Carbon-Neutral Bitcoin for Nation States

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Abstract. Sovereign adoption of bitcoin, whether as legal tender or in treasury reserves, increases the profitability of energy-intensive bitcoin mining, creating significant carbon emissions. This paper explores methods for adopting bitcoin while mitigating or eliminating associated carbon emissions. We survey three solutions: regulation/taxation, carbon offsetting, and finally, state-directed or state-supported carbon-neutral mining, arguing for the advantages of the latter. We then compare two ways of executing this last approach: (1) the state must mine all its bitcoin holdings; (2) the state must mine the same percentage of mining as its percentage of all bitcoin holdings. We show that (2) is a superior method, and that a nation state can adopt bitcoin in a carbon-neutral manner with a relatively small investment in carbon-neutral mining. At present levels of bitcoin mining and bitcoin pricing, an annual allocation of around 1% of the state's bitcoin holdings towards mining will suffice, and may generate a positive return. El Salvador is used throughout as a case study, and we make specific suggestions for how much El Salvador should mine to achieve carbon neutrality with respect to their bitcoin holdings.

Keywords: Bitcoin · environment · carbon · carbon-neutral · ESG · mining · cryptocurrency

1 Introduction

In 2021, El Salvador adopted bitcoin as legal tender alongside the U.S. Dollar, setting aside $150 million for a trust to facilitate dollar/bitcoin exchanges [1]. The bitcoin network is known to be energy-intensive—consuming a quantity of electricity somewhere between that of the Netherlands and Argentina—and El Salvador's actions would arguably, in the absence of countervailing initiatives, increase their nation's CO_2 emissions [2]. But how much emissions does such adoption involve? And what countervailing initiatives are at El Salvador's disposal? Is it possible to adopt bitcoin with no addition to carbon emissions, or even in a carbon-negative way, achieving emissions targets or commitments? If so, what would that require, and how much would it cost?

The present paper answers these questions, not just for El Salvador, but for any state exploring bitcoin adoption. We first review the energy consumption and emissions associated with bitcoin adoption and show how bitcoin holdings and transactions incentivize

S. Matsuo et al. (Eds.): FC 2022 Workshops, LNCS 13412, pp. 55–65, 2023.
https://doi.org/10.1007/978-3-031-32415-4_4

mining and its externalities. We then critically examine the options for mitigating those externalities through regulation or taxation. We next entertain carbon offsets, calculating the cost of such measures and evaluating their effectiveness. Finally, we propose an alternative, which is state-sponsored or state-incentivized carbon-neutral mining. We argue that due to the unique properties of bitcoin—its limited supply, fungibility, and fast, nearly-free transportability—such mining can fully offset the emissions from adoption.

We then compare two systems of calculating how much carbon-neutral bitcoin mining the state must either manage itself, or else incentivize through subsidy: (1) the state must mine all its bitcoin holdings; (2) the state must mine the same percentage of mining as its percentage of all bitcoin holdings. Our conclusion is that (2) is the superior method, and that a nation state can adopt bitcoin in a carbon-neutral manner with a relatively small investment in carbon-neutral mining, allotting, at present rates of mining and bitcoin pricing, only 2% of the state's bitcoin holdings annually towards mining, which should itself have a positive expected return. In the case of El Salvador, the nation is, in fact, already engaged in the sort of carbon-neutral mining that we prescribe, using geothermal energy [3]. We conclude by showing exactly how much hashrate El Salvador's pro-bitcoin policy decisions require them to generate if they wish their bitcoin adoption to be carbon neutral.

