is more power-efficient per calculation[2,25,26]. As we show in Fig. 1, the market prices of the coins, which decreased for all cryptocurrencies in early 2018, do not necessarily correlate with their respective hashrates. Thus, the hashrates for each of the networks (and energy requirements) will probably increase until all of the allotted coins have been mined.

Previously reported estimates as well as our own estimates of the power requirements of each network are given in Table 2. The methodology we used to calculate power and energy is given in the Methods and generally follows the process reported by Bevand[14], in which the power efficiency of the mining rig (joules per hash) is multiplied by the hashrate of the network (hashes per second). Unlike the other estimates in Table 2, our 2016 and 2017 values are an actual accounting of the entire 366 and 365 days of network energy demand. Our 2018 estimates account for all days until 30 June 2018. The value is based only on those 181 days and is not a forecast for the entire 2018 demand. Our estimates do not include energy required for cooling systems or other operations and maintenance aspects of running a mining operation, making this the minimum power requirement for each network[11].

On the basis of our 2017 estimates, Bitcoin alone consumed about as much energy (948 MW = 8.3 trillion kWh yr^{-1}) as Angola or Panama (ranked 102nd and 103rd by total energy consumption)[27]. The market capitalization of all cryptocurrencies is approximately US$250 billion, with Bitcoin comprising approximately 50% of that value[18]. If we assume that Bitcoin accounted for 50% of the entire crypto-energy consumed in 2017, then the total 16.6 trillion kWh yr^{-1} would be similar to Slovenia or Cuba (ranked 75th and 76th)[27]. The last estimate is made with a high level of uncertainty. Bitcoin was 73% of the total power demand of the four currencies in 2017 and 68% in 2018 (based on our power requirements in Table 2). This is, to our knowledge, the first time any power demand data have been reported for Litecoin and Monero, and Ethereum data are sparse[28]. It is unknown what the other 16 of the top 20 cryptocurrencies also demand. Moreover, there are hundreds of lesser valued currencies that use some amount of energy. Our 50% estimate for Bitcoin could be too high, in which case our total cryptocurrency energy consumption estimate of 16.6 trillion kWh yr^{-1} would be lower than the actual demand. For a comparison of all our 2016, 2017 and 2018 estimates to national energy demands, refer to Supplementary Tables 3–5.

Comparisons to metals mining

Bitcoin, in particular, has often been compared to gold or called the 'new gold'[29]. Gold is, of course, unique among metals because its primary purpose is as a store of wealth and its application in electronics is secondary. However, most metals have a primary functional purpose. Their prices are determined by the cost of extraction and market demand. We first compared the energy costs of mining Bitcoin with that of mining actual gold, normalizing to US$ generated from the raw material. However, because of gold's unique place in society and its high market price, we questioned whether the amount of energy to extract a dollar's worth of gold was itself a unique case. For a more robust comparison, we identified several other minerals of interest: platinum group metals (PGMs), rare earth metals, aluminium and copper. Each of these has unique applications in society and should give more context to the broader discussion of energy investment into these new digital currencies.

With the daily power requirements of the networks quantified every day from 1 January 2016 to 30 June 2018, we calculated the amount of energy consumed per coin mined, and then normalized that value based on the price (in US$) per coin. We discretized the timescale to a single day (rather than minutes or months) because hashrates, prices and other data are reported by third-party aggregators on a daily basis[18,21–23]. We used the power requirements for each day, and then applied the average time (in minutes) a new block was completed for that day (t_B), the number of coins rewarded per block (R) and the US$ price per coin (EX) as detailed in the Methods. Prices were collected from CoinMarketCap (https://coinmarketcap.com/), which reports volume-weighted averages across many international exchanges, reducing the influence of any one market on the prices used in this analysis.

Coin rewards (R) and mining rig power efficiencies (PEs) are shown in Table 3. The PEs of the mining rigs[11,14,30–32] were used in our power estimates presented in the previous section. As the mining rig PEs are quite important to our estimates, we have included a brief discussion in the Supplementary Information regarding our assumptions, with supporting references and data. We also performed a sensitivity analysis with Bitcoin miner PEs reported by Bevand[14] and De Vries[11], the results of which are shown in Supplementary Fig. 1. Daily hashrates, block completion times, market prices, calculated daily power requirements, network velocities and energy costs (ECs) are reported in the Supplementary Data for each day.

