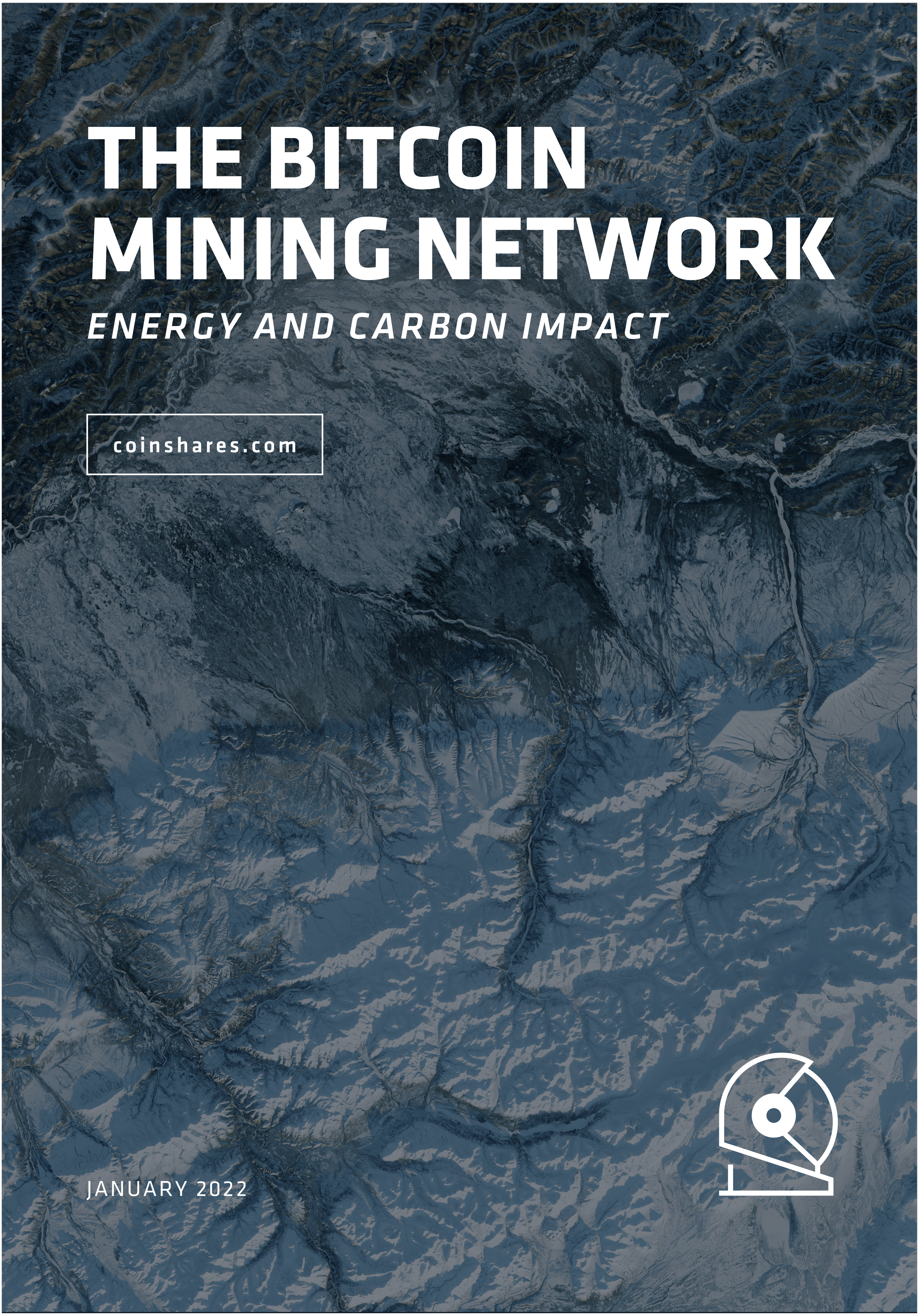

THE BITCOIN MINING NETWORK

ENERGY AND CARBON IMPACT

coinshares.com

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INTRODUCTION

Usage of energy is a contentious and much misunderstood function of the Bitcoin monetary system. Hotly debated ever since its invention, already in 2010 Satoshi Nakamoto was confronted with the claim that ‘Bitcoin minting is thermodynamically perverse’. He offered the following comment in response:[1]

> *“The utility of the exchanges made possible by Bitcoin will far exceed the cost of electricity used. Therefore, not having Bitcoin would be the net waste."*

This view is widely shared among Bitcoin proponents, and to be clear, we count ourselves among them. A common argument in support of this view is that the gross and systemic distortion of price signals caused by costless and arbitrary monetary inflation creates malinvestment, economic inefficiencies and waste on a scale that would dwarf Bitcoin’s approximate 0.05% share of global energy consumption.[2]

We find that argument reasonable. Besides, all useful technologies come at a cost, and at the end of the day, we believe the focus of our society should be on producing pollution-minimised electricity, not on reducing our standard of living through knee-jerk restrictions on useful, energy-intensive industries.

Nevertheless, discussions of Bitcoin’s energy usage and its indirect environmental impact have pressed onward, becoming a recurring subject that tends to get resurrected in full force with each successive market cycle. Sensationalist commentators have not been shy about offering their (often poorly supported) opinions,[3.4.5.6.7.8.9.10.11] and many Bitcoin-fluent commentators have offered retorts. Some of these retorts have concentrated on the question of energy cleanliness,[12,13,14,15,16] while others have focused on the necessity of objectiveness, fair issuance and censorship resistance in global, open monetary systems. The latter are only achievable through Proof-of-Work.[17,18,19,20]

The purpose of this report will not be to convey any further opinion on the necessity of Proof-of-Work. As mentioned, we believe the existence of Bitcoin is a (large) net benefit to society and given that the properties of Proof-of-Work cannot be replicated by any other process, the cost is necessary. You can find a much more detailed explanation of our position here.

Rather, we will use this paper for a detailed exploration of Bitcoin’s indirect carbon emissions via its mining network. We observe that much of the debate surrounding this issue tends to be based on qualitative and anecdotal evidence, with rare and mostly cursory attempts to directly quantify the emissions themselves. To our knowledge there exists only one recent report using a sufficiently granular methodology to achieve any hope of accurate results,[21] and as a result, we believe the analysis of Bitcoin’s indirect emissions remains incomplete.

To address this, we’ve developed a comprehensive model to calculate emissions and created our own data collection framework to populate it. In order to further the development of this specific field of research, we will (a bit further down the line) offer our model to the community as open source. We will also publish our aggregate underlying data so others can play around with both our data and their own.

The report will highlight the overall results of our model, contain an overview of patterns and trends, as well as a short section discussing the use and cost of carbon credits for offsetting emissions.

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[1] https://bitcointalk.org/index.php?topic=721.msg8114#msg8114
[2] https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf
[3] https://thephoenix.substack.com/p/bitcoin-is-now-worth-50000-and-its
[4] https://www.nature.com/articles/s41893-018-0152-7
[5] https://www.nature.com/articles/s41558-018-0321-8
[6] https://www.ft.com/content/1aecb2db-8f61-427c-a413-3b929291c8ac
[7] https://www.nature.com/articles/s41467-021-22256-3
[8] https://economictimes.indiatimes.com/tech/tech-bytes/elon-musk-decries-bitcoins-insane-energy-use-after-tesla-u-turn/articleshow/82607249.cms?from=mdr
[9] https://www.businessinsider.com/microsoft-tesla-elon-musk-cryptocurrency-climate-change-damage-economist-roubini-2021-3
[10] https://digiconomist.net/bitcoin-may-consume-as-much-energy-as-all-data-centers-globally
[10] https://fortune.com/2021/05/13/musk-bitcoin-mining-bad-planet-heres-how-bad/
[12] https://www.jbs.cam.ac.uk/faculty-research/centres/alternative-finance/publications/2nd-global-cryptoasset-benchmark-study/
[13] https://www.jbs.cam.ac.uk/faculty-research/centres/alternative-finance/publications/3rd-global-cryptoasset-benchmarking-study/
[14] https://coinshares.com/assets/resources/Research/bitcoin-mining-network-december-2019.pdf
[15] https://coinshares.com/research/bitcoin-mining-network-june-2019
[16] https://bitcoinmagazine.com/culture/comparison-of-bitcoins-environmental-impact
[17] https://medium.com/@VitalikButerin/a-proof-of-stake-design-philosophy-506585978d51
[18] https://www.seetee.io/static/shareholder_letter-6ae7e85717c28831bf1c0eca1d632722.pdf
[19] https://www.swanbitcoin.com/bitcoins-energy-usage-is-not-a-problem-heres-why-by-lyn-alden/
[20] https://coinshares.com/research/closer-look-environmental-impact-of-bitcoin-mining
[21] https://nydig.com/bitcoin-net-zero/

METHODOLOGY OVERVIEW

The overarching goal of the model is to estimate the carbon emissions indirectly resulting from the Bitcoin mining network. We are taking extra care here to note that these emissions are indirect because there seems to exist a pervasive misunderstanding among layman commentators that Bitcoin somehow requires emissions to operate. This is false. Bitcoin, like electric cars, is as green as the electricity you feed it, meaning that in a 100% renewable energy environment, Bitcoin would be 100% renewables driven.

Our resulting data can for example be used to compare Bitcoin emissions to other energy-intensive technologies and industries, or it can be used to estimate the amount of carbon credits necessary to offset the carbon footprint of bitcoin holdings at the custodial level per unit time. However, depending on the quality of the data inputs we're able to feed it, the model can also estimate time series of emissions by region, emissions by fuel, power draw by region, power draw by fuel and more.

In constructing our model, we've tried our best to keep things relatively simple. As a general principle, when faced with a choice of modeling approaches where the potential benefits do not clearly and significantly outweigh the added complexity cost, we favor simplicity over intricacy. Our suspicion is that adding intricacy, while it might look nice on the surface, quite often does not sufficiently translate into output accuracy to be worth the overhead.

The overall approach can be summarised as follows: Given the available data, the model should be as simple as possible to return a useful quality of outputs, but no simpler.

Network Efficiency

Network efficiency is a crucial component of any mining model as it is the basis of the estimation of the total network power draw. Getting the network efficiency wrong directly translates into a proportional error size in the power draw estimation.

As with our previous work on the mining network, we've chosen a bottom-up approach that models the total sum of all functional ASIC hardware units that are currently contributing to the hashrate. This approach stands in contrast to the commonly employed top-down approach of choosing a single mining unit, and its efficiency rate, as representative of the entire network.

To achieve this, we curate an ongoing time series database of all mining units ever built and make simple assumptions based on efficiency, production and breakdown rates to generate monthly estimates of how many units are available for mining, and which units out of the existing total are actually mining at any given time.

