Bitcoin Bites: Ambient pollution and labor market outcomes in Pennsylvania

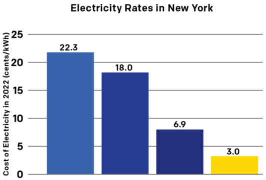
Douglas Almond, Junho Choi, Anna Papp

June 5, 2025

SNU GSIS: Global Prominence Seminar

CEEP

- Cryptocurrencies offer multidimensional benefits
  - transaction speed, privacy, security, and decentralization
- Global mining revenues estimated at $15.3 billion in 2021
- US is world's #1 miner, but systematic data on US cryptomining activity do not exist
- Weak reporting requirements in USA
  - Bitcoin mining is "largely unregulated" in USA (Guidi et al., 2025)
- US states have been inducing miners to initiate or expand cryptocurrency mining
- E.G. Texas offers miners 10-year tax abastment and sales tax credits (Malik, 2021)



New York! (yellow=crypto price)

Favoring Crypto

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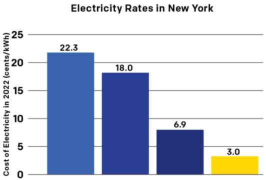

New York! (yellow=crypto price)

Meanwhile, ,:

- Sweden: 6,000% tax increase on energy used for cryptoming
- China banned Cryptomining in 2021

"Trump doesn't mince words about why he's clearing a path for the crypto industry: He aims to bring lucrative jobs and crypto-mining power to the U.S."

Forbes

News

How Trump's Bitcoin Policies Are Making The U.S. A Crypto Superpower

Trump promised during the campaign to ease regulations on crypto businesses. Forbes' expert contributors say he appears to be delivering and setting the stage for a bitcoin bull market.

By Leigh Cuen, Forbes Staff. Leigh Cuen edits Forbes contributors.

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Crypto Costs

- Power generation is main cost of Bitcoin mining
  - As mining difficulty continues to increase, electricity required to mine Bitcoin increases
  - In US, estimated at 32.3 terrawatt hours, more than LA (Guidi et al. 2025)
    - ★ Or + New York City in electricity demand (Gabriel J.X. Dance, 2023)
- Crypto Energy demand revitalizes marginal fossil generators
  - US Grid – 60% fossil generation
  - 85% of Bitcoin mining is fossil-fueled according to Guidi et al. 2025

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- Crypto Energy demand revitalizes marginal fossil generators
  - US Grid – 60% fossil generation
  - 85% of Bitcoin mining is fossil-fueled according to Guidi et al. 2025
- **Our Contribution:**
  1. Estimate local pollution impacts of cryptomining at electricity generator level
  2. Deploy new US administrative dataset of daily labor market information by zipcode
  3. First paper to estimate IV impacts of Bitcoin-induced pollution on labor market outcomes

Stronghold Digital Mining in Pennsylvania

Why analyze Stronghold?

CEEP

- Stronghold is a self-identified, vertically-integrated Bitcoin miner
- We look at Stronghold's largest energy-generation facilities
- 2 coal-fired power plants in Pennsylvania with on-site Bitcoin mining
  1. Scrubgrass: 85 MW
  2. Panther Creek: 80MW
- Scrubgrass and Panther Creek "ripe for retirement" bc inefficient and costly
  - Union of Concerned Scientists (2012)
  - Most have subsequently retired
- Scrubgrass was "set to close before pivoting to Bitcoin": from

Bitcoin miners revive a dying coal plant (Milman, 2022).

Emissions marginal, due to Bitcoin mining

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Emissions marginal, due to Bitcoin mining – evaluate empirically using mining incentives as Z

Plus Northampton Generating Co.

1. Reportedly emerged from bankruptcy in March 2021 to mine Bitcoin
2. Has a fairly typical heat rate compared to other coal power plants in the USA
3. Has the strongest first stage: Bitcoin incentives $\longrightarrow$ generation/pollution
4. Has the closest EPA monitor
5. Population density nearby the highest
6. Still, it's only a *rumored* Bitcoin miner
   - August 2021 story in mcall.com:
     "the unnamed plant is the Northampton Generating Facility in Northampton borough"
   - Absolutely behaves like a Bitcoin miner
   - "Forensic Economics" (Zitzewitz, 2012)
7. Highest nameplate capacity of the three plants: 134 MW
8. 70 miles from Manhattan...

Northampton: May 22, 2025 visit

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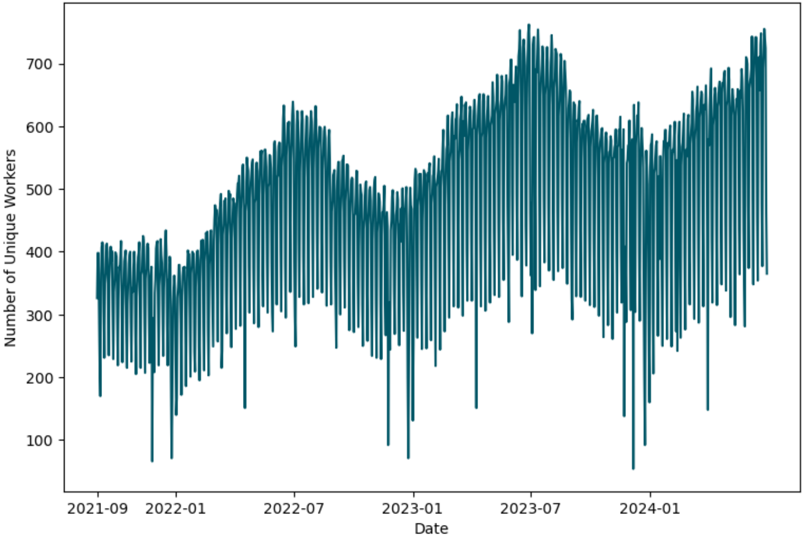
Key takeaways:

1. No onsite cryptomining that we could see
2. Northampton is an economically viable power plant thanks to green energy subsidies from State of Pennsylvania
3. Costs Northampton $200,000 to turn power plant on (avoid on/off)
   - Usual pollution limits don't apply when turning on
4. Northampton responds extremely attentively to electricity price
   1. The day ahead price, production decided by 1pm for next day
   2. The real time price
5. Can ramp 10 MW per hour
6. Local electricity price responding to Bitcoin price, presumably through local offsite mining activity
   - "Gerry" fixed effect?
   - Analyzing this relationship empirically underway
7. Our IV approach isolating variation coming from local Bitcoin energy demand

Gerry FE?

Northampton: Unique Workers within 20km



Our Data

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Leverage 1,034 daily changes in Bitcoin mining incentives over approx. 3 years (2021-09-01~2024-06-30). Combine these with:

1. Power plant emissions from EPA Clean Air Markets program
2. Ambient air quality data from EPA monitor
3. **Payroll and labor market microdata from Homebase**
    - Over half of US workers are paid hourly
    - Derived from Homebase software for tracking employee timesheets, set schedules, manage payroll its employee scheduling and time tracking tools
    - Used by more than 100,000 small business across the USA
    - Available at the daily level! For 2016-
    - By zipcode of job
        - ★ Predominantly in the restaurant, food & beverage, retail and services industries
    - Look at workers within 20 km (12.4 miles) of powerplants

Hats off to Hannah Farkas (Columbia SDEV PhD student) for unearthing these data

Administrative Payroll Data – daily by worker (Homebase)

joinhomebase.com

Basic

Get started with Homebase and set up a new team.

$0

/ location / month for 1 location, up to 10 employees

- ✓ Basic scheduling
- ✓ Basic time tracking
- ✓ Point-of-sale integration
- + Payroll add-on available

Get started for free

No credit card required

Essentials

Simplify the process of tracking & managing shifts.

~~$30~~

$27

/ location / month
unlimited employees

Save $36/year

Everything in Basic, and

- ✓ Advanced scheduling
- ✓ Advanced time tracking
- ✓ Team communication
- + Payroll add-on available

Get started for free

No credit card required

Plus

Boost your team's productivity and improve communication.

~~$70~~

$63

/ location / month
unlimited employees

Save $84 / year

Everything in Essentials, and

- ✓ Hiring
- ✓ PTO & time-off controls
- ✓ Departments & permissions
- + Payroll add-on available

Get started for free

No credit card required

Administrative Payroll Data – daily by worker (Homebase)

Variable	Description
company_id	Unique ID associated with a company
location_id	Unique ID associated with a company's location
user_id	Unique ID for each employee
industry	Industry for company
zip	Zip code for location
naics_code	NAICS code for company
business_type	Category for business
level	A user's his/her hierarchical rank
job_created_date	Date employee hired
job_archived_date	Date employee separated from location
total_wages_earned	For employees, weekly earnings in US dollars
hours_worked	For employees, # of hours worked (from timesheets)
avg_hourly_wage_rate	Average hourly wage rate

NOTE: For ID-related variables, there are no personally identifiable information.

Descriptive statistics of Homebase data

Table: Descriptive statistics, Homebase data

Variable	Obs. units	Mean	SD	P1	P5	P25	P50	P75	P95	P99
Hours worked	Worker-day	6.89	2.87	0.63	2.51	4.96	7.10	8.52	11.10	16.00
Average hourly wage rate	Worker-day	13.85	6.25	2.83	6.50	10.00	13.00	17.00	22.00	30.00
Total wages earned	Worker-day	97.22	72.39	9.06	22.23	47.41	82.41	129.10	217.61	320.00
Number of days worked	Worker	77.72	115.51	1	1	7	26	83	309	591

Note: Average hourly wage rate and total wages earned calculated only for those observations with **positive** reported wage. Total number of observations is 544,645, the number of unique workers is 7,594, and the number of days is 1,034.

Descriptive statistics, by industry

Table: Descriptive statistics: top 8 industries by number of observations

Variable	Mean	SD	P1	P25	P50	P75	P99
A. F&B places (208132, 3294, 1034)							
Hours worked	6.68	2.68	1.34	4.93	6.51	8.20	15.38
Average hourly wage rate	11.04	4.30	2.83	8.0	10.0	14.0	20.0
B. Amusement, Gambling & Recreation (33898, 637, 1033)							
Hours worked	4.42	2.60	0.01	2.96	4.13	6.19	10.33
Average hourly wage rate	11.03	3.55	8.0	8.5	10.0	12.5	22.25
C. Social assistance (31848, 250, 775)							
Hours worked	7.59	2.20	1.94	6.56	8.08	8.78	12.04
Average hourly wage rate	11.43	2.44	8.25	9.75	11.00	12.00	18.00
D. F&B stores (26226, 355, 1031)							
Hours worked	6.28	2.34	1.55	4.65	6.02	7.95	12.97
Average hourly wage rate	11.98	3.65	5.00	10.00	11.75	14.00	20.14

Note: Triple next to industry names refer to: (number of observations, number of unique workers, number of unique days) for a given industry.

Descriptive statistics, by industry (continued)

Table: Descriptive statistics: top 8 industries by number of observations (continued)

Variable	Mean	SD	P1	P25	P50	P75	P99
E. Administrative & support services (24286, 300, 1021)							
Hours worked	7.11	3.28	1.08	4.29	7.85	8.58	22.26
Average hourly wage rate	17.27	3.37	10.00	15.00	17.00	18.50	23.00
F. Healthcare services (23318, 280, 1030)							
Hours worked	7.45	2.77	1.50	5.57	7.96	8.95	12.99
Average hourly wage rate	16.84	12.32	7.25	10.00	15.00	18.00	69.00
G. Auto maintenance (21123, 173, 1021)							
Hours worked	9.58	3.02	2.04	8.50	9.13	10.80	16.00
Average hourly wage rate	20.12	4.34	8.00	18.00	20.00	21.00	30.00
H. Miscellaneous retail (15925, 192, 1031)							
Hours worked	6.77	2.52	1.64	5.28	6.82	8.04	13.45
Average hourly wage rate	13.37	3.53	7.50	11.00	13.00	15.00	25.00

Note: Triple next to industry names refer to: (number of observations, number of unique workers, number of unique days) for a given industry.

