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An Analysis of the United Nations University's Bitcoin Mining Commentary

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Executive Summary

The recent study by Chamanara et al. (2023) on the energy usage of bitcoin mining represents a troubling trend for academic papers investigating the topic. Many researchers operate in isolation, disregarding established research and best practices from both data center and blockchain literature.

The Chamanara et al. study falls short of the scientific thoroughness expected in research, rendering it unsuitable as a basis for policymaking. The Chamanara et al. study is based on historical trends which are not reliable predictors of future energy consumption in the rapidly evolving computing industry. This oversight was overlooked by both the authors and the peer reviewers at AGU's Earth's Future.

Three major flaws in the paper call into question its validity for policy guidance:

1. **Selective Bias:** The study's literature review is based on sources that have been discredited and fails to consider newer research showcasing bitcoin mining's potential to support grid reliability and advance the shift to renewable energy.

2. **Data Misapplication:** The authors project past data onto future trends without yearly updates or recognition of discontinued data sources like the CBECI.

3. **Flawed Methodologies:** Methodologies used are inappropriate for demand-side analysis, leading to unfounded assertions about bitcoin mining's impact on developing economies and social justice.

Despite these flaws, Chamanara et al. draw the unsubstantiated conclusion that bitcoin mining harms developing economies and exacerbates social and economic injustice. The authors then recommend policy action against the bitcoin mining industry and a switch on Bitcoin's part from proof-of-work to proof-of-stake to ameliorate the environmental impact of its electricity use.

These findings and recommendations are poorly evidenced and demonstrate significant gaps in the authors' knowledge of bitcoin mining. Policymakers should seek out insights from the renewable energy sector, the bitcoin mining community, and researchers to cultivate research that is both transparent and collaborative. Sound policy can only stem from robust data and cross-sector cooperation.

About the Bitcoin Policy Institute

The Bitcoin Policy Institute is a non-partisan, non-profit think tank researching the impacts of Bitcoin and other emerging monetary networks. Established as a 501(c)3, BPI provides educational resources to policymakers while empowering more than a dozen Fellows from across the country to conduct original academic research on cryptocurrency and technology policy issues.

About the Author

Margot Paez is a Ph. D candidate in the civil engineering department at Georgia Institute of Technology. She has a Master Science in Physics from GT and studies climate change related topics including the energy and environmental impact of cryptocurrency data centers. Her previous research includes robotics and physics of living systems, astrobiology instrumentation, and web-based data management systems.

Introduction

> *"We must confess that our adversaries have a marked advantage over us in the discussion. In very few words they can announce a half-truth; and in order to demonstrate that it is incomplete, we are obliged to have recourse to long and dry dissertations."* – Frédéric Bastiat, *Economic Sophisms, First Series* (1845)

Chamanara et al. made many unsubstantiated claims about the bitcoin mining industry, including misrepresentative comparisons, errors regarding the total market capitalization of the cryptocurrency industry (it's about twice as much as what they claimed) and an incorrect claim that bitcoin was a major shareholder of the total market cap for the cryptocurrency market.[1] This report, however, will focus on the three most flagrant scientific flaws of the recent *Earth's Future* commentary:

1. **The authors' selective bias concerning references from existing bitcoin mining peer-reviewed literature promotes a dubious narrative.**

The authors framed the broader research scope through the repudiated work of Digiconomist / Alex de Vries and the Mora et al. (2018) paper. Mora et al. and Digiconomist / Alex de Vries' methodologies were criticized in Lei et al. (2021) and Sai and Vranken (2023). Mora et al. received additional repudiation from Huoy (2019), Masanet et al. (2019) and Dittmar (2019). The authors ignored a recent avalanche of peer-reviewed studies that show bitcoin mining's potential use cases for grid reliability, and for accelerating the energy transition away from fossil fuels, both as a revenue source for renewable energy producers and as a method for methane mitigation.

2. **The authors' research design presents an oversimplified and limited representation of the network's energy use over time, overlooks geographic distribution changes since 2021, and likely overestimates emissions use.**

Chamanara et al. conflate past data with both the present and future. The authors used a limited dataset that covered 2020-2021 to make claims about 2022 and 2023 energy use and

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[1] The authors quoted an online news outlet called The Bankless Times as a source that there exists 1 million miners in the world. Aside from the inappropriateness of using a low reputation news outlet as a source in a peer-reviewed commentary, the authors did not differentiate between individual mining machines and facilities, an important contextualizing fact. The authors also claimed that bitcoin was a "shareholder" in the cryptocurrency market. Bitcoin is a decentralized monetary network and has no CEO, no company, and certainly no shareholders. In addition, Chamanara et al believes that increased revenue above cost to mine leads to significant growth in electricity consumption without a citation to the extant literature to assert this claim. Both CBECI (2023) and Kristofek et al (2020) challenge this claim due to additional limitations such as available generation, machines, facilities, machine efficiency, and block reward. While it is true that energy use can and likely will increase, the reasons are not only or always a result of increased revenue over cost. Lastly, the authors use electricity use for various households and regions as familiar representations of the energy required to secure the bitcoin network. However, stating that the electricity used could power millions of households around the world belies the reality that electricity is temporally and spatially trapped at the point of generation. The cheap power used in Texas and Georgia, where a significant percentage of network hashrate is located, could not be transported to power homes in Africa, for example. Bitcoin miners need cheap electricity to remain competitive (Meynkhard, 2019, Krisotfek et al., 2020, Delgado-Mohatar et al, 2019). The cheaper the power, the more likely it is that its excess electricity is stranded in a particular region of the world.

environmental footprint for bitcoin mining. The authors used the Cambridge Bitcoin Energy Consumption Index (CBECI) data but failed to note that Cambridge stopped updating their mining map data in January 2022. In our analysis, we found that our results did not match the authors' but were similar. Our investigation shows that the authors should have applied a separate analysis to each year included in their study and that they should not have used their results to make statements about the current energy mix or environmental footprint of the network, given CBECI's limited data.

3. **The authors' use of Obringer et al. (2020)'s environmental footprint is not well aligned with Ristic et al. (2019)–which both Chamanara et al. and Obringer et al. cite as the methodological foundation for their studies–and produces unrealistic results and policy recommendations that would undermine environmental impact reduction efforts.**

The authors stated that they were following the methodology developed by Ristic et al. (2019) and in particular, Obringer et al. (2020). We reviewed both papers and found that the authors were ill-advised in applying environmental factors that were designed for evaluating supply-side energy producers, to demand-side energy consumers. There is incredible value to developing metrics for comparing different energy generators but when applying these factors as an individual or industrial environmental footprint, we found that the results lead to physically impossible results. We found this to be true with Obringer et al.'s analysis of changes in Internet use during COVID-19 lockdowns and also with Chamanara et al.'s application to bitcoin mining.

Flaw 1: Selective Bias in Citations Undermines Study's Credibility

Mora et al. (2019) and Digiconomist: Overly Simplified, Unreliable, and Unrealistic

Researchers must engage with past research to find an opening for meaningful contributions. In this case, Chemanara et al. introduced limited existing literature to show the relevance of their study. The authors frame bitcoin's environmental impact around two primary sources: Digiconomist, 2021 and Mora et al., 2018. These two papers are, in particular, notoriously replete with methodological issues. Both have been thoroughly criticized in the literature.

Digiconomist provides one of at least 20 energy models published in non-academic and academic sources (Lei et al, 2021). Despite abundant criticisms for being overly simplistic and top-down in its approach (Koomey, 2018; Koomey, 2019), this particular model is one of the most cited estimates of bitcoin mining's energy use in academic literature, public policy, and commercial news articles. Koomey criticized the model's lack of transparency over averaging across periods of bitcoin's price, assumptions about economic parameters and bitcoin mining behavior, and oversimplified approach. He concluded that Digiconomist's model is not a reliable indicator of bitcoin's electricity use or its trends over time. In Lei et al., Digiconomist's methodology failed to fully meet any of the 10 best practices for modeling bitcoin's electricity consumption and completely failed 40% of the best practices.

The authors' second primary source, Mora et al., is similarly popular and error-ridden. Mora et al. claimed that bitcoin mining alone would lead to a 2-degree increase in global warming within three decades. Within a year of the paper's publication, the authors received three Matters Arising in Nature Climate Change.

These three papers repudiated the findings and pointed out major flaws in the authors' methodology. Houy 2019, criticized the unrealistic inclusion of unprofitable miners and noted that rational miners would have turned off their machines when it was not profitable to do so, which acts as a major constraint on emissions. They estimated that if bitcoin miners had behaved as assumed by Mora et al., miners would have lost at least 3 billion dollars USD in revenue in 2017 and that emissions were overestimated by a factor of 4.5. Profit losses of this scale would have wiped out the industry. Glassnode reported an average revenue of 10 million dollars USD or about 3.65 billion dollars USD for 2017.