From the estimate of the total units mining at any given time, we calculate the average efficiency factor of the network. The efficiency factor is the weighted average number of Watts drawn by the entire network per TH/s of hashrate generated (this returns the dimension of W/TH/s, but an equivalent and more commonly used dimension is J/TH).

The average network efficiency is then used to estimate the ongoing electricity draw of the network from the observable implied hashrate, sourced from the Bitcoin blockchain itself (via CoinMetrics).

Carbon Calculation Method

We then distribute the total estimated power draw across a number of individual global mining regions, each of which has its own carbon intensity of electricity generation based upon its unique combination of generation sources. Here, we are assuming that the electricity consumption of a mining operation in any given region is responsible for carbon emissions at the average regional intensity of generation. The power draw by region is measured in MW and is estimated month to month.

Once the total carbon emissions of the network are calculated we subtract out the negative CO_2 equivalent emissions of flare-mitigating oil field miners. We explain this methodology in more detail below.

Assumptions

Total Hardware

Our hardware database is generated with a mixed methodology. We have combined a number of different data sets, one from our own research team, one from CoinMetrics, and one each from Canaan and Taiwan Semiconductor Manufacturing Company's (TSMC) public disclosures.

Due to differences in miner requirements for capex/opex breakdown, as well as in wafer batch quality received from the foundries, it is common for mining manufacturers to create a variety of different unit models within each model series. For example, the Antminer S9 exists in more than 10 variations with varying performance metrics. For simplicity, we have chosen to aggregate the different models inside of each model series, average out their properties, and treat them as a single model.

To arrive at an estimate of the total units available for mining, we combine a snapshot of the estimated makeup of the mining network at a specific time (January 2020) with a set of assumptions regarding the production and breakdown rates of every individual unit. Production rates are inferred from publicly available information (Canaan, TSMC) to the largest degree possible, and augmented by a combined approach of miner interviews and network growth rate fitting where needed. This is part art, part science.

Hardware production rates are averaged out over multiple months. We know that this is not completely realistic, but we believe it estimates growth rates well enough. Breakdown levels are held constant. We are again aware that this is a simplification, but in this case the complexity overhead of adding individual and often time-based breakdown rates for each individual mining model outweighs the potential increases in accuracy. We may revisit this in later iterations.

Taken together, these datasets are used to generate an estimate of the total amount of existing functioning mining units available for mining at any given time. Being available for mining does not mean that a mining unit necessarily is mining at any given time.

Operational Hardware

The total number of functioning, available mining units serves as an upper bound of possible global hashrate production. In reality however, all existing units are rarely if ever running at the same time, and only a subset of the total units tend to be powered on at any given time. To estimate how many units are mining and which ones of the available units are plugged in, we apply another combined approach.

For two of the unit types, the Antminer S7 and S9 unit series, we have a reasonable estimation of ongoing hashrate contribution available from CoinMetrics' nonce distribution analysis. We use these figures to create a minimum amount of hashrate generated by these two model series at any given time.

From the upper bound of total existing and available units then, we subtract out the contribution from S7 and S9 units to get a remainder hashrate provided by the rest of the available mining units. We then fill in the gap based on efficiency assumptions.

Filling the gap between the total observable hashrate and that generated by S7s and S9s requires some assumptions. So we assume that at any given time, the competitive dynamics of the industry will favor the most efficient units. The result is that in our model, the difference between total observable hashrate and hashrate contributed by S7s and S9s is always assumed to be generated from the available units with the highest efficiency.

Under normal network circumstances we believe that this assumption will, more often than not, give the most accurate estimate possible. However, under the recent (summer and fall of 2021) conditions, closely following the Chinese mining ban, our assumption will likely somewhat overestimate the average efficiency factor (that is, the network will be estimated to have been more efficient than it actually was). The reason is that the removal of hashrate from Chinese operations was likely evenly distributed across all models that were operating in China prior to June 2021.

Readers should be aware that an error like this will cause a slight understatement of emissions in the months immediately following the mining ban.

Once we have estimated the composition of the mining units contributing to the total hashrate, the total network efficiency factor is calculated as the weighted average efficiency of all units that are assumed to be operating in any given month. Hardware is assumed to be equally distributed across all mining regions and so all mining regions are assumed to operate at the same network efficiency factor.

We suspect this assumption may not quite hold in reality, and that inefficient miners will actually tend to cluster in regions offering the cheapest electricity. If our suspicions are correct, our model will somewhat overestimate emissions as the cheapest available electricity globally tends to be carbon neutral or carbon negative. However, we lack concrete data to challenge the assumption and have therefore again taken a conservative approach and favored simplicity over complexity.

Hashrate and Power Draw

The network efficiency factor is used to calculate the power draw of the network from the implied hashrate. In reality, hashrate is not an exact known quantity and must be inferred from the block frequency. In the long run however, this implied hashrate will nevertheless be an accurate estimation of the real hashrate.

As our measure of implied hashrate, we have used a single monthly average of the daily 2-week moving average from CoinMetrics. From the implied hashrate, we apply the network efficiency factor to arrive at the implied total power draw of the network for every month of the year.

Miner Locations

We estimate the location of miners based on a mixed methodology. As part of our estimate in each region, we use locations and operation sizes that are verifiable either from data in the public domain, or from private data given to us by miners. Along with those locations, we add available data from Cambridge Center for Alternative Finance and from Foundry USA Pool.

The known physical locations we have found either from private correspondence or in the public domain represent 3,3 GW of capacity, or 32% of our estimated network energy draw (10,3 GW) as of the full month of December 2021.

TABLE 1: **TOTAL KNOWN POWER DRAW OF GLOBAL MINING COUNTRIES (DEC 2021)**

Country	Total Known Power Draw (MW)
Azerbaijan	36
Canada	529
China	1
Georgia	38
Iceland	153
Kazakhstan	787
Norway	66
Russia	268
Sweden	80
United States	1,380
Sum	**3,338**

We use this miner location data along with data from Cambridge and Foundry to produce an overall estimate of hashrate across each country and region in percent of total, monthly. To arrive at our estimates, the known power draw figures are first converted to hashrate using the previously explained estimates of hardware efficiency. We then compare each of the location datasets from Cambridge, Foundry, and the known list of locations, to estimate hashrate percentage in each country and region.

The highest estimated hashrate for any given region in any of the three datasets is used to reflect the highest potential hashrate percentage for that country and region. We then add all these maximum hashrates together, and at this point they will add up to more than 100%. From this upper bound of potential hashrate in each location, we then draw down each region proportionally until the total network hashrate reaches 100%. If the combined location data then suggests a regional hashrate that is lower than the one set by known projects, the known projects takes precedence and a new distribution is calculated from the remaining hashrate. The data from Foundry does not add to the total hashrate they've already reported to Cambridge, it only serves as a differentiator between states internally inside the United States. A fully detailed explanation of this methodology can be found in our code repo which we will release in due course.

It should be cautioned that over its time series, the pools surveyed by the Cambridge data set only account for 32% - 37% of the total hashrate. Our own database of publicly known mining operations accounted for about 31% by the end of December 2021, but there is an unknown amount of overlap between the two datasets. Our guess is that the two sets combined gives us a total network visibility somewhere not too far north of 50%.

We are also aware that the Cambridge data likely contains some errors (and they note this themselves as well). Their methodology assumes that the location of the IP address a miner uses to connect to its pool is the same as its real-world geographic location, so false positives will be generated in areas that are popular locations for VPNs or proxy IP address locations such as Ireland and Germany. There is also a significant allocation (8.9%, Aug 21) of hashrate to 'Global Other', meaning an undefined global location which correspondingly emits carbon at the global average intensity.

Given the large increase in supposed Irish and German hashrate after the Chinese mining ban, our suspicion remains that this hashrate is actually best attributable to Chinese miners masking their IP addresses. While the most recent Cambridge data has all three Chinese pools reporting no hashrate whatsoever out of China, we believe this is unlikely to be the actual situation on the ground and we've heard many rumors of 'guerilla-style' mining operations persevering in remote regions such as the mountains of Sichuan.

Our assumption therefore is that all Irish and German hashrate actually originates from China and is likely to be similarly distributed on a regional level month-to-month as in previous years. We have thus assigned 9.2% of the Cambridge network hashrate (Aug 21) to China and distributed it on a provincial level at equal monthly ratios as the 2020 figures. Our own compound estimate for all mining countries' hashrate can be found in Figure 7.

We will also show the exact manner in which location distribution data is applied on top of the floor of known projects once we release the code repo.[22]

Regional Carbon Intensity

The main assumption of our carbon intensity calculation is that the carbon footprint per MWh consumed by a miner, in any given region, is the same as the average footprint of each MWh produced in that same region.

Mining regions are generally defined as individual countries, but due to their large geographic size, this is not the case for the four largest countries in our sample: Canada, the United States, China, and Russia. For those four countries, we define mining regions as individual states (USA), provinces (CHN, CAN), or federal grid districts (RUS).

We split up the largest countries into smaller regions because the carbon footprint of power generation and consumption cannot reasonably be assumed equal across the entirety of countries their size. For smaller countries, however, we think this is a more reasonable assumption, albeit still not quite as accurate as we would prefer.

For each individual mining region, we have gathered the average mix of electricity generation sources on an annual basis (or monthly where possible)[23,24,25,26,27,28] From each generation source, we calculate the amount of carbon emitted per MWh produced from generalised estimates by the US Energy Information Administration.[29]

We assume that carbon intensity by generation source is similar enough in every global region that a single intensity factor suffices for generation sources in all regions (however, we will likely revisit this assumption in later iterations). Each individual mining region is thereby given an individual carbon intensity score by MWh produced/consumed.

TABLE 2: **TOTAL CARBON INTENSITY OF ALL GLOBAL MINING COUNTRIES (DEC 2021)**

Region	Carbon Intensity (g/kWh)
Azerbaijan	638
Canada	234
China	318
Georgia	95
Global	492
Iceland	0
Iran	507
Kazakhstan	787
Malaysia	589
Norway	7
Russia	477
Sweden	19
United States	447
Weighted Average	**466**

Table 2 details the individual and weighted average carbon intensity scores of each individual mining country. All numbers reflect estimates as of December 2021.