Distribution of individuals across tipped and non-tipped industries

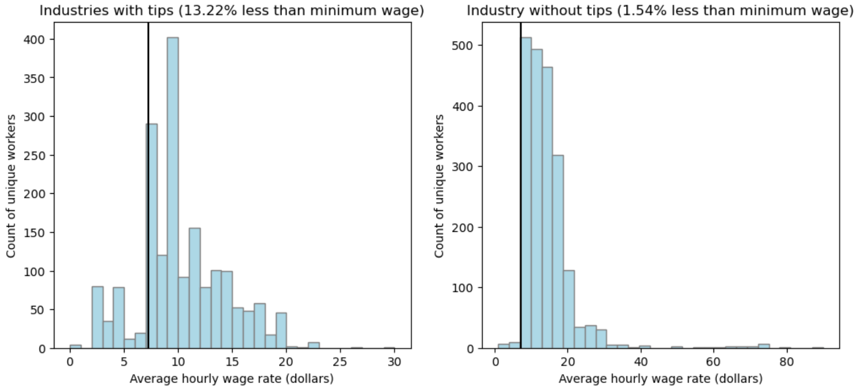

Figure: Histogram of individual workers by hourly wage

- Black vertical line refers to the PA minimum wage ($7.25 per hour)
- "Tipped" industries: accommodation, F&B service, recreation (e.g., casinos), personal & laundry services

Descriptive statistics, Bitcoin variables

Table: Descriptive statistics, Bitcoin variables

Variable	Units	Mean	SD	P1	P5	P25	P50	P75	P95	P99
Price	1000 USD	36.93	15.68	16.51	17.12	23.89	30.53	46.34	67.55	70.56
Difficulty	10^{12}	45.80	20.70	18.42	20.08	28.35	39.16	58.86	83.95	88.10
Hashrate	10^{8} hashes/sec	3.33	1.52	1.30	1.50	2.06	2.88	4.40	6.18	6.73
Total Tx. Fees	100 USD	0.42	0.76	0.07	0.09	0.13	0.19	0.35	1.51	3.99
Avg. BTC Block Size	MB	1.46	0.32	0.84	0.95	1.20	1.47	1.69	1.95	2.26
Median Tx. Confirmation Time	Minutes	8.16	2.05	4.26	4.88	6.75	8.08	9.55	11.49	13.61
BTC-USD Trade Volume	10^{9}	0.23	0.18	0.03	0.05	0.11	0.19	0.30	0.59	0.88

Descriptive statistics, emissions by plant

Table: Descriptive statistics, emissions

Variable	Units	Mean	SD	P1	P5	P25	P50	P75	P95	P99
A. Northampton										
SO_2	tonnes	0.67	0.70	0.00	0.00	0.00	0.69	1.24	1.47	2.82
NO_x	tonnes	0.54	0.48	0.00	0.00	0.00	0.73	0.99	1.14	1.19
Heat input	billions BTU	13.94	12.14	0.00	0.00	0.00	21.28	24.54	28.98	30.65
B. Panther Creek										
SO_2	tonnes	0.94	0.73	0.00	0.00	0.59	0.97	1.24	1.66	3.68
NO_x	tonnes	0.77	0.52	0.00	0.00	0.39	0.74	1.16	1.55	1.91
Heat input	billions BTU	18.62	9.53	0.00	0.00	15.62	22.34	24.98	28.67	31.39
C. Scrubgrass										
SO_2	tonnes	3.03	4.16	0.00	0.00	0.00	2.20	3.72	10.03	20.86
NO_x	tonnes	0.65	0.56	0.00	0.00	0.00	0.59	1.11	1.64	1.92
Heat input	billions BTU	13.06	9.90	0.00	0.00	0.00	14.38	22.12	26.48	29.07

Presentation Outline

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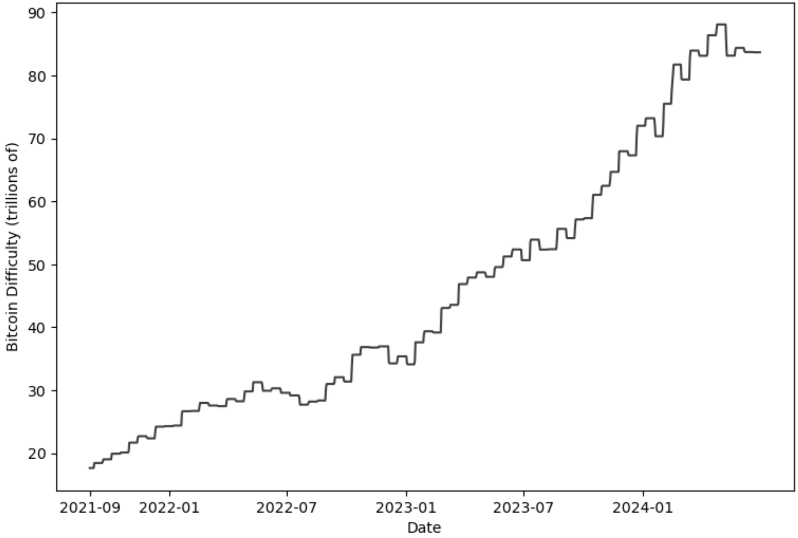
- Bitcoin miners validate transactions in the network by solving complex mathematical problems known as the "hashes"[1]
- In return for successfully solving a hash (which is related to the block), the miner receives a **reward of Bitcoins**, as well as the transaction fees associated with the block
- Potential drivers of mining activity:
  - Bitcoin price
  - Mining difficulty[2]
  - total transaction fee
  - average block size
  - median transaction confirmation time
  - BTC-USD trade volume
  - Bitcoin futures prices
- We will use the above as instrumental variables for coal use, pollution
  - Look at impact of coal use and pollution emissions on worker outcomes ≤20km of source

[1] Miner submits trillions of guesses of a random number.

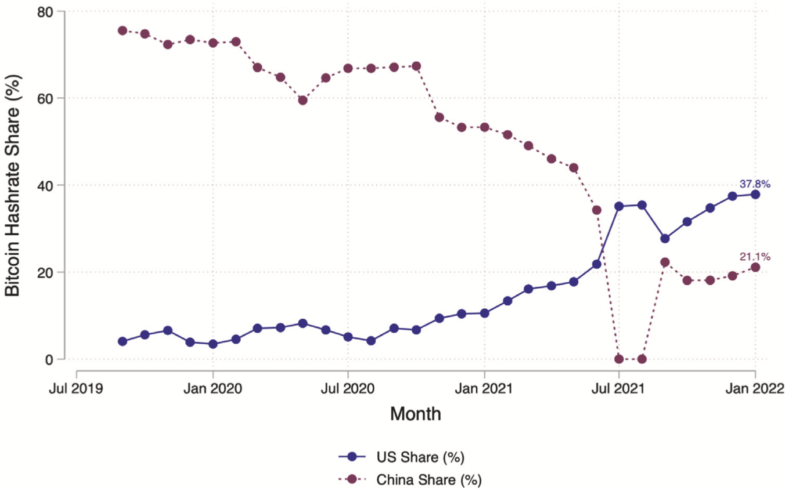
[2] The difficulty of generating a block – how tough the number is to guess – is adjusted every 2,016 blocks (approximately two weeks) to maintain an average time of ten minutes between new blocks

Bitcoin Market Price Over Time

Bitcoin Mining Difficulty Over Time



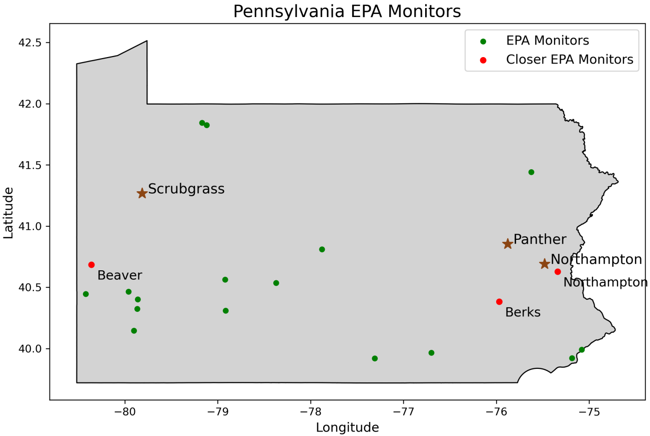
Relocation of Bitcoin Mining Activity to USA



source: Papp, Almond, and Zhang (2023)

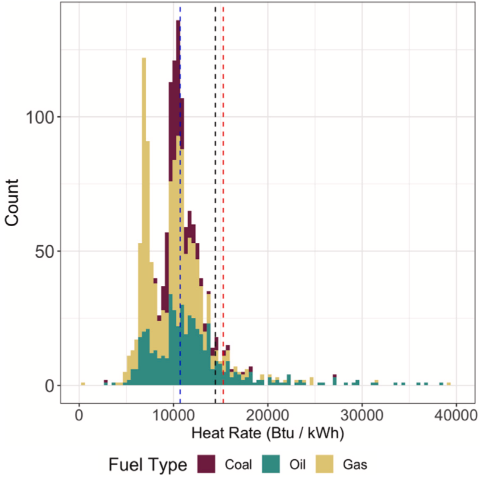
Stronghold Mining in Pennsylvania

All powerplants active in 2022



US Powerplants by heat rate

All powerplants active in 2022, dotted lines for our 3 Bitcoin miners



(Red line is for Panther Creek)

Stronghold Digital Mining – Environmental Claims

- "Stronghold is a vertically integrated Bitcoin mining company with an emphasis on environmentally beneficial operations." (2024 Report)
- "We are proud to clean up substantial piles of waste coal that have long devastated Pennsylvania" [WFMZ-TV, 3/26/24]
- "Eliminate mining waste, converting the waste to power"

  Our record of cleaning up land and water in the Commonwealth speaks for itself. Without purpose-built, emission controlled, reclamation and power facilities like Panther Creek, waste coal would sit dormant and continue to cause environmental harm.

- July 2024, PA increased the Coal Refuse Reclamation and Energy Tax Credit from $4 per ton to $8 per ton. "Stronghold estimates this increase in the waste coal tax credit will result in approximately $2 to $4 million per annum of incremental net income."
- Stronghold acquired by Bitfarms Ltd. in March 2025 (for ∼ $175 million)

Stronghold: Emissions violations and ... tire burning

- Scrubgrass: 7 air quality violations since 2018
- Panther Creek: 16 air quality violations since 2018
- Panther Creek applied to add "tire derived fuel" (TDF) as a supplement to waste coal
- June 2023 application to PA Department of Environmental Protection
  - "TDF has long been recognized as a valuable fuel in well-controlled plants, as well as cement plants."
  - "Best Available Technology (BAT) is not an applicable requirement since this is a modification of an existing source..."
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  - "Best Available Technology (BAT) is not an applicable requirement since this is a modification of an existing source..."
  - "This application triggers no new regulatory requirements"
- 100 residents of Carbon County sue Stronghold in March 2024
  - Allege that using TDF increases air pollution
  - Stronghold received over $29 million in tax credits from PA over the last two years
  - Request removal of tax credits to plant

They are causing a tremendous amount of toxic waste into the air, into the water, noise pollution to the people who live nearby, and, probably, worst of all, Pennsylvanians are paying for this. *– Freiwald, lead attorney*

Literature Review #1

"The effect of pollution on labor supply: Evidence from a natural experiment in Mexico City"

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Hanna and Oliva in Journal of Public Economics, 2015

- Use closure of a large oil refinery in Mexico City in March 1991 as a natural experiment
- Closure caused a 19.7% decline in pollution, as captured by SO2, in the surrounding neighborhoods
- Particularly within 10km, air quality improved
- The closure caused a 1.3 h (or 3.5%) increase in work hours per week.
- Effects appeared on the following week

Literature Review #2

“The Impact of Pollution on Worker Productivity”

Zivin and Neidell in AER, 2012:

- Central Valley of California (farm)
- Use daily variation in ozone
- Labor supply of agricultural workers “highly inelastic in the short run”
- Focus on intensive margin and productivity impacts
- Piece-rate compensation
- Ozone levels well below federal air quality standards have a significant negative impact on productivity 10 parts per billion (ppb) increases worker productivity by 5.5 percent

Literature Review #3

"Air Pollution and the Labor Market: Evidence from Wildfires Smoke"

Borgschulte, Molitor, and Zou (2024) in ReStat:

- Wildfires account for about 20% of US fine particulate matter
- US counties covered by wildfire smoke for 20 days per year on average (population-weighted)
- 1 additional day of wildfire smoke increases PM2.5 by 2.2 $\mu g/m^3$, .06 $\mu g/m^3$ per quarter
- Consider both short and medium term impacts
- Wildfire smoke reduces US annual labor earnings by 2% , or $125 billion
- Annual cost of lost earnings from wildfire greatly exceed the mortality costs

“Bitcoin and CO2 emissions: Evidence from daily production decisions”

CEEP

Papp, Almond, and Zhang in Journal of Public Economics, 2023:

- First paper to link cryptomining causally to externalities
- Focused exclusively on carbon dioxide emissions $\longrightarrow$ climate change
- Carbon emissions respond swiftly to mining incentives
  - 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
- Focused on Scrubgrass power plant in western Pennsylvania
- Scary Letter from Stronghold Mining's General Counsel (October, 2023)
  - We showed to Columbia University General Counsel
  - **Stronghold General Counsel:** ”Scrubgrass began mining Bitcoin in earnest in the fourth quarter of 2021 and first quarter of 2022 – not 2018 as you suggest. Prior to November 2021, there were no notable Bitcoin operations.”

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  - **Stronghold General Counsel:** ”Scrubgrass began mining Bitcoin in earnest in the fourth quarter of 2021 and first quarter of 2022 – not 2018 as you suggest. Prior to November 2021, there were no notable Bitcoin operations.”
  - **Our Reply**: “This contradicts statements in Stronghold's draft S-1 filing submitted to the SEC on May 20, 2021”

OLS: setup

Looking at workers who work within 20km of power plant:

$$Y_{i,t} = g(SO_{2t}, \text{heat input}_t) + \sum_{j=1}^{3} \tau_{p(i),j} t^j + \phi_{\text{month}(t)} + \psi_{\text{DOW}(t)} + \zeta_{\text{ZIP}(i)} + \eta_{\text{NAICS3}(i)} + \varepsilon_{i,t}$$

- $g(\cdot,\cdot)$: polynomial function of (plant-specific) SO_2 and heat input values
  - Will be testing linear and squared terms
  - NO_x data available too, but high(er) correlation with heat input
- $Y_{i,t}$: dependent variable of interest
  - Worker i's hours worked on day t
  - Or the hourly wage earned by worker i on day t
- NAICS3: grouped by the first three digits of NAICS3
- Pre- and post-trough: before and after July 2023 (end of "trough" period for BTC prices)

OLS results: HOURS WORKED for all plants

Table: OLS regression

	DV: Hours worked per individual							
	Pre-trough		Post-trough		All			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SO_2 (tonne)	0.010		-0.004		-0.005	-0.003		
	(0.009)		(0.010)		(0.006)	(0.010)		
${SO_2}^2$						-0.001		
						(0.003)		
Heat input (bn. BTU)		0.0011**		-0.001			-0.0001	0.004**
		(0.0005)		(0.001)			(0.0004)	(0.002)
Heat input^2								-0.00017**
								(0.00007)
Quadratic effects change	-	-	-	-	-	> -2.09	-	> 12.5
FE	— Month, day-of-week, ZIP, NAICS3 —							
Polyn. time trends	Cubic	Cubic	Linear	Linear	Cubic	Cubic	Cubic	Cubic
Adjusted R^2	0.154	0.154	0.200	0.200	0.166	0.166	0.166	0.166
#(Unique Workers)	5,173		4,134		— 7,594 —			
#(Days)	668		366		— 1,034 —			
N	319,967		224,678		— 544,645 —			

Note: Robust SE in parentheses. ** : $p < 0.05$.

