Can Pollution Markets Work in Developing Countries? Experimental Evidence from India

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VDEV-CEPR-BREAD Seminar
September 27th, 2022

This paper is the result of a large collaboration

Gujarat Pollution Control Board

Central Pollution Control Board

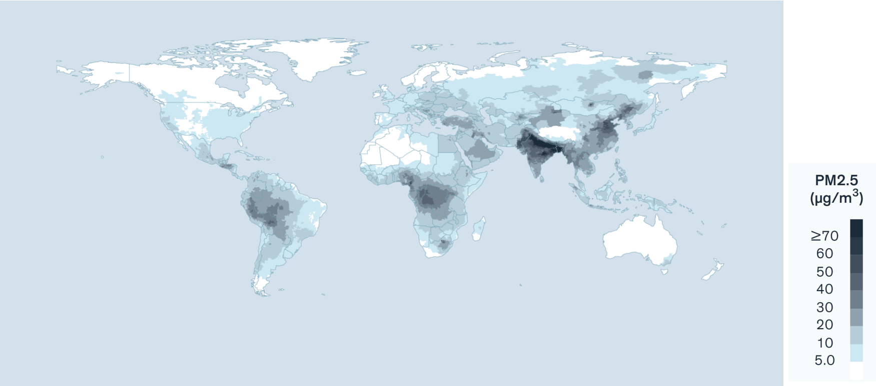
Research partner

Market operator

Industry association

Particulate matter concentrations are extraordinarily high in India and China

Figure: Global distribution of fine particulate matter

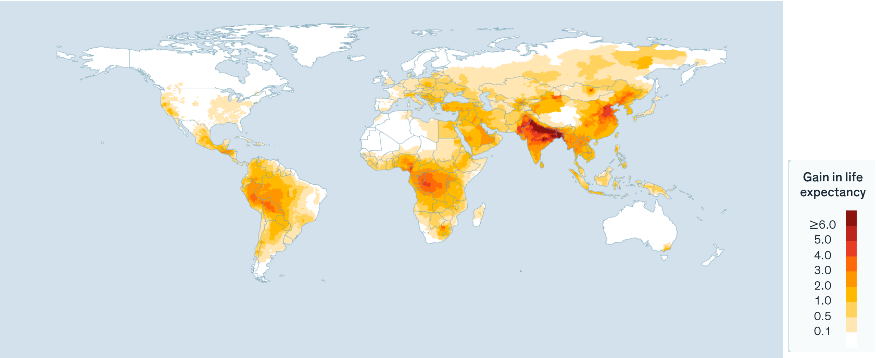


Source: EPIC AQLI index (2020)

AQLI

High particulate concentrations are estimated to reduce lifespans significantly

Figure: Potential change in life expectancy from pollution

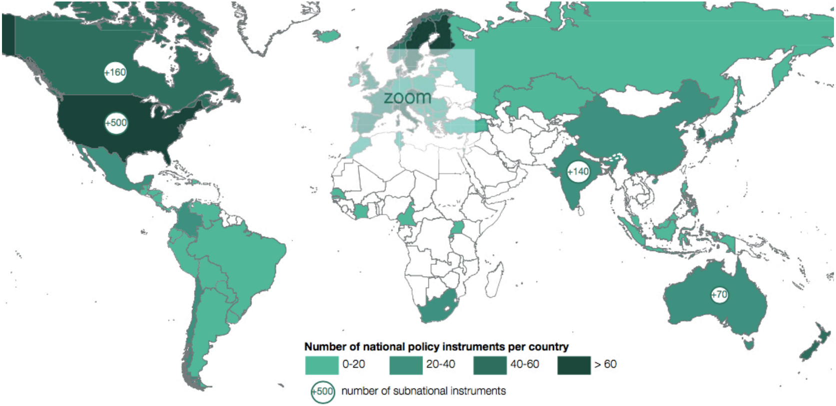


Source: EPIC AQLI index (2020)

AQLI

And yet India and China have many environmental regulations on the books

Figure: Global distribution of environmental policy instruments



Source: OECD policy instruments database

Database

Why is pollution so high?

1. Pollution levels do not balance social costs and benefits
2. Low **willingness to pay** for abatement
   1. Low incomes
   2. Poor information
3. High **marginal costs** of abatement
   - **Privately** high costs
     1. Manufacturing activity concentrated in developing countries
     2. Dirty capital or fuels traded to poor countries
   - **Socially** high costs: making agents internalize externalities
     1. High costs of regulatory enforcement (e.g. corruption)
     2. Weak monitoring and incentives

Why study environmental regulation in developing countries?

- Pollution is high
- Compliance cannot be taken for granted.
- For carbon emissions, environmental regulations in developing countries affect global damages.

