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Cryptocarbon: How Much Is the Corrective Tax?*

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ABSTRACT: With increasing awareness of past environmental damage from crypto mining, questions arise as to how persistent the problem will be in the future and how taxation can help in addressing this negative externality. We estimate that the global demand for electricity by crypto miners reached that of Australia or Spain, resulting in 0.33% of global CO₂ emissions in 2022. Projections suggest sustained future electricity demand and indicate further increases in CO₂ emissions if crypto prices significantly increase and the energy efficiency of mining hardware is low. To address global warming, we estimate the corrective excise on the electricity used by crypto miners to be USD 0.045 per kWh, on average. Considering also air pollution costs raises the tax to USD 0.087 per kWh. Country-specific estimates vary depending on their electricity sources.

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1 Introduction

The rise of crypto assets has been associated with a massive demand for electricity by crypto miners, thereby contributing to global warming.¹ In particular, the ‘proof-of-work’ mechanism²—the common protocol to authenticate Bitcoin’s transactions, among other crypto assets—is energy-hungry and tends to demand more electricity as prices of crypto assets go up. We tackle two issues here: the size of the problem and the needed corrective tax policy. Small, yet growing literature, addresses the first issue, but existing estimates remain rather scattered focusing only on Bitcoin or a specific year. We consider CO₂ emissions from the mining of Bitcoin and other crypto assets, providing systematic estimates for 2017-2022 and projections for 2023-2035. We further expand the literature by estimating the corrective tax—an issue that has been thus far left unaddressed in the literature but increasingly discussed by policymakers.

We coin the term ‘cryptocarbon’ as tons of carbon dioxide (CO₂) emissions from crypto mining. In 2021—the peak year for Bitcoin prices—, we find that authenticating one Bitcoin transaction was equivalent to roughly three years of electricity consumption for a typical Ghanaian, or three months for a typical German. Globally, we find that total crypto mining in 2021 demanded almost as much electricity as Australia or Spain, and cryptocarbon comprised 0.33% of global CO₂ emissions (about 120 million tons of CO₂), taking into account renewable energy sources of electricity.

Estimates indicate that cryptocarbon will likely remain a concern in the next years. The two key factors that determine the development of future cryptocarbon are the energy efficiency of mining equipment and crypto prices (the higher the price, the higher the return, and hence more mining). The results suggest that by 2027 cryptocarbon will contribute almost 0.9% of global CO₂ emissions in a scenario where Bitcoin prices reach USD 130,000 (double the peak Bitcoin price reached in November 2021) and the mining energy efficiency is low (at the breakeven point where a crypto miner makes neither profits nor losses).³ Eventually, under this high-price low-efficiency scenario, CO₂ emissions would decline to 0.4% of global emissions by 2035 as the share of renewable energy sources expand and the crypto rewards (given to miners for authenticating transactions) decline. We consider other scenarios: for example, if the Bitcoin price remains around USD 34,000 (the

¹Crypto mining is the process of validating and recording a unit of crypto asset on a distributed ledger, as determined by a consensus algorithm. For details, see for instance Hallaburda et al. (2022) and chapter 8 of Council of Economic Advisers (2023).

²Under the proof-of-work verification protocol, crypto miners compete over iteratively guessing a long numerical sequence (each guess is called a ‘hash’), requiring powerful computers and fans for cooling. In July 2022, for example, the probability of a successful hash was lower than 1 in 29 trillion, compared to 1 in 2 trillion in January 2018 (<https://btc.com>). The length of the numerical sequence adjusts as the level of cryptomining changes in order to regulate supply—for Bitcoin, there is one successful hash every 10 minutes on average.

³This calculation excludes Ethereum since it switched in 2022 to the proof-of-stake protocol that is less energy intensive.

2021-2023 average) in the next years, cryptocarbon would be around 0.2% and 0.1% of global CO₂ emissions by 2027 and 2035, respectively.

The alarming carbon footprint of crypto mining is now generally acknowledged, calling for better technology and/or a corrective policy to address the associated externality.⁴ There are cryptographic mechanisms that are less damaging to the environment than the proof-of-work, but they are not commonplace. Today, over 60% of the total crypto market relies on the proof-of-work.⁵ In September 2022, the second important cryptocurrency, Ethereum, moved to a ‘proof-of-stake’ mechanism⁶, thereby, in our estimation, preventing an increase in global CO₂ emissions of 0.12% annually. But expecting a rapid spread of green mechanisms of crypto assets voluntarily anytime soon remains wishful thinking. It took Ethereum seven years to make the transition. Bitcoin (and others) would require a majority of owners to agree on such a move first, and with no signs of progress, corrective measures become critical to address the negative climate externality.

To inform mitigation policy toward achieving countries’ greenhouse gas (GHG) reduction pledges, we compute corrective taxes needed to lower CO₂ emissions from crypto mining. Increasing the cost of CO₂ emissions, through a tax, would induce crypto miners to move to low-carbon sources of electricity and more energy-efficient mining hardware, and even possibly encourage a broader shift away from the proof-of-work mechanism. We consider two different corrective taxes to address cryptocarbon: an economy-wide carbon tax or a tax on the electricity used by crypto miners.

The carbon tax is imposed on the supply of fossil fuels (in proportion to its carbon content) to achieve a carbon price that results in global emissions aligned with global warming targets, taken here to be 2°C.⁷ The question in our context is: by how much should the necessary carbon tax increase to account for cryptocarbon developments? Put differently, how much do climate models miss by ignoring cryptocarbon? As surveyed in Stiglitz and Stern (2017), existing results—based on well-established models—put the additional carbon price between USD 50-100 per ton of CO₂ emissions by 2030. For example, IMF (2019) and Black, Chateau, et al. (2022) estimate it at 75 USD, close to the median of 70 USD reported in Drupp et al. (forthcoming). Such results typically consider future CO₂ emissions as linked to the development of the real economy but ignore future

⁴There are other externalities associated with crypto assets—particularly their use in illicit activities (Foley et al., 2019, Europol, 2022, Schwarz et al., 2021)—and tax policy and administration challenges, including for income and consumption taxes (Baer et al., 2023).

⁵Authors’ calculation using data from Coin Metrics (2023).

⁶Rather than a competitive validation process, the proof-of-stake protocol randomly selects a validator (among a pool of validators who put up stake upfront with crypto assets of their own) based on a weighted algorithm. For a discussion of digital asset technological options and their energy profiles, see Agur et al. (2022) and Saleh (2020).

⁷The needed carbon price can be applied through a cap and trade scheme or a carbon tax. Here, we look only at the carbon tax.

crypto mining. The global warming target-consistent carbon tax (whatever its precise level) is clearly far above the current average price on global emissions of USD 18 per ton (OECD, 2022).⁸ The objective of the carbon tax is to adjust the carbon price for any sources of CO₂ emissions to achieve a temperature target (Timilsina, 2022). As cryptocarbon is just one of many sources of CO₂ emissions, a priori we expect it to impact existing estimates of the carbon tax only if the reliance on the proof-of-work is significant. To get a sense of the involved magnitudes, we replicate Black, Chateau, et al. (2022) while incorporating trajectories of future cryptocarbon and find that in the high-price low-efficiency scenario mentioned above, the carbon tax is about USD 2.6 per ton higher than the baseline of USD 75 ignoring crypto. That is, a prototypical carbon pricing model could miss a needed increase of around 3.5% of the carbon price if crypto developments are significant.

Yet, in the absence of the needed carbon tax, a second-best corrective policy for cryptocarbon is in the form of a targeted measure, in particular a tax on the electricity used by crypto miners. Such a tax is in the spirit of the March 2023 proposal by the Biden administration to impose an ad valorem tax of 30% on crypto miners' electricity use. In 2022, another major crypto mining host, Kazakhstan, adopted a tax on electricity used by crypto miners, ranging from 1 to 25 Tenge (USD 0.002-0.056) per kilowatt-hour (kWh).⁹ A general electricity tax on crypto mining would increase the cost of mining, but—differently from a carbon tax—, does not directly encourage switching to low-carbon sources of electricity unless the tax differentiates between these sources.