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[22] Please contact us at research@coinshares.com for any pre-repo-release questions on methodology.
[23] https://ourworldindata.org/grapher/share-elec-by-source (Our World in Data)
[24] https://www.eia.gov/electricity/data/state/ (EIA-923 Report)
[25] https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510001501 (Statistics Canada)
[26] https://www.iea.org/reports/russian-electricity-reform (IEA Russian Electricity Reform)
[27] https://www.epa.gov/sites/default/files/2016-03/documents/2014_coalchinaenergymarket_fullreport.pdf
[28] https://nepis.epa.gov/Exe/ZyPDF.cgi/P100ZN9P.PDF?Dockey=P100ZN9P.PDF
[29] https://www.eia.gov/tools/faqs/faq.php?id=74&t=11

TABLE 3: **CARBON INTENSITY OF ALL NORTH AMERICAN MINING REGIONS (2021)**

Region	Carbon Intensity (g/kWh)
Alabama	360
Alberta	614
British Columbia	33
Manitoba	1
Ontario	35
Quebec	4
Georgia	381
Kentucky	810
Minnesota	391
Montana	791
Nebraska	566
Nevada	336
New York	156
North Carolina	356
US Other	398
Pennsylvania	349
South Dakota	179
Texas	411
Washington	130
Wisconsin	586
Wyoming	830
Weighted Average	**420**

Table 3 details the individual and weighted average carbon intensity scores of each individual mining region in North America. All numbers reflect estimates as of December 2021.

Power Usage Effectiveness

We estimate a network wide Power Usage Effectiveness (PUE) of 1.10 which is broadly in line with previous work done by other researchers[30,31,32] PUE accounts for all non-hashing energy expenditures incurred by datacenter operations like Bitcoin miners. A PUE of 1.10 means that all operations are assumed to consume 10% additional energy for cooling etc. on top of the energy required purely for hashing. The energy added by our PUE assumption is simply added as an additional 10% on top of our hashing energy estimate, which in turn is calculated from the observable hashrate and the efficiency estimate.

Oil Field Mining

Finally, we apply a special methodology to the still niche but rapidly growing segment of oil field mining. Oil field miners operate near or at well heads where oil or natural gas liquids are produced and dry natural gas is generated as a waste product. This natural gas cannot be economically brought to market and is therefore either vented or flared. When vented, natural gas (mostly methane) escapes directly into the atmosphere, causing ~31 times the greenhouse effect of CO_2 over a 100-year period.[33]

When flared in the absence of wind, methane can be combusted at an efficiency of up to 99%. However, this rate rapidly decays in windy conditions and levels off at levels between 10-15% in conditions above 6 m/s. In realistic outdoors wind conditions below 4 m/s, a study using data from the Alberta Research Council found that average combustion efficiencies were 68% with a standard deviation of 7%.[34]

Under perfect combustion, for **each tonne** of methane combusted, **2.75** tonnes of CO_2 is created. Assuming pipeline quality of **99%** methane content in the flared dry gas, and a **68%** combustion efficiency in the average flaring tower at average weather conditions, combusting at **99%** efficiency inside an internal combustion engine therefore reduces greenhouse gas emissions versus its default state of flaring the gas.

For each tonne of CO_2 generated by an oil field miner, approximately **0.11** tonnes of methane is prevented from leaking into the atmosphere (see calculation below).

$$1 / 2.75 * (0.99 - 0.68) * 0.98 = 0.11$$

Each tonne of methane being the greenhouse equivalent to 31 tonnes of CO_2, over a 100-year perspective, makes it so that each tonne of CO_2 emitted by an oil field miner also removes 3.4 tonnes of CO_2-equivalent emissions. We therefore count each tonne of CO_2 emitted from oil field miners as a net of -2.4 tonnes emitted.

For simplicity, the negative emissions are subtracted from the total calculated emissions. From interviews with flare miners, we estimate that such mining amounts to no more than 250MW, or a modest 2.4% of the hashing electricity draw as of December 2021. We assume this electricity is generated with the same natural gas emissions factor as the global average used elsewhere in the model.

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[30] https://nydig.com/bitcoin-net-zero/
[31] https://www.sciencedirect.com/science/article/pii/S2542435119302557
[32] https://cbeci.org/index/methodology
[33] https://unece.org/challenge
[34] https://pubmed.ncbi.nlm.nih.gov/15666465/

RESULTS

Our results reveal a series of high-level trends. Some of these are expected, others are rather surprising. For example, as expected, older mining units are progressively being phased out of the network in favor of newer, more efficient units. As a result, network power efficiency is increasing over time.

Total carbon emissions are trending up alongside the increased purchasing power of the mining reward, which is mainly price-driven and counteracted by the 4-year minting reward halvings. However, the emissions per MWh are trending down and so are the emissions per TH/s.

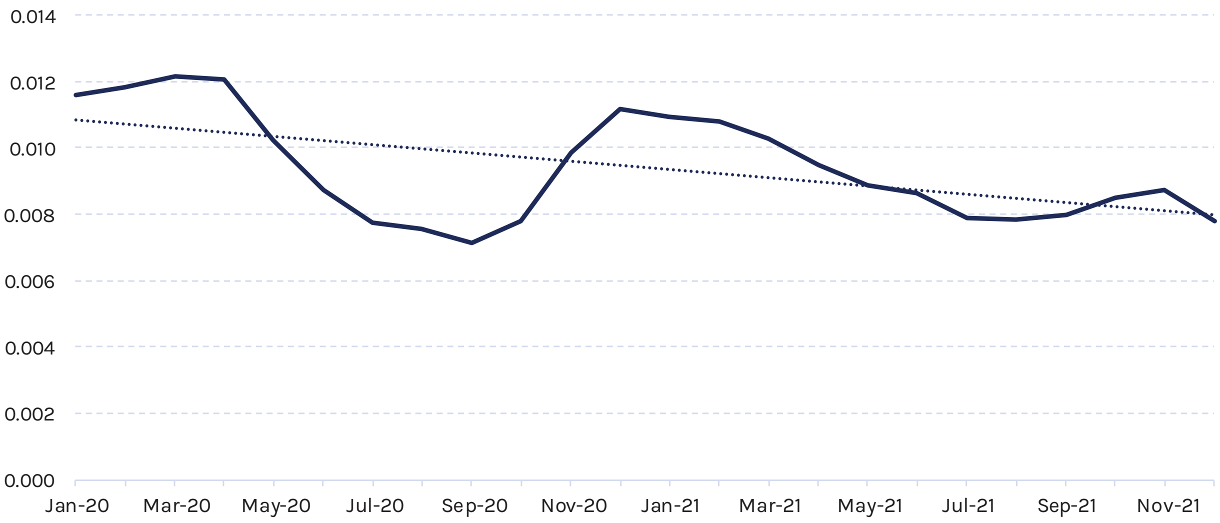
It is important to note here though, that while some commentators tend to insinuate that these efficiency gains will reduce electricity consumption over time, this is not the case. The competitive dynamics of the mining industry ensures that miners as a group will always tend to buy as much electricity as the mining reward allows them. Increased efficiency will only generate more hashrate per kWh spent. It will not reduce the electricity draw.

Hardware Units in Use

According to our assumptions, the majority of the current hashrate is generated by the Antminer S19 series. Somewhat unexpectedly though, the venerable S9 is in second place, and the Whatsminer M30 series is in third. However, we need to note once more here that under the circumstances immediately following the Chinese mining ban, our estimates were likely not quite correct. Our assumption that only the most efficient gear is mining at any time, while likely correct over the long run, will overestimate the hashrate generated by the most efficient units in such situations.

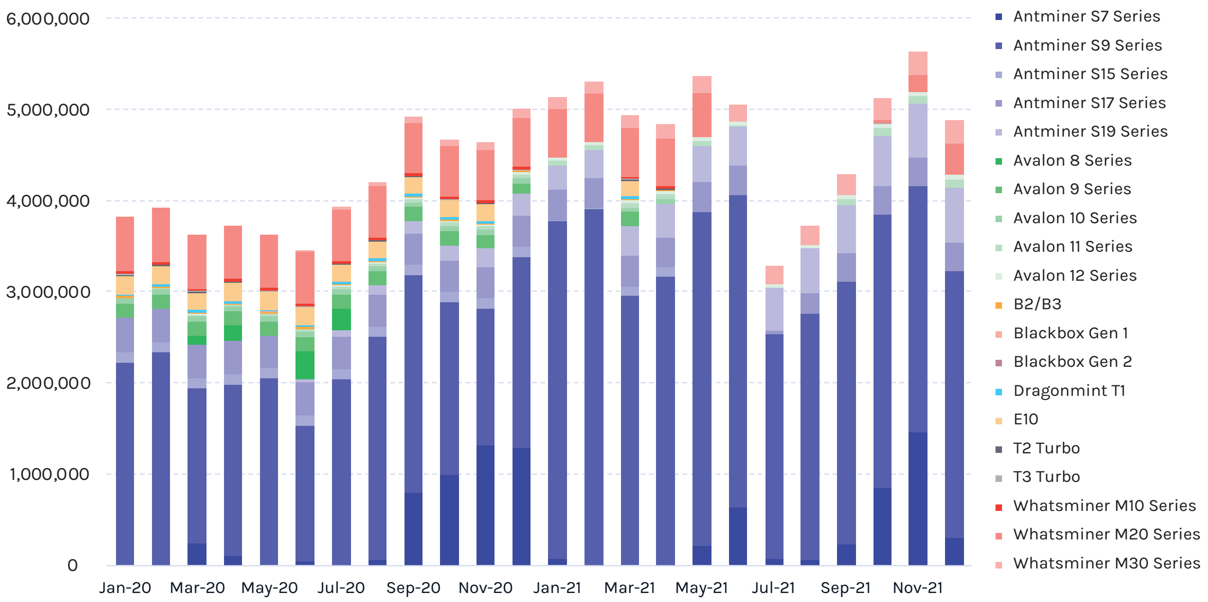
We suspect the approximately 37% of total hashrate that went offline in China was likely more or less equally distributed among all available units. In that case, our assumption simply does not hold and the model will overestimate the hashrate delivered by the most efficient units. We see this directly in the results from June, July and August, where competitive units such as the Whatsminer M20 series are assumed to be more or less entirely removed from the market.