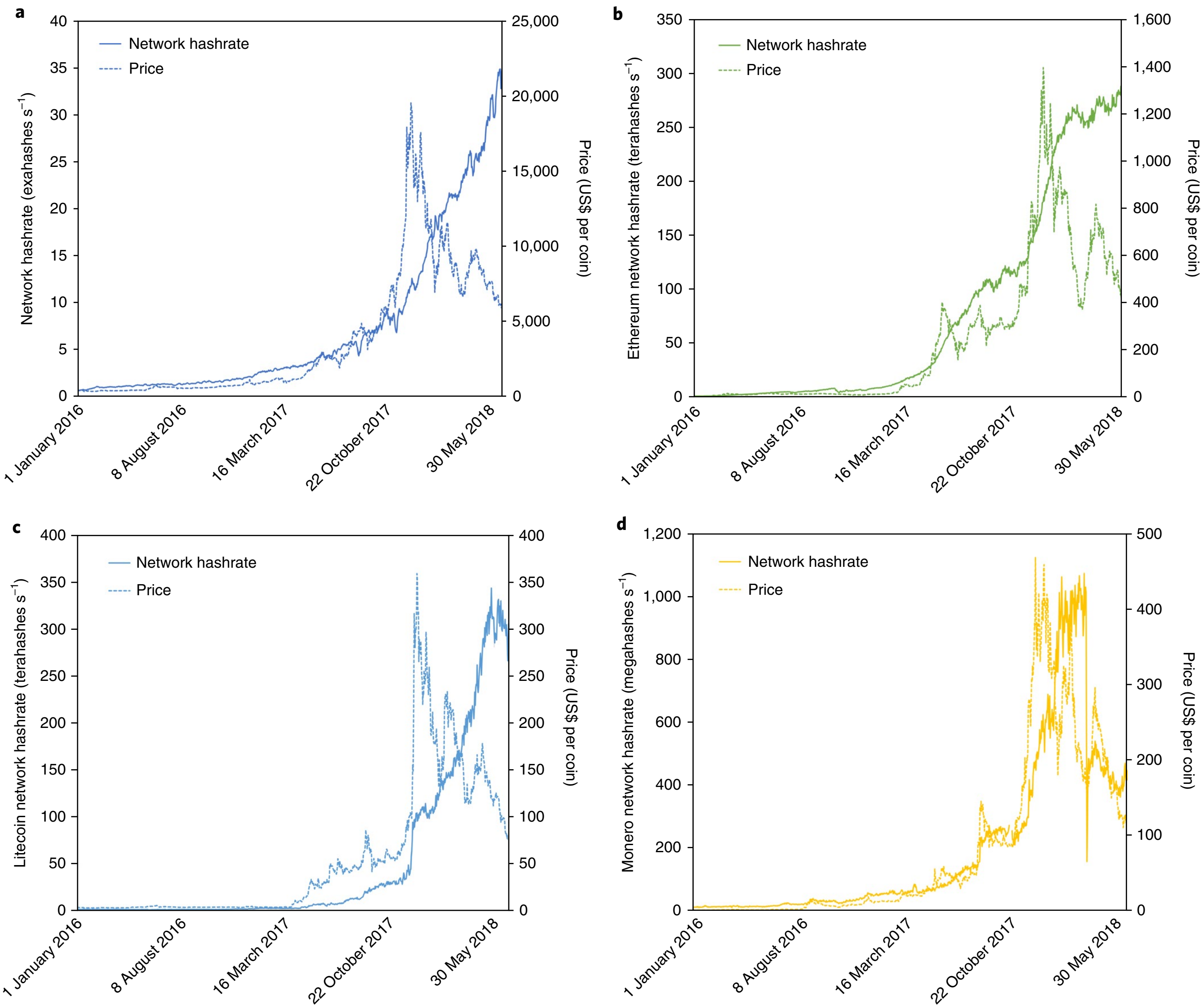

Fig. 1 Blockchain hashrates and coin exchange prices in US$ for Bitcoin, Ethereum, Litecoin and Monero. | a–d, Hashrates of Bitcoin (**a**), Ethereum (**b**), Litecoin (**c**) and Monero (**d**) indicate the intensity of mining activity. They are not necessarily comparable across networks as each coin may utilize different equipment for mining. Monero's ASIC resistance was hardcoded into the network on 6 April 2018 and is the reason for the sudden decline in hashrates. Market prices change in real time. Note, the *y* axes are different for each graph. Exa, 10^{18}; tera, 10^{12}; mega, 10^{6}. Bitcoin hashrates were downloaded from Blockchain Charts (https://blockchain.info/charts/)[22]. Ethereum hashrates were downloaded from Etherscan (https://etherscan.io/chart/hashrate)[23]. Litecoin network hashrates were downloaded from Litecoin Hashrate (https://bitinfocharts.com/comparison/litecoin-hashrate.html)[21]. Monero network hashrates were pulled directly from the Monero network (https://getmonero.org/)[24] and are reported in the Supplementary Data. Prices were downloaded from CoinMarketCap (https://coinmarketcap.com/)[18]. All network hashrate and price data are supplied in the Supplementary Data.

The modelling boundaries to determine energy requirements for metals generally considered fuel and energy inputs and excluded sources from infrastructure, such as the energy to produce roadways or develop the equipment to mine. Some of these data come from industry sustainability reports and others come from lifecycle assessments (LCAs) or similar analyses. Mudd[15] estimated that gold production consumed 143 GJ kg^{-1} Au from company sustainability reports, whereas Norgate and Haque[16] reported 199–300 GJ kg^{-1} Au in a LCA of gold production. Although LCA results in potentially larger, embodied energy estimates, the reported values are similar so the average (215 GJ kg^{-1} Au) was used in our calculations (see Supplementary Table 6). Energy consumption for the mining of PGMs ranged from 29–241 GJ kg^{-1} PGM with an average[33] of 141 GJ kg^{-1} PGM, as shown in Supplementary Table 7. Copper production requires significantly less energy (22 MJ kg^{-1} Cu), as identified in sustainability reports[34]. Sverdrup et al.