2 Externalities of Bitcoin Adoption

In the rest of this paper, "sovereign adoption of bitcoin" means any combination of the following: legal tender laws, treatment as currency (not property) under tax law, direct acquisitions in the treasury, and/or state-owned or state-guided bitcoin wallet services, bitcoin ATMS, or "airdrops" to citizens. Bitcoin stands apart from other cryptocurrencies on account of its founding, culture, and product-market fit [4]. A standard suite of reasons for individuals to use bitcoin include its censorship resistance and independence from legacy monetary institutions [5–7]. Sovereigns may or may not endorse that suite of reasons. But they have their own distinctive reasons to adopt, including enhancing financial inclusion, seeking protection from inflation, attracting foreign investment, lowering the cost of remittances, and escaping the colonial effects of dollarization [1]. These reasons are all, unsurprisingly, contested by organizations from the IMF to the Bank of England, who warn against bitcoin adoption on the grounds of volatility and regulatory risk [8].

We will not here adjudicate these disputes. Instead, we simply ask how states that have already decided to adopt bitcoin can best do so, especially with respect to emissions. The thought here is not complicated. States are positioned, perhaps uniquely, to coordinate behavior towards climate goals. Many have made explicit emissions commitments, and so are morally or legally obligated to pursue carbon-neutral or carbon-reducing strategies across the board. Bitcoin's poor environmental reputation at present offers states an additional reason to adopt bitcoin only in a way that minimizes emissions. Cleaning up bitcoin can only advance the other goals of bitcoin adoption, say, financial inclusion or monetary independence from the dollar.

We mark bitcoin adoption along two dimensions: (a) additional holdings of bitcoin due to government measures, whether by the government itself or by private entities as a result of favorable legal measures; (b) additional on-chain bitcoin transactions, again due either to the government itself engaging in bitcoin transactions or an increase in private transactions due to favorable policy. The process of calculating any particular instance of adoption in these terms lies, again, beyond the scope of this paper, which simply takes adoption as a two-fold input: additional transactions and additional holdings of bitcoin. From these two inputs, we can roughly estimate how much additional CO_2 is emitted into the atmosphere. Since this paper is a proof of concept only, we will use a rough estimate, to be refined in later work.

3 Economics of Bitcoin Mining

Mining is the process by which new transactions are published to the blockchain. Miners assemble candidate transactions from the mempool into blocks and search for a number, a nonce, which when appended to the block header and fed into double SHA-256, yields an output number. If that output number begins with a certain number of zeros, the miner's block will be accepted as valid by the network of full nodes, provided there are no competing chains of blocks that are longer.

The winning miner publishes a block and receives a block subsidy for their efforts, as well as any fees associated with candidate transactions. What matters for our purposes is that the block subsidy and transaction fees exhaust the sources of miner income, and both are denominated in bitcoin. Currently, the block subsidy is 6.25 bitcoin per block, and transaction fees are less than 2% of mining rewards.

Note three points. First, the miners' search is essentially random, and involves checking vast quantities of numbers to see if they solve the puzzle. That search, in turn, requires both energy and specialized hardware. Second, the difficulty of the search adjusts to ensure that on average, new blocks are created every ten minutes. If blocks are mined faster, the search becomes more difficult—more zeros must appear in front of the output of the nonce-appended-to-block-header input. If blocks are being mined at intervals of greater than ten minutes, the difficulty will decrease—fewer preceding zeros required—until, once again, block times return to ten minutes. Third, the issuance of bitcoin is scheduled to halve every four years. In the first epoch, miners were rewarded with 50 bitcoin for publishing one block, then 25, then 12.5, and now 6.25, and soon 3.1255, and so on. This schedule creates a capped supply approaching 21 million bitcoin prior to the year 2140, at which time mining will be incentivized entirely by fees.

Bitcoin mining, then, is a world-wide search for the next block, to be rewarded in bitcoin, and the issuance of new bitcoin is entirely predictable over a long time scale. More mining, crucially, does not, except in the very short-term, lead to more bitcoin being found. Rather, more mining simply means more computing power chasing after exactly the same amount of bitcoin, which right now is 6.25 bitcoin per block, or 900 per day.

