base on snow[8] must therefore also be used in governance of a rapidly changing Arctic. ❐

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Corrected: Publisher Correction

Bitcoin emissions alone could push global warming above 2°C

Bitcoin is a power-hungry cryptocurrency that is increasingly used as an investment and payment system. Here we show that projected Bitcoin usage, should it follow the rate of adoption of other broadly adopted technologies, could alone produce enough CO_2 emissions to push warming above 2 °C within less than three decades.

Camilo Mora, Randi L. Rollins, Katie Taladay, Michael B. Kantar, Mason K. Chock, Mio Shimada and Erik C. Franklin

Leaders from 176 countries have ratified the Paris Agreement, reached during the Twenty-first Conference of the Parties to the UNFCC (COP 21), to mitigate GHG emissions and keep anthropogenic global warming within 2 °C to avoid the impacts of ever-more-catastrophic climate hazards such as drought, heatwaves, wildfire, storms, floods and sea-level rise, among others. From 1860 to 2014, humanity emitted ~584.4 GtC from fossil fuel combustion, industry processes and land-use change, which has been mirrored by ~0.9 °C of global warming (green line in Fig. 1a). Temperature projections from 42 Earth system models (ESMs) developed for the recent Coupled Model Intercomparison Project Phase 5 (CMIP5) under four alternative emission scenarios show that an additional 231.4 to 744.8 GtC would push global warming across the 2 °C threshold (Fig. 1a; the range represents the 5th and 95th percentiles among model projections, see Methods). Reducing emissions to keep warming below 2 °C is already regarded as a very difficult challenge given the increasing human population and consumption[1] as well as a lack of political will[2]. Then came Bitcoin.

Bitcoin is a decentralized cashless payment system introduced in early 2009, and it is now accepted by over 100,000 merchants and vendors worldwide[3]. Each transaction paid for with Bitcoin is compiled into a 'block' that requires a computationally demanding proof-of-work to be resolved, which in turn uses large amounts of electricity[4]. Based on the assumptions that 60% of the economic return of the Bitcoin transaction verification process goes to electricity, at US$5¢ per kWh and 0.7 kg of CO_2-equivalent (CO_2e) emitted per kWh, Digiconomist[5] estimated that Bitcoin usage emits 33.5 $MtCO_2e$ annually, as of May 2018. Foteinis[6] repeated this approach using emissions adjusted by a broader life cycle of electricity generation and found that for 2017, the global emissions from Bitcoin and Ethereum usage were 43.9 $MtCO_2e$. Compiling data on the electricity consumption of the various computing systems used for Bitcoin verification at present and the emissions from electricity production in the countries of the companies that performed such computing, we estimated that in 2017, Bitcoin usage emitted 69 $MtCO_2e$ (s.d. = ±0.4; see Methods).

Globally, ~314.2 billion cashless transactions are carried out every year[7], of which Bitcoin's share was ~0.033% in 2017[5]. The environmental concern regarding Bitcoin usage arises from the large carbon footprint for such a small share of global cashless transactions, and the potential for it to be more broadly used under current technologies. Bitcoin usage has experienced an accelerated growth (Supplementary