[35] performed an analysis of aluminium that examined historic and future mass flows. The values taken from Sverdrup et al.[35] were the values used as input to their model and are not embodied energy outputs that would include other costs such as storage or other finished goods manufacturing. Similarly, in an exergy analysis of aluminium production, Balomenos et al.[36] identified energy consumption per 1 kg of primary production. Balomenos et al.[36] reported 99–213 MJ kg^{-1} Al and Sverdrup et al.[35] reported 227–342 MJ kg^{-1} Al. We used the average of all values (238 MJ kg^{-1} Al), as shown in Supplementary Table 8. Weng et al.[37] developed a cradle to gate lifecycle impact assessment of rare earth oxides (REOs; that is, rare earth metals). Because the scope was limited to the mining and processing and neglected the

Table 2 | Power requirement estimates for various cryptocurrency networks

Power estimates	Malone and Dwyer[12]	McCook[17]	Bevand[14]	De Vries[11]	Digiconomist[13]	This study		
Year of estimate	2014	2014	2017	2018	2018	2016	2017	2018
Currency		Network Power Requirement (MW)[b]						
BTC	100–10,000	115	470–540	2,550–7,670	8,119[a]	283	948	3,441[c]
ETH	—	—	—		2,382[a]	24	299	1,165[c]
LTC	—	—	—		—	3.4	30	330[c]
XMR	—	—	—		—	4.5	23	97[c]

[a]Reflects the power requirements estimated on 30 June 2018. [b]1 MW × 1 h = 1 MWh = 3,600 MJ and 1 MW = 8.76 GWh yr^{-1}. [c]These data reflect power requirements for the first six months of 2018 only. The energy requirements change, generally upward, for each of the networks each day. Thus, the data are presented in power (W) rather than energy (J). Malone and Dwyer[12] made several broad assumptions, resulting in estimated power consumption over three orders of magnitude. Our study follows the methodology reported by Bevand[14], in which hashrates and miner hashing efficiencies are inputs to determine energy consumed and coins generated. Our estimates are given for all of 2016, 2017 and up to 30 June 2018 for 2018. Therefore, the 2018 data is not representative of the entire year but are reported to show the continued increase in energy demand. Digiconomist[13] calculates the energy requirements by assuming operational costs spent on hardware including cooling costs. See Supplementary Information for a discussion of the methodologies.