Masanet et al., 2019, criticized Mora et al.'s energy per transaction metric and noted that the authors undermined their initial methodology when they switched from using block difficulty to the number of transactions in their future emissions projections. They also noted that the scenarios diverge significantly from historical trends in bitcoin transactions and that the basis for these extreme diversions was not justified in the paper. Additionally, they noted that efficiencies were underestimated, leading to an overestimate in energy consumption. They noted that Mora et al. held mining efficiencies and CO2 grid intensities constant over the next 100 years and committed errors in their analysis of adoption rates. Masanet et al. concluded that the study design was sufficiently unsound that even the corrections in the analysis would not be enough to salvage the study's approach. Very clearly, they stated that the public, researchers, and policymakers should not take this study seriously. Masanet et al.'s co-authors, Eric Masanet, Jonathan Koomey, and Arman Shehabi have spent decades working on improving energy modeling for the computing sector. They have published numerous papers on best practices for data center energy modeling and have worked with the United States government and national labs on forecasting of energy requirements.

In the final Matters Arising, Dittmar et al. 2019 noted the implausibility of the findings because they would require a tripling of global electricity generation within five years of the study's publication. They noted that hardware energy intensity and electricity consumption estimates were ten times higher than other estimates. Dittmar et al. also criticized the transactions approach and stated that Mora et al. ignored constraints on bitcoin's transaction processing due to limited block size and block spacing. The authors correctly note that transaction rate is not correlated with electricity use.

In a recent pre-proof, Sai and Vranken (2023), warn that current bitcoin mining energy studies lack the scientific rigor that would otherwise be expected from a mature scientific field. They lament that many researchers are working in silos and not building on previous work. This lamentation is certainly exemplified in the Chamanara et al. paper.

Finally, Chamanara et al. claimed that financial and technological motivations have suppressed the conversation around the environmental cost of the bitcoin network. However, innumerable popular news articles have centered on the environmental cost of bitcoin mining. In 2022, the White House published a study that included a review of bitcoin's environmental impact. The academic literature includes at least 21 models of bitcoin's electricity consumption, and Sapra et al. (2023) identified 60 peer-reviewed articles that addressed bitcoin's impact on the environment.

Overlooked Positive Environmental Bitcoin Mining Literature

Chamanara et al. also overlooked extant literature suggesting bitcoin mining could be a benefit to electric grid reliability and the renewable energy transition. Kristoufek, 2020 noted that the network protocol drives bitcoin mining toward the cheapest sources of electricity and that over time, renewable energy sources will become an essential part of the network's electricity mix for maintaining miner revenue as competition increases. They noted that a renewable energy system could be more stable if there exists a constant buyer of excess power.

Bastian-Pinto et al., 2021, modeled the use of wind generators with bitcoin mining to reduce investment risk from electricity spot-price volatility. They concluded that bitcoin mining could be a hedge against this risk. Other studies, such as Shan et al., 2019 and Eid, et al., 2021, found that bitcoin miners could be off-takers of curtailed solar power generation and that 50.8-79.9% of curtailed solar in CAISO could be captured and produce 5.6-48.1 million dollars in additional revenue for solar electricity providers. Eid et al. modeled the use of bitcoin mining and batteries in a renewable energy system with a solar power generator. Their results suggested that this hybrid approach could improve revenue.

Menati et al 2023a, 2023b, 2023c, and Helou et al. 2023, have produced a foundational and exhaustive look at the effect of bitcoin mining on grid reliability using Texas' ERCOT as a case study. They found that under certain conditions, bitcoin miners could provide stability to the grid, that they outperformed all other loads when it came to frequency regulation, and that emissions from bitcoin mining could be reduced if they were located in regions with low locational marginal pricing.

Fridgen et al. 2021 compared the revenue for a standalone renewable energy generator, a standalone AWS data center, and a standalone bitcoin mining operation. Then they compared these results to a renewable energy system that coupled the renewable generator with one of either type of data center. They found that coupling a renewable energy source with a data center like bitcoin mining could be more profitable than either option operating independently, which they suggest could increase the build-out of more renewable energy sources and that this kind of system could also improve grid reliability more broadly.

In Hallinan et al. (2023), the authors investigated a novel approach to globally improving equitable investment in solar micro-and mini-grids. Applying their economic model to six global case studies, they found that including bitcoin mining operations in these types of grids could improve their investment worthiness. They noted that while this was the case, there were also caveats and risks associated with the volatility of bitcoin's price on the mining reward. However, they found that including mining could significantly reduce the power rates of the microgrid and increase low-cost power after investment payback. Interestingly, in their scenarios they considered a point at which ownership of the grids would be returned to the users, increasing community benefits.

The authors found that once the loan was paid back, the community would have access to more than two times the power that a normal micro-grid could offer. This would also result in increased economic development in these otherwise underserved communities. Not every case study led to improvement investment, however. Additionally, Murphy, 2001, and Zerriffi et al. 2010 both highlight the importance of centering climate mitigation in energy poverty regions not just around technological adoption or absorption for the sake of mitigation, but to also improve rural people's quality of life.

Finally, Ibanez and Freier 2023 provide the most comprehensive review of bitcoin's potential for renewable energy expansion. It is worth noting that while there are limitations, the potential for decarbonization using bitcoin mining is a significant and consequential area of investigation. They conclude that this is one of the most important future research directions for bitcoin mining studies.

While this is not a comprehensive review of extant research in the area of bitcoin mining energy and environmental studies, it does highlight the vast body of work that Chamanara et al. ignored in their literature review. When addressing the environmental impact of bitcoin mining, it is necessary to highlight the full body of research so far. Unfortunately, the authors did not do this and the motivation for their study lacks substantial support.

Flaw 2: Oversimplified Energy Data Lead to Emissions Overestimation

Evaluating CBECI's Hybrid Model and Its Implications on Energy Consumption Estimates

Chamanara et al. use the Cambridge Center for Alternative Finance's (CCAF) Bitcoin Energy Consumption Index (CBECI) as their primary source for bitcoin energy consumption data. CBECI provides a hybrid modeling approach to estimating bitcoin mining's energy consumption. The model is hybrid because it is a compromise between top-down and bottom-up model construction (Lei et al. 2021). Top-down models tend to make simple assumptions about the network which often lead to overestimation of energy requirements. Bottom-up models rely on data collected from the industry about the required IT devices, the PUE of the facilities, and about efficiency trends for the devices. Bottom-up approaches are preferred over top-down because they give better results. However, bottom-up is very challenging to achieve because of the amount of work it takes to collect data. CBECI's hybrid approach is an attempt to minimize the errors from some of their top-down assumptions using limited data collection on mining machine efficiency. The network's mining computers are distributed around the world, which makes data collection challenging. The CBECI relies heavily on data collected from mining pools to estimate energy use, emissions, geographic distribution, and share of the network's hashrate. Their mining pool sample represents, on average, 34.8% of the total network hashrate.

The hashrate is a unit of measure that represents the number of hash functions that the combined computing power can compute every second (H/s). While CBECI's model covers a significant portion of the network hashrate (an average of 34.8%), it is unclear how representative their sample is of the entire network without a comprehensive statistical analysis, which is out of the scope of this report. However, we point this out to highlight one limitation of the CBECI model's assumptions. Still, CBECI is considered the best and most reliable bitcoin energy consumption model available today (Lei et al. 2021, Sai and Vranken, 2023).

To calculate the three environmental footprints: i) carbon, ii) water, and iii) land, the authors used the total monthly energy consumption for the global bitcoin mining network and the average monthly hashrate share for each country they analyzed in their study. These data can be downloaded directly from the CBECI website. The first can be found under the main CBECI index, the second can be found in the Mining Map section under Visualisation.

We contacted the corresponding author requesting access to their calculations and data but as of publication, received no response. As a result, we were forced to validate their methods using data requested from CCAF. The Center generously provided an older version of the model's data from before their major update to their mining efficiency table in August 2023. This was important because the August 2023 update significantly reduced the network's energy consumption due to the increased energy efficiency of bitcoin mining machines. Chamanara et al. submitted their paper for review before this update.

To calibrate and validate our approach, we used the most updated data from CBECI's website, which we downloaded on November 1, 2023. We calculated both the total monthly and total yearly energy consumption numbers from January 1, 2020, through December 31, 2021, using these data. We also verified that when summing all monthly energy consumption values for each country in the data, the sum equaled the total global energy consumption that was calculated from CBECI daily power consumption estimates.

To the best of our understanding, the authors used the following equation to calculate the monthly energy consumption share for an individual country:

$$annual\ energy\ consumption_i \ = hashrate\ share_{ij}\ x\ total\ energy\ consumption_j \quad (1)$$

$$Where\ i \in \{Mainland\ China, Russian\ Federation, \ldots\}\ and\ j \in \{January, February, March, \ldots, December\}$$

In other words, Mainland China's annual energy consumption would equal the sum of every month's country's hashrate share multiplied by the bitcoin mining network's total energy consumption for each corresponding month.

Once a country's estimated energy consumption is found, the remaining steps to calculate the carbon, water, and land footprints are fairly trivial, since it's a matter of multiplying the energy consumption by the footprint factor (after proper unit conversion to match energy units) which are given in terms of mass of emissions per unit of energy, volume of water per unit of energy, and area of land per unit of energy. However, there are some extremely non-trivial considerations for determining the appropriate footprint factors. We will address these considerations later in this report.

