nature climate change

SUPPLEMENTARY INFORMATION
https://doi.org/10.1038/s41558-018-0321-8

In the format provided by the authors and unedited.

Bitcoin emissions alone could push global warming above 2°C

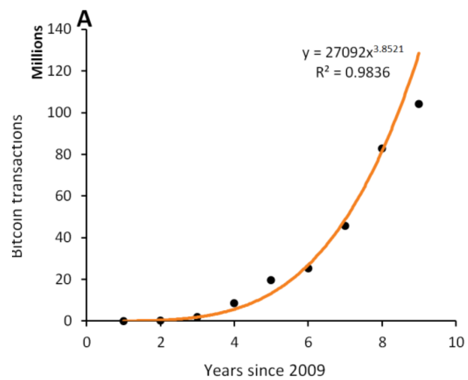
Camilo Mora[1]*, Randi L. Rollins[2,3], Katie Taladay[1], Michael B. Kantar[4], Mason K. Chock[5], Mio Shimada[5] and Erik C. Franklin[1,6]

[1]Department of Geography and Environment, University of Hawai'i at Mānoa, Honolulu, HI, USA. [2]Department of Biology, University of Hawai'i at Mānoa, Honolulu, HI, USA. [3]Pacific Biosciences Research Center, School of Ocean and Earth Science and Technology, University of Hawai'i at Mānoa, Honolulu, HI, USA. [4]Department of Tropical Plant and Soil Science, University of Hawai'i at Mānoa, Honolulu, HI, USA. [5]Department of Botany, University of Hawai'i at Mānoa, Honolulu, HI, USA. [6]Hawai'i Institute of Marine Biology, School of Ocean and Earth Science and Technology, University of Hawai'i at Mānoa, Kāne'ohe, HI, USA. *e-mail: cmora@hawaii.edu

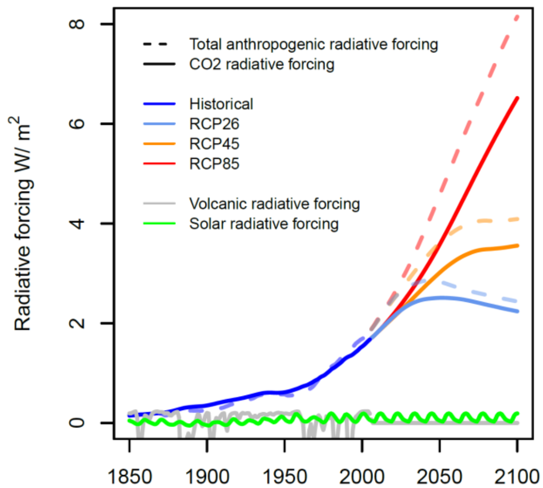
Bitcoin emissions alone could push global warming above 2ºC

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

Supplementary Figure 1. Current trend of Bitcoin usage. The use of Bitcoin as a method for payment has seen a fast growth since its introduction in 2009 that is currently best described with a power model. Exponential, logistic and polynomial models yielded lower fits.



Supplementary Figure 2. Projected radiative forcing of different climate change agents. Given that the historical and RCP experiments used by Earth System Models in the CMIP5 are based on total radiative forcing, we standardized the total anthropogenic radiative forcing to CO_2e; we did not consider the volcanic and solar forcings (see Methods).