Table 3 | The network, hardware and coin characteristics used in this analysis

Cryptocurrency	*R* (coins per block)	2016 mining PE	2017 and 2018 mining PE
BTC	25 and 12.5	0.21 J GH^{-1} (ref. [14])	0.15 J GH^{-1} (refs [11,14])
ETH	5 and 3	6.3 J MH^{-1}	4.7 J MH^{-1} (ref. [30])
LTC	25	2.1 J MH^{-1}	1.6 J MH^{-1} (ref. [31])
XMR	7.47–4.27 (see Supplementary Information)	0.21 J H^{-1}	0.15 J H^{-1} (ref. [32])

The coins rewarded per block are halved at predetermined points of total coin generation. The bitcoin reward decreased from 25 to 12.5 on 9 July 2016. The ethereum reward decreased from 5 to 3 on 16 October 2017. The Litecoin reward halved from 50 to 25 on 25 August 2015. Monero rewards continuously decrease after each new block is added, based on a smooth emission calculation. Daily rewards, block completion times and prices for all cryptocurrencies are included in the Supplementary Data.

downstream consumption and use, the energy input (1218 MJ kg^{-1} REOs) and the median of reported unit prices (US\$140,400 t^{-1}) were used here (see Supplementary Table 9). We note that their energy consumption value may include energy related to waste management and land use, which were not accounted for in our assessment of cryptocurrencies and we assume those contributions are negligible for this comparison. There is some uncertainty associated with the self-reported values in mine sustainability reports regarding onsite or offsite power generation (that is, direct versus indirect energy consumed)[34]. As we are interested in the total energy consumed to mine the metals, we can reasonably apply the total energy consumed per kilogram and normalize by price (US\$ kg^{-1}) to compare to our cryptocurrency estimates.

Commodity prices for 2016 and 2017 were taken from the United States Geological Survey (USGS) Mineral Commodity Summaries 2018[38] for gold, PGM, aluminium, REOs and copper and from Weng et al.[37] for REOs as detailed in Supplementary Tables 9 and 10. We recognize that the application of present-day commodities prices to energy demand data from multiple peer-reviewed sources, some several years old, creates some uncertainty to the estimated values. However, we believe that the changes in mining energy demands and metals prices are relatively small compared to the volatility of cryptocurrencies, and therefore, for our purposes the energy consumed per kilogram is static. In both cases (digital and physical), we are comparing ECs of the mining process (that is, cradle to gate).

Using the energy required for minerals mining, and the pricing data for 2016 and 2017 from USGS, we estimated annual ECs for aluminium, copper, gold, PGMs and REOs. Price data for 2018 were not available, so an assessment for this year was not made. For cryptomining, daily ECs were averaged for each year and all annual estimates are presented in Fig. 2. Comparing the 2016 values, we find that Bitcoin and Monero consumed more energy per US\$ generated than copper, gold, PGMs and REOs, whereas Ethereum had a higher EC than only gold and copper and the Litecoin EC was not greater than any mineral EC. In 2017, only Bitcoin mining had a higher EC than copper, gold, PGMs and REOs. Aluminium mining is much more energy-intensive on a per US\$ generated basis than all other assets. One noticeable trend among all cryptocurrencies is the increase in ECs in 2018. This is due to two important and distinct factors: the increasing network activity/energy demands across all years; and the rapid increase (2016–2017) and proceeding decrease (2018) in market value. As the numerator reflects the energy demand and the denominator reflects market prices, as energy increases and price decreases (as observed in 2018), the EC will increase. Year-over-year changes in energy per coin mined for all cryptocurrencies are given in Supplementary Table 12.

As an average of all days from 1 January 2016 to 30 June 2018, to generate US\$1, we estimate that Bitcoin, Ethereum, Litecoin and Monero mining required 17, 7, 7 and 14 MJ, respectively. In comparison, we estimate that mining aluminium, copper, gold, PGMs and REOs required 122, 4, 5, 7 and 9 MJ to generate US\$1. Again, the energy requirements we calculated consider only the amount of energy required to mathematically produce new coins. They do not include energy costs for cooling equipment that are typically used in cryptomining applications[11] and they also ignore operations and maintenance costs, and infrastructure requirements (for example, access to the Internet), meaning that these are lower bound estimates for cryptomining. Although hashrate and price data exist for previous years (for example, 2013 and 2014), there is greater uncertainty with respect to reporting of mining rig power efficiencies for previous years[2,14]. Accurate information in this regard would be valuable to make more historical estimates. We note that in our mining rig PE sensitivity analysis, replacing the average values given in Table 3 with all 15 values reported by Bevand[14] and De Vries[11] (given in Supplementary Tables 1 and 2), we found for 14 of the 15 scenarios Bitcoin mining ECs were still greater than gold ECs.