FIGURE 1: **CARBON INTENSITY OF HASHING (gCO_2/TH)**



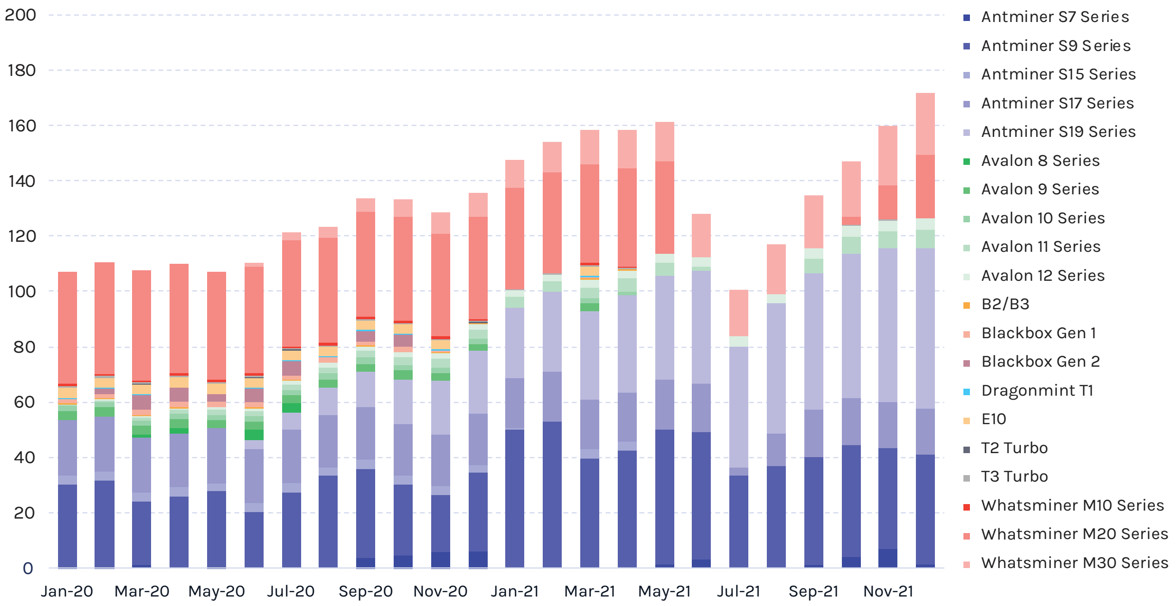
Source: CoinShares Research (Jan 2022)

FIGURE 2: **TOTAL HARDWARE UNITS IN USE**



Source: CoinShares Research (Jan 2022)

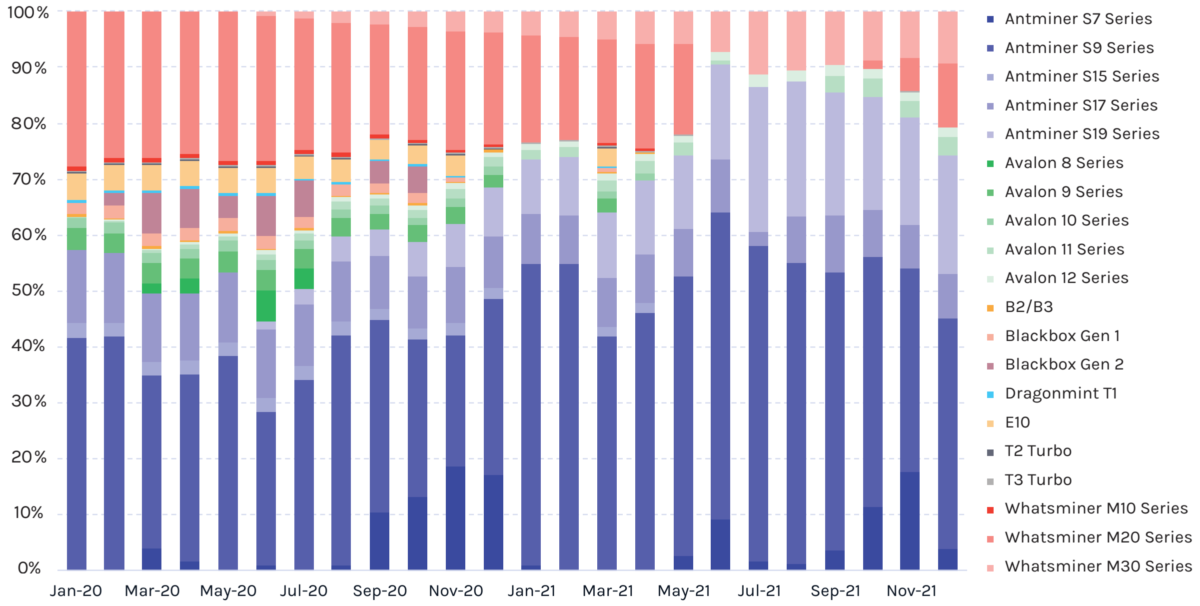
FIGURE 3: **TOTAL HASHRATE BY HARDWARE UNIT (EH/s)**



Source: CoinShares Research (Jan 2022)

We find it very interesting that, according to the nonce analysis data from CoinMetrics, the S9 series of mining hardware, even though it was first introduced as early as 2016, still generates more than 20% of the hashrate. This clearly demonstrates the current profitability levels of mining and the longevity of well-built mining hardware.

FIGURE 4: **TOTAL POWER DRAW BY HARDWARE UNIT (%)**



Source: CoinShares Research (Jan 2022)

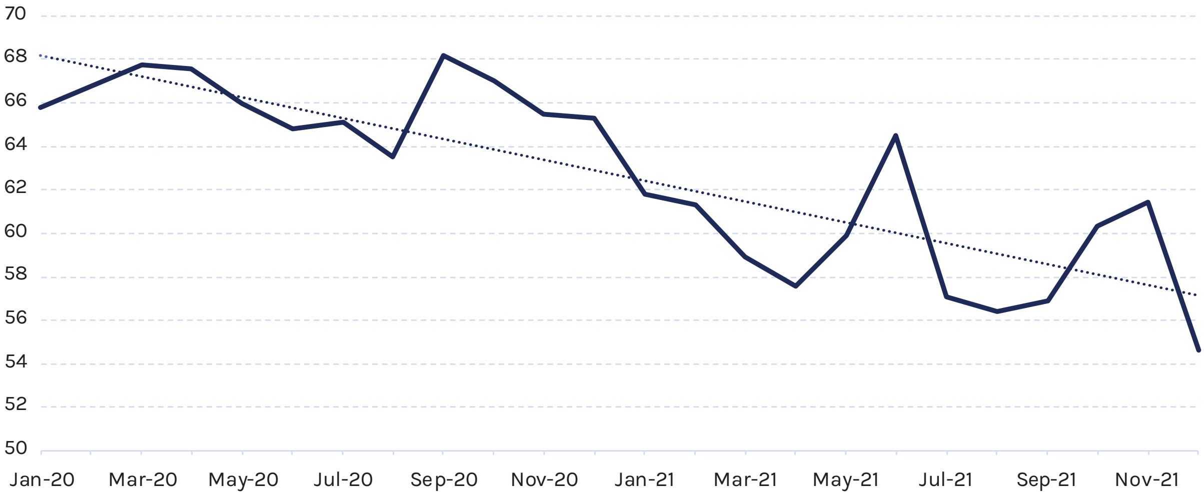
Average Network Efficiency

As expected, throughout our estimation period the overall network efficiency has been trending up (lower J/TH means higher efficiency). But there have also been several periods of brief uptrends. All of these uptrends have followed rapid increases in the bitcoin price, causing rapid increases in the purchasing power of the mining reward, and increasing short-term mining profitability.

When bitcoin prices rise rapidly, older, less efficient units that have previously been rendered unprofitable from rises in the mining difficulty may become profitable again, bringing them back into the network. This will reduce the overall network efficiency until either the price drops again, or the difficulty catches up to the new purchasing power of the mining reward.

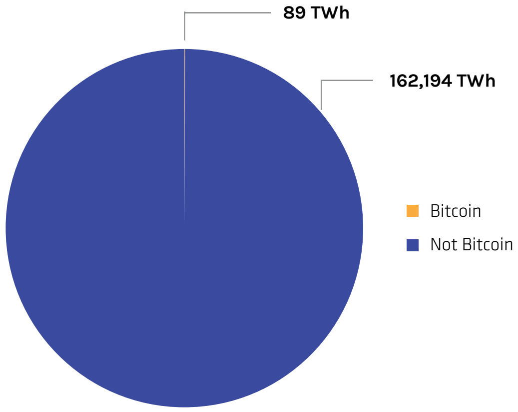
We estimate that the average annual efficiency factor in 2020 was 66 J/TH. For 2021 it was 59 J/TH.

FIGURE 5: **NETWORK EFFICIENCY (J/TH)**



Source: CoinShares Research (Jan 2022)

FIGURE 6: **BITCOIN'S SHARE OF GLOBAL ENERGY CONSUMPTION**



Source: CoinShares Research (Jan 2022)

Total Power Consumption

From our monthly average efficiency factors and implied hashrate, we estimate that the Bitcoin network drew 75 TWh of electricity in 2020 and 82 TWh in 2021.

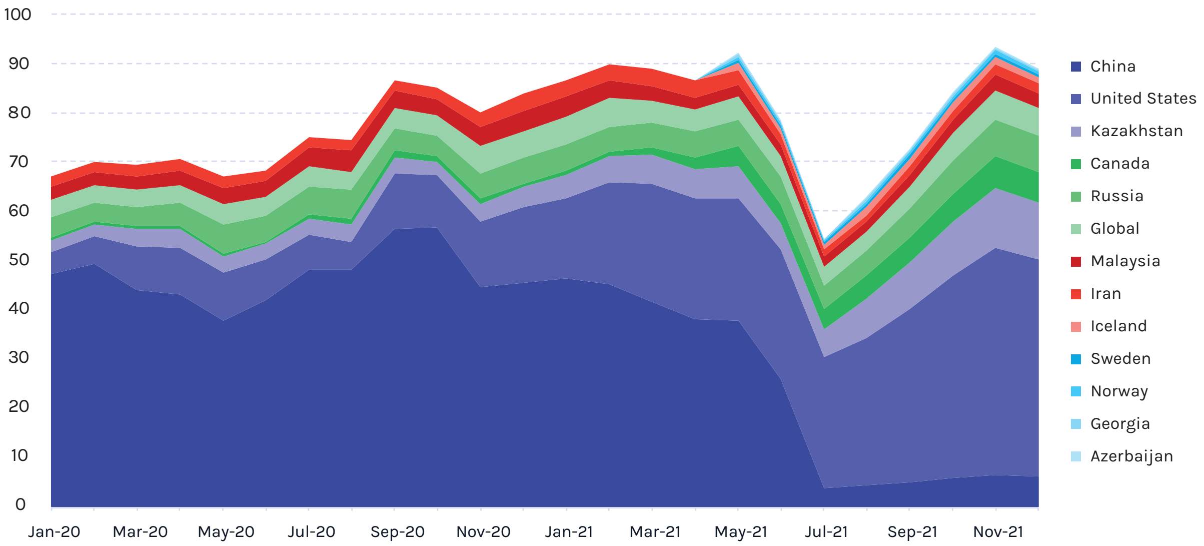
As of December 2021, the current annualised draw is 89 TWh, which is the second highest monthly estimate of 2021, the highest being November at 93 TWh. The lowest monthly estimate in 2021 was July, where we estimate that the annualised draw was 54 TWh.