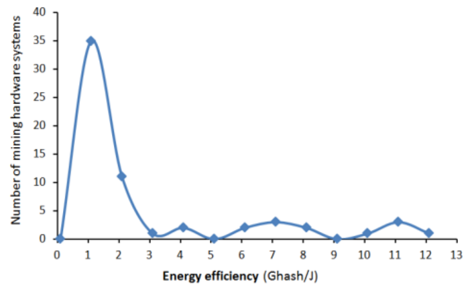


Supplementary Table 1. List of Bitcoin processing hardware and their electricity consumption. Since the introduction of Bitcoin, computing hardware has evolved through four core iterations. The evolution of CPU, GPU, FPGA to ASIC hardware trended to higher hash rates and less electricity consumption per hash rate, respectively. In doing so, the CPUs, GPUs and FPGAs have become unprofitable due to the cost of electricity required to mine Bitcoin. Additionally, given the difficulty of the SHA-256 algorithm and number of enterprises computing Bitcoin transactions, many hardware systems became obsolete. Here we list only hardware that is economically profitable by modern standards. Although the range in energy efficiency among Bitcoin hardware systems was broad [from 0.106 to 11.11 Ghash/J (Table below)], 75% of the available systems range in efficiency between 1.1 and 2.1 Ghash/J (see figure below). This large proportion of systems in that narrow range of energy efficiency explains the narrow standard deviation we encounter in CO_2 emissions from bitcoin usage.

Bitcoin computing hardware	**Hash rate** (Ghash/s)	**Consumption** (GWh)	**Energy efficiency** (Ghash/J)	**Reference**
AntMiner S1	180	0.00000036	0.500	[2, 8]
AntMiner S2	1000	0.0000011	0.909	[2, 8]
AntMiner S3	441	0.00000034	1.297	[2, 8]
AntMiner S4	2000	0.0000014	1.429	[2, 8]
AntMiner S5	1160	0.00000059	1.966	[2, 8]
AntMiner S5+	7720	0.000003436	2.247	[2, 8]
AntMiner S7	4730	0.00000121	3.909	[2, 9]
AntMiner S9	14000	0.000001375	10.448	[1, 2]
Antminer T9+	10500	0.000001332	7.332	[6, 8]
AntMiner R4	8700	0.000000845	10.296	[7, 8]
Avalon Batch 1	66	0.00000062	0.106	[2, 8]
Avalon Batch 2	82	0.0000007	0.117	[2, 8]
Avalon Batch 3	82	0.0000007	0.117	[2, 8]
Avalon6	3500	0.00000108	3.241	[2, 9]
Avalon 721	6000	0.000001	6.000	[2, 5]
Avalon741	7300	0.00000115	6.348	[2, 5]
Avalon761	8800	0.00000132	6.667	[2, 7]
Avalon821	11000	0.0000012	9.167	[2, 8]
BFL SC 5 Gh/s	5	0.00000003	0.167	[2, 8]
BFL SC 25Gh/s	25	0.00000015	0.167	[2, 8]
BFL SC 50 Gh/s	50	0.0000003	0.167	[2, 8]
BFL Single 'SC'	60	0.00000024	0.250	[2, 8]

BFL 500 GH/s Mini Rig SC	500	0.0000027	0.185	[2, 8]
BFL Monarch 700 GH/s	700	0.00000049	1.429	[2, 8]
Bitmine Avalon Clone 85 GH	85	0.00000065	0.131	[2, 8, 12]
Black Arrow Prospero X-1	100	0.0000001	1.000	[2, 8]
Black Arrow Prospero X-3	2000	0.000002	1.000	[2, 8]
BTC Garden AM-V1 310 GH/s	310	0.000000324	0.957	[2, 13]
CoinTerra TerraMiner IV	1600	0.0000021	0.762	[2, 8, 12]
Ebit E9	6300	0.000000882	7.143	[2, 5]
Ebit E9+	9000	0.0000013	6.923	[2, 8]
Ebit E9++	14000	0.00000133	10.526	[2, 8]
Ebit E10	18000	0.00000162	11.111	[2, 8]
HashBuster Micro	20	0.000000023	0.870	[2, 8]
HashFast Baby Jet	400	0.00000044	0.909	[2, 8]
HashFast Sierra	1200	0.00000132	0.909	[2, 8]
HashFast Sierra Evo 3	2000	0.0000022	0.909	[2, 11]
Klondike	5	0.000000032	0.156	[2, 8]
KnCMiner Mercury	100	0.00000025	0.400	[2, 8, 12]
KnC Saturn	250	0.0000003	0.833	[2, 8]
KnC Jupiter	500	0.0000006	0.833	[2, 8]
KnC Neptune	3000	0.0000021	1.429	[2, 13]
Metabank	120	0.00000017	0.706	[2, 8]
NanoFury NF2	4	0.000000005	0.800	[2, 8]
BPMC Red Fury USB	2.5	2.50E-09	1.000	[2, 8]
ROCKMINER R3-BOX	450	0.00000045	1.000	[2, 8]
ROCKMINER R4-BOX	470	0.00000047	1.000	[2, 8]
ROCKMINER Rocket BOX	450	0.00000048	0.938	[2, 8]
ROCKMINER R-BOX	32	0.000000045	0.711	[2, 8]
ROCKMINER R-BOX110G	110	0.00000012	0.917	[2, 8]
ROCKMINER T1 800G	800	0.000001	0.800	[2, 8]
Spondooliestech SP10	1400	0.00000125	1.120	[2, 8]
Spondooliestech SP20	1700	0.0000011	1.545	[2, 11]
Spondooliestech SP30	4500	0.000003	1.500	[2, 8]
Spondooliestech SP31	4900	0.000003	1.633	[2, 8]
Spondooliestech SP35	5500	0.00000365	1.507	[2, 8]
TerraHash Klondike 16	5	0.000000032	0.156	[2, 8]
TerraHash Klondike 64	18	0.000000127	0.142	[2, 8]
TerraHash DX Mini (full)	90	0.00000064	0.141	[2, 8]

