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Climate Impacts of Bitcoin Mining in the U.S.

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Abstract

Opinions regarding the climate impacts of Bitcoin mining deviate fundamentally between scholars and Bitcoin proponents. We validate arguments from both sides and provide empirical evidence for the extent and energy sources of Bitcoin mining in the U.S. We provide empirical evidence that at least 38% of all Bitcoin mining activity has migrated to the U.S. and Canada as of the end of 2022 and show that the carbon emissions caused by the 13 analyzed publicly listed miners in the U.S. alone add up to 7.2 $MtCO_2$ per annum. At the same time, the financial incentives of the Bitcoin network may, for instance, subsidize the sealing of orphaned wells and thereby reduce methane emissions at scale. The growing transparency on locations and energy sources of large publicly listed Bitcoin miners highlights the value of disclosure obligations and may help dismantle unsupported industry claims, improve assumption-based academic models, and point regulators to areas where Bitcoin mining may bring climate benefits.

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Introduction

Bitcoin mining is renowned for its energy intensity. As of March 25th, 2023, Bitcoin miners' power demand amounts to 15.4 gigawatts (GW).[1] In the Bitcoin network, so-called miners compete in a computational puzzle to add blocks to the chain and validate coin ownership and transactions included in the blocks. To participate in the process, miners use specialized hardware devices which consume electricity.

And while scholars and Bitcoin proponents agree that miners consume vast amounts of electricity, opinions regarding the climate impacts of Bitcoin mining deviate fundamentally. Critics view Bitcoin's electricity consumption as a calamity, while proponents perceive it as a feature rather than a bug. A growing body of academic studies compares Bitcoin's carbon footprint to the emission levels of mid-sized countries.[2,3] Concurrently, Bitcoin proponents highlight potential climate benefits from grid balancing services, support of renewable energy expansion, methane emissions reductions via flare gas utilization or sealing of orphaned wells, and use of waste heat from mining hardware for ancillary activities.[4,5]

We validate arguments from both sides and provide empirical evidence for the extent and energy sources of Bitcoin mining in the U.S., based on data from 13 publicly listed mining companies that account for one-fourth of the total network hashrate as of the end of 2022. Notably, during the winter storm Elliott in North America in December 2022, Bitcoin miners curtailed as much as 100 Exahashes per second (EH/s) – equivalent to 38% of the total Bitcoin network hashrate on that day.[6] This number provides empirical evidence that at least 38% of all Bitcoin mining activity was located in the U.S. and Canada by December 2022.

We find that the carbon intensity of electricity consumed by publicly listed Bitcoin mining companies in the U.S. of 397 grams of carbon dioxide per kilowatt-hour (gCO_2/kWh) is on par with the U.S. grid average and that carbon emissions caused by the 13 analyzed publicly listed miners in the U.S. alone surpass the carbon emissions of the State of Vermont.[7] These findings, based on grid average emission factors, stand in contrast to industry claims that the majority (58.9%) of Bitcoin mining is fueled by sustainable energy[8] as the share of non-fossil electricity from renewables (21.5%) and nuclear (18.2%) in the U.S. generation mix is significantly lower.[9] At the same time, we find that the potential climate benefits of Bitcoin mining also warrant closer attention.

To bridge the gap in this bifurcated debate, it is crucial to comprehend established carbon accounting rules and ascertain the data required to substantiate renewable energy claims. The increasing transparency of locations and energy sources for publicly listed Bitcoin miners emphasizes the value of disclosure obligations that may help dismantle unsupported industry claims, improve assumption-based academic models, and direct regulators to areas where Bitcoin mining may bring climate benefits. We argue that further transparency is vital to educate Bitcoin users and inform the public, regulators, and policymakers about the climate impacts of Bitcoin mining.