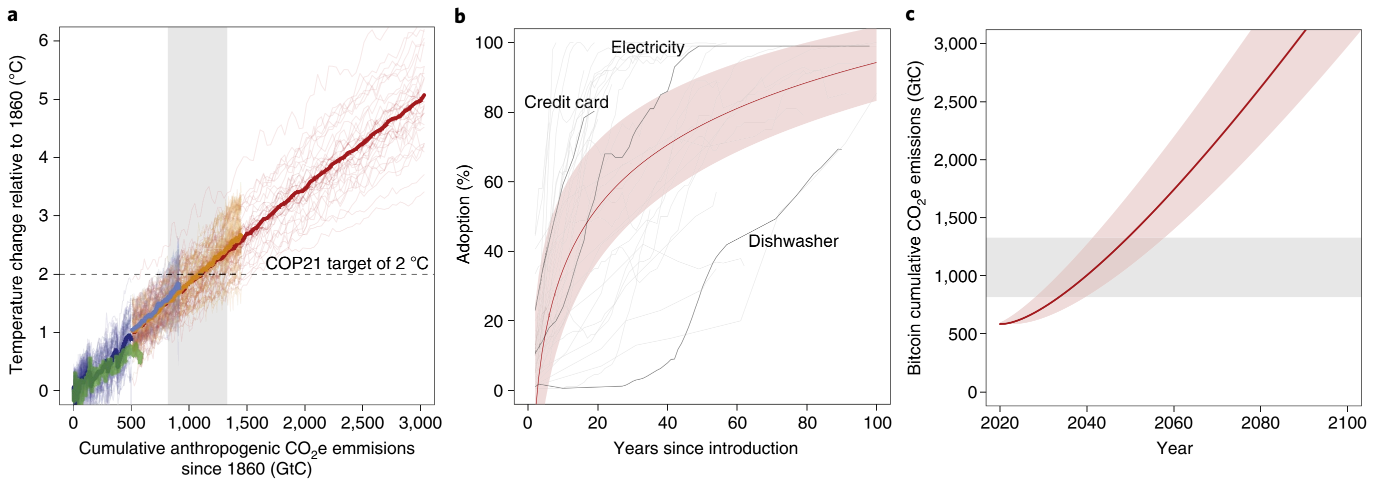

Fig. 1 | Carbon emissions from projected Bitcoin usage. a, Current and projected trends in global average temperature as a function of cumulative man-made carbon emissions. Narrow lines depict the projections of individual ESMs, while the thick lines indicate the multimodel median. The dashed line represents the COP 21 target of 2 °C global warming, and the grey shaded area represents the CO_2e emissions among ESMs at which such a threshold is crossed (values are for the 5th and 95th percentiles of all model projections). **b**, Trends in the adoption of broadly used technologies. Data are available for the United States, and used here as a reference. The red shaded area indicates the margins of the upper and lower quantiles, and the red line is the median tendency among technologies (see Methods). Grey lines indicate trends for each of the technologies (see Methods). **c**, Cumulative emissions from Bitcoin usage under the average growth rate of technologies that have been broadly adopted as shown in **b**. The grey shaded area indicates the carbon emissions above which warming exceeds 2 °C.

Fig. 1), which is a common pattern during the early adoption of broadly used technologies[8]. Should Bitcoin follow the median growth trend observed in the adoption of several other technologies (Fig. 1b), it could equal the global total of cashless transactions in under 100 years. Yet, the cumulative emissions of such usage growth could fall within the range of emissions likely to warm the planet by 2 °C within only 16 years (red line in Fig. 1b). The cumulative emissions of Bitcoin usage will cross the 2 °C threshold within 22 years if the current rate is similar to some of the slowest broadly adopted technologies, or within 11 years if adopted at the fastest rate at which other technologies have been incorporated (that is, the red area in Fig. 1b). Projections in this analysis assume that the portfolio of fuel types used to generate electricity remains fixed at today's values (see Supplementary Table 3).

The future usage of Bitcoin is a topic of considerable discussion. There is currently considerable economic motivation for companies to compute the proof-of-work for each Bitcoin block (for example, the latest block on 8 May 2018 (block 521819) gave a reward of 12.5 bitcoins plus 0.1 bitcoins for transaction fees, with a total monetary value of US$116,041 on that date's exchange rate; https://blockchain.info) — the expected time needed to resolve that proof-of-work is around 10 minutes. However, Bitcoin is set up in such a way that rewards should halve every 210,000 blocks, or approximately every 4 years (for example, 50 bitcoins in 2008, 25 in 2012, and so on). Over time, this could reduce the motivation for companies to resolve the computationally demanding proof-of-work for each block, potentially overwhelming the system and reducing general interest in the use of Bitcoin. Alternatively, Bitcoin usage may generate sufficient transaction fees to support the system, which is how Bitcoin was originally conceived.

Although we are unable to predict the fate of Bitcoin, our analysis suggests that if its rate of adoption follows broadly used technologies, it could create an electricity demand capable of producing enough emissions to exceed 2 °C of global warming in just a few decades. Given the decentralized nature of Bitcoin and the need to maximize economic profits, its computing verification process is likely to migrate to places where electricity is cheaper, suggesting that electricity decarbonization could help to mitigate Bitcoin's carbon footprint — but only where the cost of electricity from renewable sources is cheaper than fossil fuels. Certainly, high electricity cost will push the development of more efficient hardware. However, reducing Bitcoin's carbon footprint should not rest solely on some yet-to-be-developed hardware but include simple modifications to the overall system, such as adding more transactions per block or reducing the difficulty or time required to resolve the proof-of-work — both of which could result in immediate electricity reductions for Bitcoin usage. Our analysis is based on Bitcoin alone; however, the problem of high electricity consumption is common to several cryptocurrencies, suggesting that any further development of cryptocurrencies should critically aim to reduce electricity demand, if the potentially devastating consequences of 2 °C of global warming are to be avoided. ❐

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41558-018-0321-8.

