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Bitcoin and carbon dioxide emissions: Evidence from daily production decisions

Anna Papp, Douglas Almond, Shuang Zhang [*]

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Abstract

Environmental externalities from cryptomining may be large, but have not been linked causally to mining incentives. We exploit daily variation in Bitcoin price as a natural experiment for an 86 megawatt coal-fired power plant with on-site cryptomining. We find that carbon emissions respond swiftly to mining incentives, with price elasticities of 0.69-0.71 in the short-run and 0.33-0.40 in the longer run. A $1 increase in Bitcoin price leads to $3.11-$6.79 in external damages from carbon emissions alone, well exceeding cryptomining's value added (using a $190 social cost of carbon, but ignoring increased local air pollution). As cryptomining requires ever more computing power to mine a given number of blocks, our study highlights both the revitalization of US fossil assets and the need for financial industry accounting to incorporate cryptomining externalities.

Keywords: Bitcoin, cryptocurrency mining, carbon emissions, climate change

JEL Codes: Q40, Q48, Q53

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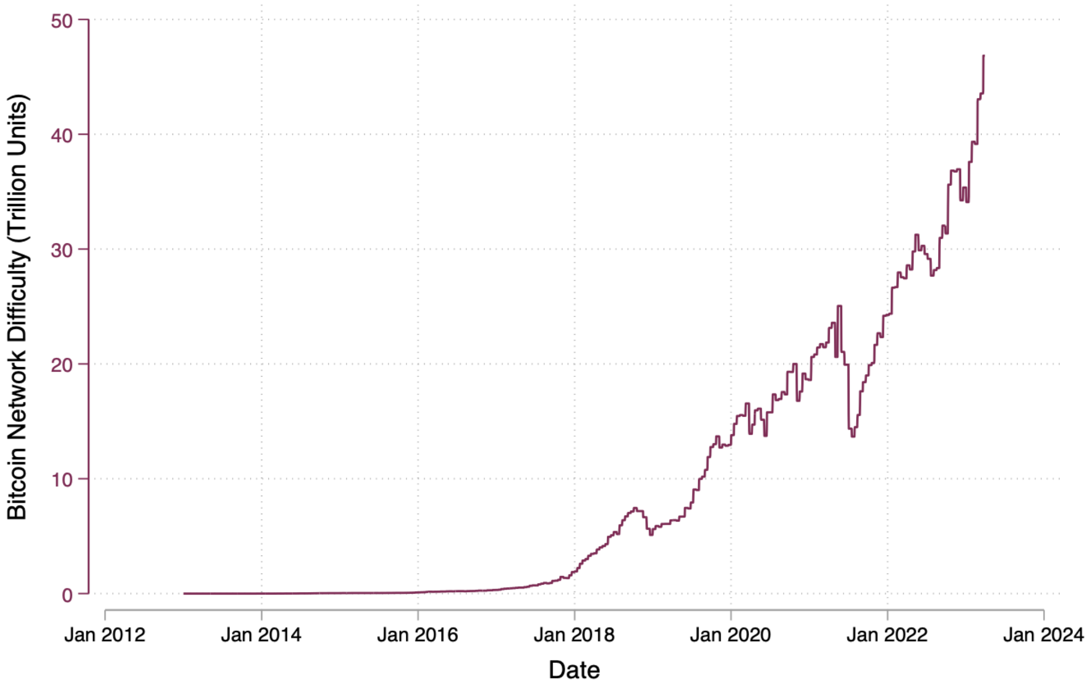
1 Introduction

Cryptocurrencies offer multidimensional benefits, including transaction speed, privacy, security, and decentralization. To mine and perform transactions with proof-of-work digital currencies, large amounts of electricity are required. The Cambridge Center for Alternative Finance (CCAF) estimates that the Bitcoin network uses about 43 to 194 terawatt hours of power per year or roughly 0.3-1.3% of global electricity production, comparable to the energy demands of a country like Portugal.[1] As fossil-fuel-generated electricity is thought to power the majority of cryptomining (Blandin *et al.*, 2020), the environmental costs of cryptocurrencies are closely tied to climate policy. Furthermore, as Bitcoin mining network difficulty continues to increase (Figure 1), the electricity required to mine a given number of Bitcoins also increases.

Figure 1: Bitcoin Network Difficulty



Notes: Figure shows Bitcoin network difficulty. Bitcoin network difficulty measures how difficult it is to solve a "hash" and mine a Bitcoin block successfully.

The US has overtaken China as the world's leading cryptominer. In mid-2021, China implemented a cryptocurrency ban motivated partly by achieving "carbon neutrality" (Pan, 2021). Meanwhile, many US states have been inducing miners to initiate or expand cryptocurrency mining.[2] For example, Texas offers miners a 10-year tax abatement and sales tax credits (Malik, 2021). The exodus of cryptocurrency mining from China accelerated the growth of mining infrastructure in

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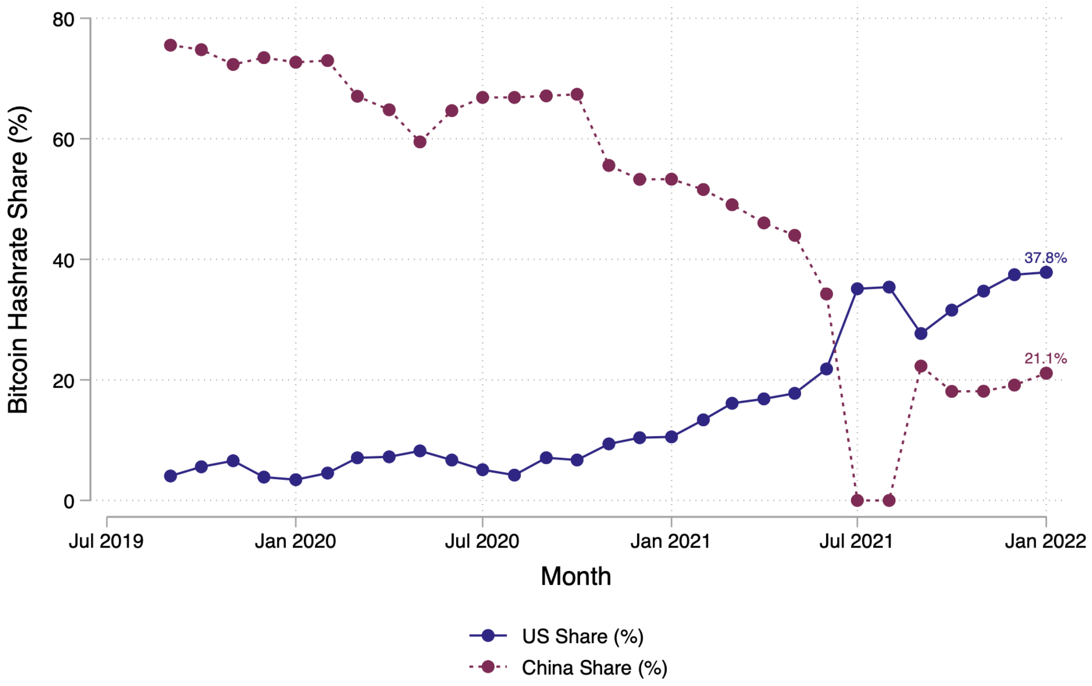
[1] `https://ccaf.io/cbeci/index`

[2] Kentucky grants a sales tax exemption for personal property and electricity used directly in the commercial mining of crypto (Adejumo, 2021). Georgia introduced a similar bill in February 2022, while Illinois is extending existing tax benefits to include data centers with mining operations (Handagama, 2022).

the United States (Figure 2). Even despite the recent uptick in underground/illicit mining in China, the US share of worldwide cryptomining continues to grow.

Figure 2: Bitcoin Hashrate Share by Country



Notes: Figure plots monthly Bitcoin hashrate share in the US and China. Hashrate measures the speed at which miners add new transactions to the blockchain and is a proxy for the amount of cryptomining conducted. Source: CCAF.

Ideally, researchers could estimate the total environmental externality of cryptomining using design-based methods and set these against cryptocurrency's benefits. But due to very weak US reporting requirements and the recent influx of mining operations to the US, systematic data on US crytomining activity do not exist. More subtly, as the carbon footprint of cryptomining depends both on the energy consumption of the network and the carbon intensity of the energy mix used to generate the electricity that powers the network, it is difficult to estimate the additional carbon emissions due to cryptomining absent comprehensive data on where and how intensively cryptomining is occurring throughout the US electricity grid.

In this paper, we take an initial step to addressing these challenges by focusing on an integrated electricity generator-cryptominer. We argue cryptomining at the Scrubgrass power plant in Pennsylvania presents a unique opportunity to study the marginal carbon emissions from Bitcoin mining due to the planned retirement of the plant in the absence of the cryptocurrency mining agreement.[3] Coupled with the fact that Bitcoin mining is conducted on-site with power generated

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[3] The Union of Concerned Scientists included the plant on their 2012 list of plants "ripe for retirement" (Union of Concerned Scientistics, 2012). Several news articles also mention that the plant was set to retire before the start of Bitcoin mining. See Section 2 for more details.

at the facility, this means that the plant's carbon emissions are marginal emissions of the on-site cryptomining activity. We account for the changing computing power requirements of mining each new Bitcoin block in multiple ways and estimate short-run and long-run elasticities of carbon emissions with respect to daily Bitcoin price.

We leverage 1,796 Bitcoin price movements over five years. In our main regression framework, the dependent variable is daily carbon dioxide emissions at the Scrubgrass plant and the independent variable of interest is daily Bitcoin price. We argue the exogeneity and stationarity of Bitcoin price variation in our setting and estimation, and therefore, we infer that the regression coefficient captures the causal effect of Bitcoin mining incentives on released carbon.

We find a long-run price elasticity of 0.33-0.40 and a larger short-run elasticity of 0.69-0.71. At a $190 social cost of carbon – proposed by the EPA (2022) and Rennert *et al.* (2022)– our findings imply that a $1 increase in daily Bitcoin price leads to an additional $3.11-$6.79 worth of daily damages from carbon emissions alone at the Scrubgrass power plant. Our elasticity estimates are robust to various alternative specifications and two falsification/placebo exercises replicating our analyses: 1) at the same power plant before Bitcoin mining and; 2) at other Pennsylvania coal refuse power plants without cryptomining operations. While local air pollution is not the focus of this paper, we also find nitrogen oxide (NO_X) emissions at Scrubgrass to increase with Bitcoin price.

Our findings provide timely information for US environmental regulators. Our basic conclusion that carbon-induced damages from cryptomining can exceed firm revenues parallels that of Muller *et al.* (2011), who found that the air pollution damages of several industries (e.g., coal-fired electric generation as a whole) exceed the value-added from the same industries. More broadly, our analysis aligns with government efforts to develop environmental national accounts.[4] While our focal analysis is on a single firm and is therefore limited in external validity, it is still a relevant case study for policymakers constructing environmental national accounts and demonstrating that the environmental damages from cryptomining can exceed value-added by a wide margin. We discuss the carbon intensity of other cryptominers and US power plants more generally in Section 6 and Figure 4. The large response of electricity generation to Bitcoin price we find reveals a more narrowly-focused financial objective than the strong and prominent sustainability claims of cryptomining companies. The elasticity estimates also highlight the possible environmental repercussions of cryptocurrency trading or other activities that inflate digital currency prices.

As cryptomining companies plan further expansion,[5] policymakers are increasingly interested in regulating cryptomining. In March 2022, President Biden issued an executive order titled "Ensuring the Responsible Development of Digital Assets". This was followed by the May 2023 proposal of the Digital Asset Mining Energy (DAME) tax, which would impose a tax equal to 30% of the cost of the electricity used in cryptomining.[6] Our analysis of Scrubgrass is a "proof of concept" for future empirical analyses leveraging plant-level decision-making and the financial

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[4] https://www.whitehouse.gov/wp-content/uploads/2023/01/Natural-Capital-Accounting-Strategy-final.pdf

[5] As described in a letter to the EPA and DOE, Senator Warren and her team's survey of seven cryptominers (including Stronghold) show these miners alone are planning to increase their capacity by 230% over the next few years (Warren *et al.*, 2022). Stronghold is currently finalizing the acquisition of a third Pennsylvania waste coal plant.