Climate benefits of Bitcoin mining

Historically, events such as the Chinese mining crackdown or a blackout in Kazakhstan provided empirical insights into the size and global distribution of Bitcoin mining activities.[2] A similar event occurred on December 24th, 2022, when winter storm Elliott hit North America, and in consequence, Bitcoin miners curtailed about 100 EH/s at peak – equal to 38% of the total Bitcoin network hashrate on that day.[6]

ERCOT, the grid operator in Texas, established a curtailment program for large flexible load (LFL) in 2022. So far, nearly the entire operational LFL can be attributed to Bitcoin mining facilities that qualify for the program; facilities with over 75 megawatts (MW) rated power. The LFL demand response during winter storm Elliott of 1.4 gigawatts, as depicted in Figure 1, provides a lower bound of the Bitcoin mining load in Texas as nearly all of the LFL operational in December 2022 can be attributed to Bitcoin mining. This corresponds to 15% of the total Bitcoin network power demand on that day.[1] This event bolsters a common argument of Bitcoin proponents: that Bitcoin mining can contribute to grid stability and resilience by providing grid operators with a resource that can rapidly adjust its power usage at a highly granular level. The latest LFL update shows that the capacity has grown further to 1.7 GW as of March 2023.[10]

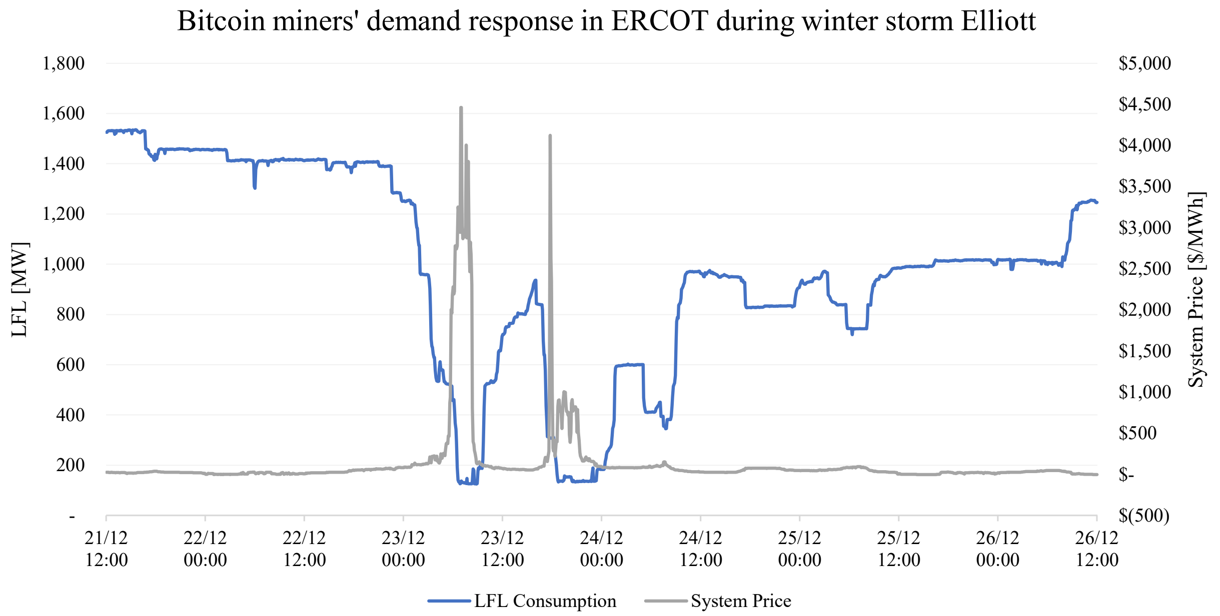


Figure 1 | Large flexible load (LFL) curtailment during winter storm Elliott according to ERCOT data (see Supplementary Data).

However, the climate benefits arising from demand response capacity and other grid-balancing services that U.S. Bitcoin miners may provide are difficult to measure. Further research is needed to assess and compare the carbon emissions and total power system costs in scenarios with and without Bitcoin mining. For instance, emissions reductions stemming from reducing the reliance on fossil-fuel-powered backup generators and other peak load resources, as well as the value of demand response via potential system cost savings could be used as reference points to quantify potential climate benefits.