How much should a tax on the electricity used of crypto miners be? Answering this question is one of the main contributions of this paper. The approach taken here is to compute the specific tax that is equivalent to the 2°C-aligned carbon tax. We find that for the miners to internalize the climate damages of their electricity consumption, a specific tax on their electricity use of USD 0.045 per kWh is needed. This tax would reduce cryptocarbon by around 45% and generate revenue of USD 5.2 billion, globally. The corrective crypto electricity tax level is relatively insensitive to the realization of a particular crypto price scenario because the carbon tax (to which it is aligned) changes by a relatively small amount across scenarios. The specific tax of USD 0.045 per kWh is equivalent to the carbon tax of USD 75 per ton, and it will increase to USD 0.0468 per kWh if the corresponding carbon tax is USD 78 per ton.

There are two caveats regarding a tax on crypto mining electricity. First, the use of fossil-based electricity has further negative externalities (beyond warming) stemming from local air pollution costs. Our computation doubles if the tax internalizes both air pollution and climate damages,

⁸This is the effective average price including existing fuel taxes and excises. The explicit average carbon price is about USD 5 per ton (Black, Parry, et al., 2022). The carbon tax would be on the top of the effective average carbon price.

⁹The five major crypto mining countries are: United States (38%), China (21%), Kazakhstan (13%), Canada (6%), and Russia (5%); see CCAF (2023a).

putting it at around USD 0.087 per kWh (which would reduce cryptocarbon by 60% and raise USD 7 billion in revenue). Second, the above estimates are based on the average emissions-intensity of crypto mining countries, weighted by their share in total mining. Country-specific estimates of the electricity tax on miners vary with the emissions-intensity across countries. The findings indicate that for the United States, for instance, a tax of USD 0.03 per kWh would internalize climate costs (but not air pollution), reducing domestic cryptocarbon by 39% and raising USD 2 billion in revenue in 2023. The tax inclusive of air pollution costs would be USD 0.056 per kWh. A corrective tax is conceptually specific, that is expressed as per unit rather than being proportional to the value (Keen, 1998). Converting the specific tax to an ad valorem tax depends on the exact prevailing price, which can differ across industries and over time. For example, the specific tax of USD 0.03 per kWh in the United States is equivalent to an ad-valorem tax of 29% if we look at the average industrial electricity price, but it is 64% if the average electricity price facing crypto miners is USD 0.05.

The paper proceeds as follows. Section 2 dismantles the relationship between crypto assets and CO₂ emissions and outlines the methodology for estimating cryptocarbon. Section 3 presents estimates of cryptocarbon during 2017-2022, provides an overview of existing studies—which mainly focus on past CO₂ emissions (in a specific year) from Bitcoin mining—, and presents projections of future cryptocarbon through 2035. Section 4 presents the findings about corrective taxes. Finally, Section 5 concludes.

2 Methodology

Computing CO₂ Emissions from Crypto Mining

Global cryptocarbon is a function of crypto mining, electricity needed for crypto mining, and CO₂ emissions per unit of electricity, summed over all countries. Let i denote a country, in each year:

$$\begin{aligned} \text{Global Cryptocarbon} = \sum_i (\% \text{ of global mining})_i \times (\text{global electricity used for mining}) \\ \times (\text{CO}_2 \text{ emissions per unit of electricity})_i. \end{aligned} \tag{1}$$

More crypto mining or higher electricity needed for mining one crypto unit would lead to higher CO₂ emissions. Applying equation (1) using past values yields cryptocarbon for 2017-2022. Data on the first term (country shares in global crypto mining) and the third term (CO₂ emissions) are readily available from the Cambridge Bitcoin Electricity Consumption Index (CBECI) and the International Energy Agency (IEA), respectively. The second term in equation (1) (global electricity

used for crypto mining measured in terawatt; tWh) is not directly observed. We compute it as the ‘average energy efficiency’ of the available crypto mining hardware multiplied by the hash rate—that is, it is multiplying the electricity needed to generate a hash (or in other words a ‘guess’ for the proof-of-work protocol) by the total number of hashes.¹⁰ While data on hash rates are readily available, we compute the average energy efficiency using the ‘break-even efficiency model’, in line with the approach in Jones et al. (2023) and de Vries et al. (2022) and as discussed below.

The idea of the breakeven efficiency model is to determine a profitability threshold of energy efficiency at which a crypto miner just recovers the electricity costs incurred for running the equipment without making profit (the breakeven energy efficiency). We observe the energy efficiency of available crypto mining hardware through published lists of equipment and their features (for example, CCAF, 2023b). We use the breakeven efficiency level to determine the threshold for ruling out nonprofitable crypto hardware. Thus, the average energy efficiency of profitable crypto miners is computed as the average efficiency of equipment that demand less energy than at the breakeven threshold. The breakeven efficiency itself is a function of electricity cost—computed as the required hashes multiplied by the electricity price—and the return to crypto mining—computed as the crypto asset price multiplied by the crypto reward (the latter is the amount of crypto assets that a miner receives for a successful hash).¹¹ The equations of this model follow existing methodologies (for example, CCAF, 2023a) and are detailed in the Appendix, together with all data sources. The gist of these relationships is further fleshed out next using a summary of comparative statics.

Comparative statics helps in setting out how changes in (crypto and electricity) prices affect energy efficiency—the key ingredients in the breakeven efficiency model. These inter-linkages (summarized in Table 1) are key for understating how cryptocarbon occurs and can evolve over time:

- A higher electricity price directly improves efficiency of crypto mining as less efficient technology becomes nonprofitable. This mechanism constitutes the fundamental rationale for using taxes as a corrective policy.
- A higher crypto asset price makes less efficient equipment more profitable, ultimately resulting in more crypto mining and electricity used for each hash. This mechanism leads to a higher demand for electricity and lower energy efficiency, thereby higher GHGs.

¹⁰The hash rate is typically measured as terahashes, or 1 trillion hashes, per second.

¹¹In 2009, at the start of Bitcoin, the reward was 50 units of Bitcoin, which since then has been halved every 210,000 blocks of transactions to control the Bitcoin supply. Currently, the Bitcoin mining reward is 6.25 units of Bitcoins per block, scheduled to be reduced in April 2024 to 3.125 per block.

- Halving (or more generally decreasing) the crypto reward makes crypto mining with low electricity efficiency nonprofitable. This mechanism lowers the demand for electricity, thereby emitting less GHGs.
- A higher hash rate—meaning an increased difficulty of a successful hash and thus more mining on the network—increases energy consumption and GHGs. Higher hash rates tend to be caused by increased mining demand induced by higher crypto prices or lower electricity prices.
- Technological improvement (in the form of more energy efficient mining hardware), *ceteris paribus*, has two offsetting effects. It raises the average energy efficiency (thereby lowering electricity consumption) and raises guesses per second (that is the hash rate) as the difficulty of solving a hash increases (thereby increasing electricity consumption). Technological improvement is accounted for in the calculation of electricity demand through the hash rate.

Table 1: *Qualitative Impacts of Technology and Prices on the Hash Rate and Efficiency*

	Effect on energy efficiency	
<i>Electricity price</i> (↑)	+	because less efficient technology becomes less profitable
<i>Crypto price</i> (↑)	–	because less efficient technology becomes profitable
<i>Crypto reward</i> (↓)	+	because mining becomes less profitable, thus less efficient equipment exits and electricity use declines
<i>Hash rate</i> (↑)	–	because more energy consumption is required
<i>Technological improvement</i> (more energy efficient equipment)	+ –	because it increases hashes per unit of energy and the hash rate, thereby having offsetting effects

Source: Compiled by the authors.

Projecting Future CO₂ Emissions from Crypto Mining

Prices and Electricity

Using projected values in equation (1) gives future CO₂ emissions from crypto mining, starting from 2023 in this study. As crypto prices swing substantially, and future crypto demand is uncertain, it is necessary to consider multiple scenarios to serve as reference points. Here, we focus on four scenarios displayed in Table 3, combining two variants of energy efficiency and Bitcoin prices.