The value of that reward, while entirely predictable in bitcoin terms, is itself a function of bitcoin's market price. A 6.25 bitcoin block reward when bitcoin trades at \$60,000, is significantly more enticing than a 6.25 bitcoin block reward when bitcoin trades at \$6,000. Miners make capital investments in specialized mining hardware, substations, copper wire, and so on. They also carry operating expenses including labor, but most of all, electricity itself. These investments are made, broadly, by estimating bitcoin's future price, the chance of winning block rewards, and the costs of power, infrastructure, and labor required to win those rewards. Predictions of a higher future price inspires miners to invest, while increasing hashrate, and therefore, increasing competition for the fixed issuance of new bitcoin, depresses miners' investment. A predicted drop or stagnation in prices depresses mining investment, and a drop in hashrate promotes mining investment, since with less competition the same block reward requires less work—computing cycles, and hence, less infrastructure and electricity, to win.

4 The Adoption-to-Mining Emissions Relationship

We have marked adoption in two ways: sustained or increased holding of bitcoin over time, and adding to the quantity of transactions. And we have seen how mining is incentivized: price of bitcoin and lack of competition from other miners over a fixed reward. We are now in a position to say how sovereign adoption of bitcoin creates bitcoin-mining-related emissions.

Begin with transactions. Each transaction carries a bitcoin-denominated fee, paid to miners for inclusion in a block. If adoption were to increase demand for scarce blockspace—on-chain transactions are limited to a maximum of about seven transactions per second—that would increase the rewards for mining, which would lead to more mining, which would lead to more emissions. Estimating the on-chain transaction increase *due to* adoption is difficult, because the state only knows its own transactions are "due to" its actions; other increases will be indirect. But again, that estimate is outside of the scope of our paper, which simply takes the increase as an input. Once given the increase in transactions over a give time period, one need only multiply the additional transactions by the average on-chain fee during the time period in question, and multiply that by the average price of bitcoin at that time to estimate the additional incentive offered to miners by the transaction-fee-related adoption of bitcoin in that time period.

$$\text{Adoption from fee incentives to miners} = \text{additional txs} \times \text{avg tx fee} \times \text{avg BTC price} \tag{1}$$

As stated earlier, transaction fees constitute only 2% of miner revenue. States will likely adopt bitcoin using more efficient second-layer solutions like the Lightning Network or other custodial payment systems, which minimize blockspace demand and thus fees, by settling on-chain infrequently. Despite dire warnings that the bitcoin network would be unable to handle the volume of transactions caused by Salvadoran adoption, blockspace has actually become cheaper and more available than before the bitcoin laws were passed, proving that second-layer solutions can support a high volume of transactions without burdening the base layer. Because transactions are such a small percentage of mining rewards and because sovereign adoption does not appear to put pressure on block space, we will hereafter ignore the channel of influence that adoption has on emissions via transaction fees. In terms of the formula above, the additional transactions are negligible, and the average transaction fees are negligible as well.

What we must focus on, instead, is the other channel of influence: sovereign adoption increasing the price of bitcoin. El Salvador, for instance, has acquired 1,400 bitcoin [9].

Doubtless, more bitcoin are also held by citizens because of the state's decision, and one may or may not want to include this increase in bitcoin holdings as well as the government's responsibility. Again, such an estimate is difficult, and again, it is beyond the scope of this paper. For the purpose of this exercise, we will limit ourselves to calculating the emissions due to the government's own holdings, leaving the additional private holdings as the responsibility of those private entities.

Here is how the state's holding, say, 1,400 bitcoin, causes carbon emissions. By buying and holding that quantity of bitcoin, the government removed that same quantity from order books, driving up price to the next-most-reluctant seller. That increase in price makes the fixed block reward more valuable. 6.25 bitcoin is worth more than it otherwise would be. That leads to more mining, which in turn leads to more emissions. This influence on price from holding, crucially, *is not a one-time event*. Purchasing bitcoin removes it from the marketplace, leaving the same dollars (bids) chasing fewer available bitcoin (asks). Additionally, every day the bitcoin holdings are not sold is a day when price is higher than it otherwise would be. This stable and high price (as opposed to a mere momentary spike) is what induces miners to make long-term investments in the aforementioned specialized mining hardware, substations, copper wire, and so on.