A second climate benefit often emphasized by Bitcoin proponents is its potential to mitigate methane emissions. Natural gas, if a by-product of oil extraction, is often uneconomical for oil producers to utilize or transport due to costly and lacking infrastructure. Consequently, producers either vent or flare the gas on site. Venting emits methane (CH_4) directly into the atmosphere – a greenhouse gas with a Global Warming Potential over a 100-year timeframe 28-36 times greater than CO_2 – and is therefore discouraged or even illegal in some jurisdictions.[11] Flaring the gas emits predominantly carbon dioxide (CO_2), and it is commonly assumed flares destroy CH_4 with 98% efficiency.[12]

Bitcoin proponents assume much higher residual CH_4 emissions from flaring and argue that emissions could be reduced if the gas were combusted in electrical generators instead. Bitcoin industry estimates suggest a potential of reducing carbon dioxide equivalent (CO_2e) emissions by 25% compared to open flares and up to 63% if accounting for the outages of flares, assuming a 99.9% generator CH_4 combustion efficiency.[13] A recent flare efficiency study, using surveys to explore flare outages and airborne sampling covering basins accountable for over 80% of U.S. flaring, finds that flare outages and inefficient combustion result in a flare efficiency of 91.1%, resulting in 4-10% of total U.S. oil and gas CH_4 emissions.[12]

Insufficient electricity demand and high investment costs often render flare gas utilization projects unfeasible. Bitcoin mining, with its location-agnostic, modular, and portable properties, offers a solution by incentivizing generator construction to convert the otherwise squandered energy into productive use and further leads to mitigating methane emissions. Critics, however, argue that this practice does not address the underlying issue of ongoing fossil fuel consumption and its environmental repercussions and may even inadvertently prolong fossil fuel dependency.[14]

Another potential climate benefit is closely related to flaring mitigation, namely, addressing the issue of orphaned and unplugged oil and gas wells. As of 2020, according to EPA research[15], the U.S. had 3,700,000 abandoned wells, of which 59% were unplugged, emitting 6.9 million tonnes of CO_2 equivalent ($MtCO_2e$) annually. Bitcoin mining, due to its location-agnostic nature and minimal local resource requirements, presents a potential solution to this problem. The financial incentives of the Bitcoin network could subsidize the sealing of these wells, with Bitcoin industry advocates lobbying for this approach.[16] By operating near orphaned wells, miners can harness the otherwise wasted energy, convert it into electricity, and generate revenue to fund well-sealing efforts while mitigating climate impact.

A third argument emphasized by Bitcoin proponents is that Bitcoin mining may facilitate the expansion of renewable energy resources. Mining in remote locations could potentially address challenges associated with integrating an increasing amount of intermittent renewable energy sources into power grids, such as the need for transmission capacity, energy storage capacity, or a lack of nearby power demand.[5] Renewable energy sources, such as wind and solar, are characterized by intermittency, resulting in volatile and non-controllable electricity production. Optimal sites for generating renewable electricity are often in remote regions with insufficient local demand and inadequate transmission infrastructure to accommodate a significant increase in electricity supply.

Quantifying the climate benefits associated with Bitcoin mining in this context, however, remains challenging, as there is no comprehensive record of Bitcoin miners who actually invested in installing additional renewable energy resources. Two notable examples are the partnership of Tesla, Block, and Blockstream to set up a 3.5 MW off-grid, solar-powered Bitcoin mine in Texas[17] and Aspen Creek's 30 MW mining facility connected behind-the-meter with a new 87 MW solar PV power plant. Other instances reveal Bitcoin miners co-locating with existing renewable energy infrastructure to secure access to low-cost electricity.[18] It is worth recognizing that higher and more stable demand for renewable electricity may support its expansion by driving down production costs via economies of scale. Consequently, Bitcoin mining may serve as a catalyst for investment in renewable infrastructure. However, some critics argue that if cryptocurrency mining increasingly relies on renewable energy sources, it may compete with other uses, potentially jeopardizing national decarbonization targets.[19] While this argument has merit, it overlooks the possibility that additional demand could increase supply by making investments in new renewable energy infrastructure more economically viable.[20]

Another argument of Bitcoin proponents concerns the utilization of heat generated by Bitcoin mining operations.[21] Bitcoin miners may have a financial incentive to capture and reutilize the waste heat, thereby reducing energy consumption elsewhere. Suggested co-locations encompass numerous applications, including greenhouses, residential buildings, water systems, swimming pools, food and wood drying, and alcohol distilleries.[22] It is important to note that the practical implementation of waste heat utilization from Bitcoin mining facilities appears to be limited to pilot projects thus far.