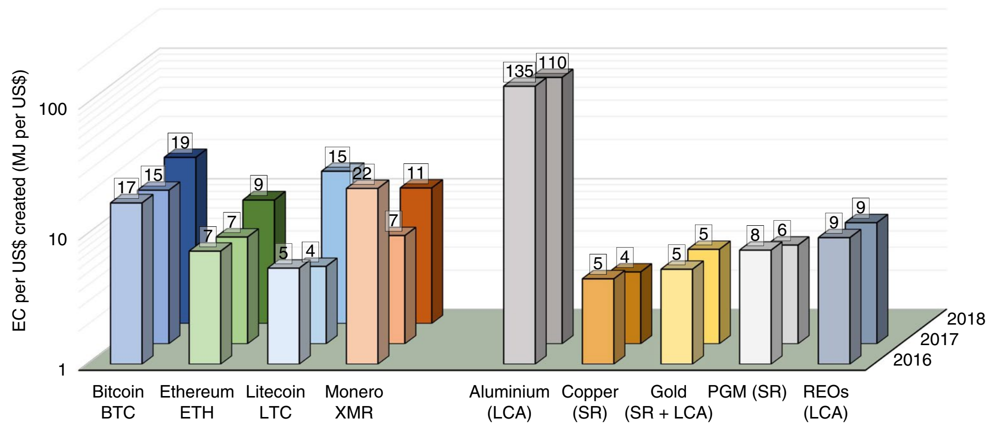

Fig. 2 | Mining cryptocurrencies generally requires more energy to generate an equivalent value in US$ than copper, gold, PGMs and REOs. Aluminium requires substantially more energy per US$ generated than all other assets. The cryptocurrency annual energy costs (MJ per US$) are averages of daily values. The mineral ECs are based on peer-reviewed literature and USGS commodity reports. The increase in cryptomining ECs from 2017 to 2018 is linked to the rapid decline in market prices in early 2018. As the EC is normalized to the value of US$, decreases in market price of cryptocurrencies will increase the EC value. SR, sustainability reports.

The highest efficiency (that is, lowest PE = 0.06 J GH^{-1}) resulted in an EC = 5 MJ per US$, equal to the gold EC. Thus, we are confident that the average values used in this analysis and presented in Table 3 are appropriate for determining the annual ECs and do not uniquely affect the results. The full range of annual Bitcoin mining ECs (5–34 MJ per US$) based on the 15 values from Bevand[14] and De Vries[11] are presented in Supplementary Fig. 1.

There may be some concern as to the applicability or appropriateness of comparisons of these seemingly incongruent entities (cryptocurrencies and metals). To be clear, the comparison made is of the energy required for the mining process, not of the cryptocurrency or mineral. Our comparison of Ethereum mining to platinum mining is not made to suggest that Ethereum could be a functional substitute for platinum. Rather, the comparison is made to quantify and contextualize the decentralized energy demand that the mining of these cryptocurrencies requires and to encourage debate on whether these energy demands are both sustainable and appropriate given the product that results from relatively similar energy consumption (when normalized by market price). We find that proof-of-work cryptocurrencies consume a considerable amount of power, although Bitcoin consumes more than others in overall magnitude, per coin and per US$ value created.

In this analysis, we identify a simple method to evaluate blockchain-based cryptonetwork power requirements and the energy required to produce one US dollar's worth of coin (here we use US$). This methodology could serve as a foundation to quantify the relative sustainability of individual cryptocurrencies, but current data gaps exist that could alter the conclusions of similar evaluations. The quantification of cryptomining operations and maintenance energy requirements, human labour, electronic waste generation, and other intrinsic costs are not fully known and would be beneficial for future studies. Moreover, management and energy requirements for metals, such as transporting and storing gold, may broaden the limited boundaries that we have applied here for a more comprehensive LCA and yield different results.