If we understand Chamanara et al.'s approach correctly, then we conclude that this is a reasonable approach–within the context of the limitations imposed by CBECI's model assumptions–for estimating the energy consumption for each country that is observed in CBECI's mining map. Although, there is an obvious limitation to this approach that was not addressed in the original study.

The hashrate is well correlated with energy use, but energy consumption also depends on mining efficiency. The authors assumed that every country has bitcoin mining machines that represent the average profitable machine efficiency of the network. We do not have any insight into whether one country would host more efficient mining facilities than another country, so for this kind of study, making this compromise is necessary. However, the authors failed to address this model limitation, and some mining operations will likely be more efficient than others. For example, Masanet et al. (2020), noted that hyperscale data centers were more energy efficient than traditional data centers. We suspect that the size and scale of a mining operation will also have some correlation with efficiency, too. More research is needed to determine this relationship for the bitcoin mining industry.

Electricity Consumption Results Do Not Match Chamanara et al.

Now that we have established the methods for determining energy consumption for each country listed in the Chamanara et al. study, we can compare our results to theirs and explore in greater detail the problems with their study's design.

Country	2020 Energy Consumption (TWh)	2021 Energy Consumption (TWh)	2020 + 2021 Energy Consumption (TWh)	Chamanara et al.'s 2020 + 2021 Energy Consumption (TWh)	Percent Change Between 2020 + 2021 Calculations (%)
Mainland China	44.45	32.89	77.34	73.48	5.25
United States	4.65	25.20	29.85	32.89	-9.24
Kazakhstan	3.18	12.06	15.24	15.94	-4.39
Russia	4.71	7.59	12.29	12.28	0.081
Malaysia	3.31	4.13	7.44	7.29	2.06
Canada	0.80	5.25	6.05	6.62	-8.61
Iran	2.33	3.06	5.39	5.13	4.82
Germany	0.67	3.31	3.98	4.18	-4.78
Ireland	0.62	2.69	3.31	3.43	-3.50
Singapore[2]	0.31	1.13	1.43	1.56	-0.083
Other (Excluding Singapore)	3.69	6.73	10.42	10.63	-1.98
Total	68.72	104.04	172.76	173.42	-0.38

Table 1. Energy consumption calculated for countries with the greatest share of hashrate. The first three columns used CBECI data that was collected prior to the August 2023 machine efficiency update while the last column is data from Chamanara et al.

In Table 1, we show a breakdown of our calculations for annual energy consumption per country. CBECI's publicly available data only identifies the top 9 countries and groups the remaining countries into a category called, "Other". However, Chamanara et al. included Singapore in their analysis. In their paper's section on data availability, they do not mention requesting the full country list from CCAF, so we assume the data was retrieved using some other method.

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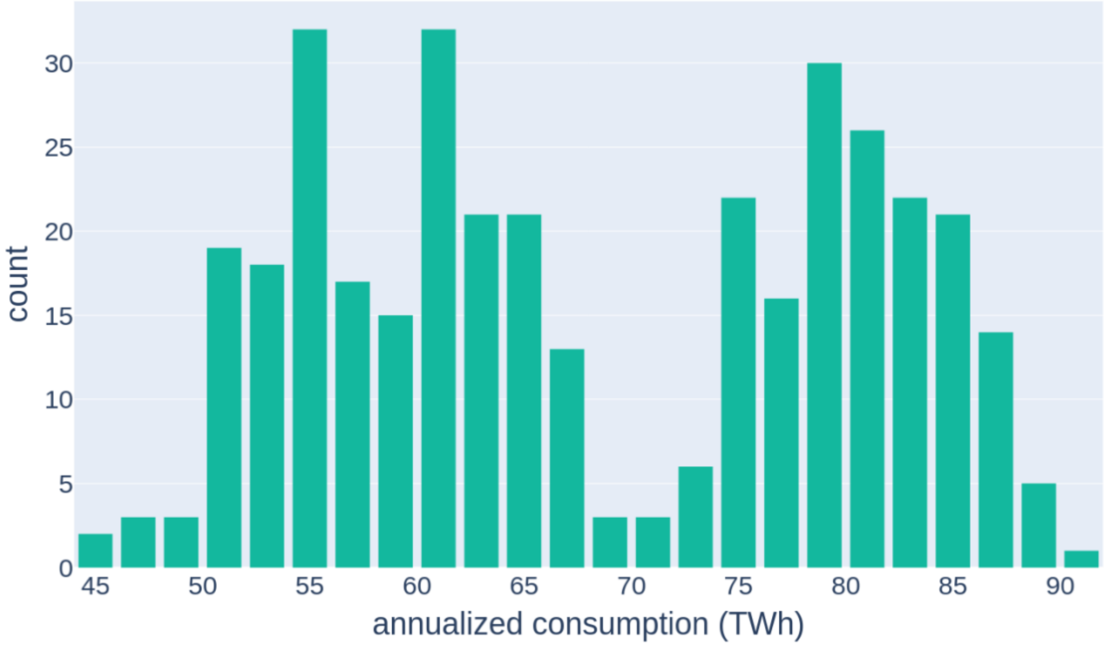
[2] Singapore is not included in the publicly available CBECI mining map data. CCAF generously shared their internal full country set in order for us to be able to make this calculation and comparison. We do not know if Chamanara et al. made the same request, or if they simply scrapped the CBECI website for percent values and computed it directly from the total energy consumption.

Our values for the total energy consumption used across 2020 and 2021 do not align with Chamanara et al.'s though they are similar. Through correspondence with CCAF, we learned that the mining map was last updated in May 2022, which was over a year before the authors' paper was submitted for review. Most significantly, China has a greater share of total energy consumption (+3.86 TWh; 5.25% increase), the United States has a smaller share of total energy consumption (-3.04 TWh; 9.24% decrease), and Canada has a slightly smaller share of total energy consumption but significant percent change relative to Chamanara et al.'s results (60.2 TWh; 8.61% decrease) in our results.

Electricity Consumption in 2020 and 2021 Reveal Different Patterns of Use

The authors provide a two-year total energy consumption, combining 2020 and 2021 into one representative number. As Table 1 shows, from 2020 to 2021, there are clear shifts in energy consumption share among the top 10 countries in the study. We will explore the differences between these two years in the next sections. The data from 2020 and 2021 suggest that two distinct analyses should have been completed rather than one that combined the two years into one.



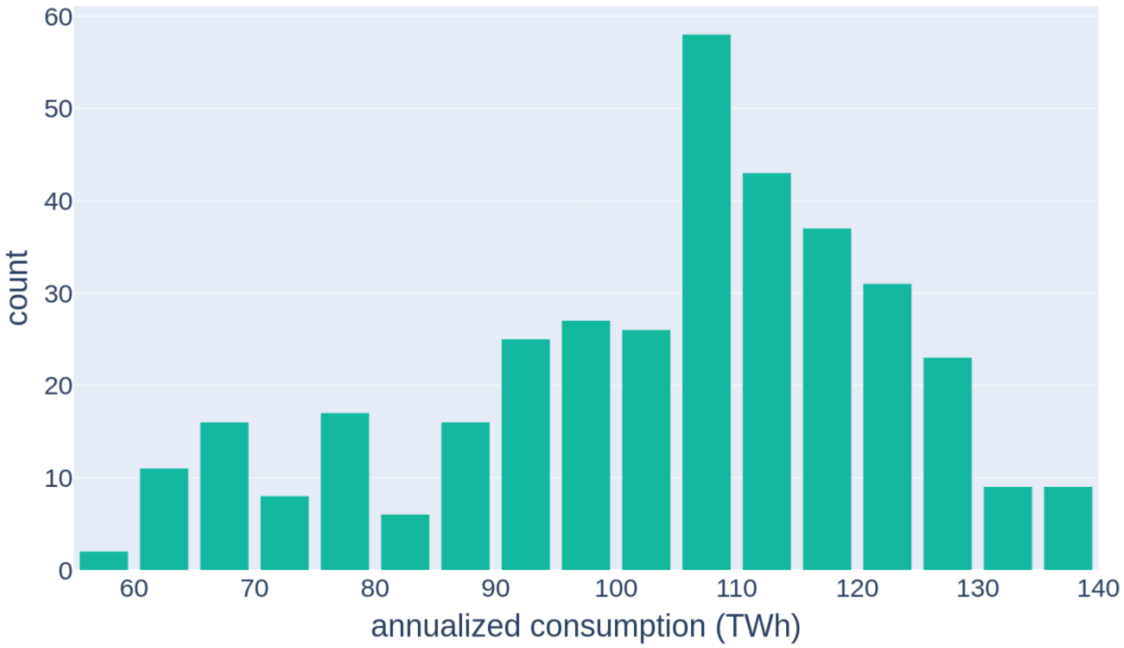


Figure 1. Distributions for CBECI estimated annualized energy consumption (TWh) for 2020 (A) and 2021 (B). The year 2020 shows a bimodal distribution while the year 2021 shows a somewhat negatively skewed distribution with a longer tail of <100 TWh estimated annualized energy consumption values. These data were collected prior to the August 2023 efficiency update and overestimate energy consumption.