OLS results: HOURLY WAGE for all plants

Table: OLS regression (continued)

	DV: *Average hourly wage rate*							
	Pre-trough		Post-trough		All			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SO_2 (tonne)	-0.027		0.035		0.044***	0.060**		
	(0.023)		(0.026)		(0.016)	(0.028)		
${SO_2}^2$						-0.006		
						(0.008)		
Heat input (bn. BTU)		-0.003**		0.002			0.0016	-0.004
		(0.001)		(0.002)			(0.0010)	(0.005)
Heat input^2								0.0002
								(0.0002)
Quadratic effects change	-	-	-	-	-	> -2.09	-	> 12.5
FE	— Month, day-of-week, ZIP, NAICS3 —							
Polyn. time trends	Cubic	Cubic	Linear	Linear	Cubic	Cubic	Cubic	Cubic
Adjusted R^2	0.422	0.422	0.382	0.382	0.384	0.384	0.384	0.384
#(Unique Workers)	2,853		2,337		— 4,129 —			
#(Days)	668		366		— 1,034 —			
N	187,275		131,146		— 318,421 —			

Note: Robust SE in parentheses. $^{**}: p < 0.05$.

OLS magnitudes & sources of endogeneity

- Overview: workers (on avg.) earn **$ 11.53/hour** and work **6.22 hours/day**
- Assuming 1 SD increase in SO2 emissions (roughly 0.7 tonnes), we see:
  - No effect to hours worked
  - About 3 cents increase in hourly wage
- Assuming 1 SD increase in heat input (roughly 12 billion BTU), we see:
  - At most $\sim$3 minutes increase in daily hours worked
  - At most $\sim$4 cents decrease in hourly wage

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  - At most ~3 minutes increase in daily hours worked
  - At most ~4 cents decrease in hourly wage

Confounding addressed in OLS

1. ZIP, industry (NAICS3), month, and DOW FE: absorbs possibly systemic differences
2. Cubic time trends: gradual changes in emissions or labor

Why IV?

1. Isolate impact of Bitcoin mining
2. Address additional high-frequency confounders, e.g. weather shocks, labor demand shocks, labor supply shocks (affecting both generation and labor market)
3. Endogenous scrubber activation (abatement)

First Stage

Pollution regressed on Bitcoin variables + time controls

In all linear-specification first-stage regressions below, we use the following equation:

$$Y_t = f(\mathcal{B}_t) + \sum_{j=1}^{3} \tau_j t^j + \phi_{\text{month}(t)} + \psi_{\text{DOW}(t)} + \varepsilon_t$$

where $\mathcal{B}_t$ is a vector of Bitcoin (BTC) variables, including:

1. BTC price in 1,000s of USD
2. BTC difficulty in trillions (1×10^{12})
3. Total transaction (tx.) fees in 100s of BTC
4. Average BTC block size
5. Tx. per block, in 1,000s
6. Median tx. confirmation time in minutes
7. BTC-USD trade volume in billions (1×10^{9})
8. Hashrate in 100 millions (1×10^{8})
9. Total miner revenues in 10 millions of USD
10. Market cap in billions of USD

and $f(\cdot)$ is a polynomial function.

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Table: "Best" First-stage Results for SO_2 Emissions and Concentration

	DV: SO_2 for Northampton		
	Emissions (tonnes)	Concentration (ppb)	
Price	0.090***	0.064***	0.028***
	(0.011)	(0.009)	(0.003)
Price^2	-0.001***	-0.0003***	
	(0.0001)	(0.0001)	
Quadratic effects change	$>$ 91.8	$>$ 170	-
Fixed effects	— Month, DOW —		
Polyn. time trends	— Cubic —		
F-statistic	44.22	50.65	86.32
N	1,034	961	961

Note: Robust SE in parentheses. *** : $p < 0.01$.

1st stage – SO2 EMISSIONS for all plants

CEEP

Table: "Best" First-stage Results for SO_2 Emissions

	DV: SO_2 emissions (tonnes)			
	Northampton	Panther Creek	Scrubgrass	
Price	0.090***		-0.091***	0.885***
	(0.011)		(0.026)	(0.154)
Difficulty			0.231***	
			(0.056)	
Price^2	-0.001***			-0.007***
	(0.0001)			(0.001)
Hashrate		-1.029***		
		(0.159)		
Hashrate^2		0.088***		
		(0.015)		
Periods		— All —		Post-trough
Month & DOW FE		— Yes —		
Polyn. time trends		— Cubic —		Quadratic
F-statistic	44.22	21.69	12.05	16.60
N	1,034	1,034	1,034	366

Note: Robust SE in parentheses. *** : $p < 0.01$.

- Results robust to using year-and-month FE instead of time trends and month FE
- Northampton: SO_2-price correlation $(+)$ for all price ranges
- Panther Creek: SO_2-hashrate corr. $(-)$ for all hashrate ranges
- Scrubgrass: **opposite** of what we generally expect
  - difficulty$\uparrow$ $\rightarrow$ harder to mine
  - price$\uparrow$ $\rightarrow$ incentive to mine$\uparrow$

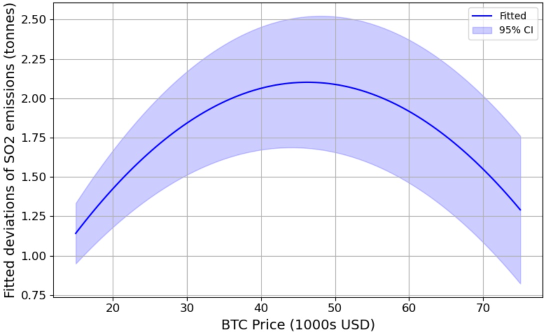
1st stage – SO2 EMISSIONS for all plants TOGETHER

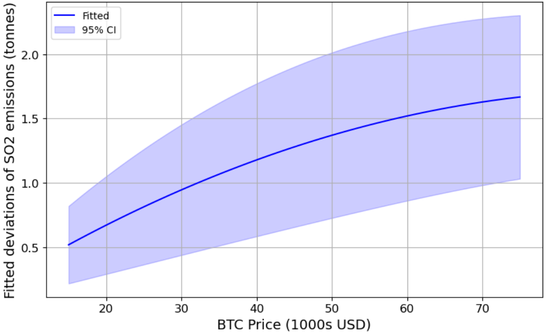
Table: First-stage Results for SO_2 Emissions, all three plants

	DV: SO_2 emissions (tonnes)		
	Altogether		Plant-specific
Price	0.089***	0.092***	0.054***
	(0.008)	(0.008)	(0.008)
Price^2	-0.001***	-0.001***	-0.001***
	(0.0001)	(0.0001)	(0.0001)
Hashrate		-0.076	0.848***
		(0.185)	(0.202)
Hashrate^2		-0.002	-0.094
		(0.017)	(0.019)
Month FE		— Yes —	
DOW FE		— Yes —	
Polyn. time trends		— Cubic, plant-specific —	
F-statistic	87.82	48.01	19.75
N	2,242	2,242	2,242

Note: Robust SE in parentheses. $^{***}: p < 0.01$. "Plant-specific" refers to regressing hashrate and hashrate^2 to Panther Creek and price and price^2 to the other two plants (via interaction terms), while "altogether" refers to using the regressors together regardless of the power plant.

- Going forward with (price, price^2) as the set of instruments
  - Best F-stat, but also...
  - Less issues with overID tests (to be shown in IV regressions)





Using cubic time trends

Using year-month FEs

Note: Daily median and 80th-percentile BTC prices (in 1000s USD) were 30.52 and 50.26

Northampton Panther Creek Scrubgrass

Instrumental Variables (IV): Setup

$$X_{p(i),t} = f(\mathcal{B}_t) + \overbrace{\sum_{j=1}^{3} \tau_{p(i),j} t^j}^{\text{plant-specific trend}} + \phi_{\text{month}(t)} + \psi_{\text{DOW}(t)} + \overbrace{\zeta_{z(i)} + \nu_{\text{NAICS3}(i)}}^{\text{likely redundant in first stage}} + \varepsilon_{it} \qquad \text{(First Stage)}$$

$$Y_{it} = X_{p(i),t}\beta + \underbrace{\sum_{j=1}^{3} \tau_{p(i),j} t^j + \mu_{\text{month}(t)}}_{\text{replaceable with } \upsilon_{\text{year-month}(t)}} + \delta_{\text{DOW}(t)} + \underbrace{\zeta_{z(i)}}_{\text{ZIP FE}} + \underbrace{\nu_{\text{NAICS3}(i)}}_{\text{industry FE}} + u_{it} \qquad \text{(Structural)}$$

where

- Y_{it}: labor outcome variable (hours worked per worker)
- $X_{p(i),t}$: plant-p endogenous variable of interest (SO_2, NO_x, heat input)
- $f(\mathcal{B}_t)$: best F-statistic function of Bitcoin variables

IV: HOURS WORKED for all plants together

Table: All plants together; each plant to its neighborhood

	DV: *Hours worked*			
	(OLS)	(IV: 1)	(IV: 2)	(IV: 3)
SO_2 (emission, tonnes)	-0.005	-0.105***	-0.084***	-0.098***
	(0.006)	(0.020)	(0.020)	(0.112)
FE	— Month, DOW, ZIP, NAICS3 —			
Polyn. time trends	— Cubic, plant-specific —			
Instruments	OLS	Price	Price & Hash	Interaction
FS F-stat.	-	87.82	48.01	19.75
K-P rk. LM (underID)	-	4.5×10^4***	4.5×10^4***	4.1×10^4***
K-P rk Wald (weak ID)	-	2.7×10^4	1.4×10^4	1.2×10^4
Hansen J (overID)	-	0.833	18.117***	1.243
#(Workers)	— 7,594 —			
N(Days)	— 1,034 —			
Total N	— 544,645 —			

Note: Coefficient estimates (using OLS or IV) for SO_2 emissions (in metric tonnes) with robust standard errors in parentheses. For instruments, "price" refers to using price and its square as instruments, "price & hash" refers to using price, difficulty and their squares as instruments, and "interaction" refers to using all of the best-F-statistic variables interacted with plant dummies as instruments.

IV: HOURS WORKED for all plants together

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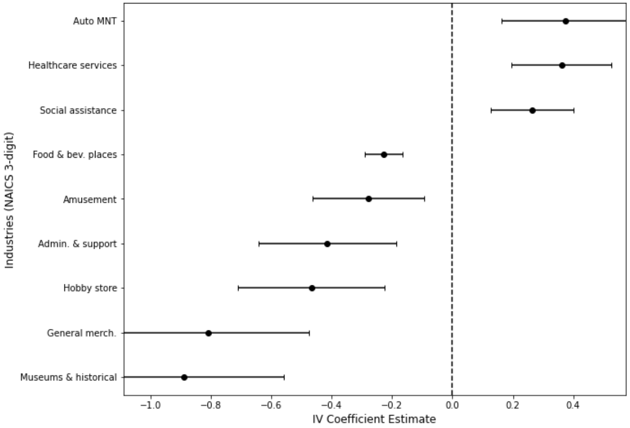
- **NoHam and Panther Creek**: emits 0.5-1.5 tonnes/day, max. of 6-7 tonnes/day
  - On avg., 5 minutes (1%) of work hours; at max., 40 minutes (10%) of work hours
- **Scrubgrass**: emits 0.003-8 tonnes/day, max. of 52 tonnes/day
  - On avg., 16 minutes (4%) of work hours; at max., 3.5 hours (50%) of work hours

Plant-level breakdowns

IV: HOURS WORKED response, heterogeneity by industry

Figure: IV estimates, significant ($\alpha = 0.05$) and with 50+ unique workers (Regressions)



"Social assistance" refers to nursing homes, elderly care, etc.

IV: HOURS WORKED, heterogeneity by wage level

Table: IV regressions by Wage Information

	DV: *Hours worked*				
	All	w/o wage info	w/ wage info	$\leq$median wage	$>$median wage
SO_2 (emission, tonnes)	-0.105***	-0.074***	-0.073***	-0.390***	-0.046
	(0.020)	(0.030)	(0.026)	(0.042)	(0.031)
FE	— Month, DOW, ZIP, NAICS3 —				
Polyn. time trends	— Cubic, plant-specific —				
Instruments	— Price and Price^2 —				
FS F-stat.	— 87.82 —				
K-P rk. LM (underID)	44722***	19781***	24673***	8052***	16168***
K-P rk Wald (weak ID)	27357	12120	15067	4830	9979
Hansen J (overID)	0.833	3.811*	0.290	0.201	0.093
Mean wage/hour	-	-	13.85	8.59	16.79
#(Workers)	7,594	4,323	3,864	1,932	1,932
#(Days)	1,034	1,034	1,034	1,034	1,034
Total N	544,645	240,946	303,699	109,008	194,691

Note: IV estimates for SO_2 emissions with robust standard errors in parentheses. * : $p < 0.1$, ** : $p < 0.05$, *** : $p < 0.01$. "Median wage" refers to the median of mean hourly wages of workers, which is about $11.17/hour in our dataset. Those "w/o wage info" include those with missing wage information or with reported wage of 0. Numbers of workers for "w/o wage info" and "w/ wage info" do not add up to 7,594 due to some workers having days with and without wage information.