As a point of reference, total global energy consumption (not production, which is considerably higher) in 2019 has been estimated at 162,194 TWh.[35] At an annual energy draw of 89 TWh, the Bitcoin mining network uses approximately 0.05% of the total energy consumed globally. This strikes us as a small cost for a global monetary system, and on the global energy balance sheet, it amounts to a rounding error.

Hashrate and Power Consumption by Miner Location

Hashrate and power consumption is geographically well distributed. There are however some jurisdictions accounting for significant shares of hashrate and power consumption. The country currently accounting for the largest hashrate is the United States, a position it only achieved in July 2021, having been a relatively distant second for many years. Number two is Kazakhstan and numbers three and four are Canada and Russia, respectively.

FIGURE 7: **TOTAL ANNUALISED NETWORK POWER DRAW BY MINING COUNTRY (TWh)**



Source: CoinShares Research (Jan 2022)

Before the ban on Bitcoin mining, China was the uncontested leader in hashrate production and power consumption, with almost 50% of network hashrate. And while its total network percentage had been trending down for some time, the ban drastically accelerated the movement of hashrate out of China, to the point where we estimate that only ~6.9% of hashrate is generated within China as of December 2021.

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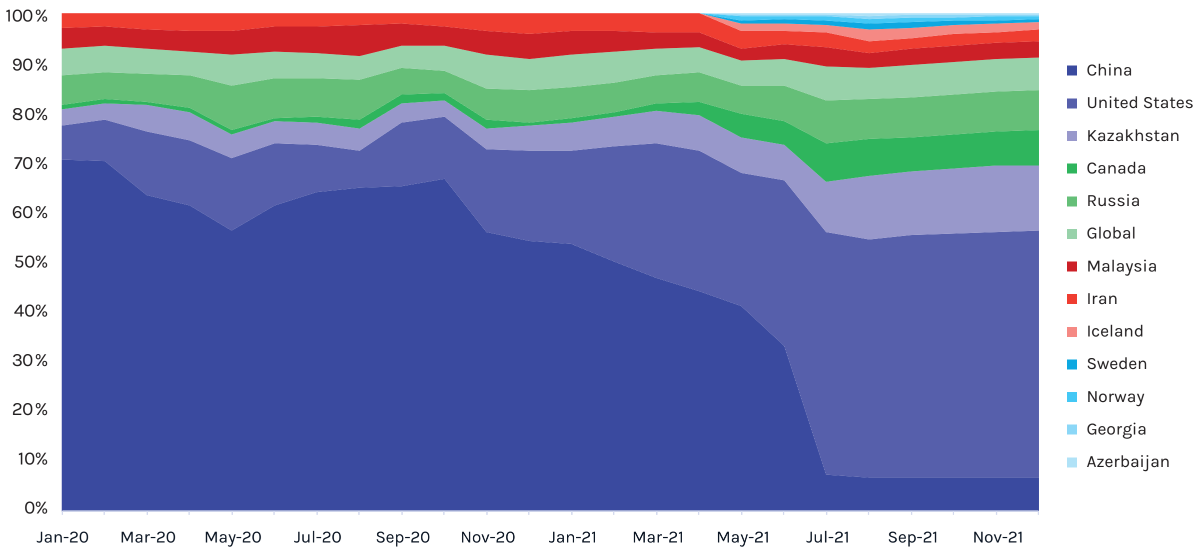
[35] https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

FIGURE 8: **PERCENTAGE DISTRIBUTION OF HASHRATE BY MINING COUNTRY**



Source: CoinShares Research (Jan 2022)

When the ban took effect in late May 2021, global hashrate fell from ~161 EH/s to ~101 EH/s in less than two months—a total drop of 37%. In April 2021, Cambridge Center for Alternative Finance estimated that ~46% of global hashrate was Chinese, suggesting that almost all of the Chinese hashrate went offline between the end of May and the beginning of August.

However, as mentioned above, we suspect that all hashrate listed as originating from Ireland and Germany is actually coming from China. This means that Chinese hashrate might have been higher than the Cambridge estimate before the shutdown, and that there is still likely to be a significant amount of hashrate produced in China today.

The movement of hashrate out of China has significantly altered the global mining distribution, with large amounts of the recovered hashrate being distributed among the remaining global mining regions, and the US, Russia and Kazakhstan likely being the main beneficiaries.

Carbon Emissions

We estimate that the Bitcoin mining network emitted 36 Mt of CO_2 in 2020 and 41 Mt in 2021. Simultaneously, flare mitigation will remove an estimated total of 2.1 Mt CO2 equivalents, bringing the total net emissions to 39 Mt. The total negative emissions from flare miners amounts to approximately 5.2 % of the total.

In a global context this is an insignificant addition to total emissions, amounting to less than 0.08%, or less than 1/1,000th, of the global total (49,360 Mt CO_2e)[36]. As a frame of reference, countries with large industrial bases such as the United States and China emitted 5,830 Mt and 11,580 Mt CO_2e in 2016, respectively.

Estimates of the emissions caused by minting and printing fiat currencies come in around 8 Mt per year and the gold industry is estimated to generate between 100 and 145 Mt of CO_2 emissions annually.[37,38] Galaxy Digital estimates that the global banking system uses 264 TWh (2019). At the average global carbon intensity of 492 gCO_2/kWh, that would correspond to 130 Mt of CO_2 emissions per year. Using the same carbon intensity calculations, NYDIG estimates that the global Aviation Industry, Marine Transport Sector, Air Conditioners and Electric Fans, Data Centers, and Tumble Dryers each emit 1,982 Mt, 1,503 Mt, 984 Mt, 100 Mt, and 53 Mt of CO_2 annually, respectively.[39]

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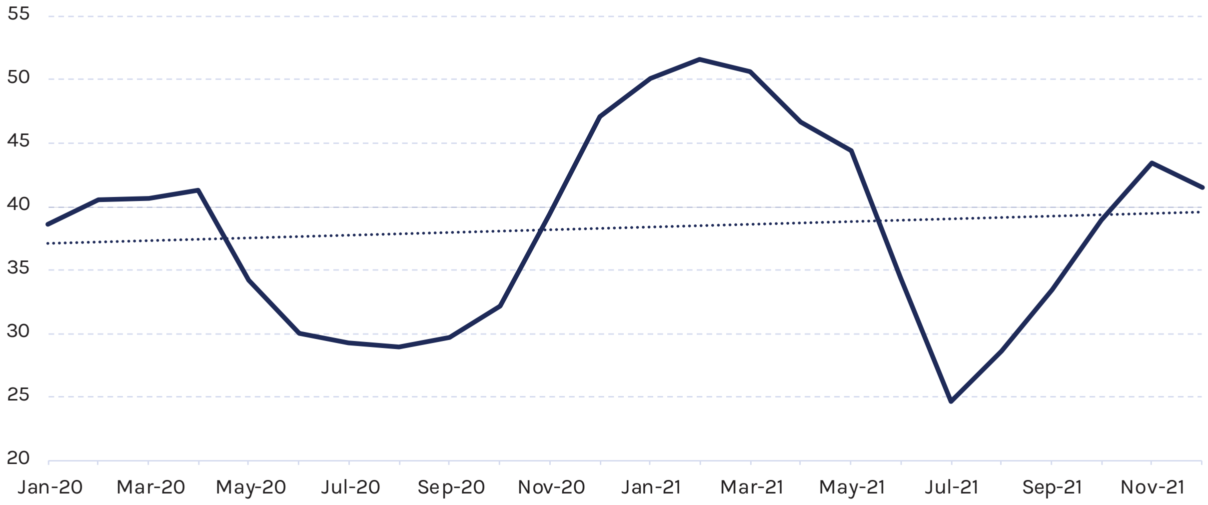
[36] https://ourworldindata.org/co2-emissions
[37] https://docsend.com/view/adwmdeeyfvqwecj2
[38] https://bitcoinmagazine.com/culture/comparison-of-bitcoins-environmental-impact
[39] https://nydig.com/bitcoin-net-zero

FIGURE 9: **TOTAL ANNUALISED NETWORK EMISSIONS BY MONTH (Mt CO_2)**



Source: CoinShares Research (Jan 2022)

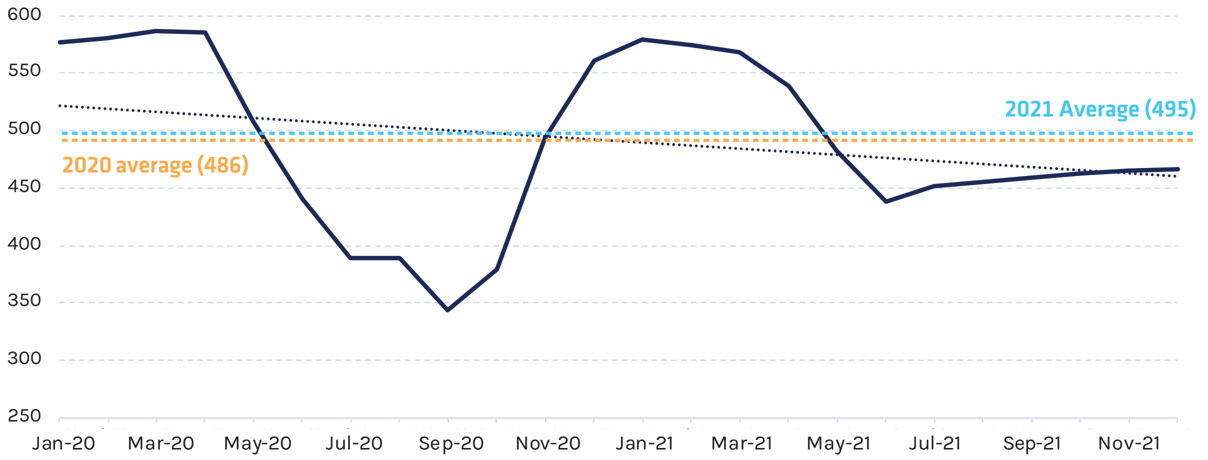
All of the emissions result from three different types of generation sources: coal, oil and gas. Out of the three, coal currently produces almost all of the emissions at 76%, with gas and oil in distant second and third place, currently emitting 21 % and 3%, respectively (see Figure 13). The average figures for 2021 are 82% (coal), 15% (gas) and 3% (oil).

Contrary to what many people might have thought, our calculations suggest that, seen in isolation, migration of hashrate out of China marginally increased the annual average carbon intensity of hashing from 486 gCO_2/kWh in 2020 to 495 gCO_2/kWh in 2021. However, the current carbon intensity of the network as of December 2021 is only 466 gCO_2/kWh.