[6] https://www.whitehouse.gov/cea/written-materials/2023/05/02/cost-of-cryptomining-dame-tax/

incentive to mine. Particularly as more establishment-level data on US cryptocurrency mining becomes available, our methodology can be scaled up to estimate industry-wide externalities and local pollution impacts.

This paper bridges two distinct areas of research: estimating the global carbon footprint of digital assets (typically from engineering models) and the economics of electricity markets. A growing literature attempts to estimate the global aggregate carbon emissions of the Bitcoin network, though consensus has not yet been reached due to the aforementioned challenges. Existing work calculates carbon emissions using various estimates of hardware energy efficiencies, locations of cryptomining activity, and average emissions associated with electricity generation based on energy mix. As all these steps require various strong assumptions, initial estimates for the same period (2017-2018) vary significantly across studies, with annual carbon emissions estimates **ranging more than an order of magnitude: from 3.6 to 69 MtCO$_2$e** (Krause and Tolaymat, 2018; Mora *et al.*, 2018; Foteinis, 2018). Using empirical data from IPO filings on hardware efficiencies along with the geographical footprint of mining activity derived from IP addresses, Stoll *et al.* (2019) estimate the global carbon footprint of Bitcoin between 22.0 and 22.9 MtCO$_2$e. de Vries *et al.* (2022) update the estimated carbon footprint of the Bitcoin network after China's cryptocurrency ban (to an annual carbon footprint of 65.4 MtCO$_2$e).

While prior studies that use engineering estimates are valuable for establishing bounds on the global carbon footprint of cryptocurrencies, there is a notable gap in assessing damages at the firm level, where the production decisions are made. Our focus on high-frequency electricity production decisions builds on the broader energy economics literature on US wholesale electricity markets (for example, Joskow (1997); Borenstein *et al.* (2002); Borenstein and Bushnell (2015)). We augment their work by demonstrating that digital asset revenues may be an additional incentive that drive electricity production decisions. Benetton *et al.* (2021) comes closest to our study, considering the price externality of cryptomining (not environmental costs) from Upstate New York cryptominers' use of local electricity. The increase in electricity demand lead to higher electricity prices for small businesses and households that were not offset by higher business taxes from the cryptomining firms (Benetton *et al.*, 2021). To the best of our knowledge, our paper is the first to directly measure the marginal carbon emissions of Bitcoin mining and examine the environmental externalities of cryptocurrency mining at the firm level.

2 Background

Bitcoin mining basics: In creating or "mining" Bitcoin, cryptominers add new transactions to the blockchain, a public ledger that records network transactions. Bitcoin miners validate transactions in the network by solving complex mathematical problems known as hashes. When a miner successfully solves a hash, they broadcast the new block of transactions to the network, along with proof that they have performed the required computational work. This process is referred to as the "proof-of-work" mechanism. It is computationally expensive due to the many calculations that must be performed to add blocks.

In return for successfully solving a hash, the miner receives a reward of Bitcoins. The number of hashes that a miner or network of miners can calculate per second is referred to as the "hashrate".[7] To maintain a stable block production rate, the Bitcoin network automatically adjusts the mining network difficulty approximately every two weeks.[8] Higher network difficulty and higher network hash rate mean it will take more computing power to mine the same number of blocks. As the collective network hashrate increases, mining difficulty increases as well. We refer to each period of constant Bitcoin mining difficulty as a Bitcoin "difficulty-era".

Bitcoin mining economics: Bitcoin mining revenues are mainly driven by the price of Bitcoin, the miner's hashrate, the network hashrate, and other Bitcoin network characteristics.[9] Bitcoin mining costs are primarily driven by the cost of power, mining operating expenses (e.g., cooling costs), and the price of miners. The cost of power makes up the vast majority of Bitcoin mining costs. Indeed, some Bitcoin miners report that electricity makes up as much as 90-95%[10] of mining costs.[11] For more details on Bitcoin mining economics, please see Appendix Section A1.1.

Scrubgrass power plant: We study carbon emissions and Bitcoin mining at the Scrubgrass power plant, an 86 MW-capacity coal refuse[12] power plant in Venango County, Pennsylvania. Stronghold Digital Mining ("Stronghold"), a public company, owns and operates the power plant.[13] Stronghold has Bitcoin mining machines on-site and uses electricity generated at the plant to power its equipment.

We offer several pieces of descriptive evidence to support the claim that the Scrubgrass power plant would have been retired without cryptomining. First, we plot the sum of total electricity generated by coal power plants in Pennsylvania, excluding the two plants owned by Stronghold. The left panel of Figure A5 shows a clear downward trend in coal-generated electricity in the region. At the same time, Scrubgrass's output has remained at approximately its 2015 level.[14]

The second piece of evidence is the retirement of similar coal plants in the US. In 2012, the Union of Concerned Scientists published a report identifying power plants "ripe for retirement".[15] The report evaluates the economic viability of coal power plants by comparing the cost of electricity generation at these power plants with the cost of electricity generated by an average natural gas power plant. The report identifies 180 plants "ripe for retirement" in the US (Union of Concerned Scientistics, 2012). Both Scrubgrass and Panther Creek are included in this list. Of the 137 other plants with available emissions data, 87 (64%) have since retired. Furthermore, Scrubgrass is among the least efficient and dirtiest of these plants (Figure A6).

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[7] The hashrate essentially measures the speed at which a miner or the network can add new blocks of transactions to the blockchain and is usually reported in exa- or terahashes per second (EH/s and TH/s). A terahash is a trillion hashes, while an exahash is a quintillion or 10^{18} hashes.

[8] The network difficulty measures how difficult it is to solve a hash and mine a Bitcoin block successfully.

[9] These other characteristics include the reward rate of Bitcoin per mining block and the block reward. The reward rate is currently 6.25 Bitcoins per block and is halved approximately every four years to reduce the number of Bitcoins mined over time and maintain a cap on the supply.

[10] 90-95% estimate reported by Bitfury CEO Valery Vavilov in Kelly (2016).

[11] For Stronghold, we estimate variable electric costs to make up approximately 56% of costs in recent years. Please See Appendix Section A1.2 for details on this back-of-the-envelope calculation.

[12] Coal refuse is material left over from earlier coal mining activity in the region.

[13] In addition to Scrubgrass, Stronghold owns a second similar coal refuse power plant in Pennsylvania (Panther Creek Plant with a generation capacity of 80 MW), which does not have carbon emissions data.

[14] Until 2013, Scrubgrass was under a power purchase agreement. Output dropped after 2013 when this expired. In 2020, due to low grid prices, Scrubgrass mostly purchased electricity to mine Bitcoin.

[15] `https://www.ucsusa.org/sites/default/files/2019-09/Ripe-for-Retirement-Full-Report.pdf`

Finally, there is anecdotal evidence that the power plant would have closed without the cryptomining deal. A news article from 2021 notes that Scrubgrass "was on the brink of financial ruin as energy customers preferred to buy cheap natural gas or renewables" (Solon, 2021). Another news report similarly writes that Scrubgrass was "set to close before pivoting to Bitcoin" (Milman, 2022).

Based on this evidence, it is plausible that the absence of Bitcoin mining would have resulted in no electricity generation at the Scrubgrass power plant. In this counterfactual scenario, other cleaner generation sources would have replaced generation from Scrubgrass.[16] Given the probable decommissioning of the plant in the absence of the cryptocurrency mining agreement, coupled with the fact that Bitcoin mining is conducted on-site at the facility, we posit that the emissions at the plant are the marginal emissions associated with the on-site cryptomining activity.

Economics of vertically integrated Bitcoin mining: Stronghold operates a vertically integrated Bitcoin mining model at the plant, meaning that the company owns the power plant and has on-site Bitcoin mining equipment. The plant is also connected to the electric grid and is part of the PJM Interconnection regional transmission organization ("PJM"). Stronghold can use Scrubgrass' generation capacity for on-site Bitcoin mining directly or sell power to the grid. Specifically, the company has the flexibility to do a mix of the following actions:

a) Generate electricity from coal and use it directly to mine Bitcoin on-site;

b) Generate electricity from coal and sell power to the grid through PJM;

c) Buy electricity from the grid and use it to mine Bitcoin.

Which actions Stronghold takes will depend on local electricity prices (P_{elec}), the expected Bitcoin revenues per electricity used (R_{BTC}), and the net cost of generating power (C_{gen}) at the plant. If local electricity prices are higher than expected revenues from Bitcoin, Stronghold will likely sell power to the grid. If electricity prices are lower than the cost of generating power on-site, Stronghold will likely buy power from the grid. (For more details, please see Appendix Section A1.3.)

In summary, the main determinants of daily generation at the Scrubgrass power plant are the price of Bitcoin (P_{BTC}), mining difficulty and network hashrate which influence the estimated electricity required to mine one Bitcoin (E_{BTC}), the local price of power (P_{elec}), and the cost of generating power at the plant (C_{gen}). We observe P_{BTC} and P_{elec} directly. We estimate the energy requirement of mining one Bitcoin at Scrubgrass (E_{BTC}) using figures reported by Stronghold and network hashrate (Appendix Section A1.4). Finally, we assume that C_{gen} is mostly driven by the cost of local coal.[17] These drivers of generation inform our empirical strategy, described in Section 4.

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[16] The average marginal emissions of the PJM grid between January and June 2023 is 0.52 kg per kWh, much lower than the carbon intensity of Scrubgrass (1.37 kg per kWh).

[17] Fuel costs make up roughly 60 to 75% of operating costs at coal power plants operating at 35-85% capacity (`https://carbontracker.org/reports/understanding-operating-cost-coal-fired-power-us-example/`).

3 Data

Power plant data: We download power plant load and emissions data for Scrubgrass and other power plants from the EPA Clean Air Markets Program (Environmental Protection Agency, 2023). Scrubgrass Plant (facility id = 50974) has two units. We sum daily CO_2 emissions mass across the two units and work with data at the plant-day level. The average daily carbon dioxide emissions at Scrubgrass is 1,034 metric tons over our period of interest (May 2018 - March 2023). We also calculate daily plant-level steam load and sulfur dioxide (SO_2), and nitrogen oxide (NO_X) emissions for supplementary analyses.

Bitcoin network data: For Bitcoin prices, we use daily data from the St. Louis Fed FRED Economic Data (Federal Reserve Bank of St. Louis, 2023). We also collect information on Bitcoin network difficulty and hashrate from blockchain.com (Blockchain.com, 2023). The mean daily Bitcoin price is $21,140 over the 131 difficulty-eras in our study period.

Other data: We supplement the above with weekly North Appalachian coal spot prices, local grid prices, and population-weighted average temperatures (an important determinant of electricity demand). We download historical North Appalachian coal spot prices from the EIA (EIA, 2023), which are prices for next quarter's delivery of coal and reflect the opportunity cost of burning coal at Scrubgrass in the present period. Scrubgrass and other Pennsylvania plants are members of PJM Interconnection, the regional transmission organization (RTO) that coordinates the multi-state electric grid in 13 states and Washington, DC. We download day-ahead hourly locational marginal pricing (LMP) from PJM's Data Miner application (PJM Interconnection, 2023). LMP reflects the cost of producing and delivering electricity to specific points across the electric grid and is used by participants in the wholesale electricity market. Finally, we use ERA5-Land weather data (Sabater, 2023),[18] and calculate a population-weighted mean daily temperature across the region covered by PJM using Google Earth Engine.

4 Research Design

We are interested in the responsiveness of carbon emissions to variations in Bitcoin prices to compare the value-added from Bitcoin mining with the external damages from the activity. Our main regression is of the form:

$$CO2_t = \beta P_{BTC,t} + \mathbf{X}_t \gamma + \delta_t + \epsilon_t \tag{1}$$

where the main dependent variable ($CO2_t$) is the daily carbon dioxide emissions at the Scrubgrass power plant and the main independent variable ($P_{BTC,t}$) is the daily price of Bitcoin. We control for the other main determinants of daily generation at the power plant ($\mathbf{X}_t$). We also add various time-related fixed effects (δ_t) to account for seasonality, including year, month, and day-of-week fixed effects.