- Some evidence that certain industries are more likely to not report wages (e.g., electronics retail)

IV: HOURS WORKED, heterogeneity by wage quartile

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Table: IV regressions by wage quartiles

	DV: Hours worked			
	wage $<$ P25	P25 $\leq$ wage $<$ P50	P50 $\leq$ wage $<$ P75	wage $\geq$ P75
SO_2 (emission, tonnes)	-0.291***	-0.388***	0.026	-0.063
	(0.068)	(0.051)	(0.045)	(0.041)
FE	— Month, DOW, ZIP, NAICS3 —			
Polyn. time trends	— Cubic, plant-specific —			
Instruments	— Price and Price^2 —			
FS F-stat.	— 87.82 —			
K-P rk. LM (underID)	3349***	4591***	6274***	9703***
K-P rk Wald (weak ID)	2028	2727	3835	6027
Hansen J (overID)	0.546	0.200	1.472	1.048
Mean wage/hour	6.69	10.02	13.16	19.43
#(Workers)	966	966	1,064	868
#(Days)	1,034	1,034	1,034	1,034
Total N	46,793	62,215	81,820	112,871

Note: IV estimates for SO_2 emissions with robust standard errors in parentheses. $^{*}: p < 0.1$, $^{**}: p < 0.05$, $^{***}: p < 0.01$. "Px" ($x \in \{25, 50, 75\}$) refers to the x^{th} percentile of mean hourly wages of workers, where P25 = \$8.82, P50 = \$11.17, and P75 = \$15.00.

IV: WAGE AS DEPENDENT VARIABLE

Table: All plants together; each plant to its neighborhood

	DV: Average hourly wage rate			
	(OLS)	(IV: 1)	(IV: 2)	(IV: 3)
SO_2 (emission, tonnes)	0.044***	0.283***	0.292***	0.236***
	(0.016)	(0.054)	(0.052)	(0.055)
FE	— Month, DOW, ZIP, NAICS3 —			
Polyn. time trends	— Cubic, plant-specific —			
Instruments	OLS	Price	Price & Hash	Interaction
FS F-stat.	-	87.82	48.01	19.75
K-P rk. LM (underID)	-	2.6×10^4***	2.6×10^4***	2.5×10^4***
K-P rk Wald (weak ID)	-	1.6×10^4	8046	7437
Hansen J (overID)	-	0.832	0.615	26.96***
#(Workers)	— 4,129 —			
N(Days)	— 1,034 —			
Total N	— 318,421 —			

Note: Coefficient estimates (using OLS or IV) for SO_2 emissions (in metric tonnes) with robust standard errors in parentheses. For instruments, "price" refers to using price and its square as instruments, "price & hash" refers to using price, difficulty and their squares as instruments, and "interaction" refers to using all of the best-F-statistic variables interacted with plant dummies as instruments.

IV: WAGE AS DEPENDENT VARIABLE

CEEP

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Instruments	OLS	Price	Price & Hash	Interaction
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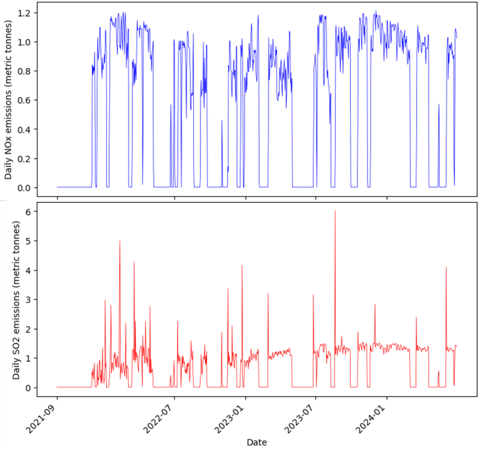
- Median of hourly wage: \$10.50
- PA minimum wage: \$7.25
- 1 SD increase in SO2 emissions ($\sim$ 0.7 tonnes) associated with
  - OLS: hourly wage $< 0.5\% \uparrow$
  - IV: hourly wage 1.8-2.7% $\uparrow$
- **Potential explanations**
  - Compositional effect
  - Compensating differentials
  - Labor demand & supply
  - (To-do) Changes in total hours worked at business level?

Dissection | Total wages earned

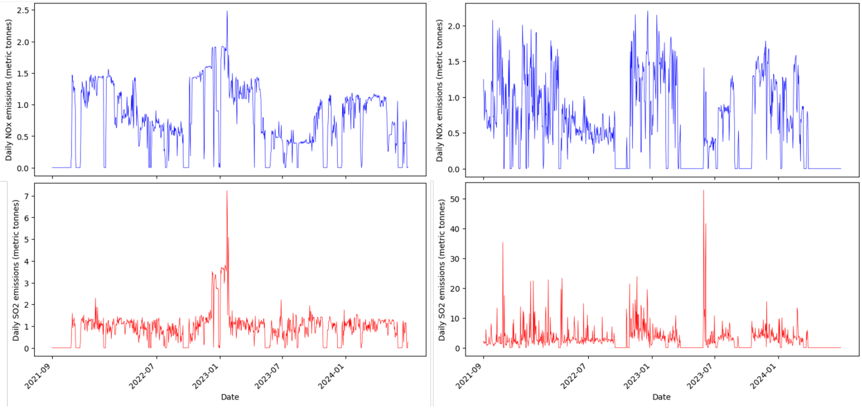
Figure: Northampton, daily NO_x (above) and SO_2 (below)



- Episodes of high-intensity "spikes" in SO_2
  - Likely due to ramping
  - NO_x has similar ramping tendencies, but the spikes are not as prominent
  - Are SO_2 scrubbers selectively operated?
- Days with 99th-percentile (among positive ones) SO_2 emissions as **events**

Event study analysis: Panther Creek and Scrubgrass

Figure: Panther Creek (left) and Scrubgrass (right), daily NO_x (above) and SO_2 (below)



→ Scrubgrass spikes have magnitudes of **7-10 times** that of others

Isolating the top SO2 emission events

Figure: Deviations from day-before-event; Scrubgrass (L), Northampton (M), Panther Creek (R)

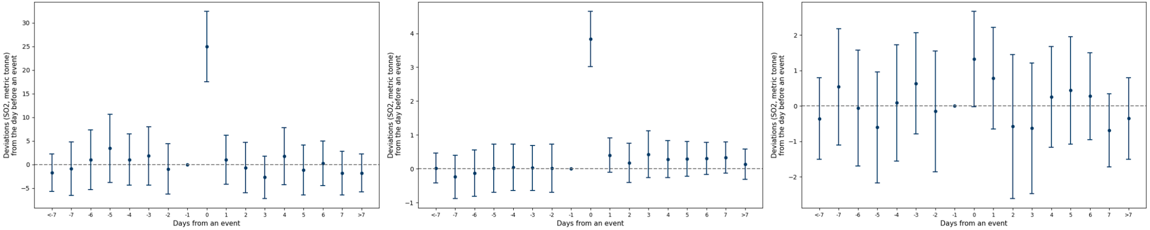
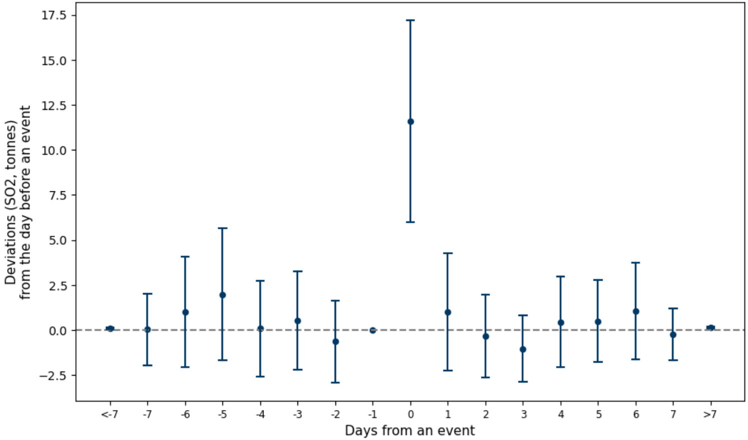


Figure: All plants together



Isolation of the top NOx and heat input events = UGLY

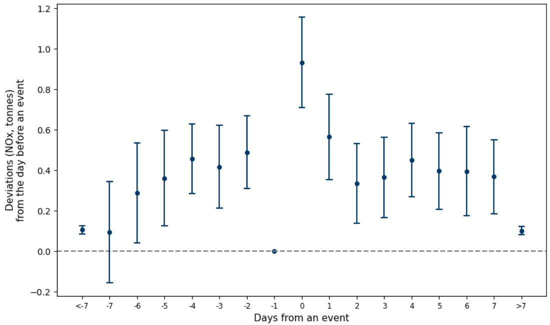


Figure: NOx events

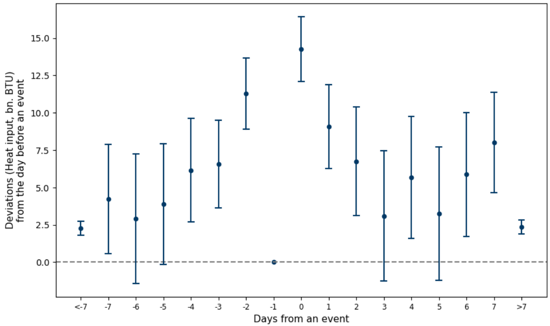
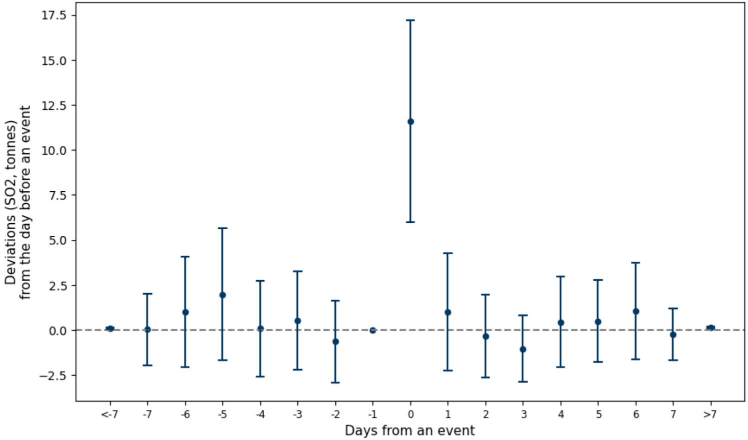


Figure: Heat input events

Isolating the top SO2 emission events

Figure: All plants together



Event study: impact on labor hours/# workers

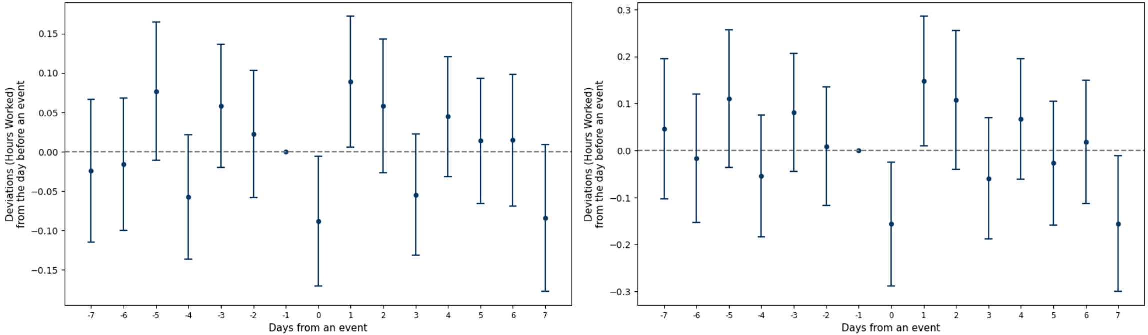
Event study regression:

$$Y_{it} = \left(\sum_{j=-D, j\neq -1}^{D} \beta_j \sum_{k=1}^{K_i} 1(t - d_k = j) \right) + \overbrace{\underline{\beta} \sum_{k=1}^{K_i} 1(t - d_k < -D) + \overline{\beta} \sum_{k=1}^{K_i} 1(t - d_k > D)}^{\text{not used in window-only regressions}}$$
$$+ \iota_i + \mu_{\text{year-month}(t)} + \delta_{\text{DOW}(t)} + \varepsilon_{it}$$

- K_i is the number of events that individual i experiences
- Y_i: hours worked by i
- Similar specification at the ZIP code level (z); Y_z: per-worker hours worked or number of workers in ZIP code z
- Throwing out most of of our data, power reduced
- Not helping ourselves by assigning everyone same daily emissions within 20km

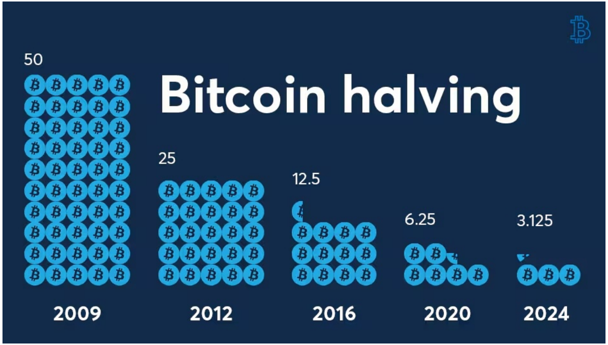
Event impact on HOURS WORKED: three plants together

Figure: All industries (L) and food and beverages (F&B) (R), within-window



- F&B results robust at the ZIP-code- or day-level aggregation and outside-window-too
- Statistically significant (−) effect on the day of emission (0.1-0.2 hour)

Bitcoin Halving - April 20, 2024



- Occurs roughly every 4 years
- In April 2024, reduced the Bitcoin supply subsidy from 6.25 Bitcoins per block to 3.125 Bitcoins per block

Heterogeneity in 1st stage responses after halving?