The ‘high’ Bitcoin price scenario of USD 130,000 roughly represents doubling the peak value of Bitcoin that was reached in November 2021,¹² whereas the low-price scenario (of USD 34,000) assumes that the Bitcoin price is at the average of 2021-2023 levels in real terms. The two variants of technology are: (i) the average energy efficiency of equipment that is profitable, above the breakeven point (described above); and (ii) energy efficiency at the breakeven level. Finally, in all projection scenarios, Ethereum is assumed to maintain its current proof-of-stake protocol and have negligible electricity use starting from September 2022.

To compute future electricity used for mining, the analysis requires (i) assumptions about the path for crypto prices (these are set out above); (ii) the crypto reward, which is a known predetermined amount for Bitcoin, assumed to be halved in 2024¹³; (iii) future hash rates, which are predicted using a dynamic regression model relating the hash rate to its lagged values; and (iv) path for electricity prices. Regarding the latter, historically, the electricity price has been exhibiting little variation (Figure A.3), and the initial value for projection is taken in all scenarios to be USD 0.05 per kWh for Bitcoin (the average price paid by electricity miners in Stoll et al., 2019 and CCAF, 2023a). Having obtained all those values, we compute future breakeven efficiency using the methodology described in the above subsection. Next, the future values of breakeven efficiency are used to predict future efficiency levels of profitable crypto miners using a linear regression model that relates the breakeven efficiency to average efficiency. Future global electricity used by miners, as above, is future energy efficiency multiplied by the future hash rate in each year.

CO₂ Emissions

Future CO₂ emissions (the last term in equation 1) are estimated using the Climate Policy Assessment Tool (CPAT) developed by the International Monetary Fund and the World Bank.¹⁴ The CPAT distinguishes 15 types of fossil and non-fossil fuels—including renewable energy—used in power generation and other demand sources across 16 sectors. The main inputs in the CPAT are (i) projections of GDP and energy prices, (ii) rates of technological improvements in energy efficiency, and (iii) income and price elasticities of demand for fuels that govern how higher GDP and changes in prices affect the demand for energy products. Electricity and fuel price elasticities are generally assumed to be between -0.5 and -0.8 based on meta analysis of thousands of elasticities (Black, Parry, et al., 2022). As outputs, the CPAT projects energy consumption and the corresponding CO₂ emissions on a country-by-country basis.

¹²Standard Chartered, for example, predicts that the Bitcoin price will be USD 120,000 by 2024.

¹³The Bitcoin reward also includes a transaction fee, which is assumed to be constant over time at the average of 2021-2023 levels (0.28 per block). Apart from Bitcoin, rewards for most other proof-of-work crypto assets also halve over time (including for Dogecoin, Litecoin, and Bitcoin Cash). Monero—another proof-of-work crypto—has completed halving and now only provides a minimal block reward.

¹⁴A full documentation of the CPAT is available at IMF-WB (2023) and Black, Parry, et al. (2022). See also the Appendix.

For comparability with available results, the aim here is not to achieve any breakthrough regarding the modelling of the CPAT, but rather take the model as given with the addition of the electricity for crypto mining. This addition is featured in the CPAT by adding the country-specific increase in electricity demand from crypto mining relative to the baseline demand and the increase in supply needed to meet additional crypto demand, some of which comes from renewable sources.

Computing Corrective Taxes

The CPAT is used for climate mitigation policy analysis, including estimating the impacts of taxes on energy consumption and CO₂ emissions. Given the temperature target of 2°C, CPAT maps the correspondent needed decrease in the CO₂ emissions (according to IPCC, 2022). The reduction in CO₂ emissions is in turn achieved by lowering the demand for, and emissions-intensity of, energy by raising the price by means of a tax on the supply of fossil fuels in proportion to its carbon content. The impact of the corrective tax on fossil fuel use, relative to the baseline, depends on (i) the change in electricity and fuel prices; (ii) switching among fuels in power generation (coal, natural gas, oil, renewables, or nuclear); and (iii) the price responsiveness of demand for electricity and fuel in other sectors (capturing changes in both energy efficiency and product use). For the purpose of this study, we replicate Black, Chateau, et al. (2022) taking all those factors as in their study, add the new demand for electricity for crypto mining, and then compute by how much the carbon tax should change if crypto developments are taken into account for each of the four scenarios outlined in Table 3.

We follow the same procedure for the targeted tax on crypto mining electricity. Having computed the carbon tax, the excise tax equivalent (that is, aligned to the 2°C target) is given as

$$Tax\ in\ USD\ per\ kWh = \frac{Carbon\ tax\ in\ USD}{Ton\ of\ CO_2} \times \underbrace{\frac{Ton\ of\ CO_2}{kWh}}_{CO_2\ emissions-intensity}, \quad (2)$$

yielding the optimal crypto mining electricity tax per kWh to internalize climate damages. The cost of air pollution is accounted for through an additive term to equation 2 that captures the increase in fine particulate matter in the air per kWh and the associated death (converted to USD as in equation 2). Those data are readily taken from Black et al. (2023).

3 Results: Cryptocarbon

Past CO₂ Emissions from Crypto Mining

Table 2 shows the estimates for 2017 throughout 2022, separately for Bitcoin, Ethereum, and the rest of crypto assets. Results suggest that in 2021 crypto mining comprised 0.9% of global electricity

use and 0.33% of global emissions. At 220 TWh, in 2021, crypto mining demanded around as much electricity as Australia or Spain. One Bitcoin transaction required the equivalent electricity consumption of a typical individual from Ghana for 3 years.¹⁵ The increase in emissions from 2017 up to 2022 (seen in Table 2) is mainly driven by (i) the increase in Bitcoin and Ethereum prices (that allowed less energy efficient mining equipment to be profitable); and (ii) the increase in the hash rates that has been faster than the improvement in the energy efficiency of new equipment (directly resulting in more electricity use and a higher hash difficulty per block). In 2022, Bitcoin prices were lower than in 2021, but the hash rate was higher resulting in higher emissions.

Existing studies are rather scattered, providing estimates for only a specific year or only for Bitcoin. Nonetheless, putting our findings in the context of the available results remains important for two reasons. Firstly, a concise overview of existing estimates is by itself informative, and secondly this step serves as a validity exercise for our projection model (that is, checking whether the results using observed data are broadly in line with the literature, before obtaining the projections from the same model).

Our estimates are within the range of available ones, summarized in the Appendix (Table A.3). For example, for 2018, for Bitcoin and Ethereum mining combined, Köhler and Pizzo (2019) estimate the CO₂ emissions at 31 million tons, close to our estimate of 29 million tons. For 2021, de Vries et al. (2022) find that global emissions from Bitcoin mining alone was 65.4 million tons, also close to our estimate at 59 million tons and that of Forexsuggest (2022) at 57 million tons. While most available estimates broadly use a similar method to the one outlined above, there is some variation across results that is mainly driven by (i) different assumptions about the emissions-intensity of electricity used for mining or (ii) the energy efficiency of mining equipment. For example, our estimate is smaller than Foteinis (2018) that uses a life-cycle model of CO₂ emissions-intensity accounting for indirect emissions.¹⁶ Results in Mora et al. (2018) (only for Bitcoin and 2017) are at the high end, largely driven by assumptions about energy efficiency, but their methodology has been challenged by Masanet et al. (2019) and Dittmar and Praktiknjo (2019).¹⁷ Overall, the evidence points out that the price of crypto assets vis-à-vis the USD and the hash rate are important factors that drives electricity use in crypto mining.

¹⁵Electricity consumption data for Australia, Germany, Ghana, and Spain are taken from the IEA.

¹⁶Statistics of the IEA used in our analysis account only for direct CO₂ emissions from electricity generation, and exclude emissions incurred to extract, process, and transport the fuels used for electricity generation. These indirect emissions are estimated to be around 15 percent of combustion emissions (Baunsgaard and Vernon, 2023).

¹⁷Mainly because results in Mora et al. (2018) are likely inconsistent with potential constraints on global electricity generation capacity and blockchain transactions rate.