Country-dependent CO_2 emissions of cryptomining

Unlike conventional mining, for which the presence of a metal at a given location is prerequisite, cryptocurrency mining can take place anywhere with the availability of electrical power, an Internet connection and the appropriate hardware. Because the amount of energy required to mine a coin is locality independent, environmental impacts are dependent on the primary energy source utilized. We applied country-specific CO_2 emission factors from Malla[39] to the median daily energy requirements of the networks to estimate the geographical effect of the energy mix on the carbon footprint for each of the cryptocurrencies (emission factors reported in Supplementary Table 13). There is some inherent uncertainty to these values as Malla[39] was published nine years ago and the data may not reflect current conditions. However, we feel that the application of these data is acceptable as the main point is to present a methodology that identifies differences in CO_2 emissions based on national energy mixes and the average amount of energy consumed to generate a coin. In this case, energy required per coin mined is the median value of all calculated values from 1 January 2016 to 30 June 2018. As shown in Supplementary Fig. 2, the energy consumed per coin mined (MWh per coin) has increased substantially in the previous two and a half years for all cryptocurrencies. Thus, we felt the median value was more appropriate than the average for this data point (see Methods).

Using primary energy mixes of India, Australia, China, the United States, Japan, Korea and Canada, we see how their carbon footprint is impacted in Fig. 3. On the basis of the emission factors from Malla[39], any cryptocurrency mined in China would generate four times the amount of CO_2 compared to the amount generated in Canada. Applying the highest and lowest carbon emission factors (India and Canada) as upper and lower bounds and based on the number of coins generated between 1 January 2016 and 30 June 2018 (2,094,699 coins; see Supplementary Table 15), 3–13 million metric tonnes CO_2 can be attributed to the Bitcoin network. Using the same approach, we estimate Ethereum, Litecoin and Monero mining generated 300,000–1.6 million tonnes CO_2 combined (see Supplementary Tables 16–18). Thus, for the study period, cryptomining of these 4 is responsible for at least 3–15 million tonnes CO_2 emitted, with Bitcoin being the largest contributor. In the short term, this may be problematic, because a large portion of cryptocurrency mining occurs in China[40,41]. However, some industrial-scale operations are moving from China to Canada to take advantage of cheaper and cleaner energy[2,40,41].

Future growth and adoption of these digital currencies is unknown. The worldwide mining of cryptocurrencies is currently performed for self-gain[11] but this alone does not preclude it from potentially benefiting society. From a long-term perspective, the mining of cryptocurrencies, such as Bitcoin, is a temporary phase

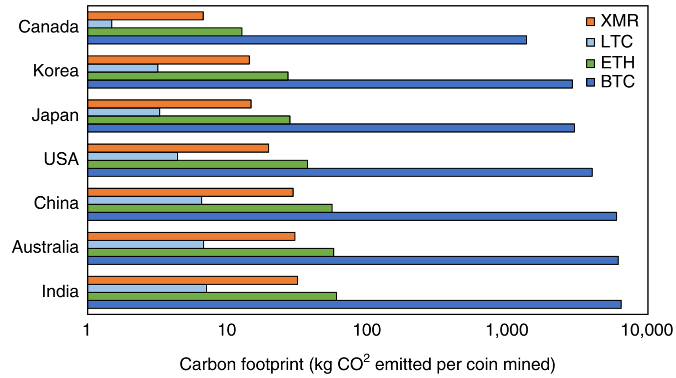

Fig. 3 | The carbon footprint of any cryptocurrency would depend on the energy demand of the network and the primary energy mix used to generate the coins. Country-specific CO_2 emission factors for energy were reported in Malla[39] and applied to the average energy demand per coin (kWh per coin) from 1 January 2016 to 30 June 2018. Note that the values are on a log scale, demonstrating that Bitcoin (BTC) produces significantly more CO_2 emissions than Ethereum (ETH), Litecoin (LTC) or Monero (XMR). The calculated values are reported in Supplementary Table 12. On 30 June 2018 (reported in the Supplementary Information), we see one Bitcoin was worth approximately 49 times 1 Monero, but potentially emitted 132 times more CO_2 per coin.

in the proposed lifecycle of the network. Currently, 81% of Bitcoins set to exist have been mined[42]. However, given the current rate of mining, the last coins will not be mined until approximately 2140[43]. Given the length of time until that point and on the basis of the data presented here, we can assume that the network energy requirements of Bitcoin and Litecoin will continue to increase for the foreseeable future. However, Monero's hard fork (that is, change in code) on 6 April 2018, observable in Fig. 1, indicates a considerable drop in network energy demand. Moreover, Ethereum's future move to proof-of-stake could reduce long-term network energy requirements. Therefore, future environmental impacts for any of the cryptocurrencies on a per-coin-mined basis may be greater or less than those determined in our current assessment.