Table: First-stage Results for SO_2 Emissions, pre- and post-halving

	DV: SO_2 emissions (tonnes)		
	Northampton	Panther Creek	Scrubgrass
A. Pre-halving (before 2024-04-20)			
BTC variable	0.093***	-0.973***	0.984***
	(0.026)	(0.165)	(0.187)
BTC variable^2	-0.001***	0.090***	-0.008***
	(0.056)	(0.017)	(0.002)
B. Post-halving (on and after 2024-04-20)			
BTC variable	0.004	-0.547***	-0.508
	(0.020)	(0.166)	(0.594)
BTC variable^2	0.0003	0.042**	0.004
	(0.0003)	(0.017)	(0.005)
Start date	2021-09-01	2021-09-01	2023-07-01
BTC Variable	Price	Hashrate	Price
Month FE	V	V	V
DOW FE	V	V	V
Polyn. time trends	3	3	3
F-statistic	29.80	16.76	8.31
N	1,034	1,034	174

Note: Robust SE in parentheses. ** : $p < 0.05$, *** : $p < 0.01$.

- Halving event: rewards for validating ("mining") a block are cut in half
  - The **only** halving event in our dataset: **April 20, 2024**
  - 6.25 $\rightarrow$ 3.125 BTC per block
- Post-halving period:
  - BTC mining incentives (as well as reactions to price or hashrate) **dampen**

Powerplant Plant EMISSIONS Fall After Halving

Table: First-stage Results for SO_2 Emissions, pre- and post-halving

	All periods			2-month period around halving		
	(1)	(2)	(3)	(4)	(5)	(6)
A. Dependent variable: SO_2 emissions (tonnes)						
Halving	-0.567***	-0.429***	-0.509***	-1.173***	-1.140***	-1.163***
	(0.091)	(0.090)	(0.095)	(0.089)	(0.113)	(0.111)
B. Dependent variable: Heat input (billions, BTU)						
Halving	-11.832***	-8.347***	-10.219***	-21.295***	-20.714***	-21.137***
	(1.559)	(1.503)	(1.480)	(1.606)	(2.026)	(1.986)
Start date	2021-09-01	2021-09-01	2021-09-01	2024-03-20	2024-03-20	2024-03-20
BTC Controls	None	Price	Price & Hash	None	Price	Price & Hash
Fixed effects			— Month, day-of-week —			
Polyn. time trends		— Cubic —			— Linear —	
N	1,034	1,034	1,034	184	184	184

Note: Robust SE in parentheses. $^{**}: p < 0.05$, $^{***}: p < 0.01$.

HOURS WORKED and halving

Table: Halving's effect on hours worked

	DV: *Hours worked*							
	All periods				2-month period around halving			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Halving	0.076***	0.038		0.326*	0.049	0.562		0.151
	(0.024)	(0.025)		(0.184)	(0.055)	(0.535)		(0.132)
SO_2 (emissions, tonnes)		-0.102***	-0.088***	-0.058**		0.683	-0.094	-0.063
		(0.021)	(0.020)	(0.029)		(0.655)	(0.086)	(0.102)
$SO_2 \times$ halving			-0.256	-0.770			4.764*	2.407
			(0.307)	(0.497)			(2.560)	(1.563)
Instruments	None	Price, Price^2	– Price, Price^2, Tx. fee –		None	Price, Price^2	– Price, Price^2, Tx. fee –	
UnderID	-	4.2×10^4***	2096***	1081***	-	761***	604***	1109***
Weak ID	-	2.6×10^4***	721	353	-	369	156	348
OverID	-	1.569	2.875*	1.164	-	3.710*	5.873**	6.764***
Start date	2021-09-01	2021-09-01	2021-09-01	2021-09-01	2024-03-20	2024-03-20	2024-03-20	2024-03-20
Fixed effects	— Month, DOW, ZIP, NAICS3 —							
Polyn. time trends	— Cubic —				— Linear —			
N	1,034	1,034	1,034	1,034	184	184	184	184

Note: Robust SE in parentheses. $^*: p < 0.1$, $^{**}: p < 0.05$, $^{***}: p < 0.01$.

- Halving associated with greater hours worked

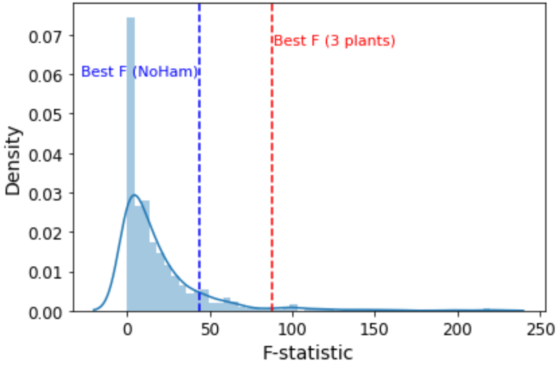


Figure: Best F-stats, all CONUS power plants

- In our 3 PA plants, F-stat drops as we mis-assign timing of pollution (match the wrong days)
- How to find "best" F-stats:
  1. Fit a LASSO using polynomials and interactions of BTC variables
  2. Among "surviving" variables, use randomized grid search to find the best F-statistic
- Power plants with $F = 0$: **263** (22.21%; out of 1184)
- Those with $F < 10$: **563** (47.55%)
- Still, 41 power plants with $F > 87.82$ (139 power plants with $F > 44.22$)

Where (and who) are these high-F-stat plants?

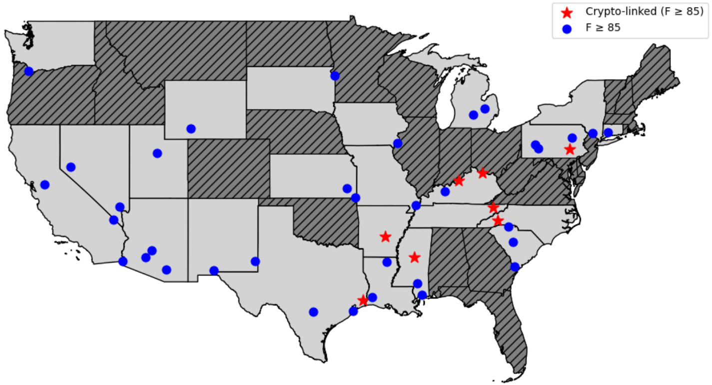


Figure: Where are the high-F-stat plants?

- States with $F \geq 85$ plant(s): WA, CA, NV, AZ, UT, NM, WY, SD, KS, TX, IA, MO, AR, LA, MS, TN, KT, NC, SC, PA, NY, CT
- Hats off to Anika Fergusson for doing this awesome detective work!

Any potential mining activities among high F-stat plants?

8 out of 21 plants with $F \geq 100$

1. **Arkansas**: White Bluff, Entergy Arkansas LLC, Redfield Jefferson
   - Entergy Arkansas: lower energy prices provided for crypto miners (Massey 2022)
2. **Kentucky**: Cane Run, Louisville Gas & Electric Co, Louisville Jefferson
   - Louisville Gas & Electric gave a discounted 10-year power contract to a Bitcoin mining facility run by Alliance Resource Partners (Niemeyer 2023)
3. **Kentucky**: HL Spurlock, East Kentucky Power Coop, Inc, Maysville Mason
   - "Some cryptocurrency mining companies have also received discounts on electricity costs from utilities including East Kentucky Power Cooperative in return for the perceived investment brought into communities" (Niemeyer 2023)
4. **Mississippi**: Attala, Entergy Mississippi LLC, Sallis Attala
   - Entergy utility crews in another MS county hooking up BTC mining pods to power lines (Huffman 2024)

Any potential mining activities among high F-stat plants?

5. **North Carolina**: Asheville, Duke Energy Progress, Arden Buncombe
   - Duke Energy exploring integration of crypto mining into its grid management and "the Duke Energy grid already hosts several Bitcoin miners on a small-scale basis." (Fox 2024)
6. **Pennsylvania**: Ironwood LLC, Helix Ironwood LLC, Lebanon
   - Ironwood was owned by Talen Energy, which purchased a crypto mining facility (Talen Energy 2024)
7. **Tennessee**: John Sevier, Tennessee Valley Authority, Rogersville Hawkins
   - "TVA gave Bitdeer an economic development grant to build its cryptocurrency facility in East Knoxville" (Fisher 2024)
8. **Texas**: ExxonMobil Beaumont Refinery, ExxonMobil Oil Corp, Beaumont Jefferson
   - Not confirmed in Texas, but ExxonMobil has pursued crypto mining tie-ins as part of its operations. (Ashraf 2023)

Guidi et al. in March 2025 *Nature Communications*

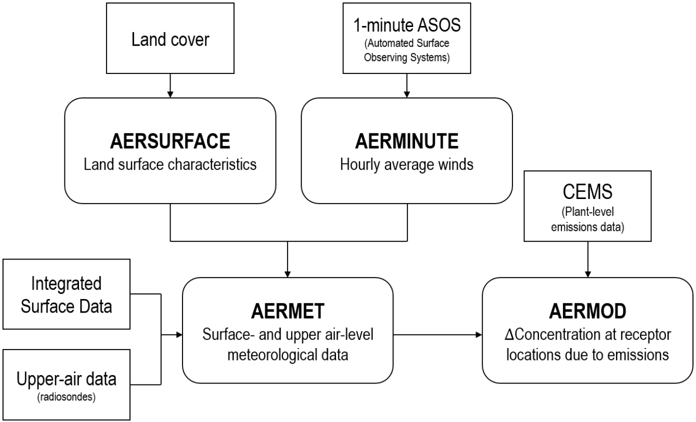
- New York Time identified 34 largest US Bitcoin mines in March 2023
- Generally, not tied to a specific power plant
- Guidi assign them to all the power plants in the geographic area – the "balancing authortiy region"
- "To find each power plant's load increase due to to Bitcoin miner's energy demand, we divide the yearly energy demand of each miner amonth teh suppling power plants within the grid region of the miner"[3]
- "Bitcoin mines and the power plants that increased generation in response to them were often separated by multiple states and hundreds of miles"

Findings:

1. Bitcoin uses 33% more electricity than LA
2. 1.9 million Americans were exposed to at least .1 $\mu g/m^3$

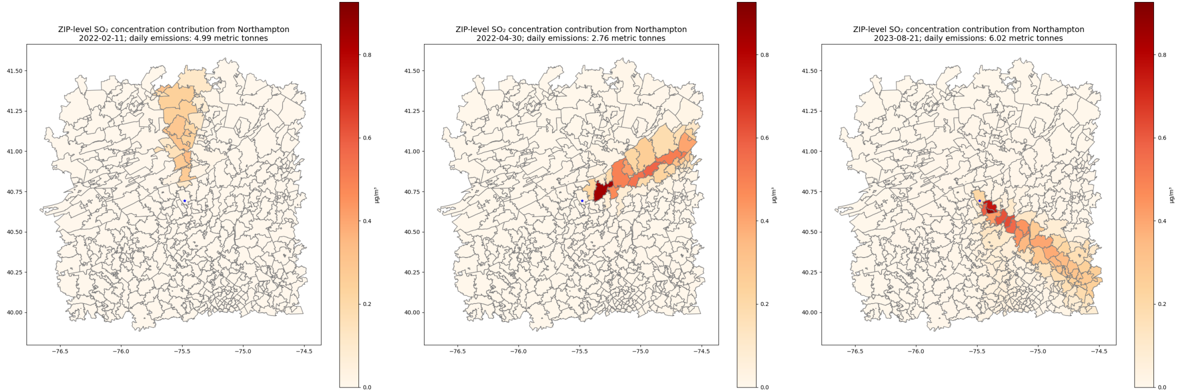
[3] "according to their respedtive MOERs, the marginal contribution to supply a marginal MWh of demand, the "marginal operating emissions rate, or MOER"

Brief introduction to AERMOD



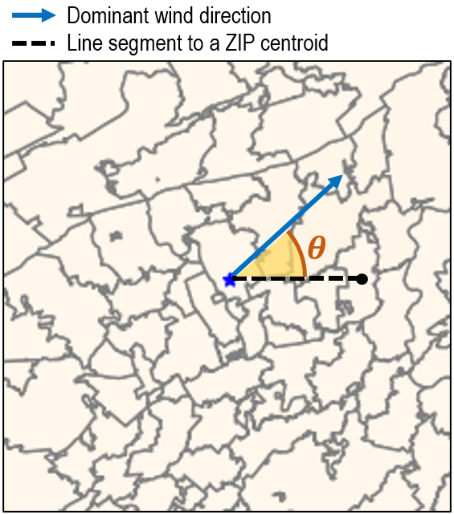
- Emissions + meteorology + land surface $\longrightarrow$ (changes in) concentrations

Quick look at AERMOD results



- At large, concentration levels and emission levels are correlated
- But meteorological conditions can affect (i) intensity and (ii) distance

Wind direction and "alignment"



Wind alignment: $\text{WA}_{z,t} = \max\{0, \cos\theta_{z,t}\}$

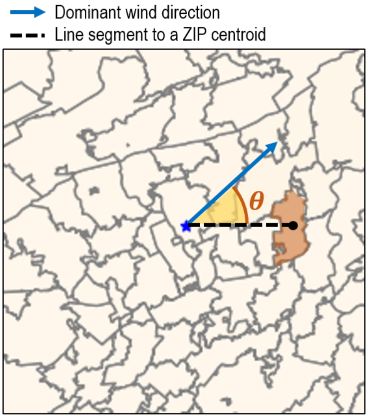
- $\theta_{z,t}$: angle between the (i) dominant wind direction at plant $p(z)$ and (ii) the ZIP z centroid at time t
- If a ZIP is upwind (beyond perpendicular), then wind alignment becomes 0

Revised instrument

$$f(\mathcal{B}_t) \times \text{WA}_{z,t}$$

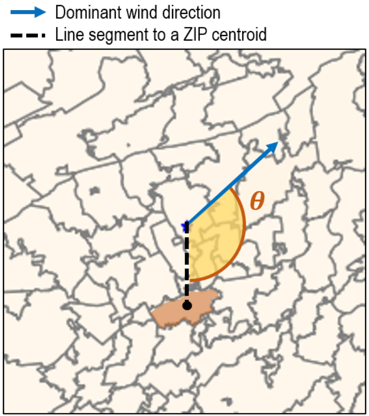
- Specifically, BTC price times wind alignment
- To-do: Incorporate wind intensity?