Table 2: Electricity Use and CO₂ Emissions from Crypto Mining

	Unit	2017	2018	2019	2020	2021	2022
<i>Electricity Use</i>							
Bitcoin	TWh	23	48	62	83	107	113
Ethereum	TWh	16	19	9	8	39	31
Other	TWh	28	68	44	50	75	90
Total crypto	TWh	67	135	115	141	221	234
Percent of global	%	0.30	0.58	0.34	0.58	0.85	0.90
<i>CO₂ Emissions</i>							
Bitcoin	mt CO ₂	14	29	37	48	59	60
Ethereum	mt CO ₂	9	11	5	5	21	17
Other	mt CO ₂	17	40	26	29	41	47
Total crypto	mt CO ₂	40	80	68	82	121	123
Percent of global	%	0.11	0.22	0.18	0.23	0.33	0.33

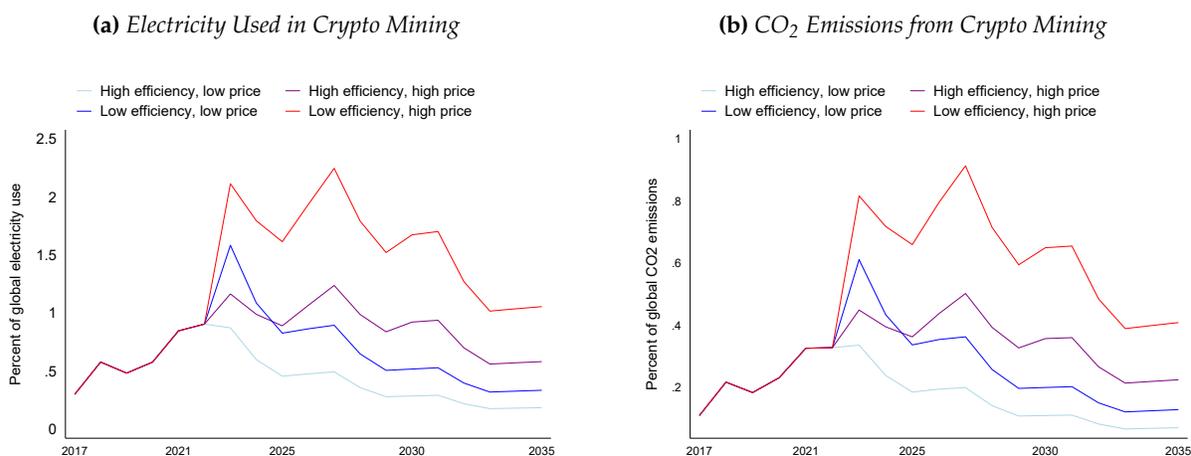
Future CO₂ Emissions from Crypto Mining

Without a sufficient increase in crypto prices, and with the ‘halving’ of crypto reward (the next one is scheduled for April 26, 2024), future electricity use for crypto mining would decline (left panel of Figure 1). The underlying reason for this decline is that less energy efficient equipment becomes no longer profitable. In contrast, raising crypto prices combined with energy inefficient equipment would result in electricity use exceeding 2% of global electricity consumption by 2027, and eventually falling to slightly above 1% by 2035 (left panel of Figure 1).

Given electricity projections, the right panel of Figure 1 presents the associated CO₂ emissions. Note that the emissions-intensity of electricity projection accounts for decarbonization of the power generation, with renewables making up a greater share of total generation. This leads to a decrease in the weighted-average emissions-intensity used by crypto miners by 22% in 2035 relative to 2019 levels. Under the scenario of high crypto prices with energy inefficient mining, the peak global CO₂ emission reaches 0.9% in 2027 and gradually declines to 0.4% in 2035 (that is, the cryptocarbon is 149 million tons in 2035 under this scenario, and the numbers here are annual, not cumulative). Again, the decline is mainly driven by the reduction in the crypto rewards without an offsetting increase in crypto prices. In the scenario of high prices with efficient mining equipment global emissions increases slightly out to 2027 but fall to 0.23% of global emissions by 2035 (right panel of Figure 1). In the baseline scenario, CO₂ emissions eventually fall below current levels.

The precise emissions-intensity of electricity specifically used by crypto miners is unobserved directly. The analysis thus far assumes that miners use electricity at the national average emissions-intensity. Here, we extend our analysis by looking at different emissions-intensities ranging from using electricity only from coal, or only from natural gas, or half-renewables half-natural gas

Figure 1: Projected Electricity for Crypto Mining and Associated CO₂ Emissions

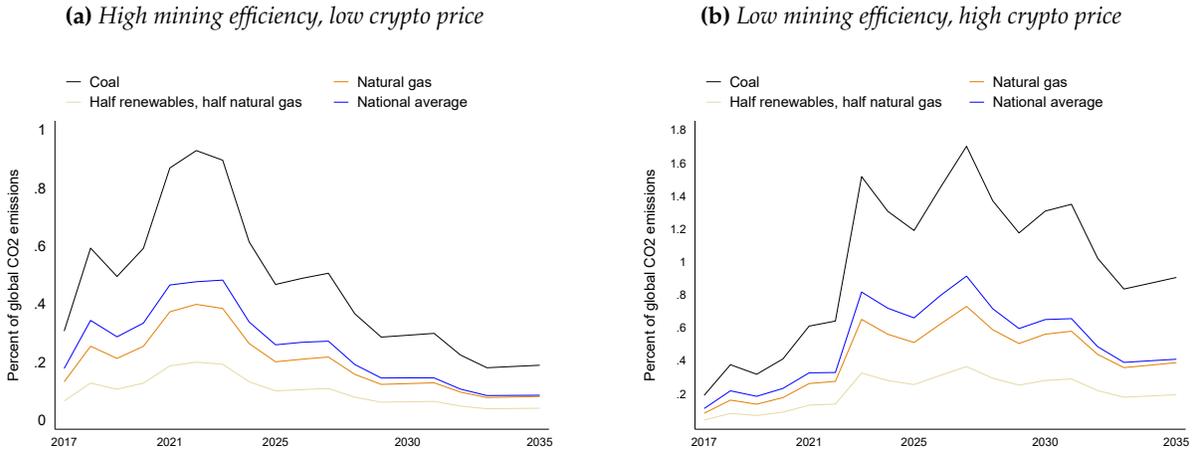


Note: Numbers up to 2022 are from Table 2. Numbers from 2023 onward are projected as described in Section 2 and the Appendix. CO₂ emissions are shown for a corresponding year, but not cumulatively.

(Figure 2). These comprise informative bounds not only as sensitivity analysis of the value of emissions-intensity per se but also as proxy for changes in the locations of future crypto mining. Strictly speaking, the analysis assumes that countries' shares in global crypto mining are stable. Varying the emissions-intensity approximates what happens if more (or less) dirty energy countries become important hosts of crypto mining. As shown in Figure (2), the worst case of all-coal-use results in peak emissions of 0.9% of global emissions in 2022 if crypto prices are relatively stable. In contrast, the figure reaches 1.7% of global CO₂ emissions in 2027 if crypto prices rise and low efficiency equipment is used. A middle case (of all natural gas) has similar results to the average emissions-intensity (Figure 1), whereas emissions peak at 0.2% to 0.4% depending on the price scenario if miners use half natural gas and half renewables for their power generation.

The varying emissions-intensities in Figure 2 also have useful interpretation in connection with the notions that crypto miners can expand renewables capacity (because their demand increases profitability of renewables) and provide grid management services. To the extent that miners use excess electricity generated by renewables, their emissions-intensity can fall below the economy-wide average. However, Bruno et al. (2023) study the case of Bitcoin mining in Texas and find that while Bitcoin mining can increase renewable penetration, it increases CO₂ emissions too.

Figure 2: Analysis of Cryptocarbon with a Varying Degree of Emission-Intensity



Note: Emissions intensities are assumed to be 1.03 kg per kWh for coal, 0.44 for natural gas, and 0 for renewables (IEA 2023). Section 2 and the Appendix describe the projection method.

4 Results: How Much Should the Corrective Tax Be?

Economy-Wide Carbon Price

Introducing an economy-wide carbon price is the most economically effective way to reduce CO₂ emissions. The findings suggest that if crypto prices remain close to their values in 2023, existing calculations of the needed carbon price to keep emissions on the path to achieve 2°C degrees warming would not significantly change. That is, the carbon tax remains very close to USD 75 (Table 3). However, the high-price low-efficiency scenario requires an increase in the necessary carbon price by USD 2.6 per ton by 2035. This constitutes an increase in the additional carbon price of about 3.5% (from USD 75 to 78).