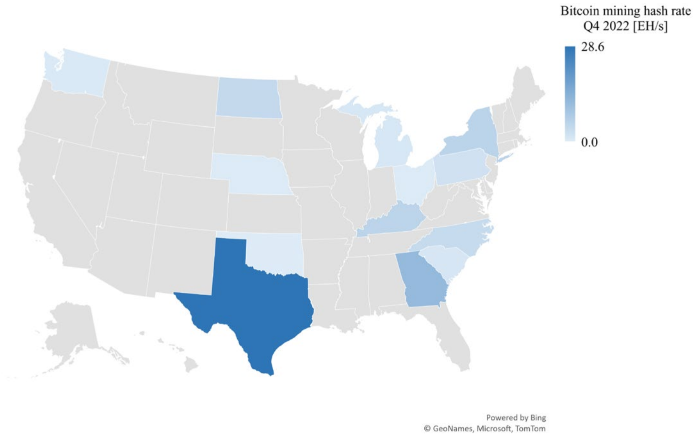
Climate costs of Bitcoin mining

Since its inception in 2008, Bitcoin's global mining footprint has increased and changed significantly. Studies estimate that two-thirds of the network was located in Asia as of 2018[3], before miners relocated to Kazakhstan and the U.S. after the Chinese mining ban in June 2021[2], with the trend of miners flocking to the U.S. continuing. According to a report from the White House Office of Science and Technology Policy, the U.S. hashrate share rose from 3.5% in 2020 to 38% in August 2022, accounting for 0.9% to 1.7% of the total electricity usage in the U.S. – comparable to all residential lighting combined.[23]

To provide additional insights into the current U.S. mining footprint, we assess the company filings of listed miners. In recent years, several Bitcoin mining companies went public, resulting in disclosure obligations for companies in an industry historically reticent about sharing information. We identify 19 publicly listed mining companies (see Supplementary Data) and analyze data from the 13 mining companies with operations in the U.S. that account for one-fourth of the total network hashrate as of the end of 2022 (see Supplementary Data).

Using the grid average emission factors, we find that the carbon intensity of electricity consumed by the 13 miners included in our analysis of 397 gCO2/kWh is nearly equivalent to the U.S. grid average of 387 gCO2/kWh.[24] Furthermore, we find that the annual emissions of 7.2 MtCO2 caused by the 13 analyzed publicly listed miners in the U.S. alone surpass the carbon emissions of the State of Vermont.

U.S. Bitcoin mining hash rate distribution



State	Number of mining facilities	Hash rate Q4 2022 [EH/s]
Texas	17	28.6
Georgia	6	11.9
New York	5	5.7
Kentucky	1	5.6
North Dakota	3	4.2
North Carolina	1	3.9
Pennsylvania	3	2.3
South Carolina	1	1.2
Michigan	1	1.1
Washington	1	0.6
Nebraska	1	0.3
Ohio	1	0.3
Oklahoma	1	0.0
Total	**42**	**65.5**

	Computing power		Power load		Carbon intensity/emissions	
Bitcoin miner	**Q4 2022* [EH/s]**	**Expansion plans [EH/s]**	**Q4 2022* [MW]**	**Expansion plans [MW]**	**Grid emission factor [gCO2/kWh]**	**Total emissions [ktCO2]**
Core Scientific	22.5	31.0	606	1,000	494	**2,620**
Riot	9.7	12.5	300	387	388	**1,021**
Marathon	7.0	23.0	245	805	416	**893**
Cipher Mining	5.2	8.2	173	267	388	**589**
CleanSpark	6.2	16.0	198	510	309	**535**
New Hut	3.1	-	135	-	365	**432**
Stronghold	2.3	3.0	105	138	330	**304**
Argo Blockchain	2.4	4.1	82	140	388	**279**
Greenidge	2.4	-	76	-	232	**154**
BitNile	1.1	2.7	36	91	455	**144**
Bit Digital	1.2	-	40	-	328	**116**
TeraWulf	1.9	5.5	50	150	207	**90**
Bitfarms	0.6	-	20	-	92	**16**
Total	**65.5**	**106.0**	**2,067**	**3,487**	**397**	**7,194**