Methods

To quantify the power requirement per cryptonetwork, the daily hashrate was multiplied by the energy consumption of a typical mining computer, as performed by Bevand[14]. A brief review and discussion of the previous estimates reported in Table 2 is given in the Supplementary Information. Values used in these calculations are given in Fig. 1, Table 3, and the Supplementary Information. For all cryptocurrencies, the daily network hashrate multiplied by the hashing or power efficiency (PE) of the mining rig (that is, computer) established the amount of power consumed by the entire network, as shown in equation (1). The hashrate is the number of computations being performed across the entire network per second. The hardware used to mine coins dictates the number of calculations performed per second and the power efficiency at which it can perform those calculations.

$$P\,(\mathrm{MW}) = \mathrm{HR}\left(\frac{\text{hashes}}{\text{second}}\right) \times \mathrm{PE}\left(\frac{\text{Joules}}{\text{Hash}}\right) \times 2.78 \times 10^{-10}\left(\frac{\mathrm{MWh}}{\mathrm{J}}\right) \times 3{,}600\left(\frac{\text{seconds}}{\text{hours}}\right) \tag{1}$$

where P is the power requirement of a cryptocurrency network, HR is the network hashrate (shown in Fig. 1) and PE is the power efficiency of the mining equipment (given in Table 3).

Then, a 'network velocity' (US\$ generated per hour) was calculated by multiplying the number of blocks generated per hour, the coin reward for block completion and the conversion from coin to US\$ (all given in Table 3), as shown in equation (2).

$$v\left(\frac{\mathrm{US\$}}{\mathrm{h}}\right) = R\left(\frac{\text{coins rewarded}}{\text{block}}\right) \times \mathrm{EX}\left(\frac{\mathrm{US\$}}{\text{coin}}\right) \div t_{\mathrm{B}}\left(\frac{\text{minutes}}{\text{block created}}\right) \times 60\left(\frac{\text{minutes}}{\text{hours}}\right) \tag{2}$$

where v is the network velocity, t_B is the daily average block completion time (in minutes), R is the coin reward for completing a block and EX is the cryptocurrency conversion price from coin to US\$.

To determine the energy required to generate US\$1, the network power (P) was divided by the velocity and multiplied by the unit conversion factor from megawatt hours to megajoules as shown in equation (3).

$$\mathrm{EC}\left(\frac{\mathrm{MJ}}{\mathrm{US\$}}\right) = P\,(\mathrm{MW}) \div v\left(\frac{\mathrm{US\$}}{\mathrm{h}}\right) \times 3{,}600\left(\frac{\mathrm{MJ}}{\mathrm{MWh}}\right) \tag{3}$$

where EC is the energy cost defined as the daily energy required to generate US\$1; P and v were defined previously.

This process was performed for Bitcoin, Ethereum, Litecoin and Monero. Although market capitalization will change with coin value (which changes in real time), these four were picked on the basis of availability of data and to identify whether different energy requirements existed among the more established coins. The value of each coin in US\$ was taken as the value at the close of each day (that is, 23:59), given in the Supplementary Data. The final EC values are averages of the study period (911 days) or annual averages for 2016, 2017 and 2018. Daily EC values are reported in the Supplementary Information. Average, standard deviation and median values for all 911 days are reported in Supplementary Table 12. Although the annual standard deviations were large for some cryptocurrencies compared to the average value, because they were less than the average and because the median values were similar to the arithmetic average, the average values are presented in Fig. 2 and reported in the text.

Literature values were sourced for the energy consumption to produce 1 kg or 1 t of gold[15,16], PGMs[33], REOs[37], and aluminium[35,36]. Market prices for the metals were obtained from the United States USGS[38]. These values were multiplied to determine the energy requirement of metal generated per US\$, as shown in equation (4). The literature-reviewed values as well as market prices are reported in the main text. This made the values of energy invested for digital and physical assets comparable, as shown in equation (4).

$$\mathrm{EC}_m\left(\frac{\mathrm{MJ}}{\mathrm{US\$}}\right) = A\left(\frac{\mathrm{MJ}}{\text{metal (kg)}}\right) \div B\left(\frac{\mathrm{US\$}}{\text{metal (kg)}}\right) \tag{4}$$

where $\mathrm{EC_m}$ is the EC for the metal of interest, m, A is the energy required to extract a kilogram of m, and B is the market price of m.