Wind alignment and a ZIP's location wrt. power plant



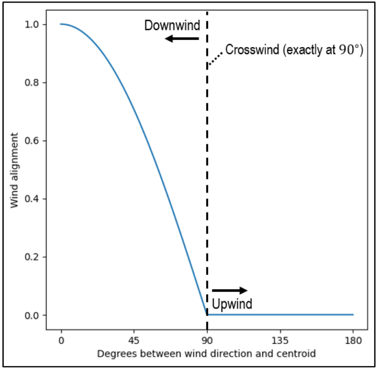
(a) Downwind case ($\theta < 90^\circ$)

Assuming $\theta = 45^\circ$, $\mathrm{WA} = \cos\left(\frac{\pi}{4}\right) \approx 0.71$



(b) Upwind case ($\theta < 90^\circ$)

Assuming $\theta = 135^\circ$, $\mathrm{WA} = \max\left\{0, \cos\left(\frac{3\pi}{4}\right)\right\} = 0$



(c) Wind alignment function

$$SO_{2\,z,t} = \beta_1 \left[f(\mathcal{B}_t) \times \mathsf{WA}_{z,t} \right] + \overbrace{\upsilon_{\text{year-month}(t)}}^{\substack{\text{Substitutable with year FE,} \\ \text{month FE, and time trends}}} + \delta_{\mathsf{DOW}(t)} + \zeta_z + \varepsilon_{z,t}$$

First stage, SO2 concentration

$$SO_{2\,z,t} = \beta_1 \left[f(\mathcal{B}_t) \times WA_{z,t} \right] + \overbrace{\upsilon_{\text{year-month}(t)}}^{\text{Substitutable with year FE, month FE, and time trends}} + \delta_{\text{DOW}(t)} + \zeta_z + \varepsilon_{z,t}$$

Table: First stage with SO2 concentration and wind alignment

	DV: ΔSO_2 concentration (ng/m^3)			
	(All plants)	(Northampton)	(Panther)	(Scrubgrass)
Price × wind alignment	0.514***	0.281***	0.953***	0.815***
	(0.075)	(0.015)	(0.209)	(0.093)
F-stat	46.57	333.65	20.85	77.49
Fixed effects	— Year-by-month, DOW, ZIP —			
Start date	2021-09-01	2021-09-01	2021-09-01	2023-07-01
# unique ZIP	49	29	13	7
# unique days	1034	1034	1034	366
N	45,990	29,986	13,442	2,562

Note: ZIP-clustered SE in parentheses. $^{***}: p < 0.01$.

OLS and IV with SO2 concentration: HOURS WORKED, all plants

Table: All plants together, each plant to its neighborhood

	DV: *Hours worked*			
	(OLS 1)	(IV 1)	(OLS 2)	(IV 2)
SO_2 (Δ concentration, $\mu g/m^3$)	-0.314**	-1.405**	-0.519***	-1.928***
	(0.146)	(0.666)	(0.159)	(0.699)
Time FE	Year-by-month, DOW		Day	
Other FE	— ZIP, NAICS3 —			
Polynomial time trends	Cubic, plant-specific		N/A	
Instruments	OLS	Price×WA	OLS	Price×WA
FS F-stat.	-	46.57	-	54.97
K-P rk. LM (underID)	-	2.3×10^4***	-	2.2×10^4***
K-P rk Wald (weak ID)	-	2.6×10^4	-	2.5×10^4
#(Workers)	— 7,594 —			
#(Days)	— 1,034 —			
Total N	— 547,368 —			

Note: Coefficient estimates (using OLS or IV) for changes in SO_2 concentrations (in $\mu g/m^3$) with robust standard errors in parentheses. "Price×WA" refers to Bitcoin price (in 1000s of USD) times wind alignment. $^{**}: p < 0.05$, $^{***}: p < 0.01$

OLS and IV with SO2 concentration: HOURS WORKED, all plants

Table: All plants together, each plant to its neighborhood

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Other FE	— ZIP, NAICS3 —			
Polynomial time trends	Cubic, plant-specific		N/A	
Instruments	OLS	Price×WA	OLS	Price×WA
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Translating to work hours lost

- 1 SD increase in SO_2 concentration: 0.02-0.07 $\mu g/m^3$ $\rightarrow$ 2-6 minutes ($\sim$ 1%) of work lost
- Max. increase: 0.6-0.8 $\mu g/m^3$ $\rightarrow$ 1.0-1.3 hour (15-18%) of work lost

(Above statistics account only for ZIP codes with labor data)

Next steps

CEEP

1. Using atmospheric transport model to better match pollution from power plant to zipcode of worker
   - HYSPLIT $\longrightarrow$ AERMOD
   - Will help address exclusion restriction of Bitcoin shocks operating through pollution
   - Will reduce measurement error/attenuation bias from mis-assignment of pollution to zipcode
   - How best use? Include wind speed as instrument? LOTS OF INSTRUMENTS!
2. Find more undeclared Bitcoin miners (outside PA) using insights from our first stage
   - United States using CEMS
   - Also pursuing in China coal-fired power plants data for 2022
3. Does indoor air quality also deteriorate: Purple Air monitors
   - Data in hand
4. Focus on smaller Bitcoin price shocks
5. Non-Bitcoin Crypto: E.G. Ethereum
   - Our power plants may not be “monogamous” wrt Bitcoin
6. TBA: Your suggestions!

1. Bitcoin mining in Pennsylvania has a negative externality on lower-wage workers
    - Externality substantially greater than carbon alone (GHG and climate forcing)
    - Already knew damage 3 times larger than benefit from carbon alone
    - Now piling on top of that with local labor market effects
    - Lowest wage workers bear the brunt $\rightarrow$ 1st order Environmental Justice (EJ) implications
2. This is an artificial problem or "own goal"
    - Proof-of-stake mechanism for cryptocurrency. Ethereum switched to proof-of-stake consensus mechanism in Sept. 2022
    - $\exists$ crypto benefits without these externalities
3. Yes, renewables are growing but more demand for fossil in absolute terms
    - Not just cryptocurrencies
    - E.G., AI larger $\uparrow$ increase in demand for electricity – in a predominantly fossil grid
    - Globally, coal use has tripled since the 1960s
    - Natural gas use projected to increase strongly, US now #1 exporter of LNG
        - ★ Natural gas arguably not any better than coal insofar as near-term warming concerned
        - ★ ~Half of warming experienced today is not from CO_2 – mitigation costs can be low
4. Homebase: vastly improved microdata to study US labor markets

Thank you!

Northampton Generating, May 22, 2025

Appendix Slides!

Descriptive statistics, Bitcoin variables

CEEP

Variable	Description
Price	Market value of 1 BTC, determined by demand and supply.
Difficulty	A measure of mining difficulty, adjusted roughly every two weeks. Increases when the actual mining time of a block is less than the "target" mining time, and vice versa.
Hashrate	The total computational power used in the Bitcoin network to mine and process transactions. It is usually measured in hashes per second (H/s). A higher hashrate means more mining power is available to validate transactions and secure the network.
Total Transaction Fees	Sum of transaction fees in BTC paid to miners per block (transactions are recorded on blocks).
Average Bitcoin Block Size	Reflects the transaction volume in the blockchain. Typically measured in (mega)bytes.
Median Transaction Confirmation Time	Median time for a transaction to be included in a block. Typically measured in minutes.
BTC-USD Trade Volume	Total trading volume of BTC against USD on exchanges.

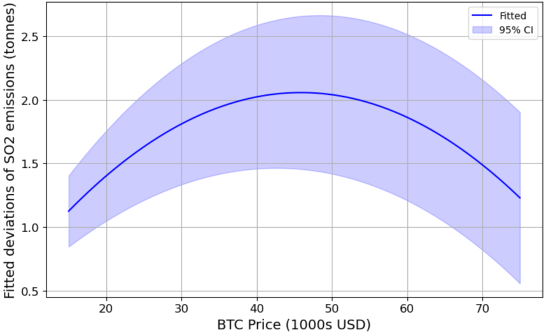
Best F-statistic First Stage

Table: "Best" Results with SO_2 as Endogenous

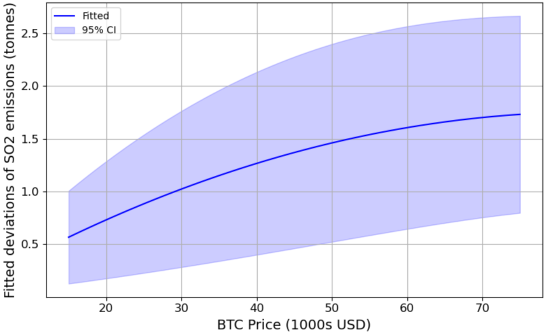
Plant	Period	Time FE	Time polyn.	Best-fit variables	F-stat
Northampton	All	Month	Cubic	$\underset{0.090^{***}}{\text{Price}}$ and $\underset{-0.001^{***}}{\text{Price}^2}$	44.22
		Year-month	-	$\underset{0.019^{***}}{\text{Price}}$ and $\underset{-0.100^{***}}{\text{Halv.} \times \text{Price}}$	102.99
	Post-trough	Month	Cubic	$\underset{-0.128^{***}}{\text{Tx. fee}}$, $\underset{0.190^{***}}{\text{Tx. fee}^2}$	51.98
		Year-month	-	$\underset{-0.119^{***}}{\text{Tx. fee}}$, $\underset{0.166^{***}}{\text{Halv.} \times \text{Tx. fee}}$, and $\underset{-0.021^{***}}{\text{Halv.} \times \text{Price}}$	91.56
Scrubgrass	Post-trough	Month	Quadratic	$\underset{0.885^{***}}{\text{Price}}$ and $\underset{-0.007^{***}}{\text{Price}^2}$	16.60
		Year-month	-	$\underset{0.898^{***}}{\text{Price}}$ and $\underset{-0.007^{***}}{\text{Price}^2}$	18.87
Panther Creek	All	Month	Cubic	$\underset{-1.030^{***}}{\text{Hashrate}}$ and $\underset{0.088^{***}}{\text{Hashrate}^2}$	21.69
	Pre-trough	Month	Cubic	$\underset{-0.418^{***}}{\text{Hashrate}}$	17.85

NOTE: *** : $p < 0.01$. In all cases, day-of-week fixed effects were additionally used. 2nd-order time polynomials were used if there is a multicollinearity problem. In all cases, dependent variable is SO_2 emissions (tonnes).

First stage, Northampton – BTC price and SO2



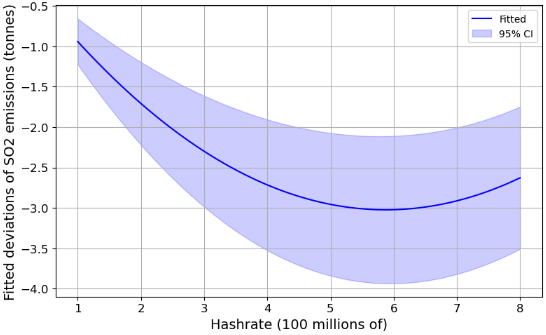
Using cubic time trends



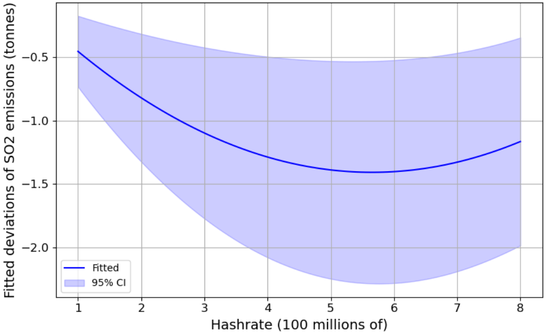
Using year-month FEs

Note: Daily median and 80th-percentile BTC prices (in 1000s USD) were 30.52 and 50.26

Back to all plants



Using cubic time trends

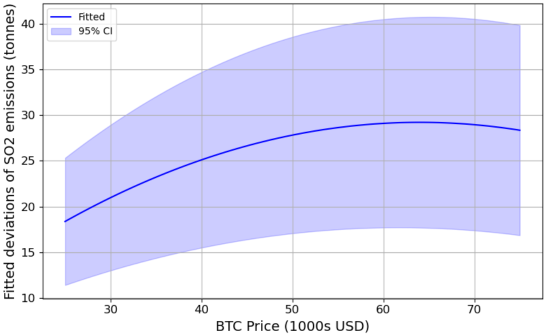


Using year-month FEs

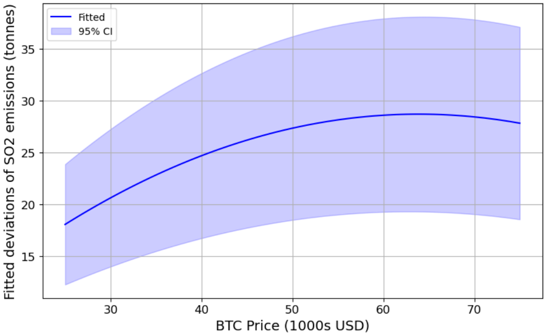
Note: Daily median and 80th-percentile hashrates (in 100 millions) were 2.88 and 4.85

Back to all plants

First stage, Scrubgrass – BTC Price and SO2



Using cubic time trends



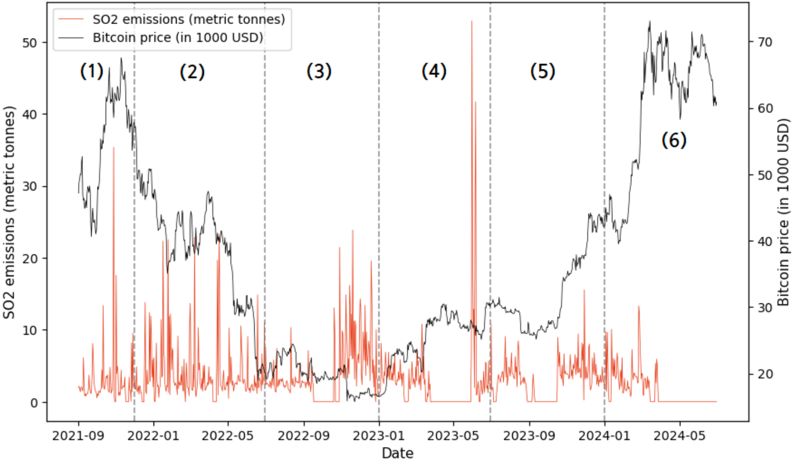
Using year-month FEs

Note: We focus on July 1, 2023 and onwards for this analysis, and daily median and 80th-percentile BTC prices (in 1000 USD) in this period were 42.57 and 65.15

Back to all plants

Digging deeper into Scrubgrass...