And, whereas the carbon intensity of the network was previously highly seasonal, it will now likely remain more or less steady throughout the year, meaning the carbon intensity of 2022 is likely to be lower than both 2020 and 2021. So overall, the longer term effect of the Chinese ban will be a reduction of carbon intensity.

The overall trend since January 2020 is also down, but we would be cautious to draw any long-term trend conclusions based on less than two years of data.

FIGURE 10: **CARBON INTENSITY OF NETWORK POWER DRAW BY MONTH (gCO_2/kWh)**



Source: CoinShares Research (Jan 2022)

Our model estimates that under average 2021 conditions, the carbon intensity of the Bitcoin mining network was slightly higher than the global average of 492 gCO$_2$/kWh. At the current run-rate of 466 gCO$_2$/kWh however, the intensity is lower than the global average.

We expect the overall carbon intensity of the network to keep trending down over time. At a minimum, we believe emissions will fall in line with the reductions in the carbon emissions of global electricity generation in general. However, we also expect the reduction to be larger than the global average since miners are more mobile than traditional industries and can move to locations where cheap renewables are constructed, almost no matter how remote the locations may be. This allows miners to take advantage of cheap newly constructed renewable energy generation at a faster rate than other industries.

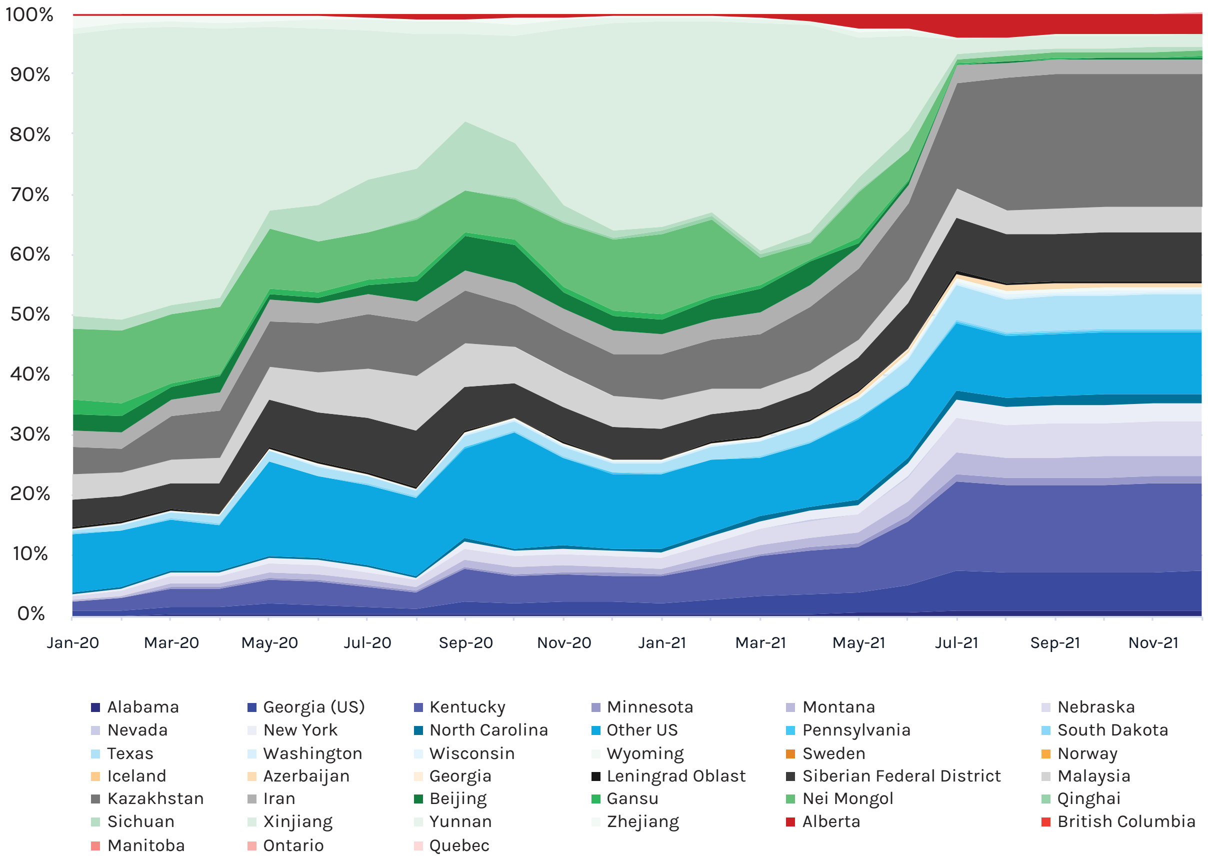
Most importantly though, we expect Bitcoin miners to start consuming large amounts of wasted flare gas. If this becomes a large enough share of the mining energy input, the mining network could become carbon negative.

Regional Differences

Emissions resulting from power generation used by Bitcoin miners are unequally distributed across the world with a small number of regions generating the majority of emissions.

The largest single current emitter is the United States which produces 47% of CO$_2$ emissions. In second and third place we find Kazakhstan (22%) and Russia, respectively. Inside of these countries certain regions are also outsized contributors such as Kentucky (USA, 15%), Georgia (USA, 6.4%), Nebraska (USA, 5.7%), Texas (USA, 5.6%), and the Siberian Federal Grid District (RUS, 8.1%).

FIGURE 11: **PERCENTAGE OF CO$_2$ EMISSIONS BY MINING REGION BY MONTH**

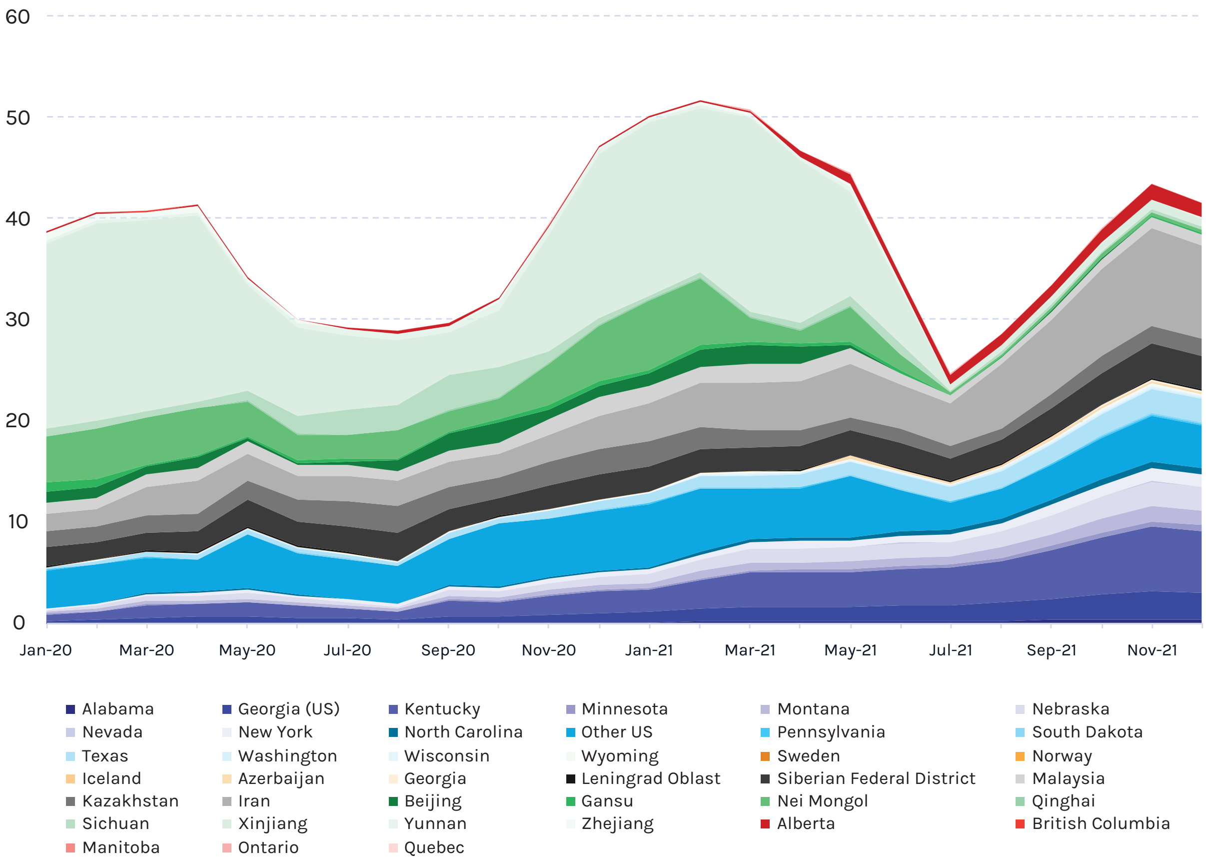


Source: CoinShares Research (Jan 2022)

Before the Chinese ban on mining however, the lion's share of CO_2 emissions came from the two Chinese provinces of Xinjiang and Inner Mongolia (Nei Mongol). Unlike the rest of the world, the Chinese carbon impact from mining has had a profound seasonal variance as miners move between the northern coal rich provinces in the dry season and the south-western hydro-rich provinces in the wet season.

Tables of regional power draw, emissions intensity and total emissions by country and by North American mining region can be found in the Appendix.