TerraHash DX Large (full)	180	0.00000128	0.141	[2, 8]
Twinfury	5	3.83E-09	1.305	[2, 8]
WhatsMiner M3	12500	0.0000022	5.682	[4, 2]



References

1. Ant Miner product page https://www.bitmain.com/
2. Bitcoinwiki Mining hardware comparison https://en.bitcoin.it/wiki/Mining_hardware_comparison
3. Ebang Ebit Miner product page http://miner.ebang.com.cn/index.html
4. WhatsMiner product page https://whatsminer.net/shop/
5. ASIC Miner Market https://asicminermarket.com/product/ebit-e9-miner-6-5t-bitcoin-miner-14nm-asic/
6. Amazon site T9+
7. Crypto Compare Ant Miner R4
8. ASIC Miner Value https://www.asicminervalue.com/miners/bitmain/antminer-r4
9. Bitcoin Mining https://www.bitcoinmining.com/bitcoin-mining-hardware/
10. Buy Bitcoin World https://www.buybitcoinworldwide.com/mining/hardware/spondoolies-sp20/
11. Top Bitcoin Mining Hardware http://www.topbitcoinmininghardware.com/hashfast-sierra-bitcoin-miner-review/
12. Mining Cloud http://miningcloud-2018.info/gpu-mining-profitability/bitcoin-mining-mhash-rate.php
13. Cyber Bitcoin http://www.cybtc.org/article-47-1.html

Supplementary Table 2. List of companies doing Bitcoin verification in 2017, and the electricity emissions of their regions/countries of origin. While the actual place of Bitcoin computing is unknown, we assume that the transaction verification process is done in the country of the company that claimed the block. Here we show the list of all companies that claimed blocks in 2017, their regions/countries of origin and the CO_2e from electricity generation in those countries. Emissions for the given countries are from Table S3.

Enterprise pool	Known server location(s)*	CO_2e/GWh Metric tons	Mining pool website
1Hash	China	661.73	http://www.1hash.com/
AntPool	China	661.73	https://antpool.com
BATPOOL	China	661.73	https://www.batpool.com/
BTC.com	China	661.73	https://pool.btc.com
BTC.TOP	China	661.73	http://btc.top/
BTCC Pool	China	661.73	https://pool.btcc.com/
BW.COM	China	661.73	https://www.bw.com
EXX & BW	China	661.73	https://xbtc.exx.com/
HaoBTC	China	661.73	https://haobtc.com/
ViaBTC	China	661.73	http://www.viabtc.com/
Bitfury	Georgia, Finland, Iceland	132.60	http://www.bitfury.org/
Bitcoin.com	Global	573.86	https://pool.bitcoin.com
Kano Pool (CKPool)	Global	573.86	http://www.kano.is
MMPool	Global	573.86	http://mmpool.org
NiceHashSolo	Global	573.86	https://solo.nicehash.com/
P2Pool	Global	573.86	http://p2pool.org
Slush	Global	573.86	https://mining.bitcoin.cz
Solo.CKPool	Global	573.86	http://solo.ckpool.org
GBMiners	India	706.44	http://52.66.51.105/
GoGreenLight	Sweden	60.32	http://www.gogreenlight.se/
BCMonster	U.S., China	580.04	http://www.bcmonster.com/
F2Pool (DiscusFish)	U.S., China	580.04	http://www.f2pool.com
BitClub Network	U.S.	498.34	https://bitclubnetwork.com
Canoe Pool	U.S.	498.34	https://www.canoepool.com
Eligius	U.S.	498.34	http://eligius.st
Telco 214	U.S.	498.34	http:///www.telco214.com/
BitMinter	U.S., E.U.	414.46	https://bitminter.com