When it comes to determining exactly how much price impact a given purchase, and subsequent period of holding bitcoin, causes, there are two distinct methods. The first is our preferred method, and that is to begin with the recognition that price is a function of the entirety of buyers-and-holders of bitcoin. That is, the price being as high as it is reflects the collective decisions of all holders of bitcoin, any of whom could sell at any moment, but doesn't. Every non-seller is like every other non-seller, who is not selling an equal amount of bitcoin, in other words. And it is the aggregate non-selling of all bitcoin holders that keeps the price from dropping. Thinking in this way, an individual holder's responsibility for price is strictly proportionate to their holdings. So, if one owns 1% of bitcoin, one is 1% responsible for price.

Extending this thought to the incentivization of mining, an individual holder can be thought to incentivize a certain percentage of all mining. For instance, if someone holds 1% of all bitcoin, one is incentivizing 1% of all bitcoin mining by bearing 1% of all responsibility for price. This formula distributes the responsibility for incentivizing mining evenly across all holders. It leaves no mining unaccounted for, and it does not double-count incentives by concluding that the total incentives created by holders is greater than the total amount of incentives.

The formula here is that at a given time:

$$\text{One's holdings as a \% of market cap} = \text{\% of all mining one incentivizes} \tag{2}$$

For El Salvador, this method would first calculate the government's share of all bitcoin. Since nearly 3 million bitcoin have been lost, the total number of bitcoin is close to 16 million, of which El Salvador's 1,400 bitcoin is 0.00875%. So, according to this method of accounting, El Salvador's adoption of bitcoin is responsible for incentivizing roughly .00875% of all bitcoin mining over the period during which they have owned that bitcoin. To determine the emissions caused by adoption, we need two further steps, which is to calculate the total energy required by the network, and then calculate the carbon emissions required to produce that amount of energy, given the mix of energy sources of the bitcoin mining network. Then we can attribute .00875% of those emissions to El Salvador's bitcoin adoption.

On the question of how much energy the bitcoin network consumes, there is little disagreement. We know the difficulty of the math problems miners are solving, and the block times, which hover around 10 min, and we know roughly the hardware mix being used by miners, and how fast that hardware solves the math problems, and, as well, how much electricity those machines must consume in order to solve the problems at the rate they are being solved. Currently, the estimates are that the bitcoin network is calculating at a rate of 165 exahash/second: 165 quintillion total guesses by miners, per second [10].

The bitcoin network's mix of power sources is more contested, with estimates ranging from 39% to 73% renewable energy [11]. The Bitcoin Mining Council is composed of large commercial miners and surveys its constituents—65.9% renewable powered—as well as estimating the power mix of non-members, arriving at a total estimate of 57.7% renewable-powered [12]. Uncertainty is multiplied because carbon-intensive forms of electricity production vary in the quantity of carbon emitted per unit of power produced. And further, miners vary in efficiency, and the exact distribution of miners in operation is unknown. Alex de Vries, a well-known critic of bitcoin mining estimates that the total emissions from the network is currently 97 megatons of CO_2 annually, or roughly equivalent to the carbon footprint of Kuwait [13]. Taking de Vries' estimate, together with one's percentage of the network, one can derive one's share of all emissions incentivized by adoption. For El Salvador, that is .00875% of 97 megatons, or roughly 8.5Kt of CO_2.