In our setting, we argue the exogeneity of Bitcoin price for the following reasons. We can convincingly rule out simultaneity as a threat to exogeneity due to the power plant's minimal share of global Bitcoin mining operations (e.g., $< 0.2\%$ of Bitcoin mined in the first half of

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[18] ERA5-Land is a reanalysis dataset that combines model data with observations from across the world into a consistent dataset.

2022). Our assumption of the exogeneity of Bitcoin price may also fail if omitted variables affect both plant generation and Bitcoin price. Due to Bitcoin's reliance on electricity generated by nonrenewables, fossil fuel commodity prices may influence digital currency prices and electricity generation independent of cryptomining. For this reason, we control for the spot price of local coal ($C_{gen,t}$), which is the main cost of electricity generation at the Scrubgrass plant, in all specifications.

The regression coefficient for the price of Bitcoin has the following interpretation: a $1 increase in Bitcoin is associated with a β metric ton increase in daily carbon dioxide emissions. We use our regression estimates to calculate the elasticity of carbon dioxide emissions with respect to daily Bitcoin prices according to the following formula:

$$\eta_{BTC} = \hat{\beta}(\frac{\overline{P_{BTC}}}{\overline{CO2}}) \tag{2}$$

where $\hat{\beta}$ is the estimated coefficient from above and $\overline{P_{BTC}}$ and $\overline{CO2}$ are the mean values of daily Bitcoin price and Scrubgrass carbon emissions between May 1st, 2018 and March 31st, 2023.

Other drivers of generation and bounding exercise: We would like to avoid confounding from other important determinants of daily power generation at Scrubgrass beyond the price of coal, specifically the approximate electricity required to mine one Bitcoin at Scrubgrass ($E_{BTC,t}$) and local electricity prices ($P_{elec,t}$). However, both of these variables are affected by Bitcoin price, which means that they are "bad controls" that partially control for omitted factors but are themselves affected by the variable of interest (Angrist and Pischke, 2009).[19]

Given some reasonable assumptions, we can establish the upper and lower limits for the true causal effect. Following Angrist and Pischke (2009), we are interested in the "long regression":

$$CO2_t = \beta P_{BTC,t} + \gamma_1 EwoBTC_t + \gamma_2 PwoBTC_t + \gamma_3 C_{gen,t} + \delta_t + \epsilon_t \tag{3}$$

where we now denote the energy requirement to mine Bitcoin *without* the impact of elevated mining activity as $EwoBTC_t$ and the local electricity price *without* the impact of elevated demand from cryptominers as $PwoBTC_t$. We are, of course, not able to observe these variables directly, but instead have access to "proxy controls", $P_{elec,t}$ (the day-ahead LMP price) and $E_{BTC,t}$ (the estimated electricity required to mine one Bitcoin). We write these as functions of Bitcoin price and the true controls:

$$E_{BTC,t} = \rho_0 + \rho_1 P_{BTC,t} + \rho_2 EwoBTC_t \tag{4}$$

$$P_{elec,t} = \mu_0 + \mu_1 P_{BTC,t} + \mu_2 PwoBTC_t + \mu_3 C_{gen,t} \tag{5}$$

We solve for $EwoBTC_t$ and $PwoBTC_t$ and plug them into equation 3. This allows us to characterize the bias to $\hat{\beta}$ when we do include $E_{BTC,t}$ and $P_{elec,t}$ in regression 1. The bias from including $E_{BTC,t}$ is $-\gamma_1 \frac{\rho_1}{\rho_2}$, while the bias from including $P_{elec,t}$ is $-\gamma_2 \frac{\mu_1}{\mu_2}$. (For more details, please see Appendix Section A1.5.)

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[19] Local electricity price is potentially affected by Bitcoin price due to changes in demand from other cryptominers using the grid, as shown by Benetton *et al.* (2021). The energy requirement of mining Bitcoin may be affected by Bitcoin price because a change in cryptomining activity leads to a change in network hashrate, the metric that drives the energy requirement of mining.

On the other hand, according to the omitted variable bias formula, a regression without including $E_{BTC,t}$ will be biased by $\gamma_1 \zeta_{EB}$, where ζ_{EB} is the slope coefficient from a regression of $EwoBTC_t$ on $P_{BTC,t}$. Similarly, a regression without including $P_{elec,t}$ will be biased by $\gamma_2 \zeta_{PB}$, where ζ_{PB} is the slope coefficient from a regression of $PwoBTC_t$ on $P_{BTC,t}$.

These formulas then allow us to establish limits for the true causal effect of Bitcoin price on carbon emissions at the power plant given some reasonable assumptions on the signs of $\gamma_1, \gamma_2, \rho_1, \rho_2, \mu_1, \mu_2, \zeta_{EB}$ and ζ_{PB}. First, $\gamma_1 < 0$ as higher electricity requirements for mining Bitcoin will likely discourage Bitcoin mining at Scrubgrass and reduce generation and emissions. We expect $\rho_1 > 0$ as higher Bitcoin prices lead to more mining and higher network hashrate. We also empirically investigate this relationship. We observe a small but statistically significant relationship between Bitcoin prices and Bitcoin network hashrate (Table A2, Columns (1) and (2)). Then $\rho_2 > 0$, as this is just the relationship between electricity requirements without the impact of Bitcoin prices and observed electricity requirements. Lastly, it's reasonable to assume that $EwoBTC_t$ and $P_{BTC,t}$ are positively related and therefore $\zeta_{EB} > 0$, since $EwoBTC_t$ is an input to cryptomining.[20] Combining these assumptions, we posit that our estimated coefficient of interest, $\hat{\beta}$, will overestimate the true causal effect when we do control, and underestimate when we do not control for the electricity requirements for mining Bitcoin.

We can similarly make assumptions about the direction of the bias when including and not including local electricity prices as controls. We expect γ_2 to be positive as at higher electricity prices, Stronghold will generate and sell more electricity to the grid, while μ_2 is the relationship between grid prices without the impact of cryptomining and observed grid prices. We investigate μ_1 by regressing electricity prices on Bitcoin price and find the coefficient on Bitcoin is statistically significant, positive, but very small (a \$1 increase in Bitcoin price corresponds to a 0.1 cent increase in day-ahead average LMPs, Table A2, Columns (3) and (4)). Therefore, the estimated $\hat{\beta}$, will underestimate the true causal effect when we do control and an overestimate when we do not control local electricity prices.

Since $E_{BTC,t}$ and $P_{elec,t}$ do not affect each other, our estimated $\hat{\beta}$ will thus be an:

- **underestimate** without $E_{BTC,t}$ but with $P_{elec,t}$ in equation 1
- **overestimate** with $E_{BTC,t}$ but without $P_{elec,t}$ in equation 1.

We, therefore, run our main specifications with these two combinations of controls that establish lower and upper limits on the true causal effect of Bitcoin on carbon emissions at the Scrubgrass power plant.

Bitcoin difficulty-eras: While we approximate the amount of electricity required to mine one Bitcoin at Scrubgrass at a daily level, there are other unobserved factors – such as Stronghold's mining equipment and hashrate – that influence generation at the plant. An alternative approach to account for Bitcoin network characteristics is examining the elasticity of carbon emissions *within* periods of constant network difficulty. Between different Bitcoin difficulty periods, the computing effort required to mine the same amount of Bitcoin changes. However, *within* the same difficulty periods, miners can adjust effort proportionally.[21] For this reason, we present

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[20] For example, if $EwoBTC_t$ decreased due to technological advancements, Bitcoin mining would be cheaper, which would be associated with lower Bitcoin prices.

[21] We note that Bitcoin price still varies considerably within difficulty-eras, the average difference between the

alternative estimates where we add Bitcoin difficulty-era fixed effects (D_t) to equation 1:

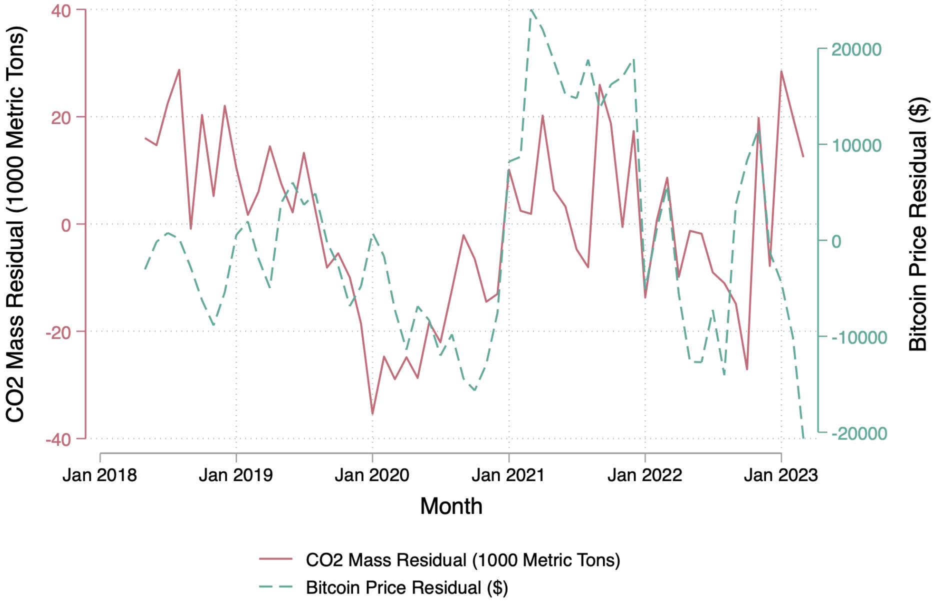
$$CO2_t = \beta P_{BTC,t} + \mathbf{X}_t\gamma + \delta_t + D_t + \epsilon_t, \tag{6}$$

Since these periods of constant network difficulty are brief ($\sim$ two weeks) and Scrubgrass is unlikely to purchase additional equipment within these periods in a way correlated with Bitcoin price, we interpret the resulting elasticity estimates as the short-run elasticity.[22] In contrast, our estimates without difficulty fixed effects – the long-run elasticity – reflect investments such as purchases of better equipment.

5 Results

Main results: We begin with a graph showing the relationship between the monthly average Bitcoin price and monthly total carbon dioxide emissions at Scrubgrass (Figure 3). In the demeaned figure, we account for monthly seasonality, coal prices, and local electricity prices. We observe a positive correlation between Bitcoin price and carbon emissions. In contrast, before cryptomining at Scrubgrass, we do not see this positive correlation (Figure A7). Next, we investigate the relationship between Bitcoin price and carbon emissions at the daily level.

Figure 3: Bitcoin Price and Carbon Dioxide Emissions



Notes: Figure shows demeaned monthly average Bitcoin price and total carbon dioxide emissions at the Scrubgrass plant, for May 2018 through March 2023.

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minimum and maximum price of Bitcoin within difficulty-eras is $3,460.

[22] We note that while coal-fired steam turbines take longer than natural gas combustion or combined-cycle systems to ramp up, coal plants can still increase generation within hours, allowing for daily response to Bitcoin price. Cold start-up time of coal-fired plants is estimated at 5-10 hours, while hot start-up time is approximately 3 hours (National Renewable Energy Laboratory, 2020).