Table 3: Reference Projection Scenarios and the Needed Increase in the Carbon Tax

Scenario	Bitcoin Price (USD)	Energy Efficiency	Increase in the Carbon Tax (in USD) on top of the USD 75
High efficiency – low price	34,000 by 2030	Profitable technology	0.20
High efficiency – high price	130,000 by 2030	Profitable technology	0.97
Low efficiency – low price	34,000 by 2030	Breakeven technology	0.89
Low efficiency – high price	130,000 by 2030	Breakeven technology	2.62

Source: Summary by the authors. Low energy efficiency is the breakeven technology level.

Targeted Sector-Specific Tax

In the absence of a carbon tax, a second-best corrective tool is a targeted sectoral measure in the form of a tax on the electricity used by miners. Such a corrective tax is relatively easy to enforce

given the high concentration of activities among large crypto miners and their observable electricity consumption. Electricity input is the key cost factor for crypto miners and their electricity demand is sensitive to electricity prices. Changes in the electricity price map into changes in the average energy efficiency of crypto mining¹⁸, and hence changes in the CO₂ emissions. Using this average efficiency model, and assuming that the tax is borne by miners (that is, miners' profit is reduced by the tax rather than passing it on to crypto users), we find that the model-based price elasticity of electricity use in crypto mining is -0.88 (that is, a 1% increase in electricity prices decreases electricity use by 0.88%; Figure A.6). This elasticity is somewhat higher than price elasticities of between -0.5 and -0.8 for traditional uses of fossil fuels, such as road transportation (Black, Chateau, et al., 2022).

The electricity tax is expressed here as a carbon tax equivalent (equation 2), using the average emissions-intensity of electricity generation as the baseline.¹⁹ An ad-valorem tax on electricity consumption is similar to the Biden administration proposal, but a corrective tax is typically specific; that is, a fixed amount per unit, rather than a percentage of value. As established in Keen (1998), the correction is meant to target the content representing the source of the externality, rather than the total value of the excisable item. Thus, in our analysis, the tax is specific rather than ad-valorem.

The excise of USD 0.045 per kWh is equivalent to the Paris Agreement aligned carbon tax of USD 75 per ton. Results indicate that this tax of USD 0.045 per kWh on electricity use for crypto mining would lead to a decrease in electricity consumption (left-hand y-axis in Figure 3) and CO₂ emissions (right-hand y-axis in Figure 3) of 45% (or 99 TWh) and 55 million tons of CO₂ in 2023, respectively. This specific tax is equivalent to an 89% ad-valorem tax, if the pre-policy reform electricity price for crypto mining is USD 0.05 per kWh.²⁰ Electricity consumption declines at a faster rate relative to the electricity price, highlighting that modest taxes could substantially reduce emissions, while raising considerable revenue. While the tax of USD 0.045 per kWh is based on equivalence to USD 75 per ton of CO₂, it remains close to USD 0.047 if the carbon price equivalence is USD 78 (the needed additional carbon tax associated with a Bitcoin price of USD 130,000 and low energy efficiency of mining). And the resulting level of electricity use by miners (the height and slope of the line in Figure A.6) ultimately depends on price, energy efficiency, and other industry characteristics.

We extend the analysis in two dimensions, considering: (i) externalities from air pollution and (ii) country-specific results. The baseline excise of USD 0.045 per kWh does not consider

¹⁸Equations A.3 and A.4 in the Appendix.

¹⁹The fuel used to generate one kWh of electricity is assumed to emit 0.6 kilograms of CO₂, which is the weighted average emissions-intensity across the top Bitcoin mining countries in 2022.

²⁰Globally, an ad hoc ad-valorem tax of 30% on mining electricity (with current electricity prices) would reduce electricity use by 25%, with a proportional decrease in CO₂ emissions.

externalities from air pollution and is based on the average emissions-intensity. It rises to USD 0.087 per kWh if it internalizes air pollution costs in addition to climate pollution (at the average emissions-intensity), and to 0.16 per kWh if power generation is only from coal (Table 4). If miners use all natural gas for their power generation, the excise is again around USD 0.047 per kWh, and it goes down to USD 0.024 per kWh when using half renewables and half natural gas.

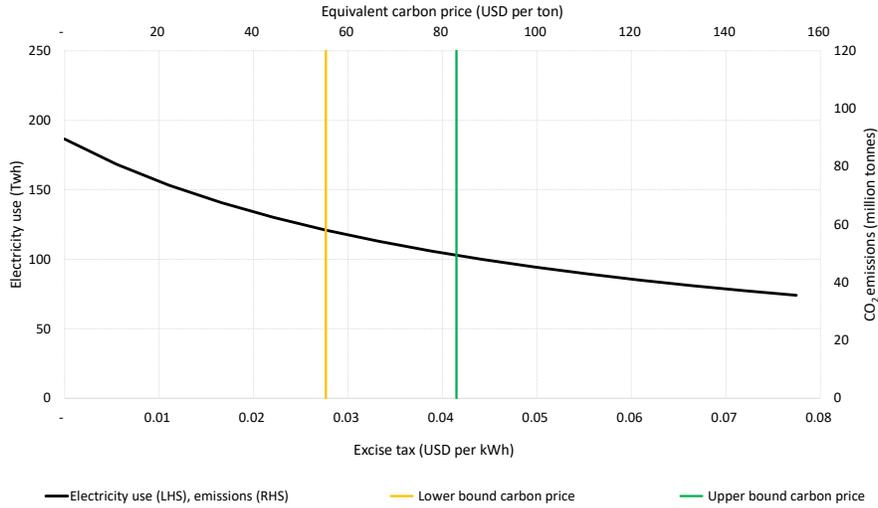
The excise on crypto mining electricity also varies with the country-specific emissions-intensity, ranging from USD 0.08 per kWh in Kazakhstan to USD 0.01 per kWh in Canada. The differences are solely driven by variation in the emissions-intensity of electricity generation in those countries (reported in Table A.2). Looking at the United States, a tax of USD 0.03 per kWh would internalize climate costs (but not air pollution), reducing domestic cryptocarbon by 39% and raising USD 2 billion in revenue in 2023. This specific electricity tax on crypto mining in the United States is equivalent to an ad-valorem tax of 64% at an electricity price of USD 0.05. The tax inclusive of air pollution costs would be USD 0.05 per kWh (Table A.2).

Ideally, all countries impose a corrective tax because raising the cost of CO₂ emissions only in a subset of countries can drive out crypto miners, eventually to other countries where emissions-intensities are possibly higher. While this cross-border effect is similar to the idea of carbon leakage, the difference in the case of crypto mining is that from the perspective of the correcting country there is no clear real economic cost or “competitiveness cost” (in terms of foregone investment or employment) if energy-inefficient crypto miners leave. On the contrary, some studies suggest that crypto mining raises the cost of electricity for local small businesses and households and worsens investment (Benetton et al., 2021). Somewhat related is the current discussion on a border carbon adjustment (BCA), whereby a tax is imposed on imported products based on their emissions content.²¹ The BCA discussion is almost entirely focused on goods, with the presumption that that carbon leakage is not prevalent for services. In a sense, crypto represents a counterexample.

The electricity tax policy on crypto mining reduces CO₂ emissions by crowding out low energy efficiency miners (and more generally making the proof-of-work protocol more expensive). This is because the electricity use for crypto mining is sensitive to the electricity price. However, unlike the carbon tax, the electricity tax does not incentivize miners to shift to clean energy sources unless the excise distinguishes between these sources. It is difficult, though, to tax end use of electricity based on the generation source since electricity mixes across sources once it enters the grid. Policies to require buyers to purchase a minimum share of clean energy, such as Renewable Purchase Obligations, for instance, may shift miners towards renewable sources but not from coal to less emitting fossil fuels.

²¹For a detailed discussion, see for example Keen et al. (2022).

Figure 3: Specific Tax on Electricity Used for Crypto Mining



Note: The yellow and green lines show the minimum and maximum increase in the price on global carbon dioxide emissions that would put emissions on track to achieve the global warming target of 2 °C.