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Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41558-018-0321-8.

Methods

Amount of CO_2e needed to surpass the 2 °C COP 21 target. The 2015 Paris Agreement set the goal to limit global warming to 2 °C. To quantify the amount of CO_2e emissions required to warm the planet by 2 °C (that is, CO_2 emissions plus the CO_2e emissions of other anthropogenic GHGs), we used temperature projections from ESMs and the driving CO_2e emissions of such models (see below). For each ESM, we estimated the CO_2e emissions at which 2 °C warming was reached (the *x* axis value at which each narrow line in Fig. 1a intercepted the 2 °C warming threshold) and grouped those results to estimate the 5th and 95th percentiles (grey box in Fig. 1a). We also collected data on 'observed' temperature change and CO_2e emissions from 1860 to 2014 as validation for model projections, to quantify current warming and cumulative emissions, and estimate the CO_2e emissions needed to surpass the COP 21 target. The observed temperature change and CO_2e emissions since 1860 are shown as a green line in Fig. 1a (temperature data from NOAA-CIRES 20th Century Reanalysis V2c[9], CO_2e emissions data from the Carbon Dioxide Information Analysis Center[10]). The observed and projected cumulative CO_2e emissions are very similar over the time period for which they overlap (see blue and green lines in Fig. 1a), however, they used different methods and emission sources. Fossil fuel emissions, industrial processes and land-use change are the main anthropogenic GHG contributing to current warming (Supplementary Fig. 2), and are all in common to both databases used in this analysis.

Temperature projections. We analysed global annual average surface air temperature from 42 ESMs developed for CMIP5. We used the historical experiment, which for all models includes the period from 1860 to 2005 and Representative Concentration Pathways (RCPs) 2.6, 4.5 and 8.5, which include the period from 2006 to 2100. The historical experiment was designed to model recent climate (reflecting changes due to both anthropogenic and natural causes) whereas the RCP scenarios represent contrasting mitigation efforts between rapid GHG reductions (RCP 2.6) and a business-as-usual scenario (RCP 8.5). For each model, under each experiment, we calculated the difference in the global average temperature between every year in the time series and 1860. For any given experiment, global annual averages from all models at any given year were used to estimate the multimodel median temperature change for that year (thick lines in Fig. 1a). Temperature change for each model and the multimodel median are shown in Fig. 1a.

CO_2e projections. Although CO_2 is the primary GHG contributing to the total anthropogenic radiative forcing (changes in the Earth's energy balance due to human activities), other anthropogenic agents also contribute to the warming trends projected by ESMs (such as methane, aerosols and so on). During the timeframe of this study, volcanic and solar radiative forcings have remained reasonably constant and proportionally very small in relation to the anthropogenic forcing (Supplementary Fig. 2), indicating that they contribute minimally to the warming trends from ESMs, and thus were not considered in this analysis. For the purpose of standardization, we calculated the CO_2e emissions for the radiative forcing from all anthropogenic activities used by the historical and RCP experiments. For this purpose, we obtained CO_2 emissions, their radiative forcing and the total anthropogenic radiative forcing under each experiment (data from Meinshausen et al.[11]). We estimate the CO_2e emissions for the total anthropogenic radiative forcing as the amount of CO_2 required to achieve the total anthropogenic radiative forcing given the ratio of actual CO_2 emissions and the actual CO_2 radiative forcing. As an example, from 1860 until 2005 the historical experiment shows that the cumulative CO_2 emissions from fossil fuels, cement, gas flaring, bunker fuels and land-use amounted to 453.247 GtC and a resulting radiative forcing of 1.675 W m^{-2}, whereas the total anthropogenic radiative forcing was 1.840 W m^{-2}. Thus, the CO_2e emissions for that total anthropogenic radiative forcing were estimated at 497.984 GtC (1.840 × (453.247/1.675)). Projected anthropogenic CO_2e emissions under different experiments are plotted against temperature change from the different models in Fig. 1a. Note that CO_2e emmisions are given in weight units of carbon, which can be converted to units of carbon dioxide (CO_2), simply multiply these estimates by 3.667.