Table 1: Daily Bitcoin Price and CO_2 Emissions at Scrubgrass Power Plant

	Dependent variable:			
	Carbon Dioxide Emissions (Metric Tons)			
	Long-Run Elasticity		Short-Run Elasticity	
	(1)	(2)	(3)	(4)
Panel A: After Bitcoin Mining (May 2018 - Mar 2023)				
Bitcoin Price ($)	0.016***	0.020***	0.035***	0.036***
	(0.003)	(0.003)	(0.008)	(0.008)
	[0.000]	[0.000]	[0.000]	[0.000]
Mean Bitcoin Price ($)	21,140	21,140	21,140	21,140
Mean CO_2 (Metric Tons)	1,059	1,059	1,059	1,059
Elasticity	0.33	0.40	0.69	0.71
Social Cost ($)	3.11	3.79	6.59	6.79
Observations	1,796	1,796	1,796	1,796
Panel B: Before Bitcoin Mining (Jan 2013 - Dec 2017)				
Bitcoin Price ($)	-0.007	-0.023	0.003	0.002
	(0.009)	(0.020)	(0.037)	(0.038)
	[0.483]	[0.247]	[0.924]	[0.961]
Mean Bitcoin Price ($)	1,106	1,106	1,106	1,106
Mean CO_2 (Metric Tons)	1,703	1,703	1,703	1,703
Elasticity	0.00	-0.02	0.00	0.00
Observations	1,826	1,826	1,826	1,826
C_{gen} Control	Y	Y	Y	Y
P_{elec} Control	Y	-	Y	-
E_{BTC} Control	-	Y	-	Y
Difficulty Era FEs (D_t)	-	-	Y	Y

Notes: Table shows results of regressing carbon dioxide emissions on daily Bitcoin price according to equations 1 and 6. Panel A shows results after Bitcoin mining (May 2018 - March 2023), while Panel B shows results before Bitcoin mining (January 2013 - December 2017). All columns control for coal prices and include year, month, and day-of-week fixed effects. Columns (1) and (3) control for local electricity prices, while columns (2) and (4) control for the approximate electricity requirements of mining Bitcoin. Columns (3) and (4) also add difficulty era fixed effects. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table 1 shows the estimated coefficients and elasticities. In columns (1) and (2), we estimate the long-run elasticity of carbon emissions, inclusive of investments. We find that a $1 increase in daily Bitcoin price leads to a 0.016 to 0.020 metric ton (16 to 20kg) increase in daily carbon emissions at the Scrubgrass power plant. As discussed in Section 4, we expect the two columns to be the upper and lower bounds of the true causal effects. Indeed, our estimates are close to each other, and the estimate *without* local electricity controls, but *with* electricity requirements of mining Bitcoin is slightly larger. At an average Bitcoin price of $21,140 and average daily carbon emissions of 1,059 metric tons, these estimates translate to an elasticity of 0.33-0.40.

Next, we include difficulty-era fixed effects in our regression and estimate the short-run elasticity of carbon emissions at Scrubgrass. We find that a $1 increase in daily Bitcoin price leads to a 0.035 to 0.035 metric ton (35 to 36 kg) increase in daily carbon emissions (Table 1, Column (3) and (4)), or an elasticity of 0.69-0.71. In the short run, increased electricity generation is the primary way Scrubgrass can respond to increased Bitcoin prices. In the long run, however, Scrubgrass can invest in more efficient miners, which can lower the plant's margin emissions rate with respect to Bitcoin generation. This explains our larger short-run elasticity estimates. We multiply the carbon estimates by the social cost of carbon (EPA, 2022; Rennert *et al.*, 2022). Our findings implicate that a $1 increase in daily Bitcoin price leads to $3.11-$6.79 external damages from carbon emissions alone at the Scrubgrass power plant. Therefore, the social costs of carbon emissions exceed value-added from cryptomining at Scrubgrass.

Robustness checks: We conduct various robustness checks of our main results. First, we test for stationarity of variables to ensure we are not recovering a spurious relationship. Table A3 presents p-values from Augmented Dickey–Fuller tests. Unsurprisingly, Bitcoin price (P_{BTC}) and the cost of power (C_{gen}) are non-stationary (Table A3, Panel A). However, when we control for time-related fixed effects used in our main regression, such as year, month, and day-of-week fixed effects, we reject the presence of a unit root for all variables (Table A3, Panel B). We also repeat the ADF tests and include polynomial time trends instead of fixed effects. Again, we reject the presence of a unit root for all variables (Table A3, Panel C).[23] We conclude that all variables are stationary or trend-stationary and spurious correlation is not driving our results.

Our estimates are robust to excluding various fixed effects and including other controls, such as population-weighted temperatures across PJM (Tables A5 and A6). We also repeat our analysis including only days with non-zero generation at the plant (Table A7), including only days with high electricity prices (Table A8), excluding the COVID-19 pandemic (Table A9), and at the weekly, instead of daily, level (Table A10). We find similarly high elasticities across all these alternate specifications.

Next, we test different ways of controlling for the non-cryptomining determinants of electricity generation. First, we control for lagged instead of contemporaneous coal prices. We lag North Appalachian spot prices by three months.[24] While the contemporaneous coal prices better reflect the opportunity price of burning coal at the plant, our results are similar (albeit slightly smaller in magnitude) when using lagged coal prices (Table A11). In our main results, we control for local electricity prices linearly to ease the comparison to results before the beginning of Bitcoin mining at Scrubgrass. However, we test alternative ways of controlling for electricity prices. First, we use binned LMP prices (by quintile) (Table A12, Columns (2) and (5)). Next, we use indicator variables constructed using the estimated daily cost of generating power (C_{gen})

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[23] We rerun our main analysis with polynomial time trends and find similar results (Table A4).

[24] Since weekly spot prices reflect prices for the next quarter's delivery of coal, lagging by three months may better reflect the price at which the coal was purchased.

and the expected Bitcoin revenues per electricity used (R_{BTC}), further described in Appendix Section A1.3. Specifically, we include two binary indicators that approximate when Scrubgrass is expected to buy and sell electricity to the grid. Table A12 Columns (3) and (6) show the results. Results are very similar across all specifications.

Finally, we also estimate the elasticity of electricity generation with respect to Bitcoin price and find that electricity generation at Scrubgrass has 0.31-0.39 long-run and 0.74-0.75 short-run elasticity (Table A13). These results allow us to address concerns about marginal emissions related to Bitcoin mining at the plant. As discussed in Section 2, we believe emissions at Scrubgrass are the appropriate marginal emissions to consider in light of the probable retirement of Scrubgrass in the absence of Bitcoin mining. However, we consider the scenario in which Scrubgrass would not have retired and instead redirected output from the grid to Bitcoin mining. In this case, the appropriate marginal emissions may be those of the sources called up to generate instead of Scrubgrass. Using recently released marginal emissions of the PJM grid, we multiply the average marginal emissions of the PJM grid[25] by the change in generation at Scrubgrass due to a $1 increase in Bitcoin price. This results in a back-of-the-envelope estimate for the carbon emissions from the grid. Table A13 shows that the social costs associated with carbon emissions calculated this way ($1.08-$2.59) still exceed the value-added from Bitcoin generation.

Falsification exercises: We conduct two falsification (refutability) exercises in addition to the robustness checks. We first repeat our analyses for January 2013 through December 2017, before cryptomining began at Scrubgrass when we do not expect Bitcoin price to impact carbon emissions at the plant. Panel B of Table 1 shows the results. The estimates are not statistically significant and close to zero, further supporting that unobservables do not drive our results.[26]

As a second falsification exercise, we rerun our analysis for five other waste coal power plants in Pennsylvania with similar generation capacity (48-134 MW) that have no rumored or confirmed cryptomining operations. Without integrated mining operations, changes in Bitcoin price do not provide an incentive or disincentive to generate electricity. Reassuringly, we do not find a statistically significant relationship of positive sign between Bitcoin price and carbon emissions at any of the other coal refuse power plants (Table A14). We also repeat our analysis at the Northampton power plant, a 134 MW waste coal power plant in Pennsylvania. While Northampton has not confirmed Bitcoin mining operations, the power plant is rumored to be the third undisclosed plant Stronghold recently acquired (Tully, 2021) and mentioned in recent SEC filings. The elasticity of carbon emissions with respect to Bitcoin price is comparable to and even exceeds the elasticity at Scrubgrass, so we suspect that the Northampton plant may have already operationalized cryptomining (Table A15). In the sleuthing spirit of "forensic economics" (Zitzewitz, 2012), our approach of leveraging time-varying financial incentives might be used to infer the rollout of cryptomining operations in the US.

Local pollutants: Moving beyond carbon emissions, we repeat the analysis for other pollutants of interest: NO_X and SO_2 (Table A16). We find that nitrogen oxide pollutants increase with higher Bitcoin prices and estimate the long-run elasticity of NO_X emissions with respect to daily

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[25] This measure was recently released by PJM and is available only beginning January 2023.

[26] We note that mean CO_2 emissions before cryptomining are higher because they include years when Scrubgrass was still under a power purchase agreement. As we note in Section 2, Scrubgrass would have likely closed without Bitcoin mining, so even though the CO_2 emissions are lower post-cryptomining, they are higher than emissions likely would have been absent cryptomining.

Bitcoin price at 0.45-0.48. Scrubgrass uses selective noncatalytic reduction (SNCR) to control NO_X emissions. This technology is typically much less efficient at reducing NO_X pollution than selective catalytic reduction (SCR). We find that SO_2 emissions are less elastic with respect to daily Bitcoin price, possibly due to the dry flue gas desulfurization technology used at the plant. Future work should investigate the health effects of Bitcoin-induced air pollution, including at the daily level using Bitcoin price variation, given the prior empirical literature on the hospitalization and mortality effects of NO_X (e.g., Deschênes *et al.* (2017)).

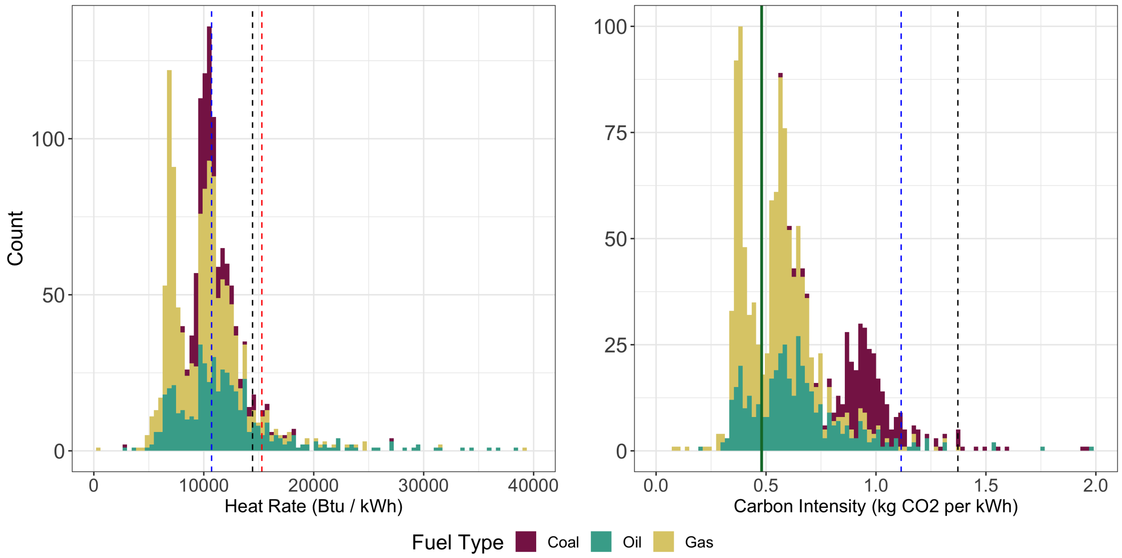
6 Discussion

Existing estimates of Bitcoin's carbon footprint have a remarkably wide range – anywhere from 3.6 to 69 $MtCO_2e$ (Krause and Tolaymat, 2018; Mora *et al.*, 2018; Foteinis, 2018). Varying assumptions regarding computer hardware efficiency, energy sources, and emission intensities each contribute to differing footprint estimates. We depart from this engineering-based approach by observing carbon output directly in CEMS data and mapping this to rapidly-changing Bitcoin mining incentives. This isolates the portion of observed emissions due to Bitcoin mining. While we are wary of extrapolating our estimates (see below), our approach is readily scaled up with additional information on miners' location and the strong relationship we find in Pennsylvania is consistent with the high carbon footprint of proof-of-work digital assets previously reported. We add that the current Bitcoin price remains higher than the mean price over our study period ($30,057 average in July 2023 vs. $21,140 average May 2018 - March 2023), i.e. even after the recent Bitcoin market volatility.