*Or latest available data

Figure 2 | Locations of mining facilities and carbon emissions of mining operations of publicly listed mining companies in the U.S. (for data sources, see Supplementary Data).

At the same time, the Bitcoin mining industry claims that the average carbon intensity of the applied electricity mix lies considerably below the grid average. For instance, the Bitcoin Mining Council states that 58.9% of the electricity comes from sustainable energy sources. Assuming the remainder relies on fossil fuel sources in line with the current shares of gas, coal, and oil in the U.S., this would lead to a carbon intensity of 272 gCO2/kWh, almost one-third below the U.S. grid average. However, the claims are solely survey-based and lack information to verify the credibility of renewable energy use claims.

For the Bitcoin mining industry to substantiate climate benefit claims, it is therefore essential to understand how established carbon accounting rules function. The GHG Protocol, the most widely used carbon accounting standard, offers two complementary approaches to account for emissions from purchased electricity, warranting their concurrent use in what is known as ‘dual reporting’.[25] First, the location-based approach requires companies to report emissions associated with the delivered electricity. In most instances, this corresponds to the average emissions intensity of the local grid, as the approach only considers direct deliveries of electricity generated from renewable sources. Second, the market-based approach requires companies to report emissions associated with the purchased electricity, reflecting contractual instruments, such as power purchase agreements, supplier-specific contracts, or energy attribute certificates.

The market-based approach allows Bitcoin miners to verify their renewable energy usage claims, but they must obey report criteria to make credible claims. Global initiatives, such as RE100, provide guidance based on the GHG Protocol to standardize the definition of renewable electricity sources and require that reporting companies possess attribute certificates of renewable electricity. The same applies to self-generated electricity and direct-line connections to avoid somebody already accounts for the attribute certificates.[26] As the Bitcoin mining industry matures, we expect to see better data quality on credible renewable energy usage which would allow researchers and regulators to go beyond using grid averages to assess the climate cost of Bitcoin mining.

State of the regulatory debate

Regulation has the potential to shape a more comprehensive understanding of the environmental consequences associated with Bitcoin mining. Although mandatory disclosure obligations for publicly listed Bitcoin miners provide valuable information regarding operational scale and geographical distribution, crucial details, such as the energy mix, often remain inadequately disclosed. Introducing additional environmental disclosure requirements and extending specific transparency measures to large-scale private miners could further enhance transparency concerning climate costs. However, it is essential to pay closer attention to potential climate benefits as well. The current debate frequently attributes a negative connotation to energy consumption per se, while there might be instances where this is not warranted. Nonetheless, it remains crucial to exercise caution and rigorously examine the efficacy of potential climate benefits to avoid greenwashing.

Given its growth and direct impacts on local communities, Bitcoin mining is already subject to regulatory considerations in the U.S. at both the federal and state levels. In September 2022, a White House report highlighted the need for increased transparency[23], and the Crypto-Asset Environmental Transparency Act of 2022 provided further direction on how to assess the impact of crypto mining in the U.S. The latter bill suggests that the Environmental Protection Agency (EPA) should require crypto miners with over five megawatts of rated power to report their greenhouse gas emissions.[27] The call for the Crypto-Asset Environmental Transparency Act was renewed in March 2023 by Senator Edward Markey and Representative Jared Huffman.[28] Additionally, the EPA itself is considering imposing reporting rules on crypto-mining facilities to assess their environmental impact.[29] Most recently, the fiscal year 2024 budget proposal of President Biden targets to introduce a 30% tax on electricity costs associated with their operations.[30] On a state level, Bitcoin mining regulations vary greatly. Some states, such as Rhode Island, Kentucky, Iowa, Montana, and Wyoming, and Pennsylvania, encourage mining activities, for instance, through tax breaks.[31] In Montana, blockchain-based coins are exempt from security laws. In Wyoming, digital currency developers, sellers, and exchanges benefit from exemption from certain securities and money transmission laws, and Pennsylvania offers tax benefits worth $4 per tonne to waste-coal generators[32], with the generated electricity, among others, being used to mine cryptocurrencies.[33]