FIGURE 12: **MONTHLY ANNUALISED EMISSIONS (Mt CO_2) BY GLOBAL MINING REGION**



Source: CoinShares Research (Jan 2022)

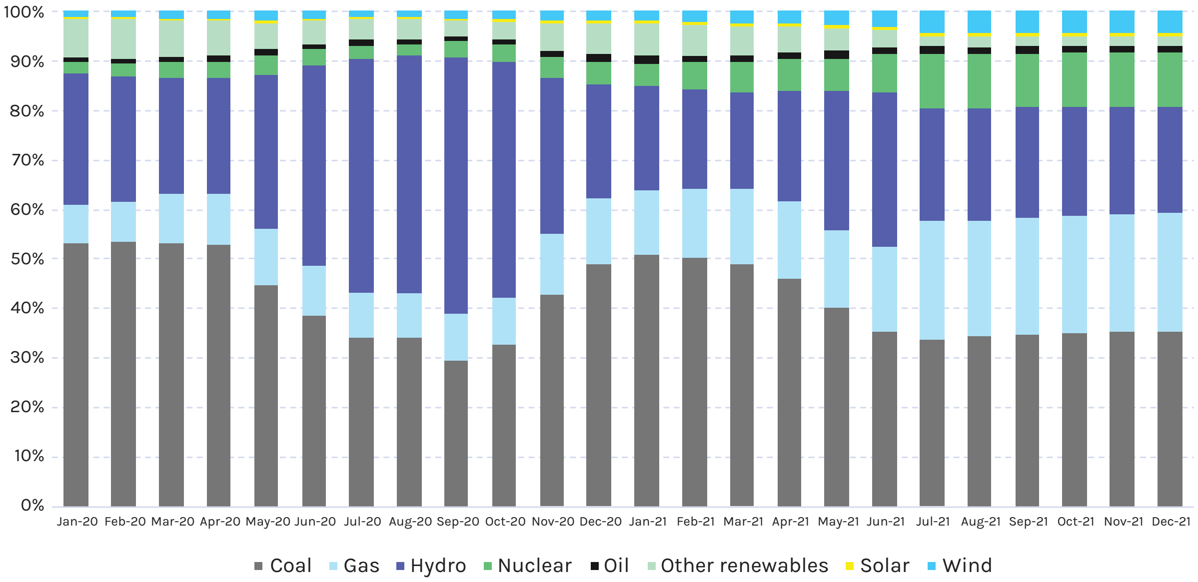
By Power Source

For years, the energy of the Bitcoin mining network has likely predominantly been generated from coal and hydropower, in a seasonal oscillation. After the Chinese mining ban, a large chunk of both generation sources have gone offline, creating significantly larger relative impacts from gas, nuclear and wind.

At the time of writing, the network's electricity generation mix is more balanced than it has ever been since anyone attempted to quantify it. As of December 2021, we estimate the relative contributions of coal, gas, hydro, nuclear and wind at 35%, 24%, 21%, 11%, and 4%, respectively. The remaining generation of 5% is a mixture of small amounts of oil, solar, and other renewables (mainly geothermal).

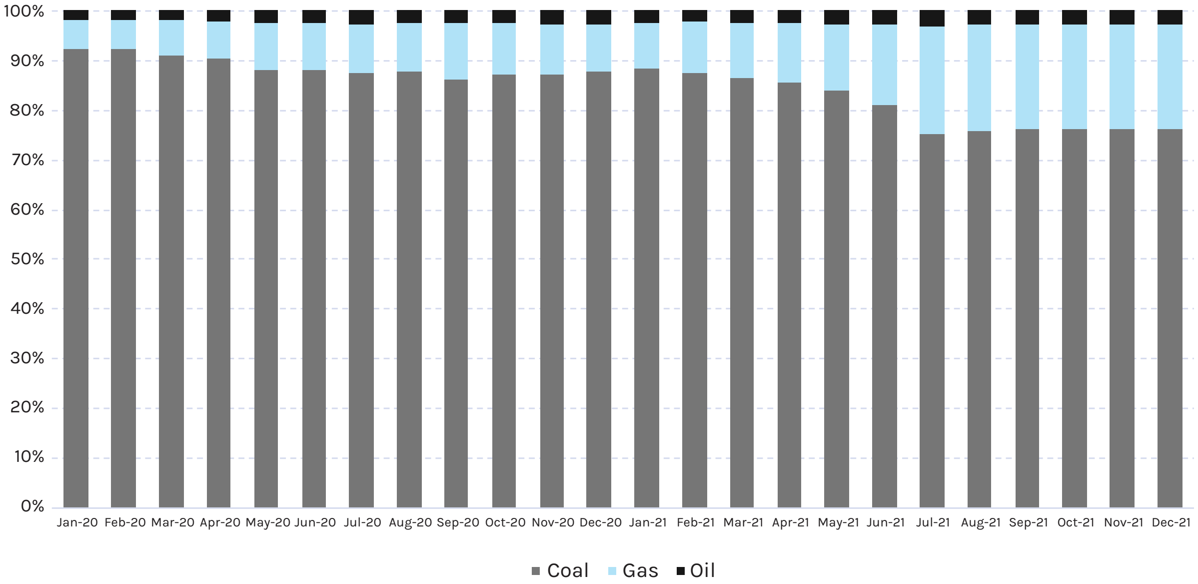
Whereas in the past, the predominant power source of hashrate generation fluctuated dramatically with the Chinese wet and dry season, we now suspect the power sources to be much more stable throughout the year. The Chinese ban has reduced and stabilised both the impacts of coal and hydropower significantly, with natural gas making up most of their relative impact reduction.

FIGURE 13: **NETWORK ENERGY DRAW BY SOURCE (%)**



Source: CoinShares Research (Jan 2022)

FIGURE 14: **TOTAL NETWORK EMISSIONS BY FUEL TYPE**



Source: CoinShares Research (Jan 2022)

Interestingly, even after seeing its total impact on hashrate generation lowered from peaks of more than 50%, down to current levels of around 35%, coal still generates the vast majority (76%) of emissions. As a distant second, we find natural gas which, even though it powers approximately 24% of hashrate, generates only 21% of emissions. Oil is another outsized contributor, generating 2.6% of emissions while generating a paltry 1.3% of hashrate.

DISCUSSION

Overall our findings are broadly in line with recent comprehensive work on the topic.[40] Much of this overlap is to be expected since our input data is largely the same, however, we do believe that the added granularity of our regional breakdowns is more likely to make our model more accurate over time.

Average Network Efficiency

Due to significant and consistent increases in ASIC performance, the overall trend of the mining network is one of reductions in the Joule cost of each hash. We expect this trend to continue for as long as there are more efficient Bitcoin ASIC technologies to be discovered. This causes a gradual and persistent shift in the hardware pool from older inefficient units to newer more efficient ones.

So long as the bitcoin price or on-chain transaction fees paid rise faster than the halvings reduce miner revenues, more hashrate will keep entering the market. Latest-generation machines are often favored in these scenarios as they generate a higher amount of hashrate per unit of electricity input. As the hashrate increases, the difficulty inevitably forces the least efficient machines out, booting the marginally least profitable units off the network.

Even though it holds over time, this dynamic need not be strictly unidirectional. Bitcoin prices can rise much faster than new hardware can be produced, and deployments of latest generation gear can lag investment decisions by 6 months or more. In such periods, previously cashflow-negative hardware can become cashflow-positive again, and since these machines already exist and often reside at or near the facilities they used to inhabit, they may be switched on again.

Re-entrance of previously unprofitable mining gear is however always temporary, as new, more efficient hardware eventually becomes operational, bringing the difficulty back up to levels where less efficient hardware yet again become cashflow-negative.

This dynamic is likely to continue for as long as there remain significant technological efficiency gains to be unlocked from ASICs. While it is implausible that there remains an endless amount of achievable high-magnitude efficiency gains (barring major breakthroughs in microprocessor technology), there may very well be incremental improvements achievable for decades to come.

Alternatively, there could come a time where ASICs are entirely commodified. Under these conditions ASICs would be more or less indistinguishable from one another and compete only on price. Such a scenario would open up a whole new specter of business models such as solar mining or even mining as domestic, commercial, and industrial heat sources.

We find it best to leave the discussion of the likelihoods and potential timings of these scenarios to experts in microprocessing.

Carbon Intensity

Throughout its history, the vast majority of the mining network's carbon output has likely been generated in non-western countries. Prior to June 2021, the four mining regions of Kazakhstan, Iran, Xinjiang and Inner Mongolia alone produced 53% of the total carbon emissions.

Currently, the worst carbon intensity is found in Kazakhstan, Montana, Kentucky and Alberta where large amounts of electricity is generated using particularly carbon intensive fossil fuels such as oil and coal. These four regions generate 43% of emissions while generating only 26% of hashrate.

On the other end of the scale, regions such as Norway, Iceland, Sweden, Quebec and Manitoba produce almost no emissions at all despite generating an estimated 5.2% of current hashrate. What these low-emission regions all have in common is an abundance of hydropower resources, and a relatively large distance between large generation capacities and major demand centers.

Because electricity is not easily transported over long distances, and the marginal cost of hydroelectricity is extremely low, hydropower in locations that are geographically separated from large centers of demand is often some of the cheapest electricity in the world.

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[40] https://nydig.com/bitcoin-net-zero/

The marginal carbon impact of each additional kWh of electricity produced from hydroelectric power generation is effectively zero, and many dams globally operate at suboptimal levels due to seasonal fluctuations in magazines or uneconomical distances to markets. Bitcoin mining is therefore an excellent opportunity to increase the profitability of hydropower facilities without generating emissions, and without consuming resources that are demanded by other market actors.

Using our carbon intensity figures by generation source (which may overestimate carbon intensity versus reality), each kWh consumed for powering Bitcoin mining currently generates 466g of CO_2 whereas the global average is 492g. The average intensities for 2020 and 2021 are 486 gCO_2/kWh and 495 gCO_2/kWh, respectively.

See the appendix for tables of carbon intensities for all mining regions.

Effects of Policy on Emissions

We believe that the regional difference in carbon impact of mining is mainly a policy consequence resulting from the jurisdictions in which miners reside. While western countries are not entirely free from fossil-fuel subsidies, they are much smaller than in countries such as China, Kazakhstan and Iran, where coal, oil and gas are all heavily subsidised by the state.[41,42,43]

Because the mining network is free for anyone to join, and profitability of participation is heavily dependent on the electricity rates paid by miners, it is obvious that mining will have a tendency to flow to jurisdictions with heavy subsidies.

With this in mind, if western jurisdictions—who tend to have much higher penetrations of renewables in their generation mix—have a sincere interest in reducing the carbon impact of the Bitcoin mining network, they should do their utmost to incentivise miners to set up operations in western jurisdictions.

Conversely, the worst thing western governments can do with regards to limiting carbon emissions from Bitcoin mining is to force them out of their jurisdictions via outright bans, punitive taxation or overly burdensome regulation. Such initiatives will have the exact opposite of the desired effect by driving miners further into the jurisdictions where fossil fuels are heavily subsidised, thereby increasing emissions.

Costs of Bitcoin Carbon Offsets

Another interesting take away from the emissions figures is that they can be used to calculate the carbon offsetting cost of holding one bitcoin for one year. Assuming the cost of emissions is shared equally among all holders of bitcoin, at 18.9 million bitcoin outstanding, each bitcoin would require offsetting 2.2 tonnes of CO_2 per year, or roughly the same as one return flight on business class between New York to Tokyo.[44]

The cost of offsetting 2.2 tonnes of CO_2 per year will vary depending on the carbon credits one wants to purchase. If using the European carbon credit market, for example, at 79 EUR/tonne[45] (11 January 2022) the total offsetting cost of holding one bitcoin for one year would be 176 EUR, or 200 USD (11 January 2022). At a bitcoin price of 42,000 USD, this would amount to an annual cost of 0.48%.