Because data on US Bitcoin miners are so sparse, we cannot compare Scrubgrass to the subset of fossil plants engaged in Bitcoin mining. Instead, we can compare the efficiency and carbon intensity of Scrubgrass to other US power plants. Figure 4 shows the distribution of the heat rate and carbon intensity of all power plants active in the US in 2022. As a waste coal power plant, Scrubgrass is on the higher end of the distribution of heat rates (less efficient) and has an especially high carbon intensity. Still, there are at least 15 plants with higher carbon intensity operating in the US as of the end of 2022. These topmost carbon-intensive plants have 4,655 MW of total capacity.

The high carbon intensity of Scrubgrass suggests that our estimated elasticity may overestimate the average carbon emissions elasticity of the Bitcoin mining industry. Nevertheless, we believe that other Bitcoin miners may be similarly carbon-intensive. The Panther Creek Bitcoin miner – another of Stronghold's confirmed, integrated miners – has an even higher heat rate than Scrubgrass. Figure 4 shows its heat rate with red vertical line, to the right of the black one for Scrubgrass. This relative inefficiency suggests a higher carbon intensity than Scrubgrass, but unfortunately we do not observe Panther Creek's carbon intensity to confirm. The coal-fired Hardin Generating Station in Montana is similar to Scrubgrass in its heat rate *and* carbon intensity, and was a confirmed Bitcoin miner until 2022 (Milman, 2022). There is also anecdotal suggestion of cryptomining activity at other old, inefficient coal power plants in the US. But again, the lack of cryptomining activity data prevent the more systematic carbon-intensity comparisons we would like to conduct.

Figure 4: Power Plant Heat Rate and Carbon Intensity



Notes: Figure shows heat rate (left) and carbon intensity (right) distribution of all active power plants in the US as of 2022. Calculated based on total 2022 load output, heat input, and carbon emissions. Black (red) dashed lines represent the heat rate and carbon intensity of the Scrubgrass (Panther Creek) plant, with confirmed cryptomining. Blue dashed lines represent the Northampton plant's heat rate and carbon intensity, with suspected cryptomining.

Additionally, that Scrubgrass is less efficient than the broader set of coal-fired power plants may mean that it is less responsive to high-frequency changes in Bitcoin price than more efficient plants. This could lead us to underestimate the industry elasticity. Data from the Northampton plant in Pennsylvania, which has *rumored* on-site cryptomining, provides some support. Compared to Scrubgrass, the plant is about 25% more efficient and has a 19% lower carbon intensity (blue dashed lines for Northampton in Figure 4). However, its elasticity of carbon emissions with respect to Bitcoin price is higher (0.42-0.57 long-run elasticity and 1.18-1.28 short-run elasticity).

Perhaps most importantly, as we expect mining difficulty to keep increasing as the number of Bitcoins nears its limit (see Figure 1), our current carbon elasticity estimate is likely an underestimate of future carbon elasticities, *ceteris paribus*.

Finally, we note that even at similar responsiveness of electricity generation to Bitcoin price as at Scrubgrass, the external damages associated with cryptomining would exceed the value-added from mining at much lower carbon intensities. Specifically, this cutoff intensity is 0.38-0.48 kg CO_2 per kWh, and represented by the solid green line on the right panel of Figure 4 (*cf.* 1.37 kg CO_2 per kWh at Scrubgrass, shown with the black dashed line).[27] Indeed, 63.7% of US plants and 27.8% of load balancing authorities (Figure A8) had carbon intensity higher than 0.48 kg CO_2 per kWh[28], suggesting that damages from cryptomining across most regions may exceed

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[27] We calculate the break-even carbon intensity using Column (1) of Table A13, which shows a 10.709-13.818 kWh increase in generation due to a \$1 increase in Bitcoin price. Therefore, $\frac{\$1}{.010976MWh \times \$190} = 0.48$ kg per kWh.

[28] Individual plant data uses 2022 CEMS numbers, while load balancing authority figures use *average* carbon intensities from 2021.

the value-added from the activity.

Our study underscores the need for improved environmental national accounts, which should include the rapidly-growing cryptomining industry. Such accounts would help contextualize the strong claims to sustainability and environmental benefit by cryptomining firms, including those using fossil energy. The Stronghold company website states:

> *Stronghold employs 21st-century crypto mining techniques to remediate the impacts of 19th- and 20th-century coal mining in some of the most environmentally neglected regions of the United States. ....Coal refuse is classified by Pennsylvania as a Tier II alternative energy resource (same as large-scale hydropower), and we receive both Coal Refuse Energy and Reclamation Tax Credits and Pennsylvania Tier II Alternative Credits to incentivize reclamation.*

Another common claim is "stabilizing" fragile electric grids through cryptomining (Noronha, 2022). The strong response of electricity generation to Bitcoin price fluctuations reveals a more narrowly-focused financial objective. Even when local electricity prices are high, we estimate a large elasticity of carbon emissions (Table A8). Furthermore, our results highlight that trading activity that inflates Bitcoin price could lead to underestimation of the carbon emissions precipitated by financial institutions, e.g., through banks' cryptocurrency purchases or launching IPOs by cryptominers. However, most of the carbon accounting frameworks for the financial sector do not account for emissions from cryptocurrency trading.[29]

The high social costs of Bitcoin mining imply that schemes with lower computational costs than proof-of-work may achieve many of the same cryptocurrency benefits with vastly lower damages. Proof-of-stake mechanisms constitute an appealing alternative, given our findings. A change between the two processes is not unprecedented. Ether, the second largest cryptocurrency according to market capitalization, and the currency's platform, Ethereum, switched to a proof-of-stake consensus mechanism in September 2022.

Such a change is likely to be resisted fiercely by energy-intensive cryptominers like Stronghold, even if it is welfare improving. A more palatable interim step would be for policymakers to require vastly improved disclosure of US cryptomining activities.

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[29] See `https://carbonaccountingfinancials.com/`.

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Appendix for:

Bitcoin and carbon dioxide emissions: Evidence from daily production decisions

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A1 Supplementary Text

A1.1 Bitcoin Mining Economics

Mining revenues: Bitcoin mining revenues are mainly driven by the price of Bitcoin, the miner's hashrate, the network hashrate, and other Bitcoin network characteristics. The number of Bitcoins mined by an individual miner can be approximated as

$$\text{Bitcoin mined} = \frac{\text{miner hashrate}}{\text{network hashrate}} \times \text{Bitcoin per block} \times \text{block reward} \tag{A7}$$

where "Bitcoin per block" refers to the mining reward for each block added to the blockchain[30] and "block reward" is the predetermined rate of creation of a block every 10 minutes.[31] Bitcoin mining revenue is then calculated by multiplying the number of Bitcoins mined by the price of Bitcoins.

Mining costs: Bitcoin mining costs are primarily driven by the net cost of power, mining operating expenses (e.g., cooling costs), and price of miners and infrastructure costs. The cost of power makes up the vast majority of Bitcoin mining costs. Some Bitcoin miners report that the cost of electricity makes up as much as 90 to 95%[32] of mining costs. As such, cryptomining operations are often located near cheap, abundant power.

A1.2 Stronghold's Variable vs. Fixed Costs

We calculate a very rough estimate of Stronghold's share of variable electric vs. fixed costs. Stronghold reported that at 285 EH/s network hashrate, \$45 to \$50 net cost of power corresponds to \$12,500 to \$13,000 costs of mining Bitcoin. At a network hashrate of 285 EH/s, approximately 7.89 miners of 110 TH/s each mining capacity are required to mine one Bitcoin ($285 \times 10^6 \times \frac{1}{328500} \times \frac{1}{110} = 7.89$). This corresponds to 0.13 Bitcoin per year on one miner. As most state of

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[30] This is currently 6.25 Bitcoins per block. This reward rate is halved approximately every four years in order to reduce the number of Bitcoins mined over time and maintain a cap on the supply.

[31] For example, in Stronghold's FY2022 presentation, the company reported a hashrate of 1.3 EH/s at the end of 2021 and 2.4 as of the end of March 2023. Based on this, we can assume an average of about 1.85 EH/s hashrate for 2022. In 2022, the average Bitcoin network hashrate was 219.50 EH/s. The network reward was 328,500 Bitcoin per year (6.25 Bitcoin per block × 0.1 block per minute × 525600 minutes per year). This means that we can calculate the approximate number of Bitcoins mined by Stronghold as: $\frac{1.85}{219.50} \times 328500 = 2769$. Indeed, Stronghold reported that the company mined 2089 Bitcoins in 2022. The discrepancy is likely due to the fact that Stronghold is not always mining at full capacity.

[32] 90 to 95% estimate reported by Bitfury CEO Valery Vavilov in Kelly (2016).

the art miners last at least 5 years, this corresponds to a conservative estimate $0.13 \times 5 = 0.63$ Bitcoin per miner lifetime. Stronghold reported to have bought 12,000 Bitmain Antminers for a total of $75 million, or $6,250 per miner. Therefore, we can approximate fixed mining equipment costs of $9,859 per Bitcoin. This is about 44% ($\frac{\$9859}{\$9859+\$12750}$) of the sum of power and mining equipment costs. This estimate reflects higher difficulty of mining in more recent years. While it's a simplified back-of-the-envelope estimation, it still shows that power costs make up the majority of Bitcoin mining costs.

A1.3 Bitcoin Mining Economics at Stronghold

Stronghold is a vertically integrated Bitcoin mining operation. This means that the company owns two power plants and is able to use the power generated directly on site for Bitcoin mining. The power plants are also connected to the grid and therefore the company has the flexibility to do a mix of the following actions:

a) Generate electricity from coal and use it directly to mine Bitcoin on-site

b) Generate electricity from coal and sell the electricity to the grid through the local load balancing authority (PJM Interconnection)

c) Buy electricity from the grid and use it to mine Bitcoin

Which actions Stronghold takes will depend on local electricity prices (P_{elec}), the expected Bitcoin revenues per electricity used (R_{BTC}), and the cost of generating power (C_{gen}) at the plant (all measured in $ per MWh). We can then assume Stronghold will do each of the above actions given the following conditions:

- If $P_{elec} > C_{gen}$

  and $R_{BTC} > P_{elec} \rightarrow$ (mostly) mine Bitcoin from generated electricity (option a)

  and $P_{elec} > R_{BTC} \rightarrow$ sell (some) generated electricity to the grid (option b)

- If $P_{elec} < C_{gen} \rightarrow$ buy (some) electricity from grid (option c)

We are able to observe the daily local electricity price (P_{elec}) in the Scrubgrass plant's load balancing authority. Furthermore, we estimate the daily cost of generating power (C_{gen}) and the daily expected Bitcoin revenues per MWh (R_{BTC}) at the plant based on some figures that Stronghold has reported. Please see Appendix Section A1.4 for more details. We create two binary indicators using the relative magnitude of these variables that we then use in robustness checks of our main analyses:

- $D_{buy,t} = 1$ if $P_{elec,t} < C_{gen,t}$ and we expect Scrubgrass to buy some electricity
- $D_{sell,t} = 1$ if $P_{elec,t} > R_{BTC,t}$ and we expect Scrubgrass to sell some electricity

A1.4 Stronghold Net Cost of Power and Bitcoin Revenue per MWh Estimation

Daily cost of power: In their 2022 10-K form, Stronghold reported a net cost of power of approximately $45 to $/50 per MWh in 2023. Since about 80% of a coal power plant's costs are fuel costs,[33] we adjust the \$47.50 average cost of power per MWh as of 2023 using the weekly spot price of North Appalachian coal.[34] We use the following formula to calculate the daily estimated net cost of power on day t

$$C_{gen,t} = \Big(((\frac{P_{coal,t}}{P_{coal,2023-03-31}} - 1) \times 0.78) + 1\Big) \times C_{gen,2023-03-31} \tag{A8}$$

where $C_{gen,2023-03-31}$ is the average net cost of power (\$47.50 per MWh) reported by Stronghold on March 31, 2023, $P_{coal,2023-03-31}$ is the weekly spot price on the same day (\$83.00 per short ton), and $P_{coal,t}$ is the weekly spot price on day t.