Table 4: Specific Electricity Tax Internalizing Air and Climate Pollution from Crypto Mining

Emissions-intensity	Climate pollution	Air pollution	Climate and air pollution
Weighted average	0.045	0.042	0.087
Coal	0.077	0.087	0.165
Natural gas	0.033	0.014	0.047
Half renewables, half natural gas	0.017	0.007	0.024

Note: Numbers are in USD.

5 Conclusions

Two questions are closely linked to the discussion of taxing the electricity used for crypto mining. First, is there a role for regulation? Crypto mining is prohibited in some countries like Bangladesh and Egypt, reflecting broader concerns about externalities from crypto assets in connection with consumer protection, financial stability, and anti-money laundering. And with anxiety about crypto continuously fueled by scandals of investment fraud and further serious criminal activities, other countries (where crypto is not outright prohibited) attempt to address such externalities using regulation. For example, in April 2023 the EU approved the Markets in Crypto-Assets (MiCA) regulation as a comprehensive regulatory framework for crypto. There is also rationale for using taxation in complement to regulatory measures, for instance in analogy to taxing gambling or akin to financial transactions taxes (as discussed in detail in Baer et al., 2023). Climate externalities, however, are best dealt with using a carbon tax on any GHGs, which would subsume a tax on electricity of crypto mining and does not entail singling out a particular sector; neither crypto nor others. The market failure would be addressed through correcting prices. The extent to which

crypto mining uses renewables or non-energy-hungry authentication protocols reduces the need for corrective measures. And if there are concerns about other externalities, then other instruments would be needed. If crypto mining, however, continues to rely on dirty energy and the proof-of-work—and in the absence of a carbon tax—there is a climate concern that can be addressed with a tax on the electricity used for crypto mining. Such an excise can be an effective and a relatively easy-to-enforce tool to raise the cost of CO₂ emissions from crypto mining activity.

The second question is on the role of international coordination. The issue here is conceptually similar to the literature on tax competition over profit and capital (Keen and Konrad, 2013), and the notion of carbon leakage. In the sphere of mitigation policy, coordination results in superior outcomes with higher welfare than under an equilibrium with uncoordinated unilateral actions. The tax on electricity of crypto miners is no exception in this regard. Crypto mining is now highly concentrated in a few countries, but it remains mobile: if it is taxed in one country but not the other, crypto mining can move across borders, possibly where the emission-intensity is even higher. Ideally, international coordination over corrective measures would be most effective in curbing crypto mining CO₂ emissions. But, in the absence of coordination, it is unclear what countries would benefit from competing over hosting crypto miners that would increase pressures on the power grid with no obvious macroeconomic benefits. Thus, overall, while crypto miners' mobility remains a concern, from the standpoint of a country that imposes a unilateral tax on electricity for crypto mining, the result is merely driving away less profitable crypto miners with energy inefficient mining equipment in exchange for less pressures on electricity and less CO₂.

In this paper, our contribution has been to shed light on the involved magnitudes of cryptocarbon and needed corrective taxes. Results suggest that the carbon price in the range of USD 75 to achieve temperature targets is robust against moderate increases in crypto prices and the proof-of-work mining. A tax on electricity of crypto miners at a global average of USD 0.045 per kWh would achieve a similar reduction in cryptocarbon as a USD 75 carbon tax per ton, mainly through improving the energy efficiency of crypto mining. However, the exact level of the tax would need to vary by country to account for differences in emissions-intensity of electricity production.

Appendix: Method and Data

This Appendix documents the equations and data sources behind the calculation of cryptocarbon. The aim is to apply the following equation:

$$\begin{aligned} \text{Global Cryptocarbon} = \sum_i (\% \text{ of global mining})_i \times (\text{global electricity used for mining}) \\ \times (\text{CO}_2 \text{ emissions per unit of electricity})_i. \end{aligned} \quad (\text{A.1})$$

For past years, the first and third terms are directly observed, and thus we need to compute global electricity used for crypto mining to apportioned to countries based on their shares of global mining.

Electricity equations:

The amount of annual global electricity used for crypto mining is estimated as follows:

$$\begin{aligned} \text{Global electricity used for mining (TWh)} = \text{average energy efficiency (J/TH)} \times \text{hash rate (TH/second)} \\ \times 60 \times 60 \times 24 \times 365 \times (\text{PUE}), \end{aligned} \quad (\text{A.2})$$

where TWh is terawatt hours; J is joules; TH is terahash (1 trillion hashes per second); PUE is 1 divided by the percent of energy used by miners to produce hashes rather than other activities, such as cooling; and the average energy efficiency is the average of equipment more efficient than at the breakeven level (see equation A.4). The 'breakeven energy efficiency' is the level at which a miner is neither making profits nor losses, computed as:

$$\text{Breakeven energy efficiency} \left(\frac{J}{TH} \right) = \frac{\text{Block reward} \left(\frac{BTC}{Block} \right) \times \text{Crypto price} \left(\frac{USD}{BTC} \right)}{\text{Hashes required} \left(\frac{TH}{Block} \right) \times \text{Electricity price} \left(\frac{USD}{J} \right)}. \quad (\text{A.3})$$

$$\text{Average energy efficiency} = \text{Average of equipment more efficient than breakeven energy efficiency} \quad (\text{A.4})$$

Equations A.1-A.4 are used for Bitcoin and for Ethereum separately. For Ethereum, the calculation is done only until 2022. Since Ethereum' switch to the proof-of-stake protocol was in September, the computation is done first for the entire 2022, emissions assumed to be uniformly distributed across months, and then the annual figure for 2022 was adjusted downward by 25%.

To calculate global electricity used for the proof-of-work of other crypto assets, we scale the

Bitcoin's electricity consumption based on its share in crypto market capitalization as reported in Table A.1 (and excluding Ethereum's contribution starting from 2022):

$$\text{Electricity used for mining (TWh)}_{other} = \text{Electricity used for mining (TWh)}_{BTC} \times \frac{\text{Market share}_{other}}{\text{Market share}_{BTC}}. \quad (\text{A.5})$$

Table A.1: Crypto Market Share

	2017	2018	2019	2020	2021	2022
Ethereum	13 %	13 %	8 %	9 %	18 %	20 %
Bitcoin	39 %	36 %	54 %	56 %	48 %	45 %
Other	48 %	51 %	38 %	34 %	34 %	36 %

Source: Author's calculations using [COINMETRICS, 2023](#).

CPAT: Future CO₂ emissions and the carbon tax calculation:

We apply the CO₂ emissions-intensity of electricity generation to total electricity used for cryptocurrency mining, with emissions-intensity referring to the weighted average across mining countries and emissions-intensities obtained from the Climate Policy Assessment Tool (CPAT):

$$\text{Emissions (mln tons)}_c = \text{Electricity used for mining (TWh)}_c \times \frac{\text{CO}_2(\text{kg})}{\text{kWh}}. \quad (\text{A.6})$$

For energy consumed by households and industry, demand is projected forward using equation A.7:

$$E_{t,s,f} = E_{t-1,s,f} \times \left(\frac{\text{GDP}_t}{\text{GDP}_{t-1}} \right)^{\theta_{s,f}} \times \left(\frac{1}{1 + a_{s,f}} \right)^{1 + \epsilon_{s,f}} \times \left(\frac{p_{t,s,f}}{p_{t-1,s,f}} \right)^{\eta_{s,f} + \epsilon_{s,f} + [\eta_{s,f} \times \epsilon_{s,f}]}, \quad (\text{A.7})$$

where t = year, s = sector, f = energy source, θ = income elasticity of demand (0.3 to 1, varying with fuel and sector), p = consumer price (specific to country and fuel), a = rate of exogenous energy efficiency improvement (0.5% to 1% per year, varying with fuel and sector), ϵ = price elasticity of demand (intensive margin, -0.1 to -0.7 varying with fuel, sector, and income level), η = elasticity of consumption rate (extensive margin, -0.2 to -1.2), GDP = gross domestic product. There are 32 income elasticities of energy demand in the in CPAT covering eight energy sources (coal; natural gas; gasoline; diesel; other oil products like LPG and kerosene; biomass; small-scale renewables like solar photovoltaics; and electricity) as well as four sectors (transport including road, rail, aviation and shipping; residential; heavy industry; and public and private services). CO₂ emissions factors for fuels are assumed fixed over time.