CBECI provides estimated annualized energy consumption values which are calculated daily from the estimated daily power demand. These annualized values give us insight into what bitcoin mining's yearly energy consumption would be if a particular day's energy use were held constant for an entire year. Figure 1 shows the distribution of every estimated annualized energy consumption calculated for the years 2020 and 2021 using data collected before the August 2023 efficiency update. From here, we can see that the two years show very different distributions. For the year 2020, there is a clear bimodal distribution while for the year 2021, there is a negatively skewed distribution with a long tail representing a wide range of days where the estimated annualized energy consumption was less than 100 TWh.

In the Chamanara et al. study, the authors remarked that the annual electricity consumption for bitcoin mining exceeded 100 TWh per year. Before the August 2023 efficiency update, CBECI's methodology estimated the total annual consumption for 2021 to be 104 TWh. However, since the update, CBECI estimates the total annual consumption for 2021 at 89 TWh. While it is unfair to hold the authors accountable for not reporting an updated estimate after their paper was submitted to Earth's Future for review, it is important to note that Figure 1 shows a significant number of days where the network did not consume over 100 TWh of power. This is because demand fluctuates depending on several factors like bitcoin's exchange rate, hashrate, block reward, and difficulty adjustment. This also highlights the importance of recognizing and acknowledging the limitations of the model one uses to make energy estimates. Studies like Chamanara et al. ought not inform public policy.

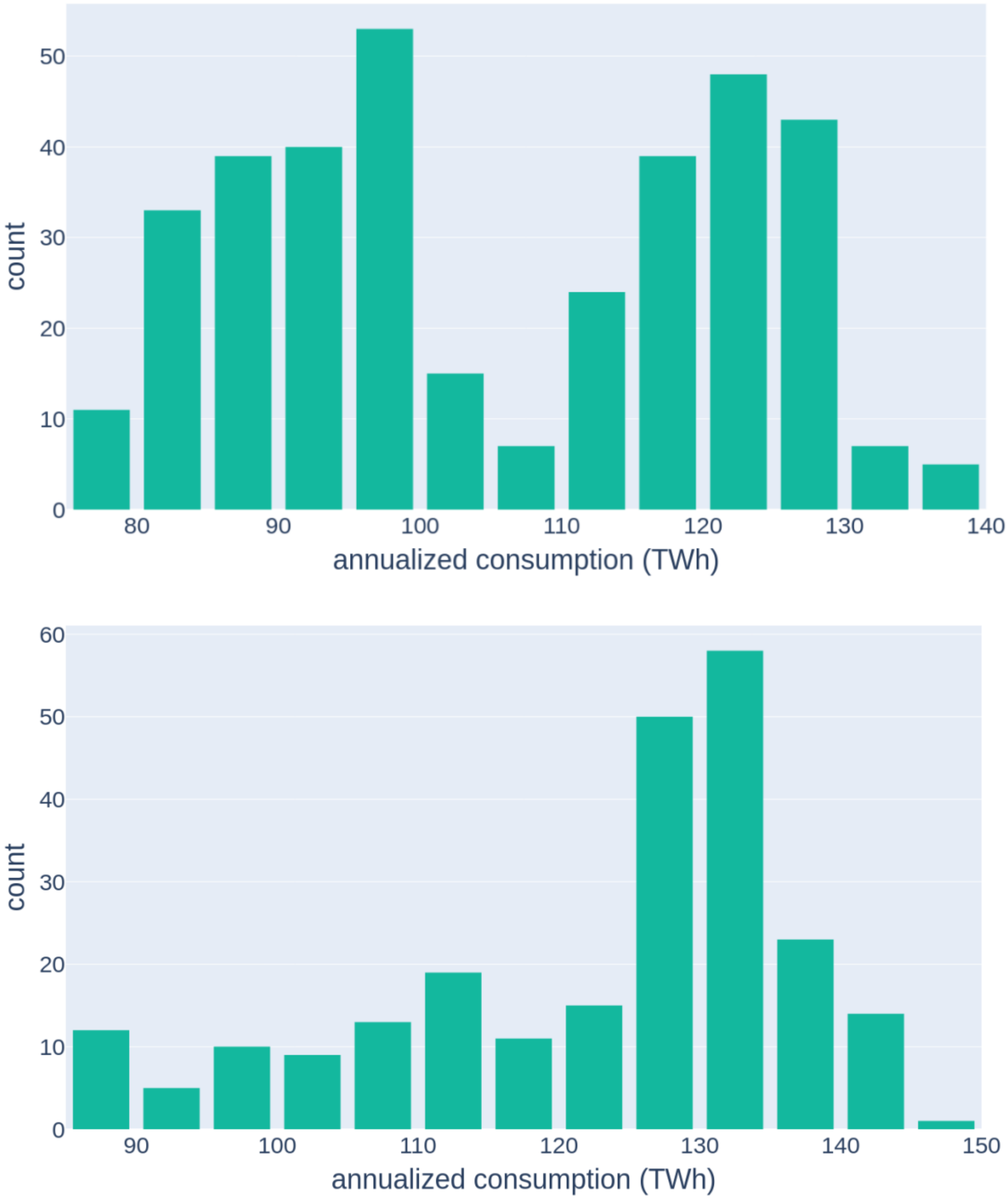


Figure 2. Distributions for CBECI estimated annualized energy consumption (TWh) for 2022 (A) and 2023 (B). The year 2022 shows a bimodal distribution while the year 2023 shows a negatively skewed distribution with a longer tail of <119 TWh estimated annualized energy consumption values. These data were collected prior to the August 2023 efficiency update and overestimate energy consumption and as a result 2023 shows data through August 31 only.

To better understand events that occurred during 2021 in comparison to adjacent years, we should also consider the annualized estimated energy consumption for the year 2022. For the year 2022, we see another bimodal distribution with a significant number of days with energy consumption below 100 TWh. Additionally, we see a significant number of days with an estimated annualized energy consumption above 100 TWh.

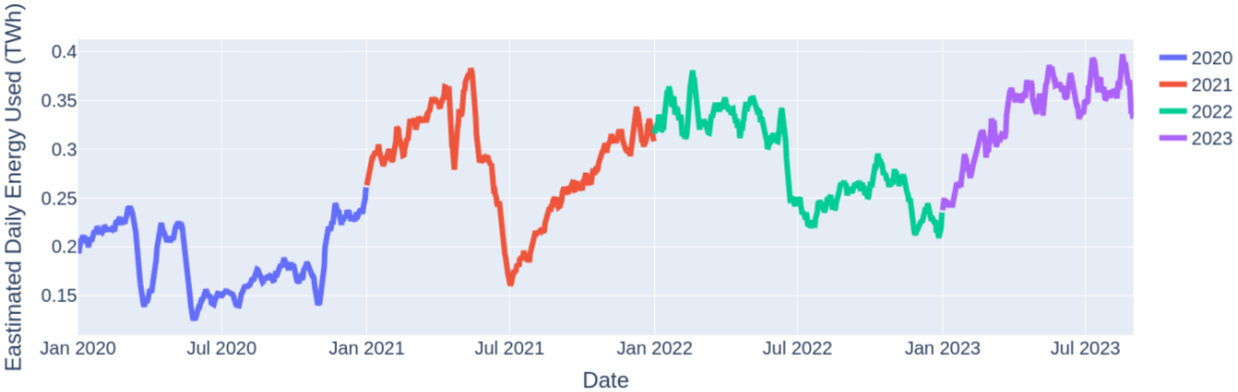


Figure 3. Daily energy consumption estimates from January 2020 through August 31, 2023. The estimates are based on CBECI's older network efficiency model. Since September 1, 2023, CBECI uses a different approach and these energy use estimates are lower under the updated model. Each year has a different color to show how the network's energy use varies from year to year.

While it's difficult to make any broad generalizations based on these figures, it is clear that there is high variability in energy use over time and that bitcoin mining does not draw a constant load like a typical data center. Even though we suspect that load flexibility (the ability to power on and off in response to price or grid operator signals) is fairly common, we do know that some mining operations are more flexible than others. Operations that are on regulated grids or drawing from base loads like a hydroelectric power generator are likely to have constant uptimes like a typical data center. Yet, it appears that overall, the network's energy use is responding to certain influences. Some possible influences on energy use could be bitcoin price, difficulty adjustment, and machine efficiency. More macroscale influences could be as a result of regulation, such as the Chinese bitcoin mining ban that occurred in 2021. We hope to explore this in more detail in future research. However, it is important to note that operations with high variability in energy use over time are generally not suitable for emission studies that use averaged annual emission factors (Miller et al, 2022). Had the authors engaged with existing literature, rather than operating in a silo (Sai and Vranken, 2023), they might have noted this limitation in their study.