In sum, adoption incentivizes mining in two ways: by creating new block demand, driving up transaction fees, and by elevating the price of bitcoin. We suggest that transaction fees are, at this time, such a small percentage of miner's income, and so unaffected by sovereign adoption due to layer-2 payment systems built atop bitcoin's main chain, as to be safely ignored at this time. We also propose that the right way to calculate the percentage of all mining due to bitcoin price increases resulting from adoption is to treat the entirety of bitcoin investment as the entirety of price-based incentive for mining, and then to determine how particular holdings incentivize mining, calculate the same percentage of all mining as the percentage of all holdings: if a state's adoption is x% of all bitcoin holdings, the state has incentivized x% of all mining. Finally, to calculate the emissions caused by adoption, find x% of all bitcoin-mining-related emissions during the period of adoption. This total number is difficult to estimate, depending as it does, on a number of factors including the energy mix and the efficiency of mining hardware. There are further complications to any simple calculation due to the substitution of bitcoin mining for existing electric heating, and mining's role in stabilizing the electrical grid. Those are important, but will be ignored in this paper for the sake of simplicity.

5 Three Emissions Mitigation Strategies

In this section, we examine three strategies for reducing the carbon footprint associated with sovereign adoption of bitcoin: regulation, carbon offsets, and carbon-neutral bitcoin mining, arguing for the advantages of the latter. We then present two strategies for calibrating carbon-neutral bitcoin mining: purchasing only renewably-mined bitcoin and creating or subsidizing renewably-powered hashrate in ongoing fashion, in proportion to state holdings.

5.1 Coase and Pigou

The policymaker's toolkit for managing externalities derives from work by Ronald Coase and Arthur Cecil Pigou [14, 15]. The former argues that with sufficiently clear property rights, information about externalities, and bargaining power, externalities will be properly priced in and efficiency achieved by free exchange. The latter argues that externalities are best managed by a tax that adds the social cost to the price of a good. Coase's observations are inapplicable to bitcoin mining because the externalities of bitcoin mining are diffuse, spanning the entire global population and following generations, who lack the standing or the ability to sue for ill-defined damages and thereby prompt bargaining before creation of the externality. Pigouvian taxes, on the other hand, are feasible, and might be implemented as a tax on miners using carbon-intensive methods of power generation so as to discourage the activity and prompt miners to shift to using renewable sources of energy.

The problem with taxing carbon-intensive mining operations, or for that matter, banning them entirely, is the global, frictionless, nature of the mining market, as well as the difficulty of enforcement. When China banned bitcoin mining, global hashrate dropped by 50%, but recovered within a few months, with a significant proportion still happening in China itself [16]. The mining incentives outlined above do not recognize national borders, and with a ban in one country, mining will simply move elsewhere. Because bitcoin's payment network is expensive to censor and pseudonymous, there is also no viable way to tax bitcoin that has been mined using carbon-intensive energy sources, as one could, for instance, with manufactured goods, by interdicting them at ports and other borders.

Indeed, bitcoin mining represents the limit case of carbon arbitrage. A carbon tax or a ban moves production elsewhere while affecting total mining not in the least. Bitcoin's issuance is an inelastic 900 bitcoin per day, and that remains the same regardless of who is banning mining. So a ban in one location drops global hashrate and makes profitability per unit of computing power rise, thereby spurring additional mining elsewhere.

5.2 Carbon Offsets

A second mitigation strategy is the purchase of carbon offsets. We have already calculated, very roughly, the carbon footprint of El Salvador's adoption, for instance, at 8.5 Kt annually. Carbon offsets are devices that either remove carbon from the atmosphere, e.g., by planting trees, or prevent other greenhouse gas emissions, e.g., burning landfill methane to generate power, or not harvesting a forest that otherwise would have been harvested. Thus, the emissions that result from mining are offset by emissions removals or reductions elsewhere.

Carbon offsets currently range widely in price, and are projected to rise dramatically in value over the next decade, as it is a common means of meeting pledges to achieve "net zero emissions" for firms and organizations, and there simply are not enough offsets available to meet all of those pledges via offsetting. At a price of $10 per ton of CO2, for quality offsets, El Salvador's annual cost for offsetting its holdings would be $80,500 on their $150,000,000 holding or .054%.