Figure: BTC prices and Scrubgrass SO_2 emissions



- Detected number of structural breaks ≥ 5 (Bai and Perron 1998; Ditzen, Karavias, and Westerlund 2024)
- 6 "regimes" guided by Bitcoin price trends and estimated break points

First-stage for Scrubgrass, by regime

Table: "Best" Results for Scrubgrass SO_2 by Regime

Regime #	Begin	End	Best-fit variables	F-stat	Selling to grid?
(1)	2021-09-01	2021-11-30	Difficulty and Difficulty^2 29.411^{**} -0.730^{**}	< 10	Maybe
(2)	2021-12-01	2022-06-30	BTC-USD trade volume -2.427^{**}	< 10	Likely
(3)	2022-07-01	2022-12-31	Total tx. fee 14.415^{**}	< 10	Likely
(4)	2023-01-01	2023-06-30	Market cap. -29.388^{**}	< 10	Unlikely
(5)	2023-07-01	2023-12-31	Price 0.485^{***}	21.38	Very unlikely
(6)	2024-01-01	2024-06-30	Price and Price^2 0.865^{**} -0.007^{**}	< 10	Very unlikely
(5) & (6)	2023-07-01	2024-06-30	Price and Price^2 0.885^{***} -0.007^{***}	14.45	Very unlikely

NOTE: ** : $p < 0.05$, *** : $p < 0.01$. Month and day-of-week fixed effects were used. 3rd-order time trends were used, unless there was a multicollinearity problem, in which 2nd-order ones were used. In all cases, dependent variable is Scrubgrass SO_2 emissions (tonnes).

$\rightarrow$ Focus on regime (5)+(6) (July 2023 and onward)

First-stage for Panther Creek, by regime

Table: "Best" Results for Panther Creek NO_x by Regime

Regime #	Begin	End	Best-fit variables	F-stat
(1)	2021-09-01	2021-11-30	Difficulty and Difficulty^2 4.990^{***} -1.384^{***}	< 10
(2)	2021-12-01	2022-06-30	BTC-USD trade volume -0.286^{**}	< 10
(3)	2022-07-01	2022-12-31	Difficulty and Difficulty^2 1.389^{**} -0.020^{**}	< 10
(4)	2023-01-01	2023-06-30	Price 0.089^{***}	< 10
(5)	2023-07-01	2023-12-31	Price and Difficulty -0.082^{***} 0.135^{***}	17.88
(6)	2024-01-01	2024-06-30	Price -0.020^{***}	< 10
(5) & (6)	2023-07-01	2024-06-30	Price -0.028^{***}	13.15

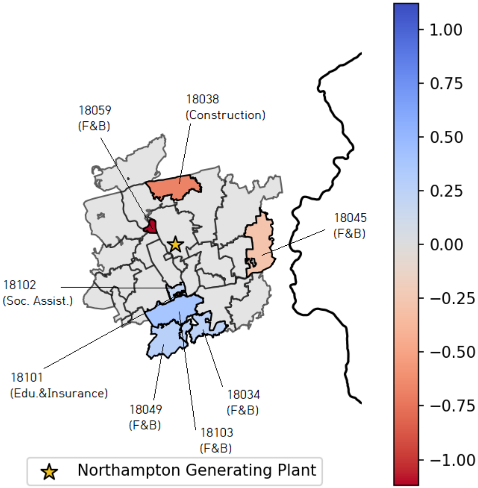
NOTE: ** : $p < 0.05$, *** : $p < 0.01$. Month and day-of-week fixed effects were used. 3rd-order time trends were used, unless there was a multicollinearity problem, in which 2nd-order ones were used. In all cases, dependent variable is Panther Creek SO_2 emissions (tonnes).

→ **opposite** of what we see for Scrubgrass

IV: Heterogeneous Impacts by ZIP Code

CEEP

Figure: Stat. sig. IV estimates by ZIP code (predominant worker composition)



IV: Power plant-level breakdowns

Table: Separate IV regressions by power plant

	DV: Hours worked				*DV: Hourly wage rate*			
	Northampton	Scrubgrass	Panther Creek		Northampton	Scrubgrass	Panther Creek	
SO_2 (emission, tonnes)	-0.079***	-0.116	-0.291***	0.005	0.291***	-1.823	0.394*	-1.530***
	(0.021)	(1.410)	(0.066)	(0.118)	(0.056)	(2.357)	(0.213)	(0.486)
FE	— Month, DOW, ZIP, NAICS3 —							
Polyn. time trends	— Cubic, plant-specific —							
Instruments	Price	Price	Price	Hashrate	Price	Price	Price	Hashrate
FS *F*-stat.	44.22	16.60	19.95	21.69	44.22	16.60	19.95	21.69
K-P rk. LM (underID)	4.5×10^4***	37.333	4104***	1090***	2.4×10^4***	19.911***	1417***	292.26***
K-P rk Wald (weak ID)	2.7×10^4	19.342	2569	563.29	1.5×10^4	10.393	875.88	148.26
Hansen *J* (overID)	0.833	0.002	0.198	1.882	1.401	0.003	0.537	15.289***
#(Workers)	6,762	81	751	751	3,872	32	225	225
N(Days)	1,034	174	1,034	1,034	158	1,032	1,032	
Total *N*	489,609	3,723	51,311	51,311	297,168	2,067	19,186	19,186

Note: IV estimates for SO_2 emissions (in metric tonnes) with robust standard errors in parentheses. For instruments, "price" refers to using price and its square as instruments and "hashrate" refers to using difficulty and its square as instruments.

Back to all plants together

IV: Effect on hours worked per worker – Scrubgrass

Table: IV regression, Scrubgrass

	DV: Hours worked per individual Post-trough			
	(1)	(2)	(3)	(4)
SO_2 (tonnes)	0.057	-0.144		
	(0.055)	(0.547)		
${SO_2}^2$		0.023		
		(0.062)		
Heat Input (bn. BTU)			0.018	-0.052
			(0.018)	(0.185)
Heat Input^2				0.003
				(0.007)
FE	— Month, day-of-week, ZIP code —			
Polyn. time trends	— Quadratic —			
K-P rk. LM (underID)	405***	96.5***	270***	113***
K-P rk Wald (weak ID)	266	45.4	265	28.9
Hansen J (overID)	0.137	-	0.145	-
#(Unique Workers)	— 100 —			
#(Days)	— 337 —			
N	— 6,546 —			

Note: Robust SE in parentheses. * : $p < 0.1$, ** : $p < 0.05$, *** : $p < 0.01$. On an emitting day, Scrubgrass on average emits roughly 4 metric tonnes of SO_2 (maximum: 52 tonnes).

IV: Effect on hours worked per worker – Panther Creek

CEEP

Table: IV regression, Panther Creek

	DV: Hours worked per individual					
	Post-trough		All			
	(1)	(2)	(3)	(4)	(5)	(6)
SO_2 (tonnes)	-0.263		0.009	-3.998		
	(0.196)		(0.112)	(3.972)		
${SO_2}^2$				0.999		
				(0.991)		
Heat Input (bn. BTU)		-0.091			-0.017	-0.213
		(0.070)			(0.027)	(0.234)
Heat Input^2						0.005
						(0.006)
FE	— Month, day-of-week, ZIP code —					
Polyn. time trends	— Cubic —					
K-P rk. LM (underID)	574***	33.8***	1356***	14.21***	220***	16.52***
K-P rk Wald (weak ID)	644	33.7	806	4.70	109.93	8.226
Hansen J (overID)	-	-	1.149	-	0.753	-
#(Unique Workers)	— 437 —		— 751 —			
#(Days)	— 668 —		— 1,034 —			
N	— 25,924 —		— 51,312 —			

Note: Robust SE in parentheses. $^*: p < 0.1$, $^{**}: p < 0.05$, $^{***}: p < 0.01$. On an emitting day, Panther on average emits roughly 1 metric tonne of SO_2 (maximum: 7 tonnes).

IV: SO2 concentration reading from EPA monitors

CEEP

Table: IV regressions by industry (NAICS3 code)

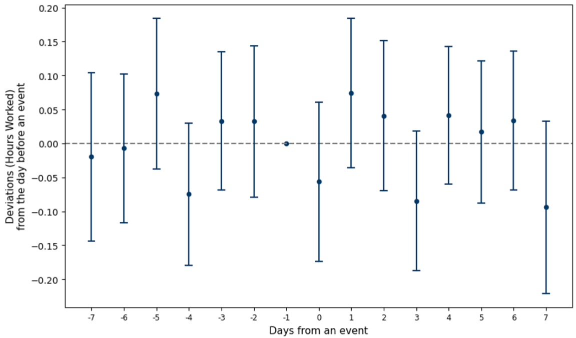
	DV: Hours worked						
	[All]	[F&B Sto.]	[Misc. Ret.]	[Hobby Sto.]	[Admin. Spt.]	[Recrea.]	[F&B Pl.]
SO_2 (ppb)	0.213**	0.876***	1.284	-1.072***	0.279*	0.856	0.427***
(0.097)	(2.706)	(0.238)	(1.222)	(0.323)	(0.181)	(1.277)	(0.115)
FE	— Month, DOW, ZIP —						
Polyn. time trends	— Cubic, plant-specific —						
Instruments	— Price and Price^2 —						
FS F-stat.	— 50.65 —						
K-P rk. LM (underID)	2132***	183***	39.7***	222***	290***	12.7***	1408***
K-P rk Wald (weak ID)	1470	117	28.01	158	223	18.26	1004
Hansen J (overID)	23.06***	13.03***	0.089	6.64***	22.36***	< 0.0001	64.38***
#(Workers)	601	89	4	28	42	2	414
#(Days)	1,029	1,025	432	1,025	799	110	1,026
Total N	44,106	7,975	719	3,430	4,922	127	29,223

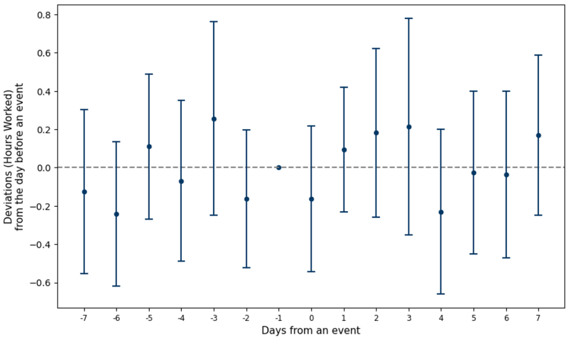
Note: IV estimates for SO_2 emissions with robust standard errors in parentheses. $^{*}: p < 0.1$, $^{**}: p < 0.05$, $^{***}: p < 0.01$.