Bitcoin revenue per MWh: For any Bitcoin mining operation, the amount of Bitcoin per MWh electricity used or generated, x, can be estimated as

$$x\frac{\text{BTC}}{\text{MWh}} = \frac{HR_{miner}}{HR_{BTC}}\frac{\frac{\text{TH}}{\text{s}}}{\frac{\text{TH}}{\text{s}}} \times (y \times 52560)\frac{\text{BTC}}{\text{yr}} \times \frac{1}{8760}\frac{\text{yr}}{\text{h}} \times \frac{1}{z}\frac{1}{\text{MW}} \tag{A9}$$

where HR_{miner} is the miner hashrate, HR_{BTC} is the network hashrate, y is the amount of Bitcoin per block and z MW is the power requirement of the Bitcoin mining equipment. Publicly available information is available for all variables other than the company hashrate and the power requirement. We can rewrite the above as

$$x\frac{\text{BTC}}{\text{MWh}} = \frac{1}{HR_{BTC}}\frac{1}{\frac{\text{TH}}{\text{s}}} \times (y \times 52560)\frac{\text{BTC}}{\text{yr}} \times \frac{1}{8760}\frac{\text{yr}}{\text{h}} \times \frac{HR_{miner}}{z}\frac{\frac{\text{TH}}{\text{s}}}{\text{MW}} \tag{A10}$$

where the unknown part specific to a given miner is the company hashrate per MW:

$$\text{company hashrate per MW} = \frac{HR_{miner}}{z}\frac{\frac{\text{TH}}{\text{s}}}{\text{MW}}$$

In the 2022 10-K Stronghold also reported that the \$45 to \$50 per MWh net cost of power corresponds to a cost per Bitcoin of \$12,000 to \$13,500 "with modern miners and assuming a network hash rate of approximately 285 exahash per second"[35]. Based on this, we can approximate the average hashrate per MW of Stronghold's machines. First, we know that the above figures correspond to a BTC per MWh rate of

$$\frac{\$47.50}{\$12750}\frac{\frac{\$}{\text{MWh}}}{\frac{\$}{BTC}} = 0.003725\frac{\text{BTC}}{\text{MWh}}.$$

Therefore, using equation A10, we can estimate the hashrate per MW as

$$0.003725\frac{\text{BTC}}{\text{MWh}} \times 285 \times 10^6\frac{\text{TH}}{\text{s}} \times \frac{1}{6.25 \times 52560}\frac{\text{yr}}{\text{BTC}} \times 8760\frac{\text{h}}{\text{yr}} = 28346\frac{\frac{\text{TH}}{\text{s}}}{\text{MW}}.$$

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[33] According to the Nuclear Energy Institute, in 2017, approximately 78% of coal power plant operating costs consisted of fuel costs (https://www.world-nuclear.org/gallery/nuclear-power-economics-and-project-structuring-re/breakdown-of-operating-costs-for-nuclear,-coal-and.aspx).

[34] The weekly spot price reflects next quarter delivery prices of Northern Appalachian coal, measured in dollars per short ton, collected from the EIA (https://www.eia.gov/coal/markets/#tabs-prices-1).

[35] https://ir.strongholddigitalmining.com/static-files/d72f00f6-7b6a-4565-ab09-a310adc0536d

This rate then allows us estimate the electricity required to mine one Bitcoin (E_{BTC}) on a daily bases given network hashrate (HR_{BTC}) and Bitcoin reward per block (y):

$$E_{BTC,t} = HR_{BTC,t}\frac{\text{TH}}{\text{s}} \times \frac{1}{y_t \times 52560}\frac{\text{yr}}{\text{BTC}} \times 8760\frac{\text{h}}{\text{yr}} \times \frac{1}{28346}\frac{\text{MW}}{\frac{\text{TH}}{\text{s}}} \tag{A11}$$

as well as the daily revenue of Bitcoin per MWh of electricity (R_{BTC}) given Bitcoin price P_{BTC}:

$$R_{BTC,t} = \frac{1}{HR_{BTC,t}}\frac{1}{\frac{\text{TH}}{\text{s}}} \times \frac{y_t \times 52560}{1}\frac{\text{BTC}}{\text{yr}} \times \frac{1}{8760}\frac{\text{yr}}{\text{h}} \times 28346\frac{\frac{\text{TH}}{\text{s}}}{\text{MW}} \times P_{BTC,t} \tag{A12}$$

A1.5 Bounding Exercise Details

Following Angrist and Pischke (2009), we are interested in the "long regression":

$$CO2_t = \beta P_{BTC,t} + \gamma_1 EwoBTC_t + \gamma_2 PwoBTC_t + \gamma_3 C_{gen,t} + \delta_t + \epsilon_t \tag{A13}$$

where we denote the energy requirement to mine Bitcoin *without* the impact of elevated mining activity as $EwoBTC_t$ and the local electricity price *without* the impact of elevated demand from cryptominers as $PwoBTC_t$. We are not able to observe these variables directly, but do have access to a "proxy controls", $P_{elec,t}$ (the day-ahead LMP price) and $E_{BTC,t}$ (the estimated electricity required to mine one Bitcoin). We can write these as functions of Bitcoin price and the true controls:

$$E_{BTC,t} = \rho_0 + \rho_1 P_{BTC,t} + \rho_2 EwoBTC_t \tag{A14}$$

$$P_{elec,t} = \mu_0 + \mu_1 P_{BTC,t} + \mu_2 PwoBTC_t + \mu_3 C_{gen,t} \tag{A15}$$

We solve for $EwoBTC_t$ and $PwoBTC_t$:

$$EwoBTC_t = \frac{1}{\rho_2}E_{BTC,t} - \frac{\rho_0}{\rho_2} - \frac{\rho_1}{\rho_2}P_{BTC,t} \tag{A16}$$

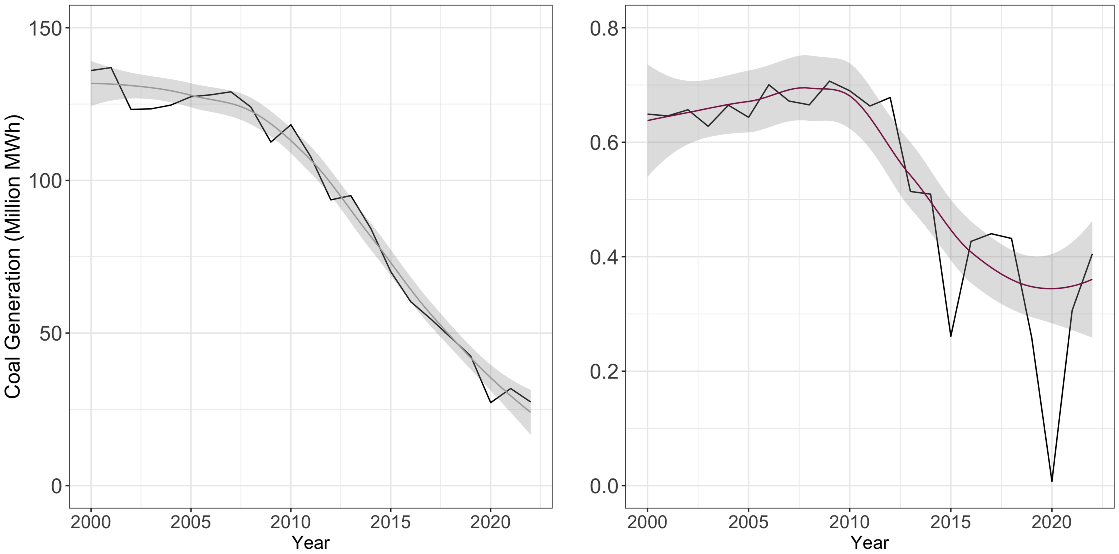
$$PwoBTC_t = \frac{1}{\mu_2}P_{elec,t} - \frac{\mu_0}{\mu_2} - \frac{\mu_1}{\mu_2}P_{BTC,t} - \frac{\mu_3}{\mu_2}C_{gen,t} \tag{A17}$$

And can then rewrite the long regression as:

$$\begin{aligned}
CO2_t &= \beta P_{BTC,t} \\
&\quad + \gamma_1\big(\frac{1}{\rho_2}E_{BTC,t} - \frac{\rho_0}{\rho_2} - \frac{\rho_1}{\rho_2}P_{BTC,t}\big) \\
&\quad + \gamma_2\big(\frac{1}{\mu_2}P_{elec,t} - \frac{\mu_0}{\mu_2} - \frac{\mu_1}{\mu_2}P_{BTC,t} - \frac{\mu_3}{\mu_2}C_{gen,t}\big) \\
&\quad + \gamma_3 C_{gen,t} + \delta_t + \epsilon_t \\
&= (\beta - \gamma_1\frac{\rho_1}{\rho_2} - \gamma_2\frac{\mu_1}{\mu_2})P_{BTC,t} \\
&\quad + \frac{\gamma_1}{\rho_2}E_{BTC_t} + \frac{\gamma_2}{\mu_2}P_{elec,t} + (\gamma_3 - \frac{\mu_3}{\mu_2})C_{gen,t} + \delta_t - \gamma_1\frac{\rho_0}{\rho_2} - \gamma_2\frac{\mu_0}{\mu_2} + \epsilon_t
\end{aligned} \tag{A18}$$

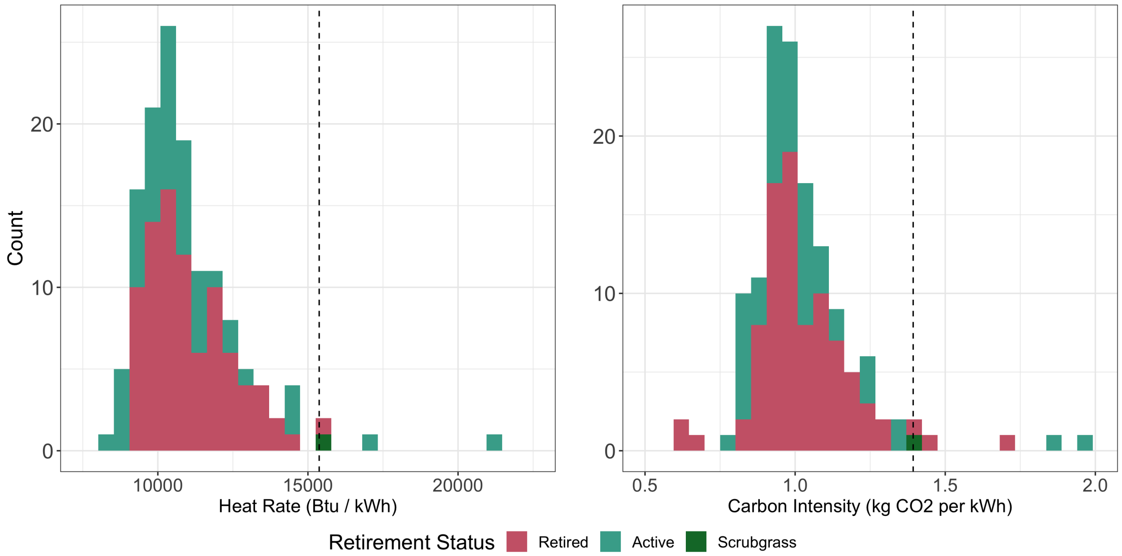
A2 Supplementary Figures

Figure A5: Pennsylvania Coal Power Generation



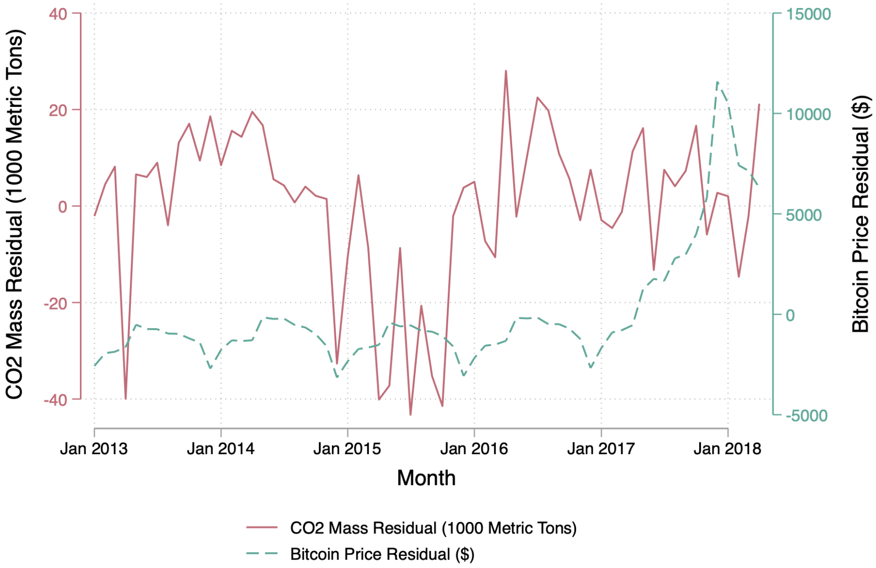
Notes: Figure shows total electricity generated by all coal power plants in Pennsylvania excluding plants owned by Stronghold (left) and Scrubgrass (right). Black lines show annual values, while gray and dark red lines show LOESS smoothed trends. We drop 2020 from the smoothed trendline, as it was an unusual year in which Scrubgrass purchased most of the electricity for Bitcoin mining from the grid.