Carbon offsetting may work as intended. But it has two major drawbacks. The first is cost: while .054% annually is minor at present, these prices are expected to rise ten-fold, and potentially more, as the technique becomes more widespread. Second, and more worryingly, it is unclear that carbon offsets actually work as intended. For instance, the Massachusetts Audubon Society pledged not to log 10,000 acres of forest land, and in turn was awarded and then sold ½ million carbon credits, which were then sold to oil and gas companies for $6 million [17]. The oil and gas companies could then claim to have offset the emissions associated with their product, while arguably no actual offsetting was achieved. Had the credits not been sold, the Audubon Society would still not have logged their forest, destroying bird habitat and angering their donors. So while money exchanged hands, no additional carbon was removed from, or prevented from entering, the atmosphere by the purchase of those carbon credits.

This example is by no means unique. Some estimates suggest that over half of offsets induce no net change in carbon emissions [18]. And other analysts estimate that more than 90% of offsets deployed by large corporations are pointless and may even exasperate global climate change [19]. Of course, such abuses may be tamed, but they remain a concern, and if an option is available that simply prevents carbon emissions associated with mining, that would seem more certain a reduction, other things equal, than an option that first emits carbon, then attempts to find carbon savings elsewhere.

5.3 State-Sponsored Carbon-Neutral Bitcoin Mining

The final approach to mitigating mining's externalities is for the state either to engage in mining itself, or to incentivize private companies to mine bitcoin, but on the condition that such production is accomplished with carbon-neutral sources of energy. We will consider two such methods.

First, the state could simply buy bitcoin directly and only from "green" miners, i.e., mining operations that have used renewable energy sources to mine their bitcoin. At scale, this would create a price premium for "green" bitcoin. Equivalently, firms could issue one token for each "greenly-mined" bitcoin, and sell the tokens to nation states and other actors wishing to hold "green bitcoin."

The problems with simply buying "green" bitcoin are many. Some stem from the nature of mining incentives from holding bitcoin reviewed above. Miners are incentivized to make capital investments not by a single purchase, but by the sustenance or increase in bitcoin price due to holdings over time. A long holding period of a given amount of bitcoin incentivizes mining over that entire period, whereas a short holding period of the same amount of bitcoin provides less incentive. To illustrate, some of the earliest coins were mined with a negligible amount of energy, as the network was very small, difficulty was low, and there was almost no competition from other miners. Those coins were "green", if any are. But despite that unimpeachable provenance (they have been held since 2009), those coins have incentivized a great deal of mining. For the non-selling of those coins has been equivalent to the non-selling of any other coins in the period. Simply buying "green" coins ignores this temporal variable entirely: once green always green, regardless of holding period, which is a mistake. Green provenance is not enough.

Along these same lines, more than 90% of all bitcoin have already been mined. Since the "greening" designation is a recent introduction, at most around 10% of coins can be deemed green. To see the absurdity of this limitation, consider that if the entire bitcoin network were to operate on renewable energy in perpetuity, and the network as a whole produced zero carbon, only 10% of bitcoin would be considered green under the provenance accounting. This would be another serious mistake.

Finally, the designation of some bitcoin as green and other bitcoin as non-green threatens the fungibility of bitcoin itself. Since fungibility is a key property of money, and bitcoin's promise and value is tied to its monetary functions, the sacrifice of fungibility threatens the value and identity of bitcoin itself. Essentially, designating some coins as "green," one is creating a new token--green bitcoin--which is a bitcoin fork and only has, at most, 2 million coins. This is a non-started for any parties interested in bitcoin as an emerging asset and monetary network.

There is a better way.