An Individual Country's Electricity Consumption Trends

Another interesting observation that can be drawn from the CBECI data and which was overlooked in Chamanara et al.'s study is the effect of the China ban on the hashrate. In the authors' study, their decision to combine 2020 and 2021 into one single calculation gives the appearance that certain countries deserved greater attention in their discussion than others. However, when plotting the share of hashrate for each country over time, we see some interesting trends that suggest that certain countries were left out of the discussion and that others probably did not deserve as much attention. One could argue that these countries did use a significant amount of energy during this period, but the authors were advocating for policy recommendations that reflect the present. They used past behavior, without investigating how this past behavior was trending, to then extrapolate future energy use. This is a dangerous oversimplification and is generally discouraged when doing energy estimates for fast-evolving technologies (Lei et al, 2021). We should also note that relying on these energy trends from 2020 and 2021 is also not sufficient for making future projections about energy use. The best practice from data center energy use modeling is to rely on bottom-up trends of necessary IT devices and energy efficiency. Also, given the volatile political environment for bitcoin mining, we must consider the effects of future legislation that could influence geographic shifts of hashrate. Knowing these caveats, given the data we do have, we are primarily demonstrating that at minimum, Chamanara et al. should have conducted a more detailed, year-to-year, analysis of the CBECI data.

The major focus of the results discussion was centered on these countries: China, Kazakhstan, the United States, and Russia. However, the study included these countries as well as Malaysia, Canada, Germany, Iran, Ireland, and Singapore. Figures 4 through 13 show the percent hashrate share and the absolute hashrate share (EH/s) for each country in the study.

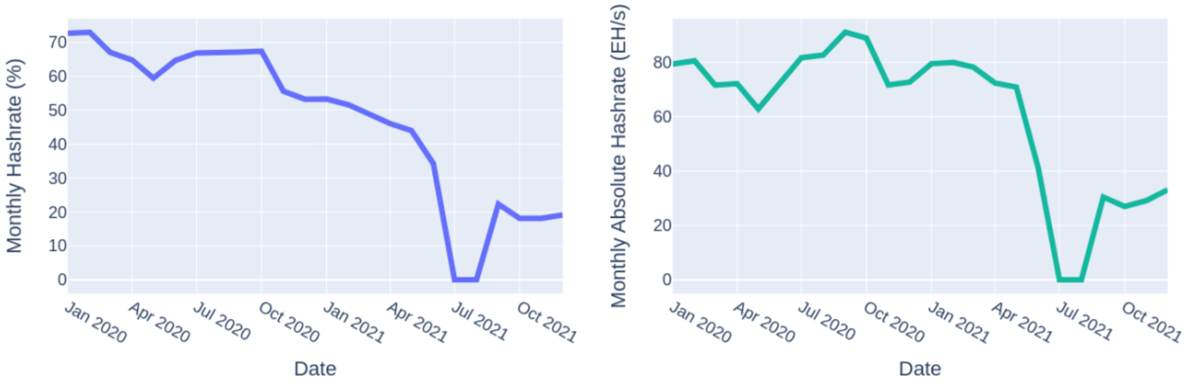


Figure 4. Mainland China's relative monthly hashrate measured as a percentage of total hashrate (blue line) and the same country's absolute hashrate (red line) measured in EH/s show the rapid drop in hashrate and modest recovery from July 2021 through January 2022.

In discussing China's impact on the hashrate share and subsequent impact on bitcoin's environmental footprint, the authors correctly noted that China banned bitcoin mining in mid-2021 and that hashrate moved either out of the country or temporarily onto VPNs. We suspect that it would have been difficult to ignore the presence of these large loads on the grid even with hidden IP addresses unless they were operating off-grid. Using their environmental footprint methodology, they estimate that there were significant reductions in greenhouse gas emissions, water, and land use footprints as a result of hashrate leaving China. This finding contradicts de Vries et al. 2022, which found that emissions increased after the China ban. However, Sai and Vranken 2023 reviewed the de Vries et al. paper and found serious issues with the methodology. As a result, we should not commit to either of these assessments of bitcoin's environmental footprint until the blockchain energy science literature addresses the issues outlined in Sai and Vranken.

Problematically, the authors then use the results from their combined 2020 and 2021 energy use calculations to calculate the network's greenhouse gas emissions but do not clearly state that these results include China as the dominant region for network hashrate until July 2021 (75% of the period studied). The language is as follows:

> *"The reduction of China's BTC mining interest has resulted in a shift in the energy supply mix of BTC mining network… This number was reduced to 46% in 2022, which is associated with 34% reduction in the carbon footprint, 32% decrease in the water footprint, and 25% decrease in the land footprint of the global BTC mining over a year.* ***However, the global BTC mining network is still very dependent on fossil fuels****."* *(Emphasis added.)*

In Figure 3 of the Chamanara et al. paper, they show their results for the network's energy mix, but in the discussion, they write about the percent changes in the amount of natural gas between 2021 and 2022 but do not include 2022 in the results presented in their figures. This goes beyond the described methods and could potentially confuse the reader. The use of the present tense for describing bitcoin's dependence on fossil fuels (the emphasized sentence in the above quote) also suggests that the author's study looked at mining distribution data that goes through 2023. However, the CBECI mining map data goes only through January 2022 and the authors' methods state that they focused on the years 2020 and 2021.

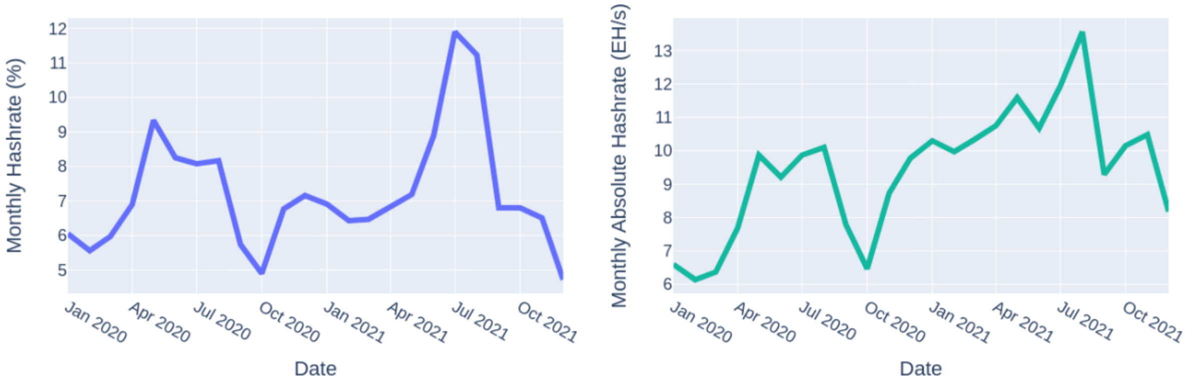


Figure 5. Russia's relative monthly hashrate measured as a percentage of total hashrate (blue line) and the same country's absolute hashrate (red line) measured in EH/s show that while there was a brief spike in relative hashrate after China's hashrate collapsed to zero, the absolute hashrate and relative hashrate show that their share eventually dropped considerably by the January 2022.

The authors also include Russia in their discussion, however as we can see in Figure 5, Russia's hashrate declines significantly in both absolute and percent terms after a brief boost in share at the moment when China's hashrate went to zero (EH/s and %) in CBECI's mining pool data (Figure 1). This could be a signal that at least temporarily, some Chinese miners were using VPNs to hide their IP address. By the end of 2021, Russia's share of hashrate dropped below 5% and also dropped in absolute terms to pre-bull run levels. This result in miner behavior suggests that China's hashrate did not move to Russia, making it a less important player for projecting present-day hashrate and energy use shares when relying solely on the available data from CBECI. News reports on Russia's bitcoin mining industry do not give clear indications of how the hashrate has fared since the end of 2021.

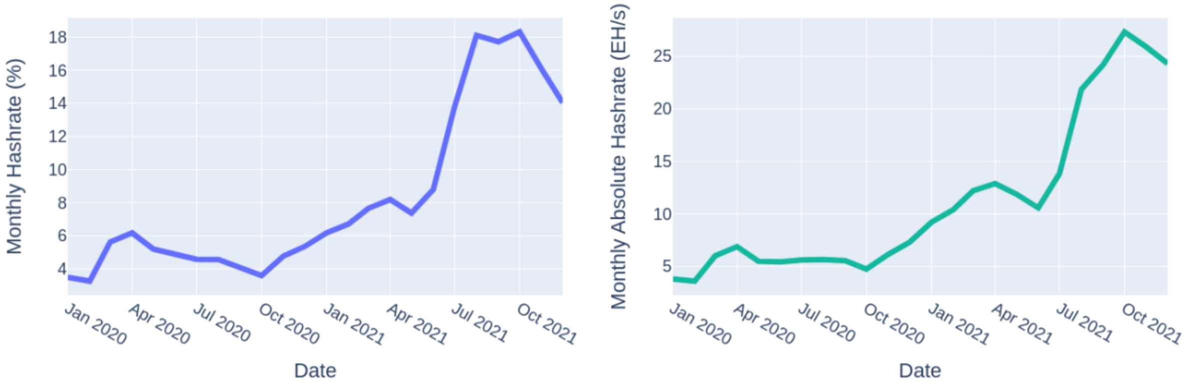


Figure 6. Kazakhstan's relative monthly hashrate measured as a percentage of total hashrate (blue line) and the same country's absolute hashrate (red line) measured in EH/s show the rapid growth in hashrate after China's hashrate collapse and potentially hints at the coming decline of hashrate share in the country due to the government's crackdown on bitcoin mining in 2022.