Cross-price elasticities are used to determine the mix of fuel used to generate electricity in each country:

$$F_{t,f} = F_{t-1,f} \times \left\{ (g_{t,f}/g_{t-1,f})^{\xi_f} + \sum_{j \neq f} F_{t-1,j} \left[\frac{1 - (g_{t,j}/g_{t-1,j})^{\xi_j}}{1 - F_{t-1,j}} \right] \right\}, \quad (\text{A.8})$$

where F = the share of fuel in total generation, g = the cost of producing electricity (a function of fuel costs, generation efficiency, and transmission and distribution costs), f = energy source, ξ = conditional own-price elasticity—the percent reduction in fuel i due to switching from that fuel to other fuels, per a one-percent increase in fuel i 's generation cost, conditional on a fixed level of electricity generation (-0.5), j = an index of all energy sources. The generation mix in turn provides the emissions-intensity of electricity generation and the pre-tax consumer price for electricity (in cases where electricity prices are liberalized).

The carbon tax is converted to a specific tax on crypto mining electricity through:

$$\text{Tax in USD per kWh} = \underbrace{\frac{\text{Carbon tax in USD}}{\text{Ton of CO}_2} \times \underbrace{\frac{\text{Ton of CO}_2}{\text{kWh}}}_{\text{CO}_2 \text{ emissions-intensity}}}_{\text{Climate externality term}} + \underbrace{\frac{\text{Ton of PM}_{2.5}}{\text{kWh}} \times \frac{\text{Death}}{\text{Ton of PM}_{2.5}} \times (\text{Monetary cost of death in USD})}_{\text{Air pollution externality term}} \quad (\text{A.9})$$

where $PM_{2.5}$ = particulate matter with diameter less than 2.5 microns. The second term on air pollution externality is set to zero when computing the excise that corrects only for global warming. The data and methodology for computing air pollution externality are taken from Black et al. (2023).

Table A.2: Emissions-Intensity

	CO ₂ Emissions-intensity	Excise tax	Ad-valorem equivalent (at a price of USD 0.05 per kWh)*	Industry electricity average price	Ad-valorem equivalent (average industry price)**
Canada	0.12	0.009	19%	0.11	8%
China	0.61	0.046	91%	0.11	40%
Kazakhstan	1.11	0.083	166%	0.05	170%
Malaysia	0.69	0.051	103%	0.11	48%
Russia	0.45	0.034	67%	0.04	77%
USA	0.43	0.032	64%	0.11	29%
Weighted average	0.6	0.045	89%	0.01	45%

Note: The excise tax is computed from equation 2 with a USD 75 carbon tax, without accounting for externalities from air pollution. * Average electricity price for crypto miners (de Vries et al., 2022). ** Average industrial electricity price in the country.

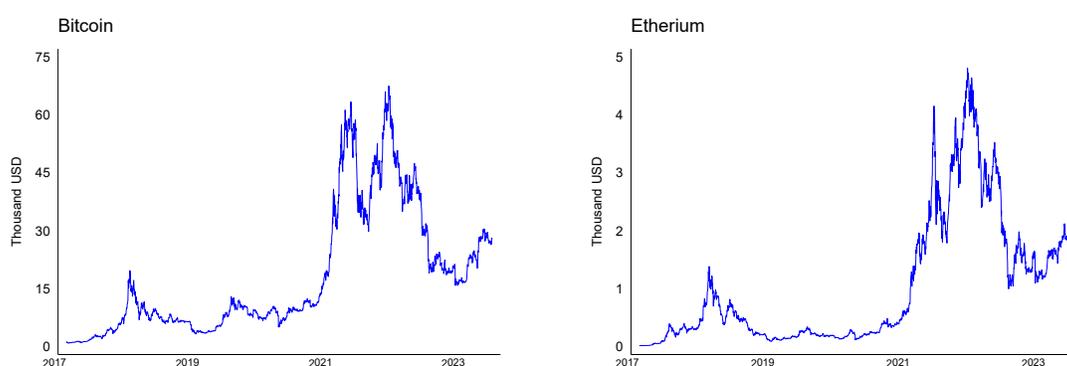
Table A.2 displays that the emissions-intensity varies substantially across mining countries and so does the excise equivalent of a USD 75 per ton carbon tax. Note that for the United States, the emissions-intensity is a weighted average across states, and it was 430 grams per kWh in 2019 (Table A.2). Numbers can slightly differ across studies. For instance, for 2021, de Vries et al. (2022) report an emissions-intensity of electricity generation in the United States of 363 grams per kWh. Given indications that crypto mining is relocating away from New York state following a partial

ban²², the emissions-intensity in the United States increases to 427 grams per kWh if New York is excluded. In this study, our average for the United States for 2021 at 397 grams per kWh is slightly higher than de Vries et al. (2022) but lower than the average excluding New York. Table A.2 also provides the equivalent ad-valorem tax, which is simply calculated by dividing the excise tax by the pre-tax electricity price. This calculation assumes an electricity price of USD 0.05 per kWh.

Data sources:

- Bitcoin (BTC) and Ethereum (ETH) prices are from [Coin Metrics \(2023\)](#), plotted in Figure A.1.

Figure A.1: Prices of Bitcoin and Ethereum

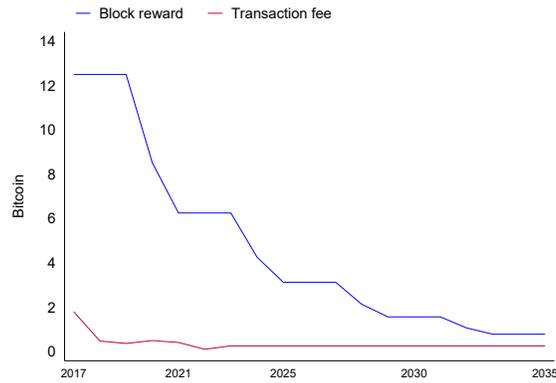


Note: The left panel shows the price of 1 unit of a Bitcoin per US\$. The right panel shows the price of 1 unit of a Ethereum per US\$. Data are from Coin Metrics.

- The block rewards and transaction fees are from [Coin Metrics \(2023\)](#), and are shown in Figure A.2. In 2009, at the start of Bitcoin, the reward was 50 BTC, which since then has been halved every 210,000 blocks of transactions to control the Bitcoin supply. In 2017—the starting year of this study—the Bitcoin mining reward was 12.5 BTC per block and is currently at 6.25 BTC per block. The reward is scheduled to be halved in April 2024 to 3.125 per block. As in the past, future block rewards are assumed to be halved every four years starting from the scheduled halving in 2024. Transaction fee is assumed to be constant in the future at 0.3 BTC.
- The location of crypto mining is estimated by extrapolating location data provided directly from large bitcoin miners to the Cambridge Bitcoin Electricity Consumption Index (CBECEI). The proportion of bitcoin in a given country is obtained from the CBECEI, with Ethereum assumed to follow the same geographical pattern as Bitcoin (a similar assumption is made by [Digiconomist, 2022](#)).

²²In November 2022, New York banned crypto mining for two years unless its electricity use is fully based on renewables. See for instance Ferré-Sadurní and Ashford (2022) and French (2023).

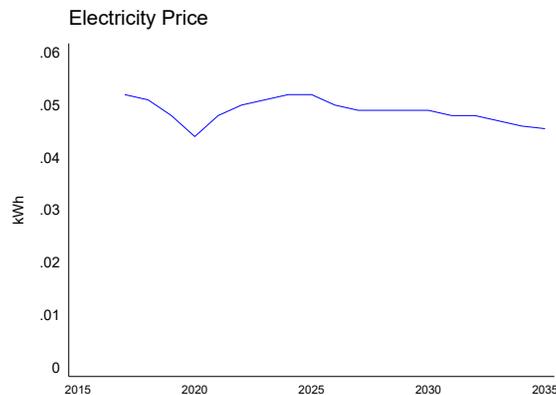
Figure A.2: *Crypto Mining's Block Reward and Transaction Fees*



Note: Data are from [Coin Metrics \(2023\)](#).