Amount of CO_2e produced by Bitcoin usage. Any given transaction using Bitcoin is compiled into a block requiring a proof-of-work to be resolved, with the winning company/pool being awarded a certain amount of new bitcoins plus any extra transactions fees. The CO_2e emissions from this procedure emerge primarily from the electricity demands of the hardware used and the location where the electricity is generated. To assess the carbon footprint of the global Bitcoin Network, using as reference the year 2017, we used the following approach. We started by compiling a list of current hardware suitable for Bitcoin and their energy efficiencies (hashes per electricity consumed, Supplementary Table 1). To each block mined in 2017 (data from https://blocktrail.com), we assigned a random hardware from Supplementary Table 1 and multiplied the number of hashes required to solve the block by the energy efficiency of the random hardware; this returned the amount of electricity consumed to solve the given block. Note that the available data for mined blocks include their difficulty, which can be used to estimate the number of hashes as (hashes = difficulty × 2^{32}; equation from O'Dwyer and Malone[12]). For each block mined in 2017, we also collected data on the company claiming the given block, and searched for their country/countries of operation (Supplementary Table 2). For the resulting list of countries, we collected data on the types of fuels used for electricity generation (Supplementary Table 3), and using average standards of CO_2e emissions for the generation of electricity with those types of fuels (under a life-cycle carbon approach, Supplementary Table 4), we estimated the total carbon emission equivalents to produce electricity in those countries (Supplementary Table 2). By multiplying the electricity consumption of every block in 2017 by the electricity emissions in the country where the proof-of-work was likely to be resolved, we were able to estimate the total CO_2e emissions for computing every block in 2017. Summing the CO_2e emissions from all blocks in 2017 yielded the Bitcoin emissions in that year. This approach was repeated 1,000 times to capture the variability in the random selection of hardware, and this is described as the s.d.

Projected usage and carbon emissions from Bitcoin. The likely future of Bitcoin has been broadly discussed in online forums with opinions ranging from it being a case of boom and bust, or alternatively, an early stage in a 'new industrial revolution'. We studied the carbon emissions of Bitcoin if it follows the adoption trends of other broadly used technologies. For this, we used the incorporation rate of 40 different technologies for which data are readily available: the automatic transmission, automobile, cable TV, cellular phone, central heating, colour TV, computer, credit card, dishwasher, disk brakes, dryer, e-book reader, electric power, electric range/burners, electronic ignition, flush toilet, freezer, home air conditioning, household refrigerator, Internet, landline phone, microcomputer, microwave, nitrogen oxides pollution controls (boilers), podcasting, power steering, radial tires, radio, refrigerator, Real Time Gross Settlement adoption, running water, shipping container port infrastructure, smartphone, social media, stove, tablet, vacuum, washer dryer, washing machine and water heater (data for the USA from ref. [13], credit card data from ref. [14]). Data include the year and percentage of population using the given technology. The first year of usage for each technology was set to one, to allow comparison of trends among technologies (narrow grey lines in Fig. 1b). For each year, we calculated the average and lower and upper quantiles of per cent population using all technologies and applied a logistic model to such trends (the red line and red shading in Fig. 1b). The projected trends of technology usage adoption were used to estimate likely Bitcoin usage assuming a global total of ~314.2 billion cashless transactions. We used only cashless transactions that are likely to occur in places where infrastructure is already in place for the usage of Bitcoin as a reference (for example, we do not assume that Bitcoin will replace transactions using fiat currency). The CO_2e emissions of projected Bitcoin usage were estimated using the CO_2e emissions for Bitcoin transactions in 2017 as a reference. We randomly sampled blocks mined in 2017 until their total number of transactions were equal to the projected number of transactions, then we added the CO_2e emissions from computing such randomly selected blocks. The approach was repeated 1,000 times.

Code availability. Raw code used for this study are publicly available online at https://github.com/moracamilo/Bitcoin/.

Data availability

The authors declare that all data supporting the findings of this study are available within the article, its Supplementary Information files and at https://github.com/moracamilo/Bitcoin/.

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