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[41] https://www.iisd.org/gsi/faqs/china
[42] https://www.oecd.org/env/outreach/Energy%20subsidies%20and%20climate%20change%20in%20Kazakhstan.pdf
[43] https://www.iea.org/topics/energy-subsidies
[44] https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx
[45] https://ember-climate.org/data/carbon-price-viewer/

CONCLUSION

In the grand scheme of things, the carbon emissions emitted by electricity providers supplying the Bitcoin mining network are inconsequential. At 0.08 % of global CO_2e emissions, removing the entire mining network from global demand—and thereby depriving hundreds of millions of people of their only hope for a fair and accessible form of money—would not amount to anything more than a rounding error.

The Bitcoin network provides a global, freely available, censorship resistant, debasement protected, and human rights preserving monetary network for the entire world. Within that context, we believe the small addition to global emissions is absolutely worth the cost, and clearly, so do the several hundred million global Bitcoin users who are all voluntarily sharing the energy costs of the mining network, while foregoing alternative consumption.

In order to provide its combined services of open, peer-to-peer, objective, censorship resistant and trust-minimised participation in a global monetary network, Bitcoin strictly requires a non-zero amount of input energy in perpetuity. The future magnitude of this requirement is unknown.

Currently, the vast majority of this energy is used for minting new coins, but minting is programmatically preset to geometrically decay to zero over the next 100 years or so. Already by the decade of 2040, more than 99% of all bitcoins will have been minted. Once minting is effectively over, the vast majority of the energy requirement will have to result directly from market demand for bitcoin transaction settlement through transaction fees offered to miners by consumers.

While it is clear that there currently are emissions created as a result of Bitcoin mining, these emissions are not only insignificant on a global scale, but they are in no way necessary in and of themselves. Bitcoin will be 100% renewable as soon as our electricity generation is 100% renewable. Our focus should be on building out renewable power generation, not on stifling the development of monetary technology.

Moreover, the current emission cost must be seen within the context of what the likely future global emissions profile will be in perpetuity, what the market currently requests in terms of monetary technology, and what benefits Bitcoin already provides its users. When analysed over the long term and in proper context, we believe that the emission costs of Bitcoin are dwarfed by its benefits.

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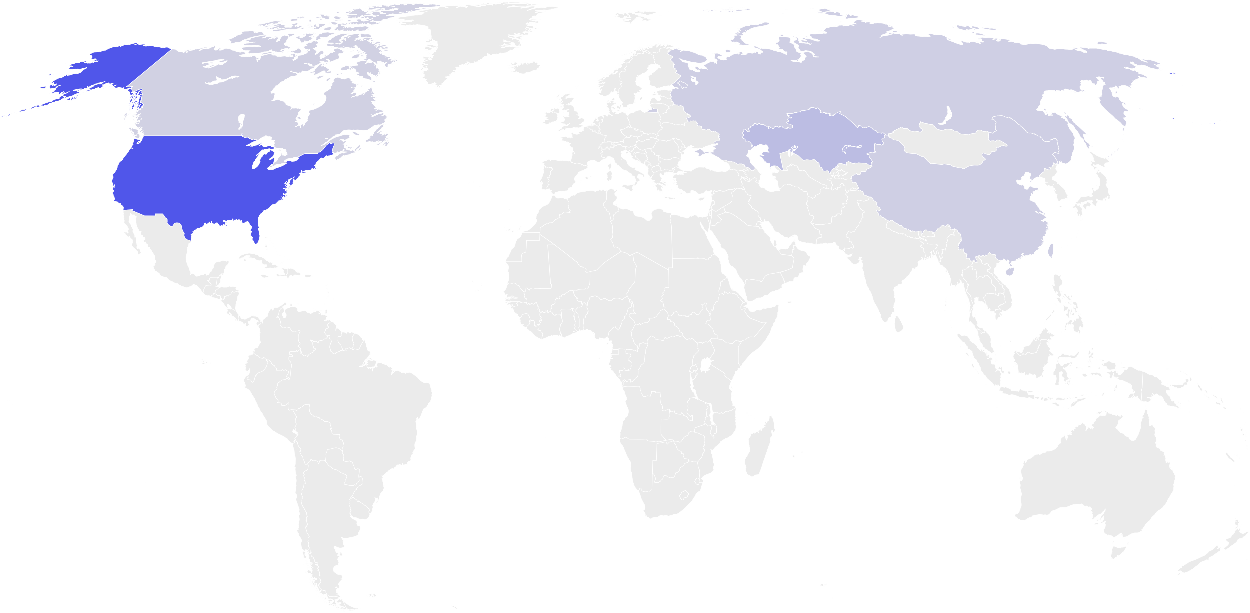
APPENDIX

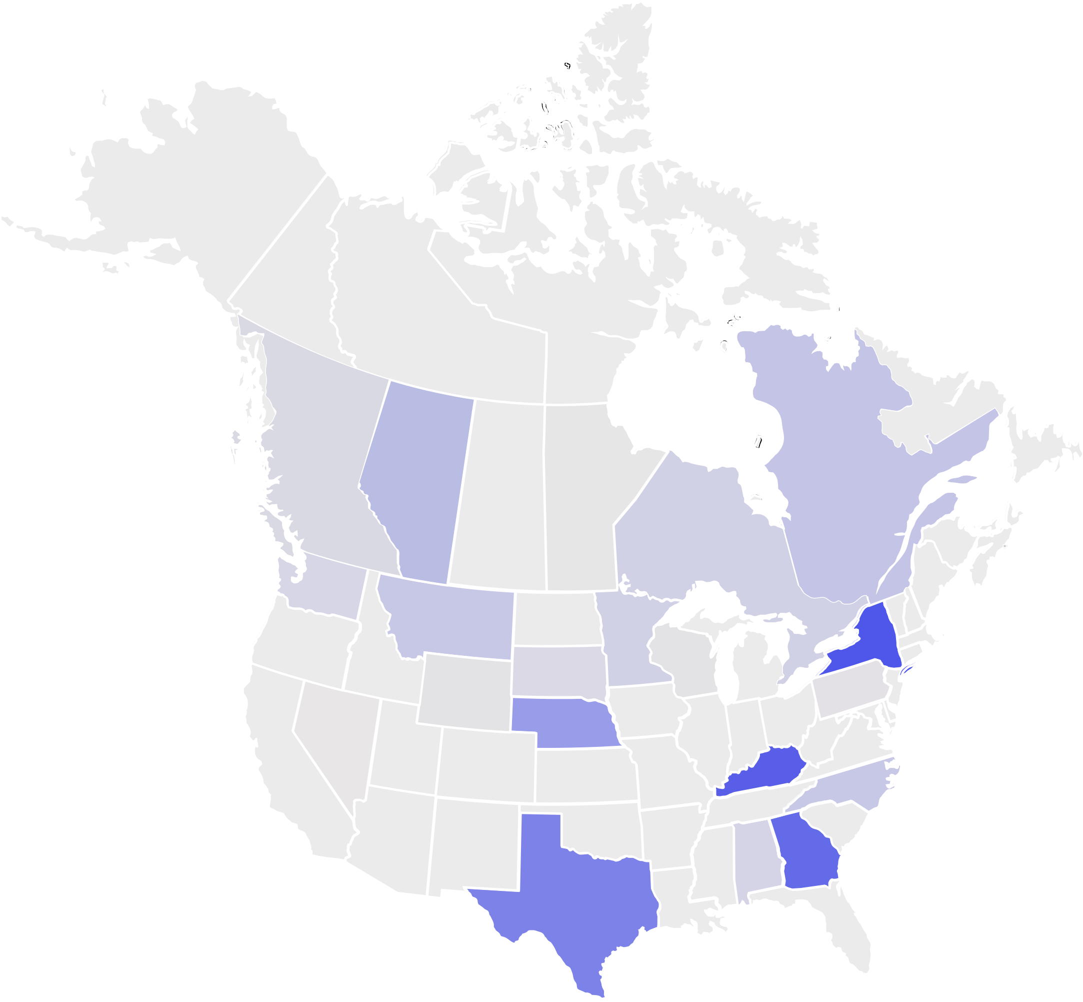
APPENDIX FIGURE 1: **RELATIVE DISTRIBUTION OF HASHRATE IN GLOBAL MINING COUNTRIES**



Appendix Figure 1 shows a map of all global mining countries shaded by MWs of mining hardware deployed. The largest global mining country on the map is the United States with an estimated 49% of total global hashrate.

APPENDIX

APPENDIX FIGURE 2: **RELATIVE DISTRIBUTION OF HASHRATE IN NORTH AMERICAN MINING REGIONS**



Appendix Figure 2 shows the breakdown of mining regions within North America on a relative basis. The largest mining region in this map, New York, is estimated to generate approximately 7.8% of the current hashrate.

APPENDIX

APPENDIX TABLE 1: **ESTIMATED POWER DRAW (INCLUDING PUE), EMISSIONS INTENSITY, AND ESTIMATED EMISSIONS OF GLOBAL MINING COUNTRIES (2021)**

Region	Total Estimated Power Draw (MW)	Carbon Intensity (g/kWh)	Total Estimated Emissions (MT, annualised)
Azerbaijan	31	638	0.17
Canada	712	234	1.4
China	712	318	2.0
Georgia	41	95	0.03
Global	660	492	2.8
Iceland	144	0	0
Iran	237	507	1.0
Kazakhstan	1,350	787	9.2
Malaysia	341	589	1.7
Norway	62	7	0
Russia	846	477	3.5
Sweden	72	19	0.01
United States	5,095	447	20
Sum	**10,300**		**41**
Weighted Average		**466**	

APPENDIX

APPENDIX TABLE 2: **ESTIMATED POWER DRAW (INCLUDING PUE), EMISSIONS INTENSITY, AND ESTIMATED EMISSIONS OF NORTH AMERICAN MINING REGIONS (2021)**

Region	Total Estimated Power Draw (MW)	Carbon Intensity (g/kWh)	Total Estimated Emissions (MT, annualised)
Alabama	134	360	0.4
Alberta	256	614	1.4
British Columbia	83	33	0.02
Manitoba	21	1	0
Ontario	134	35	0.04
Quebec	217	4.1	0.01
Georgia	805	381	2.7
Kentucky	867	810	6.1
Minnesota	144	391	0.5
Montana	206	791	1.4
Nebraska	484	566	2.4
Nevada	10	336	0.03
New York	928	156	1.3
North Carolina	206	356	0.6
Other US	351	398	1.2
Pennsylvania	41	349	0.1
South Dakota	82	179	0.1
Texas	650	411	2.3
Washington	113	130	0.1
Wisconsin	41	586	0.2
Wyoming	31	830	0.2
Sum	**5,807**		**21**
Weighted Average		**420**	

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