- The electricity price is assumed to be USD 0.05 per kWh for Bitcoin (Stoll et al., 2019, CCAF, 2023a) and USD 0.10 per kWh for Ethereum in 2021 (de Vries et al., 2022), and extrapolated backward and forward based on changes in BTC mining country electricity prices using CPAT. Electricity prices exhibit little variation (Figure A.3).

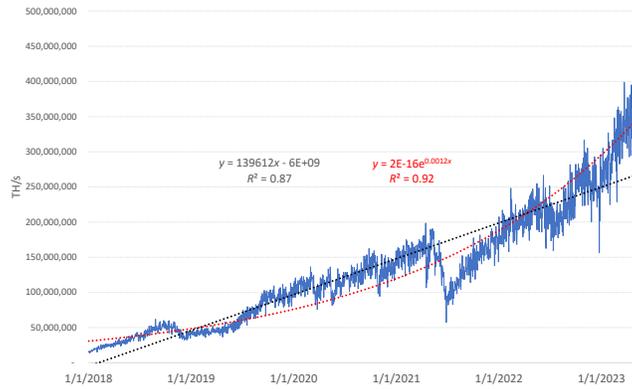
Figure A.3: *Electricity Prices*



Note: Electricity price shown in 2021 real USD based on various sources, including [ClimateScope](#) and the [IEA](#) for historical prices.

- The number of hashes per solved puzzle is obtained from [Coin Metrics \(2023\)](#) and the percent of energy consumed that is used for mining (PUE) is assumed to be 1.1 as in CCAF (2023a). To project forward the hash rate, the trend prediction is used (Figure A.4).
- For the calculation of the average energy efficiency, we use a list of each available mining equipment and its corresponding energy efficiency obtained from CCAF (2023b), and take

Figure A.4: Hash Rates



Note: data are from [Coin Metrics \(2023\)](#).

the average energy efficiency of the equipment that has an energy efficiency better than the breakeven efficiency (computed as in equation A.3). Average energy efficiency of new equipment has improved over time (A.5).

- Future values of average efficiency are predicted using a regression relating average efficiency to breakeven efficiency, in particular:

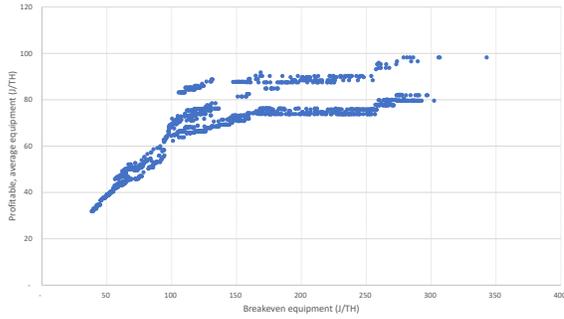
$$\text{Profitable equipment} = a \times \text{Breakeven energy efficiency}. \quad (\text{A.10})$$

The estimated $\hat{a} = 0.45 > 0$, and thus higher breakeven energy efficiency (that is, less energy efficient equipment can be profitable) feeds into a less energy efficient equipment used by miners. This relationship does not differ when using daily or annual data.

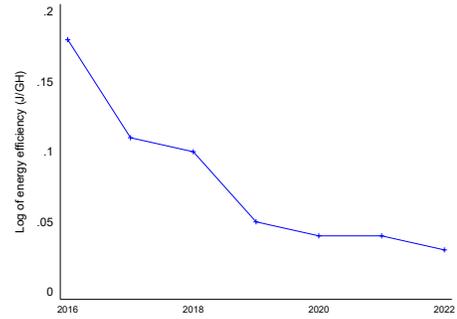
- Past CO₂ emissions per unit of electricity are obtained from the statistics of the International Energy Agency (IEA). The figures account for the decomposition of dirty and clean energy sources in each country, and assume country-specific emissions-intensity for each fuel source within a country to account for differences in the efficiency of power generation equipment.
- Figure A.6 depicts the correspondence between changes in electricity prices and changes in CO₂ emissions.

Figure A.5: Crypto Mining Technology

(a) Breakeven Energy Efficiency



(b) Improvement in Average Energy Efficiency



Note: The left panel shows daily breakeven prices compared to the average profitable equipment since 2019. The right panel shows the average energy efficiency of new mining equipment introduced to the market in each year. Authors calculations using data from Coin Metrics (2023) and CCAF (2023b).

Figure A.6: Changes in Electricity Prices and CO₂ Emissions

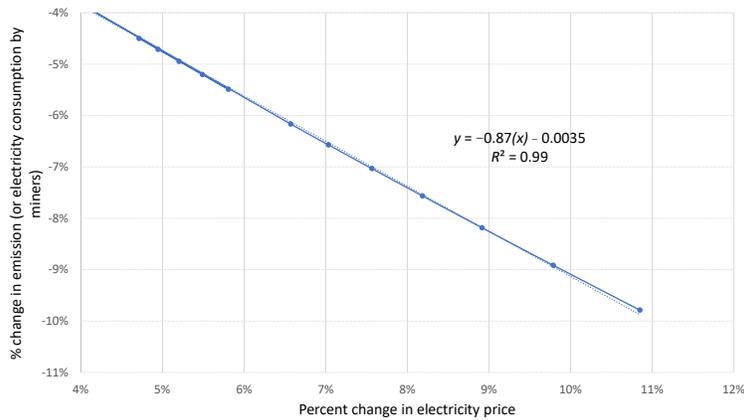


Table A.3: Overview of Studies on Crypto Mining Carbon Footprint

Paper	Year	Methodology	Electricity (TWh)	Emissions (million tons)
CBECI (2022)	2022	Same as Equation (A.3) for electricity consumption Assumes full life-cycle emissions using location specific emissions-intensity for emissions	118 (Bitcoin)	54 (Bitcoin)
Digiconomist (2022)	2022	Same as Equation (A.3) for electricity consumption De Vries et al 2022 for emissions intensity used for emissions	190 (Bitcoin); 34 (Ethereum)	114 (Bitcoin); 58 (Ethereum)
Coin Shares (2022)	2021	Same as Equation (A.3) for electricity consumption Assumes location specific emissions-intensity for emissions	190 (Bitcoin)	41 (Bitcoin)
Forexsuggest (2022)	2021	Third party sources on transactions for each crypto and the carbon-intensity of each crypto	Not provided	57 (Bitcoin); 22 (Ethereum)
de Vries et al. (2022)	2021	Same as Equation (A.3) for electricity consumption Assumes location specific emissions-intensity for emissions	117 (Bitcoin)	65 (Bitcoin)
Frankfurt School (2021)	2021	Same as Equation (A.3) for electricity consumption Assumes location specific emissions-intensity for emissions	91 (Bitcoin)	38 (Bitcoin)
Jones et al. (2023)	2021	Same as Equation (A.3) for electricity consumption Assumes location specific emissions-intensity for emissions	75 (Bitcoin)	113 (Bitcoin)
Gallersdörfer et al. (2020)	2020	Available equipment used to determine energy efficiency	37 (Bitcoin)	Not provided
Stoll et al. (2019)	2018	Efficiency disaggregated between different sized miners Location of mining using mining pools IP location and device IP location Country-level emissions-intensity of electricity	45.8 (Bitcoin)	22.0-22.9 (Bitcoin)
Foteinis (2018)	2017	Same as Equation (A.3) for electricity consumption Assumes full life-cycle emissions for GHG	Not provided	43.9 (Bitcoin & Ethereum, combined)
Mora et al. (2018)	2017	Calculate electricity use based on block difficulty and available technology. Use lifecycle emissions-intensity	Not provided	69 (Bitcoin)
Köhler and Pizzo (2019)	2018	Use lifecycle emissions-intensity	17 (Bitcoin)	31.29 (Bitcoin)

Krause and Tolaymat (2018)	2016-18	Same as Equation (A.3), but different methods to determine energy efficiency of equipment	30 (Bitcoin)	3-13 (Bitcoin)
de Vries (2018)	2017	Same as Equation (A.3)	22-67 (Bitcoin)	Not provided

Source: Compiled by the authors.

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