A final assessment of the potential environmental footprint of each of the networks was made by applying peer-reviewed data of country-specific emissions factors (kg CO_2 per kWh^{-1}) for energy supply by the daily calculated energy required to produce a single coin, as shown in equation (5). The emission factors and calculated carbon costs are reported in Supplementary Table 14.

$$N_{\mathrm{C}}\left(\frac{\mathrm{kWh}}{\text{coins mined}}\right) = P\,(\mathrm{MW}) \times t_{\mathrm{B}}\left(\frac{\text{minutes}}{\text{block}}\right) \div 60\left(\frac{\text{minutes}}{\text{hours}}\right) \times 1{,}000\left(\frac{\mathrm{kWh}}{\mathrm{MWh}}\right) \div R\left(\frac{\text{coins}}{\text{block}}\right) \tag{5}$$

where N_C is the daily energy required to produce a coin on a given day and the other parameters have been previously defined.

For the study period of 911 days, the median daily N_C value for each cryptonetwork was then determined (see Supplementary Table 12). The median is used here because the standard deviation of the data set was greater than the arithmetic average, indicating a non-normal distribution of values (given in the Supplementary Information). Whereas ECs change with respect to energy and price, N_C values change only with respect to network energy requirements. Then the country-specific emission factors (Y) were applied to estimate the emissions of CO_2 per coin as shown in equation (6). This created several potential values for each cryptocurrency, as shown in Fig. 3.

$$T_C\left(\frac{CO_2 \text{ emitted (kg)}}{\text{coins mined}}\right) = Y\left(\frac{CO_2 \text{ emitted (kg)}}{\text{kWh}}\right) \times \text{median}\left(N_C\left(\frac{\text{kWh}}{\text{coins mined}}\right)\right) \quad (6)$$

where T_C is the carbon cost defined as the mass of carbon dioxide emitted per coin mined, Y is the mass of CO_2 emitted per kilowatt hour of energy generated for a country or region and median(N_C) refers to the median N_C value.

As the location of each miner cannot be determined, the attribution of emissions can be only broadly estimated. In this case, we estimate using the highest and lowest country-specific emission factors (India and Canada, respectively) as the upper and lower bounds, as presented in Supplementary Tables 15–18. To identify the total CO_2 emissions attributable to each cryptocurrency network from mining, we determined the daily number of coins created from the daily average block completion time and block reward as shown in equation (7).

$$r_C\left(\frac{\text{coins}}{\text{day}}\right) = \frac{24 \text{ h}}{\text{day}} \times \frac{60 \text{ min}}{\text{hour}} \div t_B\left(\frac{\text{minutes}}{\text{block}}\right) \times R\left(\frac{\text{coins}}{\text{block}}\right) \quad (7)$$

where r_C is the daily rate of coins generated (coins per day) and all other parameters have been previously defined. Summing the r_C values for each day from 1 January 2016 to 30 June 2018 (that is, 911 days), we determine the cumulative number of coins generated for this study period as shown in equation (8).

$$C_m = \sum_{i=1}^{911} r_C \quad (8)$$

where C_m is the cumulative number of coins generated during the study time (that is, 911 days) and r_C was defined previously.

Therefore, the total CO_2 emissions is the carbon cost (T_C) multiplied by the number of coins as shown in equation (9).

$$C_C(\text{t } CO_2 \text{ emitted}) = T_C\left(\frac{CO_2 \text{ emitted (kg)}}{\text{coins mined}}\right) \div 1{,}000\left(\frac{\text{kg}}{\text{t}}\right) \times C_m(\text{coins mined}) \quad (9)$$

where C_C is the metric tonnes of CO_2 emitted due to cryptocurrency mining and all other parameters were previously defined.

Data availability

All data analysed here are included in this published article (and its Supplementary Information) or publicly available online as noted.

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Author contributions
M.J.K. and T.T. conceived the manuscript. M.J.K. aggregated and analysed the data and drafted the manuscript. T.T. provided writing contributions to the manuscript.

Competing interests
M.J.K. declares financial holdings of less than US$5,000 of BTC, ETH, XMR, LTC, MIOTA and other cryptocurrencies. T.T. declares no competing interests.

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