Figure A6: Ripe for Retirement Coal Power Plant Heat Rate and Carbon Intensity Distribution



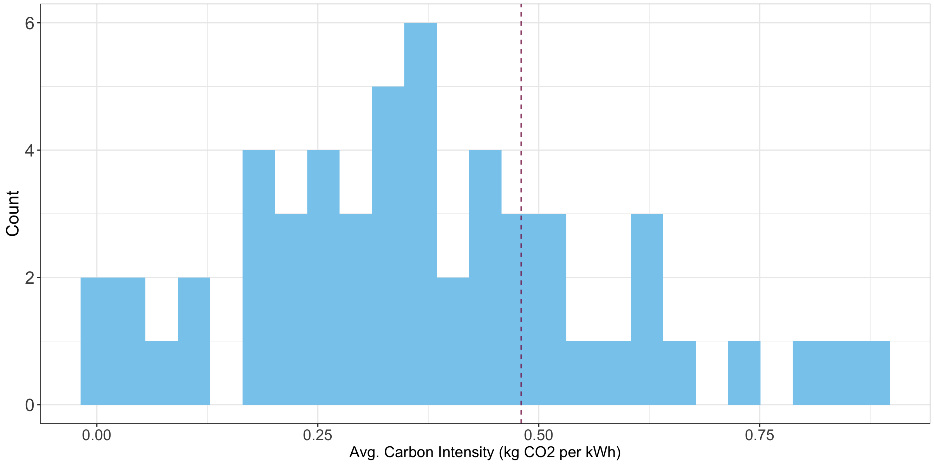
Notes: Figure shows distribution of heat rate (left) and carbon intensity (right) of US coal power plants identified as "ripe for retirement" in 2012 by the Union of Concerned Scientists. Heat rate and carbon intensity for 2012 shown. Dashed lines represent heat rate and carbon intensity of Scrubgrass power plant.

Figure A7: Bitcoin Price and Carbon Dioxide Emissions at Scrubgrass Power Plant



Notes: Figure shows demeaned monthly average Bitcoin prices and total CO_2 emissions at Scrubgrass plant prior to cryptomining.

Figure A8: Carbon Intensity of US Load Balancing Authorities



Notes: Figure shows the average carbon intensity of US load balancing authorities from 2021. Dashed line shows the carbon intensity at which BOTE calculations suggest damages from cryptomining exceed value-added.

A3 Supplementary Tables

Table A2: Daily Bitcoin Price and Electricity Prices and Network Hashrate

	Dependent variable:			
	Day-Ahead LMP ($)		Network Hashrate (EH/s)	
	(1)	(2)	(3)	(4)
Bitcoin Price ($)	0.003*** (0.00005) [0.000]	0.001*** (0.0001) [0.000]	0.0001*** (0.00003) [0.001]	0.001*** (0.0001) [0.000]
Coal Price Control	Y	Y	Y	Y
Temperature Control	-	Y	-	Y
Mean Network HR (EH/s)	65.34	65.34	-	-
Mean Day-Ahead LMP ($)	-	-	35.62	35.62
Observations	3,742	3,742	3,742	3,742

Notes: Table shows results of regressing Bitcoin network hashrate (columns (1) and (2)) and average PENELEC and PJM zone electricity LMPs (columns (3) and (4)) on daily Bitcoin price for January 2013 - March 2023. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A3: Stationarity - Augmented Dickey-Fuller Test

	Augmented Dickey-Fuller Test p-value:		
	w/o trend (1)	w/ trend (2)	w/ drift (3)
Panel A: Values			
Carbon Emissions ($CO2_t$)	0.0000	0.0000	0.0000
Bitcoin Price ($P_{BTC,t}$)	0.6165	0.4777	0.0922
Cost of Power ($C_{gen,t}$)	0.3495	0.5357	0.0312
Electricity Required for Bitcoin ($E_{BTC,t}$)	0.0023	0.0000	0.0001
Local Electricity Price ($P_{elec,t}$)	0.0000	0.0000	0.0000
Panel B: Residuals (Year, Month, DoW FEs):			
Carbon Emissions ($CO2_t$)	0.0000	0.0000	0.0000
Bitcoin Price ($P_{BTC,t}$)	0.0000	0.0000	0.0000
Cost of Power ($C_{gen,t}$)	0.0000	0.0004	0.0000
Electricity Required for Bitcoin ($E_{BTC,t}$)	0.0000	0.0000	0.0000
Local Electricity Price ($P_{elec,t}$)	0.0000	0.0000	0.0000
Panel C: Residuals (5th Order Poly. Time Trends):			
Carbon Emissions ($CO2_t$)	0.0000	0.0000	0.0000
Bitcoin Price ($P_{BTC,t}$)	0.0213	0.0892	0.0008
Cost of Power ($C_{gen,t}$)	0.0172	0.0749	0.0000
Electricity Required for Bitcoin ($E_{BTC,t}$)	0.0000	0.0000	0.0000
Local Electricity Price ($P_{elec,t}$)	0.0000	0.0000	0.0000
Observations	3,741	3,741	3,741

Notes: Table shows p-values from Augmented Dickey-Fuller (ADF) test of stationarity for main dependent and independent variables used. ADF tests the null hypothesis that a unit root is present in a time series sample.

Table A4: Daily Bitcoin Price and CO_2 Emissions at Scrubgrass Power Plant

	Dependent variable:			
	Carbon Dioxide Emissions (Metric Tons)			
	(1)	(2)	(3)	(4)
Bitcoin Price ($)	0.018^{***} (0.002) [0.000]	0.017^{***} (0.002) [0.000]	0.046^{***} (0.008) [0.000]	0.047^{***} (0.008) [0.000]
C_{gen} Control	Y	Y	Y	Y
P_{elec} Control	Y	-	Y	-
E_{BTC} Control	-	Y	-	Y
Difficulty Era FEs (D_t)	-	-	Y	Y
Mean Bitcoin Price ($)	21,140	21,140	21,140	21,140
Mean CO_2 (Metric Tons)	1,059	1,059	1,059	1,059
Elasticity	0.35	0.34	0.91	0.94
Social Cost ($)	3.34	3.24	8.69	8.91
Observations	1,796	1,796	1,796	1,796

Notes: Table shows results of regressing carbon dioxide emissions on daily Bitcoin price according to equations 1 (Columns (1) and (2)) and 6 (Columns (3) and (4)) for May 2018 - March 2023, with fifth order polynomial time trends instead of year, month, and day-of-week fixed effects. All columns control for North Appalachian coal prices. Columns (1) and (3) control for local electricity prices, while columns (2) and (4) control for the electricity requirements of mining one Bitcoin. Columns (3) and (4) also add difficulty era fixed effects. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A5: Daily Bitcoin Price and CO2 Emissions at Scrubgrass Power Plant - Robustness Checks

	Dependent variable:						
	Carbon Dioxide Emissions (Metric Tons)						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bitcoin Price ($)	0.010***	0.005***	0.020***	0.005***	0.019***	0.016***	0.020***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.003)	(0.003)
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Difficulty FEs	-	-	-	-	-	-	-
Year FEs	-	-	-	-	-	Y	Y
Month FEs	-	-	-	-	-	Y	Y
DoW FEs	-	-	-	Y	Y	Y	Y
C_{gen} Control	-	Y	Y	Y	Y	Y	Y
P_{elec} Control	-	Y	-	Y	-	Y	-
E_{BTC} Control	-	-	Y	-	Y	-	Y
Temperature Control	-	-	-	-	-	Y	Y
Elasticity	0.21	0.10	0.39	0.10	0.39	0.32	0.4
Social Cost ($)	1.97	0.98	3.71	0.98	3.7	3.04	3.78
Observations	1,796	1,796	1,796	1,796	1,796	1,796	1,796

Notes: Table shows results of regressing carbon dioxide emissions on daily Bitcoin price according to equations 1 for May 2018 - March 2023. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A6: Daily Bitcoin Price and CO2 Emissions at Scrubgrass Power Plant - Robustness Checks

	Dependent variable:						
	Carbon Dioxide Emissions (Metric Tons)						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bitcoin Price ($)	0.043***	0.042***	0.044***	0.042***	0.043***	0.034***	0.034***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Difficulty FEs	Y	Y	Y	Y	Y	Y	Y
Year FEs	-	-	-	-	-	Y	Y
Month FEs	-	-	-	-	-	Y	Y
DoW FEs	-	-	-	Y	Y	Y	Y
C_{gen} Control	-	Y	Y	Y	Y	Y	Y
P_{elec} Control	-	Y	-	Y	-	Y	-
E_{BTC} Control	-	-	Y	-	Y	-	Y
Temperature Control	-	-	-	-	-	Y	Y
Elasticity	0.86	0.85	0.87	0.84	0.86	0.67	0.69
Social Cost ($)	8.14	8.06	8.28	7.99	8.17	6.42	6.55
Observations	1,796	1,796	1,796	1,796	1,796	1,796	1,796

Notes: Table shows results of regressing carbon dioxide emissions on daily Bitcoin price according to equations 6 for May 2018 - March 2023. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A7: Daily Bitcoin Price and CO2 Emissions at Scrubgrass Power Plant - Non-Zero Generation Days

	Dependent variable:			
	Carbon Dioxide Emissions (Metric Tons)			
	(1)	(2)	(3)	(4)
Bitcoin Price ($)	0.010***	0.012***	0.022**	0.023***
	(0.003)	(0.003)	(0.008)	(0.008)
	[0.001]	[0.000]	[0.011]	[0.007]
C_{gen} Control	Y	Y	Y	Y
P_{elec} Control	Y	-	Y	-
E_{BTC} Control	-	Y	-	Y
Difficulty Era FEs (D_t)	-	-	Y	Y
Mean Bitcoin Price ($)	24,355	24,355	24,355	24,355
Mean CO_2 (Metric Tons)	1,602	1,602	1,602	1,602
Elasticity	0.15	0.18	0.33	0.35
Social Cost ($)	1.94	2.23	4.11	4.33
Observations	1,187	1,187	1,187	1,187

Notes: Table shows results of regressing carbon dioxide emissions on daily Bitcoin price according to equations 1 (Columns (1) and (2)) and 6 (Columns (3) and (4)), for May 2018 - March 2023, on days with non-zero generation. All columns control for North Appalachian coal prices and include year, month, and day-of-week fixed effects. Columns (1) and (3) control for local electricity prices, while columns (2) and (4) control for the electricity requirements of mining one Bitcoin. Columns (3) and (4) also add difficulty era fixed effects. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A8: Daily Bitcoin Price and CO2 Emissions at Scrubgrass Power Plant - High Electricity Prices