*Server location data sourced from BitcoinChain

Supplementary Table 3. CO_2e emissions from electricity generation in regions/countries known to be computing Bitcoin. This table lists regions/countries with active Bitcoin companies, their electricity generation portfolio by fuel type and corresponding metric tons of CO_2e/GWh. CO_2e/GWh data were calculated using conversion factors from Table S4. These values are used for the current and projected emissions of Bitcoin usage. One limitation that can emerge for our future projection calculations are changes in this mix of types of fuel for electricity generation. In our case, we assume that the global energy mix remains fixed at today's values. Unfortunately, the alternative of modifying the energy portfolio of the countries carries several confounding uncertainties. On one hand, it is the uncertainty of each country using a different mix of fuel types; and on the other hand, it is the fact that the computing of Bitcoin transactions can easily migrate among most countries. With that said, our results suggest that, if broadly implemented, Bitcoin could generate a considerable carbon footprint within less than three decades: a timeframe in which available projections of fuel type usage suggest that non-renewable sources (i.e., coal, gas, oil) will still be a considerable contributor [i.e., 55-65% of electricity generation; The International Energy Agency's World Energy Outlook (WEO) forecasts electricity generation until 2040 (https://www.iea.org/weo/)].

Region/Country	**Percent electricity source by fuel type***						**CO_2e/GWh** Metric tons
	Coal	*Gas*	*Hydroelectric*	*Nuclear*	*Oil*	*Other*	
India	72	8	12	3	-	6	706.44
China	72	2	20	5	0.5	3.5	661.73
Asia and Oceania	59	13	15	4	4	5	573.86
Global	39	22	17	11	5	7	504.49
United States	38	30	6	19	-	7	498.34
Europe	25	16	17	24	1	17	330.58
Finland	17	-	22	37	4	20	208.53
Georgia	-	27	73	-	-	-	153.71
Sweden	1	-	42	41	-	17	60.32
Iceland	-	-	71	-	-	29	35.57

*Source: The World Bank- World Development Indicators for 2014; Iceland data from https://nea.is/the-national-energy-authority/energy-statistics/generation-of-electricity/.

Supplementary Table 4. CO_2e emissions from electricity generation for different fuel types. Here we list the CO_2e for electricity production by fuel type using lifecycle greenhouse gas emission assessments.

Fuel type	**Mean metric tons** CO_2e/GWh	**Source**
Coal	888	[1]
Natural Gas	499	[1]
Hydroelectric	26	[1]
Nuclear	29	[1]
Oil	733	[1]
Solar PV	85	[1]
Geothermal	80	[2]
Biomass	45	[1]
Wind	26	[1]
Other *	59	

Sources:

1. World Nuclear Association Report (http://www.world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/comparison_of_lifecycle.pdf).
2. IPCC, 2011. Chapter 4. Our reported value is the unweighted average of CO2e emissions from binary plants and district heating systems. https://ipcc.ch/pdf/special-reports/srren/drafts/Chapter%2004%20SOD.pdf

* Many countries do not specify fuel source for “renewables” in their electricity production portfolios. Therefore, we use the term *Other* to denote the average of solar PV, geothermal, biomass, and wind.