We are disappointed that Chamanara et al. ignored the recent Kazakhstan crackdown, where the government imposed an energy tax and mining licenses on the industry, effectively pushing hashrate out of the country. The authors overemphasized Kazakhstan as a current major contributor to bitcoin's energy use and thus environmental footprint. If the authors had stayed within the limits of their methods and results, then noting the contribution of Kazakhstan's hashrate share to the environmental footprint for the combined years of 2020 and 2021 would have been reasonable. Instead, not only do they ignore the government crackdown in 2022, but they also claim that Kazakhstan's hashrate share increased by 34% based on 2023 CBECI numbers. CBECI's data has not been updated since January 2022 and CCAF researchers are currently waiting for data from the mining pools that will allow them to update the mining map (confirmed via private correspondence with Alexander Neumueller, Research Lead at CCAF). The journal, *Earth's Future*, included a "Key Points" section to go along with the commentary which explicitly states that Kazakhstan is "among the top contributors to the environmental footprint of the global Bitcoin mining network". There is little question that the authors used old data to make claims about the present, despite clear indications that the hashrate global distribution has changed and more data is needed before claims about the present-day energy mix can be made.

Figure 7. A broad look at the bitcoin network's energy use (blue line), global hashrate (red line), bitcoin price (green line), and hash price (purple line).

A final comment on Kazakhstan's role in bitcoin mining's energy use, while we do not yet have mining map data for 2022 and 2023, we suspect based on news reports that the country's hashrate share is likely no more than a few percent on the high end, and possibly closer to zero percent on the low end. Our reason for this lower estimate is that mining profitability is at the margins (see hash price trend over time in Figure 7) and any additional operational costs like energy taxes would make mining in that region less competitive and likely unprofitable (Meynkhard, 2019). Anecdotal evidence in a 2023 MIT Technology Review [report]() supports this conclusion.

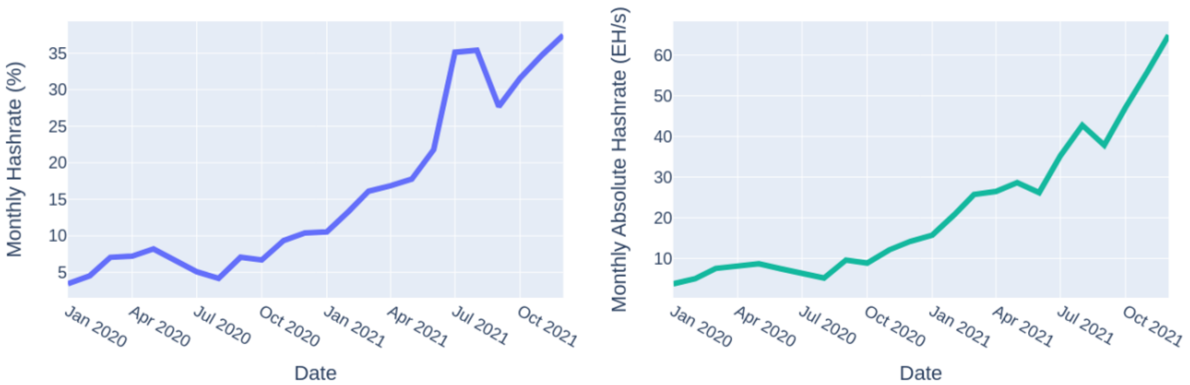


Figure 8. The United States' relative monthly hashrate measured as a percentage of total hashrate (blue line) and the same country's absolute hashrate (red line) measured in EH/s show the rapid increase in hashrate through January 2022.

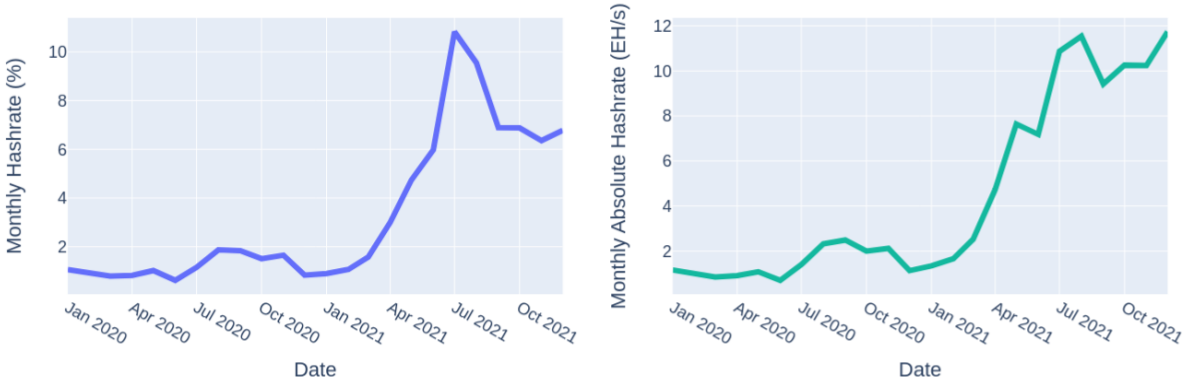


Figure 9. Canada's relative monthly hashrate measured as a percentage of total hashrate (blue line) and the same country's absolute hashrate (red line) measured in EH/s show the rapid increase in hashrate through January 2022.

The contribution to the network's energy use through the CBECI hashrate share data suggests that both the United States and Canada have had lasting increases in absolute hashrate share during the two years that the authors studied (Figures 8 and 9) and both should be taken into consideration for considering a present-day contribution to energy use. The authors list the hashrate share percent breakdown for states in the United States but do not note that this represents the hashrate from January 2022. The citation for CCAF is for 2023 which is misleading. Again, the authors' results and discussion did not stay within the boundaries of their methods and did not narrowly answer their research question within the scope of both the limits of the CBECI model data and the two-year boundary (2020 and 2021). Notably, CBECI collects the remaining hashrate share into a category called, "Other" in their publicly available data. There's also a clear signal that while the hashrate share is smaller, there is a significant shift in hashrate to these other regions after the China bitcoin mining ban.

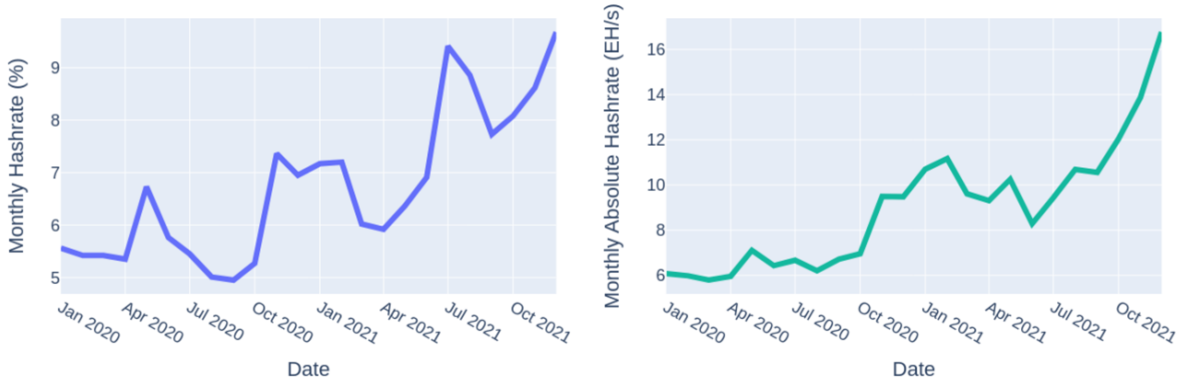


Figure 10. Other countries' relative monthly hashrate measured as a percentage of total hashrate (blue line) and the same country's absolute hashrate measured (red line) in EH/s show the rapid increase in hashrate through January 2022.

Figure 11. Singapore's relative monthly hashrate measured as a percentage of total hashrate (blue line) and the same country's absolute hashrate (red line) measured in EH/s show the rapid increase in hashrate through January 2022.

Singapore, which is included in Chamanara et al.'s results but not in the publicly available CBECI spreadsheet data, is seen in Figure 11. Upon request, CBECI generously shared the full mining map data which allowed us to produce the Singapore data. CBECI only shared the percent hashrate share, so to compute the absolute hashrate share, we took the raw hashrate data from Blockchain.com and averaged it over each month, and then multiplied this with the percent hashrate share to get the averaged monthly absolute hashrate. While Singapore is not extensively discussed in the results (Singapore only appears twice in the article, once in the body and once in the Key Points section), when looking at the hashrate share over the two years, there is strong evidence that the China hashrate may have moved to Singapore. The hashrate growth from January 1 follows a similar trend to that of the United States, Canada, and Kazakhstan (until what appears to be early signs of a crackdown toward the end of 2021).