5.4 Our Proposal: Proportional Green Bitcoin Mining

What we propose, rather than the state buying "green" bitcoin, is that the state itself mines with renewable energy, or incentivizes a certain amount of such mining with subsidies or tax breaks, in proportion to their holdings. To review our explanation of miner incentives, recall that sovereign adoption of bitcoin incentivizes the same proportion of all mining as the proportion of all bitcoin that adoption entails. Our proposal is that the state should mine, or sponsor, this very same amount. In other words, our proposal is that, in order to claim their bitcoin adoption is carbon neutral, the state should, in a carbon-neutral way, mine the amount of all mining that their adoption incentivizes, which is—recall Eq. 2—the same percentage of all mining as their percentage of all bitcoin.

$$\begin{aligned}\% \text{ of all mining one incentivizes } \times \text{ all mining for the duration of holding} \\ = \text{amount of mining required}\end{aligned} \tag{3}$$

To illustrate, El Salvador's $150m in bitcoin holdings represent 0.00875% of all bitcoin. The total rate of mining is 165 exahash/second. That same percentage of all mining is 14.4375 petahash/s. Our recommendation is that, right now, El Salvador use its geothermal facility to achieve this same hashrate: 14.44 petahash/s. If they do, they will have done the very same amount of mining that their holdings incentivize. They will have done their part to make their portion of bitcoin carbon-neutral: no more, no less.

What would such a mining facility look like? An Antminer S19 Pro operates at 100 TH/s; to achieve 14.44 PH/s would require 144 machines. Each machine draws 3,050W of power, so the whole mining operation would only require 440 KW.

How much would that cost? We might attempt to model an entire facility and its costs. But there is an easier way. First, assume that mining operates on at least a break-even basis. Find the ratio of bitcoin's market cap to miner revenue for a given period. Total annual mining revenue is approximately $16b, of which El Salvador is incentivizing $1.4m. If mining is break-even for El Salvador, then, they should spend $1.4m on mining annually--approximately 1% of their total bitcoin reserve--or $350,000 quarterly, in order to achieve carbon-neutral bitcoin adoption.

Note that mining is, in truth, profitable–those $350,000 quarterly investments in mining will inject new bitcoin into the country's reserves–so they may, on net, actually spend less than our estimate. They will also have to readjust their investment over time, as hashrate and price both fluctuate, and the percentage of all holdings El Salvador holds will also drop slowly with new issuance, in order to make sure they continue to mine all of the bitcoin mining they incentivize.

6 Conclusion

We have surveyed three strategies for ensuring that bitcoin adoption by states is carbon neutral. The first strategy--taxation and regulation--while familiar to policymakers, is uniquely ill-suited to managing bitcoin's externalities. Because bitcoin is fungible, easily-transported, uncensorable, and not easily located, and because its issuance is fixed by the protocol, any attempt to heavily tax or ban carbon-intensive bitcoin mining will simply displace mining to friendlier locales with no effect on the bitcoin network's total emissions.

The second strategy, carbon offsets, fares better, but has at least two drawbacks: a rising cost and difficulty proving "additionality," i.e., that one's offsets are actually reducing carbon emissions.

Finally, the third strategy of the state mining itself, or incentivizing such mining with tax breaks, in a carbon-neutral way, can take two forms. The first is for the state to mine all of its own coins with renewable power, or to purchase its coins from a green miner. We criticized this solution on a number of fronts: it both recommends too much green mining, since if the entire network were green mined in perpetuity, this system would wrongly deem 90% of all bitcoin non-green, and it also recommends too little green mining, since it ignores the temporal variable, the length of one's bitcoin holding period, in calculating mining incentives.

We offer a different formula. We suggest that a state should mine, using carbon-neutral sources of energy, the same percentage of all mining as the percentage of all bitcoin that it owns during the entirety of its interval of ownership. In this way the state will mine all of the incentive that it provides to bitcoin miners by virtue of its holdings. The state will, therefore, be responsible for no additional mining except its own. What this means in practice is that the ratio of a state's holdings to its mining budget for a period is equal to the ratio of bitcoin's market capitalization to bitcoin's entire mining budget for a given period. As of this writing, that ratio is close to 99-to-1 on an annual basis, and higher if we choose a shorter time period. What we conclude, then, is that a relatively small amount of bitcoin mining is sufficient to "green" a large bitcoin holding. Sovereign adoption of bitcoin can, therefore, very easily be made carbon neutral, and consistent with any emissions commitments. All of this is possible without the aid of either carbon offsets or more drastic regulatory measures.

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