In contrast, New York State was the first state to ban crypto mining with a two-year moratorium on new fossil fuel-powered projects.[34] In Texas, large-scale power users need clearance from the grid operator, and ERCOT announced the creation of a task force to evaluate the impact of large consumers in greater detail.[35] Further Bitcoin mining hotspots such as Oregon and Washington are also considering mining regulation in the future.[36]

The Bitcoin mining industry will also be impacted by rules currently being developed by financial regulators such as the U.S. Securities and Exchange Commission (SEC) and the Federal Reserve System (FED). The SEC is set to release carbon accounting and climate risk disclosure rules in April, which will likely entail carbon disclosure rules for publicly listed miners, and the FED is working on rules to ensure that banks participating in crypto-related endeavors have risk controls in place, including climate-related risk controls.

Conclusions

Our Perspective provides empirical evidence that at least 38% of all Bitcoin mining activity has migrated to the U.S. and Canada as of the end of 2022. Furthermore, based on data from publicly listed mining companies, we show that the carbon intensity of electricity consumed by publicly listed Bitcoin mining companies of 397 gCO2/kWh is on par with the U.S. grid average. The total carbon emissions caused by the 13 analyzed publicly listed miners in the U.S. alone add up to 7.2 $MtCO_2$ per annum and surpass the annual carbon emissions of the State of Vermont.

The growing transparency on locations and energy sources of large publicly listed Bitcoin miners, which account for one-fourth of the total hashrate, highlights the value of disclosure obligations and may help dismantle unsupported industry claims, improve assumption-based academic models, and point regulators to areas where Bitcoin mining may bring climate co-benefits. Financial incentives of the Bitcoin network may, for instance, subsidize the sealing of orphaned and unplugged wells, and thereby, reduce methane emissions at scale.

The data disclosed by publicly listed miners – and potential future industry-wide disclosure – may help to improve existing mining maps.[37] Our results for the U.S. suggest that, for instance, the previously estimated share of total Bitcoin mining activities in Texas of slightly more than 4% (December 2021) has increased to over 15% (December 2022). Furthermore, U.S. and Canadian share has likely increased significantly beyond the 44% previously assumed.

If the Bitcoin mining industry wants to substantiate climate benefit claims, it must understand how established carbon accounting rules function and report in line with common standards. In the past, Bitcoin advocacy groups failed to provide evidence to substantiate renewable energy claims, making it difficult to go beyond applying grid averages when assessing the climate costs of Bitcoin mining. However, as the industry matures, we expect to see increased reporting quality entailing credible renewable energy claims which would allow for even more detailed analyses.

Given the expected growth of the Bitcoin mining industry in the U.S., more transparency is crucial to quantify climate benefits and costs. Crypto miners have applied to connect to Texas's power grid up to 33 GW, equal to almost a quarter of the current total ERCOT operational capacity.[38,39] EU regulators have demonstrated proactivity and are ahead in demanding increased transparency through additional ESG disclosure rules in the forthcoming Markets in Crypto-assets (MiCA) framework. Furthermore, carbon disclosure obligations under the Corporate Sustainability Reporting Directive (CSRD) in the EU, or the upcoming SEC rules will also apply at least to publicly listed miners. We argue that transparency is the vital first step to educate Bitcoin users, and inform the public, regulators and policymakers about the climate-related benefits and costs associated with Bitcoin mining.

Declaration of interests

U.G., L.K., and C.S. are co-founders of CCRI GmbH which provides sustainability metrics for digital assets.

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