One final comment on the study design. The authors wrote, "Evidently, the growth of the BTC market is not purely motivated by financial incentives, this makes it difficult to explore the causal relationship between the average BTC price and energy consumption daily. Nonetheless, *we see a 77% correlation between these two variables* over the January 2020-December 2021 period." Several factors go into energy use, which in this study was measured indirectly through average hashrate shares (which is also an indirect measurement). Price is not the only contributing factor to bitcoin mining's energy use over time. As we can see in Figure 7, the hashrate continued to grow despite the collapse in price during the bear market (2022-2023). Interestingly, between July 2022 and January 2023, we see a hashrate increase but energy use remains steady.

Many practical factors affect energy use as well. Some of these include the time between when an order for newer, more efficient machines is placed, and when they are received and connected to the network, and the time from planning to development to production of a new mining facility. While the authors acknowledged that it is for these reasons that it is "difficult to explore the causal relationship", they still proceeded to indirectly hint at a causal relationship. Additionally, the authors failed to reference existing literature that has indeed explored this question (Kristoufek, 2015, 2020, 2022; Fantazzani and Kolodin, 2020). A strong correlation only really tells us that BTC price and energy consumption were linearly dependent but does not tell us much else. It does not tell us that price will drive energy use indefinitely. It does not tell us that energy use drives price. Curiously, the authors' 77% correlation does not align with our calculation for the same period (January 1, 2020 through December 31, 2021). We found a higher correlation of 83% and over the period between January 1, 2022, through August 31, 2023, we found a 66% correlation.

Overall, we hope that through the above discussion, we have successfully shown that the authors failed to distinguish between the years 2020, and 2021. We went a step further and looked at 2022 and 2023 which were often mentioned in the text despite not being included in their original research design. We also believe that we have successfully shown that the authors failed to distinguish among these years as well when discussing the results of their study. We found that the authors often conflated the results from the historical analysis with the present state of the network, which is currently unknown because CCAF is still collecting data from the mining pools. Between the China ban, the Kazakhstan crackdown and energy tax, and the notable insights from our rudimentary CBECI hashrate share analysis, we know that the network as it is distributed today is likely to be very different from what it was during the January 2020-December 2021 period. We believe that due to these oversights, the results of the energy use per country should not be used for present-day policy considerations, but rather should be viewed as one snapshot into the history of the network.

Figure 12. Malaysia's relative monthly hashrate is measured as a percentage of total hashrate (blue line) and the same country's absolute hashrate is measured in EH/s.

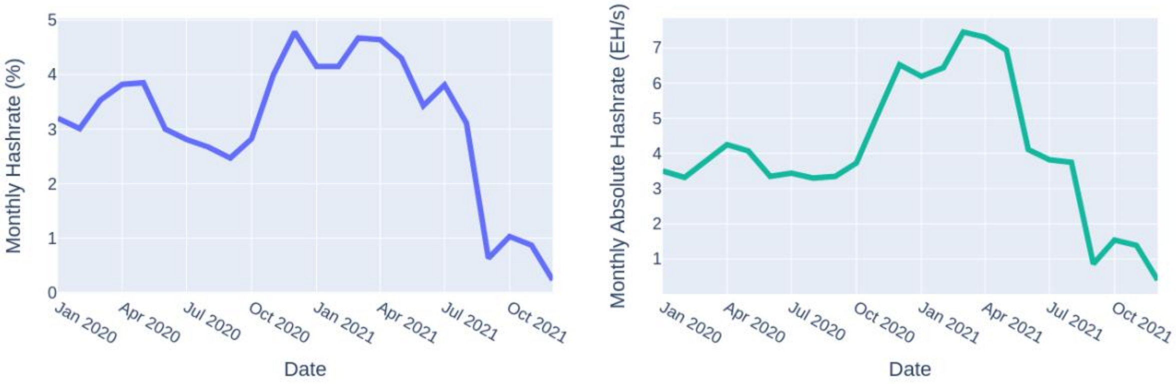


Figure 13. Iran's relative monthly hashrate is measured as a percentage of total hashrate (blue line) and the same country's absolute hashrate is measured in EH/s.

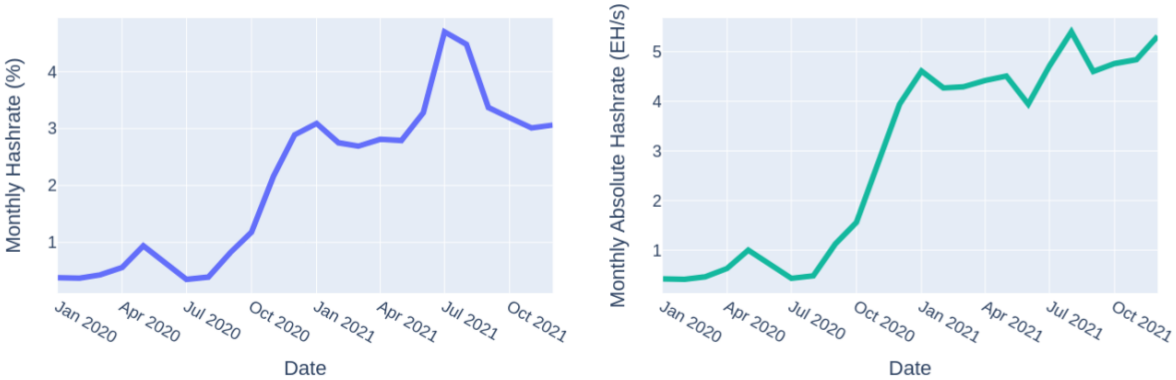


Figure 14. Germany's relative monthly hashrate is measured as a percentage of total hashrate (blue line) and the same country’s absolute hashrate is measured in EH/s.

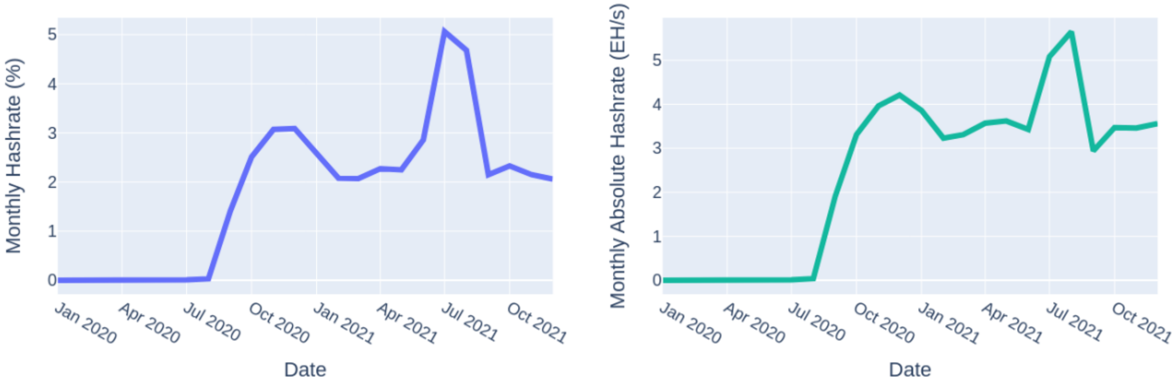


Figure 15. Ireland’s relative monthly hashrate is measured as a percentage of total hashrate (blue line) and the same country’s absolute hashrate is measured in EH/s.

Flaw 3: Methodological Misalignment Produces Unrealistic Results and Unsound Policy Recommendations

In the previous section, we strictly limited our analysis to the calculation of the energy use for each country included in the Chamanara et al. study. We will now address the issues concerning the use of the Ristic et al. environmental footprint factors for attributing land, water, and carbon use to bitcoin mining.

The authors referred to both Ristic et al. (2019) and Obringer et al. (2020). First, we will give a brief overview of these papers and then share our concerns about applying this approach to a particular industry as an attributional method of accounting.

Ristic et al. (2019)

In Ristic et al., the authors developed a metric for evaluating electricity generators across multiple environmental impacts. Their approach was to develop a relative aggregate footprint (RAF) of power generators that evaluated not only their various impacts but also accounted for geographic placement. In other words, the RAF could facilitate a comparative analysis for a water-intensive generator that might be placed in a water-stressed region rather than one that benefited from abundant water resources (Haghighi et al. 2018, Ristic et al. 2019).

To develop the RAF, they used environmental footprints for carbon, water, and land. These factors were measured in relevant units per unit of energy (i.e., m^3/GJ for water footprint). Ristic et al. collected these values from various papers (Schlomer et al., 2014, WEC, 2004, Gerbens-Leenes et al., 2009, Mekonnen et al., 2015). They also incorporated a levelized cost of energy into their RAF algorithm. Applying a Monte Carlo Multi-Criteria Decision Making method and incorporating these factors, they found and evaluated scores for various electricity generators.

The use of environmental footprints in this case was to determine the appropriateness of building a new type of generator within the context of the technology's environmental impact given the generator's geographic placement. For example, they found that nuclear has a good or low RAF in general, regardless of geographic placement. While wind power performed well in terms of water and carbon footprint, Ristic et al. found wind, especially offshore, has a high land footprint, which signals that wind power is sensitive to resource availability conditions.