- Focus on the ZIP codes either containing the nearest-to-NoHam monitor or those contiguous to it
  - Turns out it's just one ZIP code area (18045)

Event impact on hours worked: Northampton and Scrubgrass

Figure: Northampton (L) and Scrubgrass (R), within-window

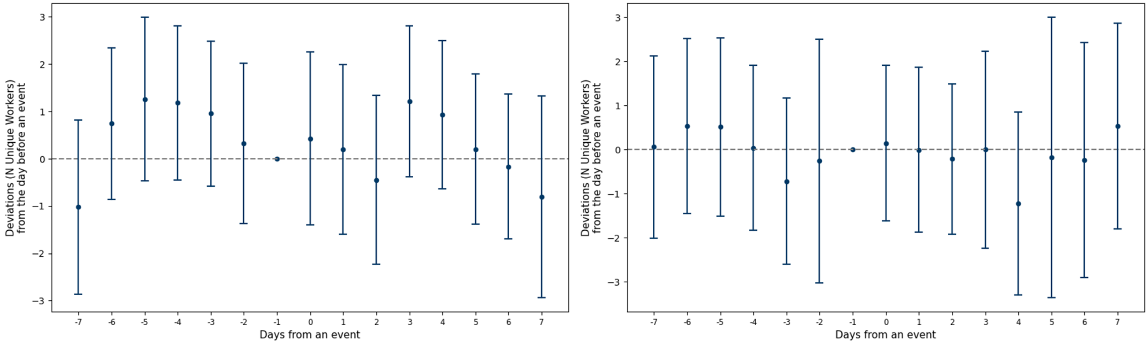




- Results robust at the ZIP-code- or day-level aggregation and outside-window-too
- Some specifications for Scrubgrass (with 20-30km workers as control) show stat. sig. (−) on day 0

Event impact on number of workers: Northampton and Scrubgrass

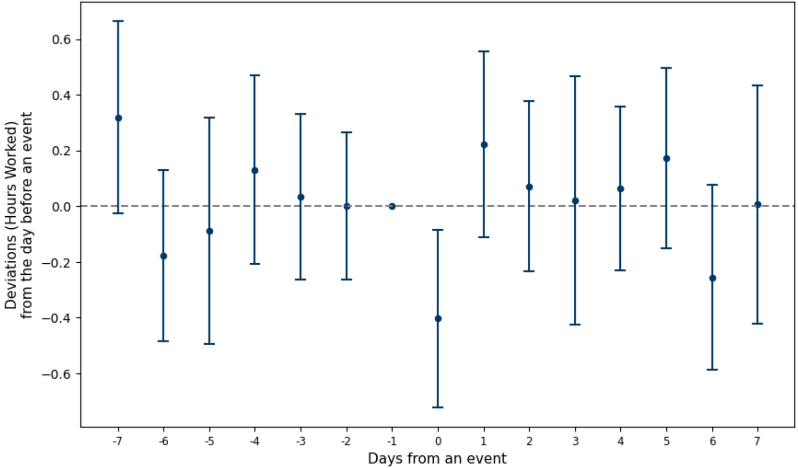
Figure: Northampton (L) and Scrubgrass (R), within-window



- Results robust at the day-level aggregation, without-controls, outside-window-too
- In sum, questionable impact of SO_2 spikes on number of workers near Scrubgrass and Northampton

Event impact on hours worked: Panther Creek

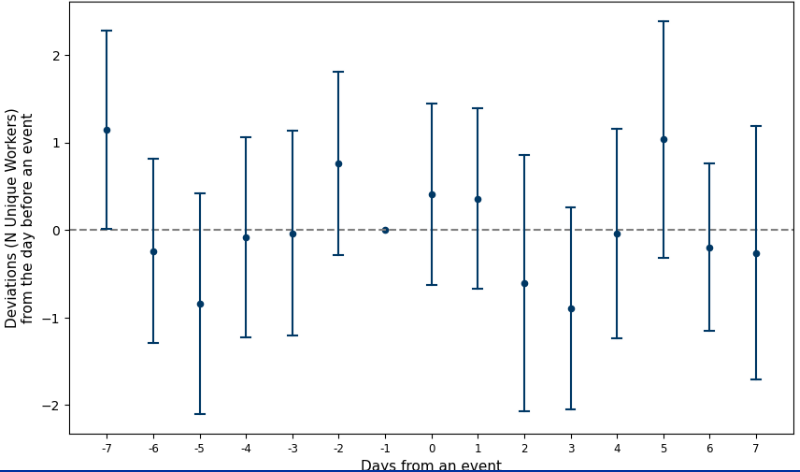
Figure: Panther Creek, within-window



- Stat. sig. ($\alpha = 0.05$) result on hours worked, despite "duller" spikes
- Robust at the ZIP-code- and daily-level
- Better controls needed (synthetic controls?)

Event impact on number of workers: Panther Creek

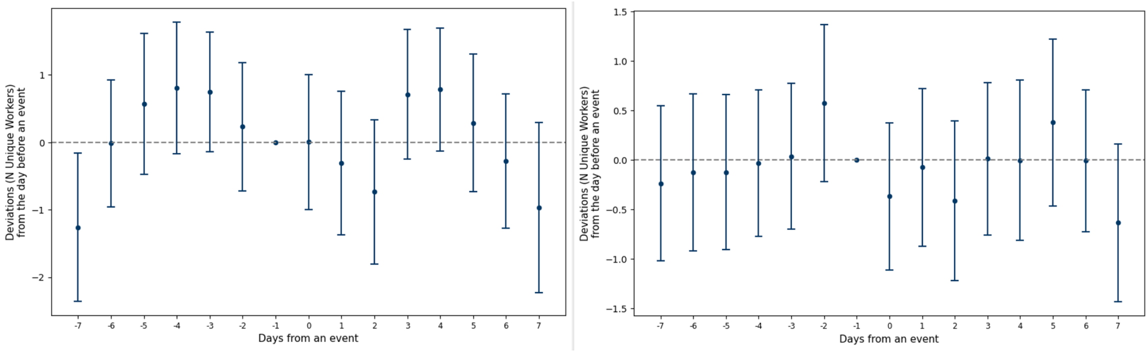
Figure: Panther Creek, within-window



- Robust also at the daily-level

Event impact on number of workers: three power plants **together**

Figure: All industries (L) and food and beverages (F&B) (R), within-window



- Results robust at the day-level aggregation and outside-window-too

IV, Industry Breakdowns, Hours Worked: All Results

Table: IV regressions by industry (NAICS3 code)

	DV: Hours worked							
	[Crop]	[Resid. Cnst.]	[Cnst. Cntrct.]	[Nonmet. Manu.]	[Furn. Sto.]	[Elec. Sto.]	[F&B Sto.]	[Health Sto.]
SO_2 (emission, tonnes)	0.828**	-4.859	0.036	0.778*	0.198	-17.670	0.010	0.198
	(0.395)	(3.033)	(0.096)	(0.422)	(1.107)	(26.606)	(0.081)	(0.178)
FE	— Month, DOW, ZIP —							
Polyn. time trends	— Cubic, plant-specific —							
Instruments	— Price and Price^2 —							
FS *F*-stat.	— 87.82 —							
K-P rk. LM (underID)	98.489***	9.863***	752.389***	73.763***	16.801***	1.071	1877***	252.95***
K-P rk Wald (weak ID)	327	5.352	469	43.05	8.174	0.407	1159	160.05
Hansen *J* (overID)	0.437	2.233	1.630	0.447	1.487	0.143	4.710**	0.543
#(Workers)	46	15	51	8	14	9	355	15
#(Days)	78	226	788	791	493	65	1031	748
Total *N*	485	305	9,839	1,184	1,430	193	26,226	2,598

Note: IV estimates for SO_2 emissions with robust standard errors in parentheses. $^{*}: p < 0.1$, $^{**}: p < 0.05$, $^{***}: p < 0.01$.

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IV, Industry Breakdowns, Hours Worked: All Results (continued)

Table: IV regressions by industry (NAICS3 code)

	DV: Hours worked							
	[Unkn. Ret.]	[Hobby Sto.]	[Gen. Mer. Sto.]	[Misc. Ret.]	[Truck]	[Insur.]	[Real Est.]	[Prof. Serv.]
SO_2 (emission, tonnes)	-0.249	-0.439***	-0.670***	0.089	-8.514	-0.421***	-0.053	-0.211*
	(0.198)	(0.124)	(0.178)	(0.107)	(7.658)	(0.085)	(0.182)	(0.116)
FE	— Month, DOW, ZIP —							
Polyn. time trends	— Cubic, plant-specific —							
Instruments	— Price and Price^2 —							
FS F-stat.	— 87.82 —							
K-P rk. LM (underID)	514.95***	834.95***	470.40***	1122.2***	1.227	388.218***	301.170***	852.834***
K-P rk Wald (weak ID)	324	517	307	671	0.560	243	192	529
Hansen J (overID)	0.753	15.072***	0.051	1.155	0.514	0.014	9.843***	0.525
#(Workers)	103	170	83	192	2	23	162	79
#(Days)	1,004	1,029	985	1,031	23	844	837	789
Total N	7,786	10,999	6,519	15,925	41	4,594	9,134	11,372

Note: IV estimates for SO_2 emissions with robust standard errors in parentheses. * : $p < 0.1$, ** : $p < 0.05$, *** : $p < 0.01$.

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Table: IV regressions by industry (NAICS3 code)

	DV: *Hours worked*							
	[Mgmt.]	[Admin Spt.]	[Edu. Serv.]	[Healthcare]	[Soc. Asst.]	[Arts&Sports]	[Museum]	[Recrea.]
SO_2 (emission, tonnes)	-0.540***	-0.415***	-0.590	0.358***	0.264***	0.301	-0.547***	-0.276***
	(0.200)	(0.117)	(1.565)	(0.084)	(0.070)	(0.264)	(0.141)	(0.093)
FE	— Month, DOW, ZIP —							
Polyn. time trends	— Cubic, plant-specific —							
Instruments	— Price and Price^2 —							
FS F-stat.	— 87.82 —							
K-P rk. LM (underID)	473***	973***	9.16**	1940***	2794***	118	581***	1962***
K-P rk Wald (weak ID)	295	650	4.68	1188	1769	130	349	1200
Hansen J (overID)	0.071	4.804**	0.057	0.053	2.524	0.375	2.422	4.257**
#(Workers)	91	300	52	280	250	81	156	637
#(Days)	915	1,021	287	1,030	775	709	832	1,033
Total N	6292	24,286	2,538	23,318	31,848	3,669	6,355	33,898

Note: IV estimates for SO_2 emissions with robust standard errors in parentheses. $^{*}: p < 0.1$, $^{**}: p < 0.05$, $^{***}: p < 0.01$.

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IV, Industry Breakdowns, Hours Worked: All Results (continued)

Table: IV regressions by industry (NAICS3 code)

	DV: Hours worked				
	[Accommo.]	[F&B Place]	[Auto Mnt.]	[Pers. Serv.]	[Civic&Soc.]
SO_2 (emission, tonnes)	2.005	-0.244***	0.373***	-0.075	-0.014
	(2.706)	(0.032)	(0.107)	(0.102)	(0.229)
FE	— Month, DOW, ZIP —				
Polyn. time trends	— Cubic, plant-specific —				
Instruments	— Price and Price^2 —				
FS F-stat.	— 87.82 —				
K-P rk. LM (underID)	514.95***	834.95***	470.40***	1122.2***	1.227
K-P rk Wald (weak ID)	324	517	307	671	0.560
Hansen J (overID)	0.753	15.072***	0.051	1.155	0.514
#(Workers)	57	3,294	173	156	25
#(Days)	54	1,034	1,021	989	761
Total N	507	208,132	21,123	14,219	2,978

Note: IV estimates for SO_2 emissions with robust standard errors in parentheses. $^{*}: p < 0.1$, $^{**}: p < 0.05$, $^{***}: p < 0.01$.

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IV, Wage Channel: Dissecting by Wage Information

Table: IV regressions by Wage Information

	DV: Average hourly wage rate		
	w/ wage info	$\leq$median wage	$>$median wage
SO_2 (emission, tonnes)	0.283***	-0.358***	0.056
	(0.054)	(0.049)	(0.060)
FE	— Month, DOW, ZIP, NAICS3 —		
Polyn. time trends	— Cubic, plant-specific —		
Instruments	— Price and Price^2 —		
FS F-stat.	— 87.82 —		
K-P rk. LM (underID)	2.6×10^4***	8216***	17190***
K-P rk Wald (weak ID)	1.6×10^4	4949	10586
Hansen J (overID)	0.832	7.428***	0.309
#(Workers)	4,129	1,932	1,932
#(Days)	1,034	1,034	1,034
Total N	318,421	111,112	207,309

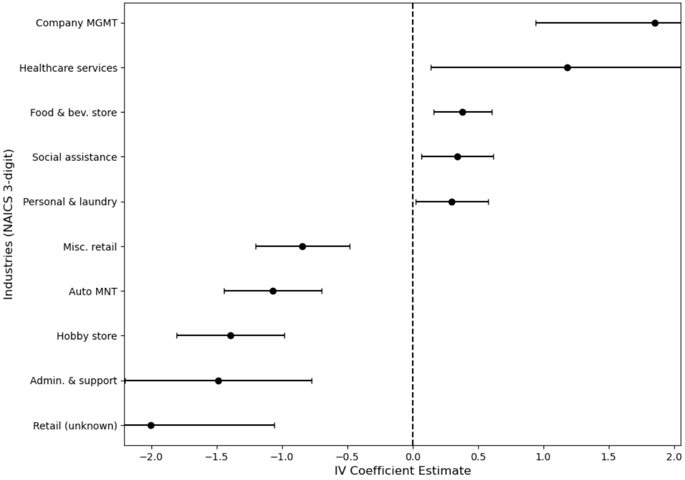
Note: IV estimates for SO_2 emissions with robust standard errors in parentheses. ** : $p < 0.05$, *** : $p < 0.01$. "Median wage" refers to the median of mean hourly wages of workers.

Note that overID test is **rejected** for those earning less than median wage

(prev. slide)

IV: Industry breakdowns, Hourly Wage

Figure: IV estimates, significant ($\alpha = 0.05$) and with 50+ unique workers (prev. slide)



IV: TOTAL WAGES EARNED as dependent variable

Table: IV regressions by Wage Information

	DV: Total wages earned		
	w/ wage info	$\leq$median wage	$>$median wage
SO_2 (emission, tonnes)	1.664***	-0.409	0.743
	(0.447)	(0.282)	(0.572)
Hours worked	16.569***	8.786***	16.902***
	(0.175)	(0.112)	(0.180)
Hours worked^2	-0.022	-0.081***	0.100***
	(0.014)	(0.009)	(0.014)
FE	— Month, DOW, ZIP, NAICS3 —		
Polyn. time trends	— Cubic, plant-specific —		
Instruments	— Price and Price^2 —		
FS F-stat.	— 87.82 —		
K-P rk. LM (underID)	2.5×10^4***	8050***	1.6×10^4***
K-P rk Wald (weak ID)	1.5×10^4	4829	9980
Hansen J (overID)	0.083	1.583	0.003
#(Workers)	4,129	1,932	1,932
#(Days)	1,034	1,034	1,034
Total N	318,421	111,112	207,309

Note: IV estimates for Total Wages Earned with robust standard errors in parentheses. ** : $p < 0.05$, *** : $p < 0.01$. "Median wage" refers to the median of mean hourly wages of workers.

Back to hourly wages