	Dependent variable:			
	Carbon Dioxide Emissions (Metric Tons)			
	(1)	(2)	(3)	(4)
Bitcoin Price (\$)	0.021**	0.022***	0.082***	0.081***
	(0.009)	(0.009)	(0.017)	(0.017)
	[0.017]	[0.010]	[0.000]	[0.000]
C_{gen} Control	Y	Y	Y	Y
P_{elec} Control	Y	-	Y	-
E_{BTC} Control	-	Y	-	Y
Difficulty Era FEs (D_t)	-	-	Y	Y
Mean Bitcoin Price (\$)	32,896	32,896	32,896	32,896
Mean CO_2	1,558	1,558	1,558	1,558
Elasticity	0.44	0.47	1.73	1.70
Social Cost (\$)	3.96	4.21	15.55	15.32
Observations	449	449	449	449

Notes: Table shows results of regressing carbon dioxide emissions on daily Bitcoin price according to equations 1 (Columns (1) and (2)) and 6 (Columns (3) and (4)), for May 2018 - March 2023, on days with day-ahead LMPs in the top 25th percentile. All columns control for North Appalachian coal prices and include year, month, and day-of-week fixed effects. Columns (1) and (3) control for local electricity prices, while columns (2) and (4) control for the electricity requirements of mining one Bitcoin. Columns (3) and (4) also add difficulty era fixed effects. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A9: Daily Bitcoin Price and CO2 Emissions at Scrubgrass Power Plant - Dropping the COVID-19 Pandemic (2020)

	Dependent variable:			
	Carbon Dioxide Emissions (Metric Tons)			
	(1)	(2)	(3)	(4)
Bitcoin Price ($)	0.019***	0.025***	0.035***	0.036***
	(0.004)	(0.004)	(0.009)	(0.009)
	[0.000]	[0.000]	[0.000]	[0.000]
C_{gen} Control	Y	Y	Y	Y
P_{elec} Control	Y	-	Y	-
E_{BTC} Control	-	Y	-	Y
Difficulty Era FEs (D_t)	-	-	Y	Y
Mean Bitcoin Price ($)	23,720	23,720	23,720	23,720
Mean CO_2	1,322	1,322	1,322	1,322
Elasticity	0.33	0.44	0.64	0.65
Social Cost ($)	3.54	4.70	6.73	6.93
Observations	1,430	1,430	1,430	1,430

Notes: Table shows results of regressing carbon dioxide emissions on daily Bitcoin price according to equations 1 (Columns (1) and (2)) and 6 (Columns (3) and (4)), for May 2018 - March 2023, dropping 2020. All columns control for North Appalachian coal prices and include year, month, and day-of-week fixed effects. Columns (1) and (3) control for local electricity prices, while columns (2) and (4) control for the electricity requirements of mining one Bitcoin. Columns (3) and (4) also add difficulty era fixed effects. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A10: Daily Bitcoin Price and CO2 Emissions at Scrubgrass Power Plant - Weekly Results

	Dependent variable:	
	Carbon Dioxide Emissions (Metric Tons)	
	(1)	(2)
Bitcoin Price	0.017^{**}	0.023^{***}
	(0.007)	(0.007)
	[0.013]	[0.002]
C_{gen} Control	Y	Y
P_{elec} Control	Y	-
E_{BTC} Control	-	Y
Mean Bitcoin Price ($)	21,124	21,124
Mean CO_2 (Metric Tons)	1,057	1,057
Elasticity	0.35	0.37
Social Cost	3.3	4.39
Observations	261	261

Notes: Table shows results of regressing carbon dioxide emissions on daily Bitcoin price according to equation 1 for May 2018 - March 2023, aggregate to a weekly level. All columns include control for North Appalachian coal prices and include year, month, and day-of-week fixed effects. Columns (1) controls for local electricity prices, while column (2) controls for the electricity requirements of mining one Bitcoin. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A11: Daily Bitcoin Price and CO2 Emissions at Scrubgrass Power Plant, Lagged Coal Prices

	Dependent variable:			
	Carbon Dioxide Emissions (Metric Tons)			
	(1)	(2)	(3)	(4)
Bitcoin Price ($)	0.007**	0.008***	0.035***	0.036***
	(0.003)	(0.003)	(0.008)	(0.008)
	[0.013]	[0.007]	[0.000]	[0.000]
C_{gen} Control	Y	Y	Y	Y
P_{elec} Control	Y	-	Y	-
E_{BTC} Control	-	Y	-	Y
Difficulty Era FEs (D_t)	-	-	Y	Y
Mean Bitcoin Price ($)	21,140	21,140	21,140	21,140
Mean CO_2 (Metric Tons)	1,059	1,059	1,059	1,059
Elasticity	0.15	0.17	0.69	0.72
Social Cost	1.40	1.60	6.60	6.81
Observations	1,796	1,796	1,796	1,796

Notes: Table shows results of regressing carbon dioxide emissions on daily Bitcoin price according to equations 1 (Columns (1) and (2)) and 6 (Columns (3) and (4)). Panel A shows results after Scrubgrass began Bitcoin mining (May 2018 - March 2023), while Panel B shows results before Scrubgrass began Bitcoin mining (January 2013 - December 2017). All columns control for 3-month lagged North Appalachian coal prices and include year, month, and day-of-week fixed effects. Columns (1) and (3) control for local electricity prices, while columns (2) and (4) control for the electricity requirements of mining one Bitcoin. Columns (3) and (4) also add difficulty era fixed effects. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A12: Daily Bitcoin Price and CO2 Emissions at Scrubgrass Power Plant

	Dependent variable:					
	Carbon Dioxide Emissions (Metric Tons)					
	(1)	(2)	(3)	(4)	(5)	(6)
Bitcoin Price ($)	0.016***	0.015***	0.016***	0.035***	0.035***	0.034***
	(0.003)	(0.003)	(0.003)	(0.008)	(0.008)	(0.008)
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
C_{gen} Control	Y	Y	Y	Y	Y	Y
P_{elec} Control	Lin	Bin	D B/S	Lin	Bin	D B/S
E_{BTC} Control	-	-	-	-	-	-
Difficulty Era FEs (D_t)	-	-	-	Y	Y	Y
Mean Bitcoin Price ($)	21,140	21,140	21,140	21,140	21,140	21,140
Mean CO$_2$ (Metric Tons)	1,059	1,059	1,059	1,059	1,059	1,059
Elasticity	0.33	0.29	0.32	0.69	0.7	0.67
Social Cost ($)	3.11	2.79	3.06	6.59	6.69	6.42
Observations	1,796	1,796	1,796	1,796	1,796	1,796

Notes: Table shows results of regressing carbon dioxide emissions on daily Bitcoin price according to equations 1 (Columns (1) - (3)) and 6 (Columns (4) -6 (4)) for May 2018 - March 2023). All columns control for North Appalachian coal prices and include year, month, and day-of-week fixed effects. Columns (4) - (6) also add difficulty era fixed effects. “Lin” P_{elec} control refers to linear control for day-ahead LMP; “bin” uses binned (by quintile) day-ahead LMP; “D B/S” uses dummies for when Scrubgrass is expected to buy and sell electricity from the grid (Appendix Section A1.3). Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A13: Daily Bitcoin Price and CO2 Emissions at Scrubgrass Power Plant

	Dependent variable:			
	Electricity Generation (kWh)			
	(1)	(2)	(3)	(4)
Bitcoin Price	10.976***	13.818***	26.191***	26.701***
	(2.277)	(2.354)	(5.513)	(5.526)
	[0.000]	[0.000]	[0.000]	[0.000]
C_{gen} Control	Y	Y	Y	Y
P_{elec} Control	Y	-	Y	-
E_{BTC} Control	-	Y	-	Y
Mean Bitcoin Price ($)	21,140	21,140	21,140	21,140
Mean Load (kWh)	750,480	750,480	750,480	750,480
Elasticity	0.31	0.39	0.74	0.75
Mean PJM Marginal Emissions (kg per kWh)	0.52	0.52	0.52	0.52
Implied CO_2 Emissions (Metric Tons)	0.006	0.007	0.014	0.014
Implied Social Cost ($)	1.08	1.36	2.59	2.64
Observations	1,796	1,796	1,796	1,796

Notes: Table shows results of regressing electricity generation on daily Bitcoin price according to equations 1 (Columns (1) and (2)) and 6 (Columns (3) and (4)), for May 2018 - March 2023. All columns control for North Appalachian coal prices and include year, month, and day-of-week fixed effects. Columns (1) and (3) control for local electricity prices, while columns (2) and (4) control for the electricity requirements of mining one Bitcoin. Columns (3) and (4) also add difficulty era fixed effects. Mean PJM Marginal Emissions calculated using Jan 2023 - Jun 2023 data. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A14: Non-Cryptomining Pennsylvania Waste Coal Plants

	Dependent variable:				
	Carbon Dioxide Emissions (Metric Tons)				
	Cambria	Colver	Gilberton	Mt. Carmel	St. Nicholas
	(1)	(2)	(3)	(4)	(5)
Bitcoin Price ($)	0.007	-0.009^{**}	-0.008^{***}	0.002	-0.003
	(0.023)	(0.004)	(0.002)	(0.003)	(0.004)
	[0.770]	[0.017]	[0.001]	[0.466]	[0.435]
C_{gen} Control	Y	Y	Y	Y	Y
P_{elec} Control	Y	Y	Y	Y	Y
E_{BTC} Control	-	-	-	-	-
Observations	518	1,796	1,796	1,614	1,796

Notes: Table shows results of regressing carbon dioxide emissions on daily Bitcoin price according to equations 1 at other Pennsylvania Waste Coal Plants, for May 2018 - March 2023. All columns control for North Appalachian coal prices and include year, month, and day-of-week fixed effects. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A15: Daily Bitcoin Price and CO2 Emissions at Northampton Power Plant

	Dependent variable:			
	Carbon Dioxide Emissions (Metric Tons)			
	(1)	(2)	(3)	(4)
Bitcoin Price ($)	0.012***	0.017***	0.035***	0.038***
	(0.004)	(0.004)	(0.009)	(0.009)
	[0.004]	[0.000]	[0.000]	[0.000]
C_{gen} Control	Y	Y	Y	Y
P_{elec} Control	Y	-	Y	-
E_{BTC} Control	-	Y	-	Y
Difficulty Era FEs (D_t)	-	-	Y	Y
Mean Bitcoin Price ($)	21,140	21,140	21140	21140
Mean CO_2 (Metric Tons)	620	620	620	620
Elasticity	0.42	0.57	1.18	1.28
Social Cost ($)	2.33	3.17	6.60	7.16
Observations	1,796	1,796	1,796	1,796

Notes: Table shows results of regressing carbon dioxide emissions at Northampton Power Plant on daily Bitcoin price according to equations 1 (Columns (1) and (2)) and 6 (Columns (3) and (4)) for May 2018 - March 2023. All columns control for North Appalachian coal prices and include year, month, and day-of-week fixed effects. Columns (1) and (3) control for local electricity prices, while columns (2) and (4) control for the electricity requirements of mining one Bitcoin. Columns (3) and (4) also add difficulty era fixed effects. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table A16: Daily Bitcoin Price and NO_x and SO_2 Emissions at Scrubgrass Power Plant

	Dependent variable:			
	NOx Emissions (kg)		SO2 Emissions (kg)	
	(1)	(2)	(3)	(4)
Bitcoin Price ($)	0.014***	0.015***	0.029	0.024
	(0.002)	(0.002)	(0.018)	(0.018)
	[0.000]	[0.000]	[0.105]	[0.196]
C_{gen} Control	Y	Y	Y	Y
P_{elec} Control	Y	-	Y	-
E_{BTC} Control	-	Y	-	Y
Mean Bitcoin Price ($)	21,140	21,140	21,140	21,140
Mean Emissions (kg)	644	644	2169	2169
Elasticity	0.45	0.48	0.29	0.23
Observations	1,796	1,796	1,796	1,796

Notes: Table shows results of regressing nitrogen oxide and sulfur dioxide emissions on daily Bitcoin price according to equation 1 for May 2018 - March 2023. All columns control for North Appalachian coal prices and include year, month, and day-of-week fixed effects. Columns (1) and (3) control for local electricity prices, while columns (2) and (4) control for the electricity requirements of mining one Bitcoin. Standard errors are shown in parentheses; p-values are shown in brackets (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).