Ristic et al. note the challenges of developing such a metric, "Attempting an assessment integrating the multiple systems we considered is fraught with complexity and opportunities for misjudgment abound." They also noted several limitations of their approach, including the choice of data used. The authors used global performance ranges that overlook local condition variability, despite the effects of this variability on, for example, climatic, regulatory, and other factors for water footprint.

Ultimately, the goal of the Ristic et al. paper was to provide reasonable guidance to stakeholders for developing low-carbon electricity generation portfolios to meet European Union decarbonization goals. Their results showed that accounting for a comprehensive environmental footprint plus sensitivity to geographic location could give an optimal metric for choosing the most appropriate generators given regional resource sensitivity.

Obringer et al. (2020)

In the Obringer et al. commentary, the authors compiled the environmental footprint data for generators from Ristic et al. as well as data from the EIA and Aslan et al. 2018 to develop footprint factors that could be used to measure the environmental footprint of Internet usage across various nations. They also studied COVID-19 stay-at-home orders' effect on Internet usage and environmental footprint. Obringer et al.'s approach provided the study design blueprint for Chamanara et al.

A major question that arises from Obringer et al. is the appropriateness of applying the metrics from Ristic et al. to an individual's environmental footprint. Obringer et al. reference Ristic et al. when discussing the need for a comprehensive assessment of the environmental cost of Internet use. Yet, Ristic et al.'s approach was focused on providing metrics for determining the best forms of electricity generation to meet climate goals.

We must be careful when addressing this appropriateness because there is value in attributional and marginal accounting of carbon emissions. We do not want to claim that there is never a case for this kind of analysis. Rather, we want to highlight some of the absurdity of taking metrics developed for planning new power generation and using them to determine how the end user can reduce their water, carbon, and land footprint. We also believe that Obringer et al. and Chamanara et al. could have framed their analysis from a marginal accounting perspective, using regional electricity marginal factors, which would have better insight into the environmental effects of changes in Internet use or bitcoin mining.

From the perspective of how the distribution of Internet infrastructure creates demand for power generation, we agree that a study in the vein of Obringer et al. is worthwhile. We recognize that supply and demand are intertwined and that there should be a shared responsibility for the environmental impact of electricity supply. However, Obringer et al. claim that end users could reduce their environmental footprint if they take practical steps to reduce their Internet use. The authors found that streaming services require 7 GB per hour of streaming in Ultra HD or 4K. They found that reducing video streaming quality would save 53.2 million liters per 100,000 users per month and that turning off video during conference calls would save 10.7 million liters per 100,000 users per month.

The issue with these claims is that power generation is trapped both temporally and geographically. If a well-meaning person wanted to reduce their environmental impact, watching YouTube in standard definition would not reduce the total water use for the electrical grid that is powering the infrastructure that made it possible for that person to watch a video on YouTube.

These large-scale hydro plants are generally situated alongside a reservoir. Water is released on a schedule, but the environmental impact of that hydro plant is already embodied in the reservoir itself (Ristic et al is fundamentally based on this implicit observation). Furthermore, less demand for electricity for serving high-quality video streaming would likely lead to excess power. Some hydropower generators are *run-of-the-river*, meaning that upstream water flows through the generator, and only what is needed is used, the rest is water with unlocked potential that passes through. In either case, the water itself is not wasted in the process as it ultimately flows back into the original body of water. When there is excess power or excess potential to generate power, the hydro plant owner would likely seek a new off-taker for this power using a lower cost price as an incentive. The excess power that could have gone to high-quality streaming, might then be used for another purpose, such as a direct carbon capture or data center facility that is looking for cheap power and reliable uptime.

We know that excess power like in the example above happens in practice because cheap, excess power is a huge part of bitcoin mining's success. Bitcoin miners are driven to cheap electricity because of its near-perfect market competition environment (Lasi & Saul, 2020, Derks et al 2018, Marthinsen & Gordon 2022, Delgado-Mohatar et al 2019, Meynkhard 2019, Kristoufek 2020).

In Koomey and Masanet, 2021, the authors criticized Obringer et al. along different lines. They chided the assumption that short-term changes in demand would lead to immediate and proportional changes in electricity use. This critique could also be applied to Chamanara et al., which looked at a period when bitcoin was experiencing a run-up to an all-time high in price during a unique economic environment (low interest rates, COVID stimulus checks, and lockdowns). Ignoring the non-proportionality between energy and data flows in network equipment can yield inflated environmental-impact results. (Koomey and Masanet, 2021)

Studies like Ristic et al. are preferable to studies like Obringer et al. in the long term because the most effective way to reduce environmental impact is to phase out carbon-intensive power generators and only allow for new generation that meets low environmental footprint standards (The Production Gap Report, 2019, 2023). Market design and the need for power for some other off-taker may complicate attempts for individual footprint efforts to make a difference on a broader scale. Many papers have looked at using excess renewable power generation for producing green hydrogen or battery storage (Wohland et al., 2018; Singh and Colosi, 2022; Al-Ghussain, et al., 2022; Jovan et al., 2022; Javed, et al., 2020; Divya and Ostergaard, 2009) and there are likely other possibilities for optimizing excess power. Additionally, we should be cautious with individual footprint analysis because there is evidence that in the early 2000s, BP developed the individual footprint concept as a propaganda tool to stop wide-scale policy shifts and place blame on the consumer (Supran and Oreskes, 2021).

Still, if one wanted to undertake a study like Obringer et al. or Chamanara et al., then a more appropriate approach would be to use marginal environmental factors to look at the impact from a consequential perspective. Obringer et al. make individual footprint reduction recommendations based on attributional factors, but it would be better to look at what would happen if increased or decreased demand for certain Internet services or bitcoin mining would have on the kind of marginal generation that would need to come online or offline to meet the change in demand. Chamanara et al. overlooked a 2019 study that investigated the bitcoin network's life cycle impact from both the attributional and consequential approach using a set of scenarios to explore future projections for the network's impact (Köhler and Pizzol, 2019). Building on the research in Köhler and Pizzol would have likely improved Chamanara et al.'s methods and made a more impactful contribution to the literature.

Lastly, Chamanara et al.'s faulty environmental impact methodology leads them to claim that bitcoin mining's unchecked growth is harmful to developing economies and exacerbates social and economic justice (without citing evidence for these findings). These exaggerated and unsubstantiated claims are not well evidenced in their results and lead them to call for policymakers to act against the industry. The authors also use their results to advocate–without evidence–for a switch from proof-of-work blockchain consensus models (which is the foundation for bitcoin mining) to proof-of-stake blockchain consensus models as a means to ameliorate the environmental impact of bitcoin's electricity use.

Conclusion

The discourse around bitcoin mining's energy consumption is critical, and as such, demands rigorous scholarly scrutiny. Reflecting on Bastiat's observation, we are reminded that countering unsubstantiated claims requires significantly more effort than producing them. We extend our gratitude to readers willing to engage with these complex scientific discussions.

Our analysis leads to profound disappointment with the Chamanara et al. study and the peer review process of AGU's *Earth's Future*. Given the current challenges in blockchain energy research, as indicated by Sai and Vranken (2023), it is clear that the peer review process is facing a crisis of its own in adjudicating studies on bitcoin mining. This is a longstanding issue that continues to afflict the field of data center energy studies.

We identified three primary flaws in the Chamanara et al. study:

1. **Selective Bias in Citations:** The authors have cherry-picked references, promoting a questionable narrative on bitcoin mining.
2. **Simplistic Research Design:** The study offers an incomplete depiction of the network's energy consumption, disregarding or possibly ignoring geographical shifts since 2021, leading to a likely overestimation of emissions.
3. **Methodological Discrepancies:** The application of Obringer et al. (2020)'s environmental footprint does not cohere with the foundational methodology cited, resulting in potentially counterproductive policy suggestions.

Our critique elucidates that the study's design is fundamentally flawed, failing to appropriately engage with existing literature, conflating data over an extended period, and relying on historical trends that lead to inflated projections and policies. Additionally, the environmental footprint methodology employed is unsuitable for demand-side energy assessments.
We advise future researchers to immerse themselves in the workings of the blockchain to avoid similar pitfalls. A thorough review of energy modeling criticisms should become a standard practice in literature reviews within this domain. It is concerning that despite nearly a decade since the inaugural studies on bitcoin mining's energy use, only modest advancements have been made, with the CBECI model remaining one of the few notable developments.

We urge policymakers to refrain from hasty conclusions and policy measures until more refined models are established. Relying on underdeveloped studies such as Chamanara et al.'s could risk undermining climate initiatives. There is emerging evidence suggesting that bitcoin mining may contribute positively to the renewable energy sector and methane mitigation efforts. Therefore, policymakers should seek comprehensive consultations with the renewable energy sector, the bitcoin mining industry, and academic researchers to chart a course towards more informed research outcomes. Effective policy is predicated on transparent data sharing and collaborative efforts among all stakeholders.

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