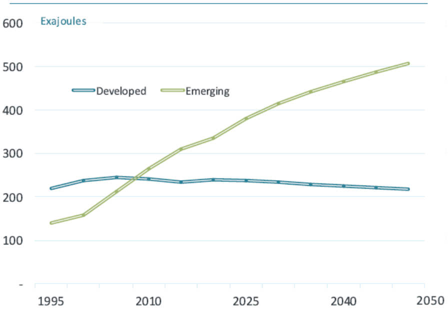


Figure: Global energy demand, 1995-2050

Is effective regulation "too" expensive in low capacity states

> *I must emphasise that standards are not enough. They must also be enforced which is often difficult. . . . It is also necessary to ensure that these regulatory standards do not bring back the License Permit Raj which we sought to get rid of in the wake of economic reforms of the nineties.*

Former Indian Prime Minister Manmohan Singh, Delhi Sustainable Development Summit, 2011.

- Most environmental regulation is command-and-control
  - High cost and inefficient at inducing abatement action; large, infrequent penalties (Duflo, Greenstone, Pande and Ryan, 2013; 2018)

→ Inefficient regulation means policy-makers choose to regulate less

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Can pollution markets be used in developing countries?

- Pollution markets abate pollution at lowest possible cost (Dales, 1968)
  - Tremendous success of cap-and-trade or pollution markets in the US and EU (e.g., US SOx and NOx markets and EU ETS)
- But basic assumptions of pollution markets may be violated in low-income and/or low capacity countries:
  1. Unreliable monitoring of emissions
  2. Insufficient force or credibility of regulator to ensure polluters hold sufficient permits

  → Pollution markets have rare been adopted to regulate pollution in developing countries

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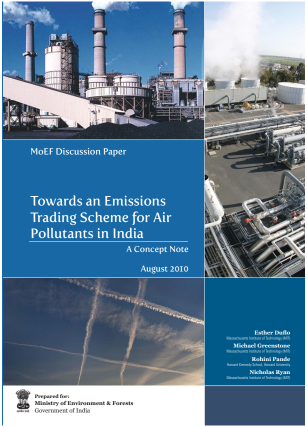
The development of the world's first particulates emissions market



White paper

- 2010: White paper
- 2013: CEMS standards
- 2013: CEMS installations start
- 2014: CEMS national mandate
- ...
- 2019: MoEFCC greenlight
- 2019: CEMS installation complete
- 2019: Trading platform complete
- 2019: Market launch

This paper evaluates the world's first market for particulates emission (in India)

1. **This project**. Introduce a new market for particulate matter
   - Would plants trade?
   - Would plants comply?
   - What would it cost to abate?

2. **Experimental counterfactual**.
   - Market in treatment group only
   - Control plants remain in command-and-control regime

3. **Pollution and cost analysis**.
   - Treatment effects on pollution
   - Simple model to use permit bids to estimate abatement costs

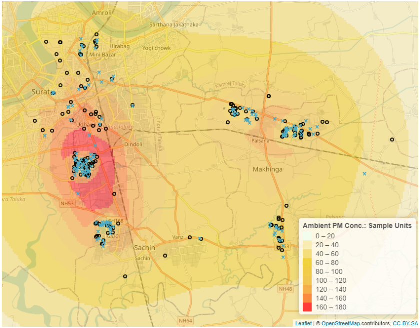


Figure: Surat, Gujarat airshed

Results

1. **The market works well**
    - Compliance with permit-holding requirement almost perfect
    - Active trading at low prices (up to 20% of cap on single days)
    - Ending permit ownership differed greatly from initial allocations, leaving few unused permits
2. **Emissions fall**
    - Emissions cut 20-30% relative to control
    - Emission reduction reflects improved compliance and greater stringency
3. **Abatement costs are low**
    - Variable abatement costs are approximately 12% higher in the command-and-control regime, than under the emissions market. This results comes from plants' bidding data and the assumption that bids reflect their expectation of marginal abatement costs.
    - Treatment plants did not increase expenditures on air pollution abatement capital equipment, which is not surprising given the form of regulation in India.

→ Markets offer a way to reduce emissions in India at relatively low cost.

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Literature: Development economics

Contribution $\Rightarrow$ Testing a market-based regulatory instrument in a setting with weak institutions.

Development economics of environmental regulation.

- Enforcement of environmental regulations
  (Greenstone and Hanna, 2014; Blackman, Li and Liu, 2018)
- Poor or corrupted monitoring
  (Duflo et al., 2013; Oliva, 2015; Duflo et al., 2018; Zou, 2021)
- Behavioral responses to coarse regulation
  (Montero, Sanchez and Katz, 2002; Davis, 2008; He, Wang and Zhang, 2020)

Literature: Environmental economics

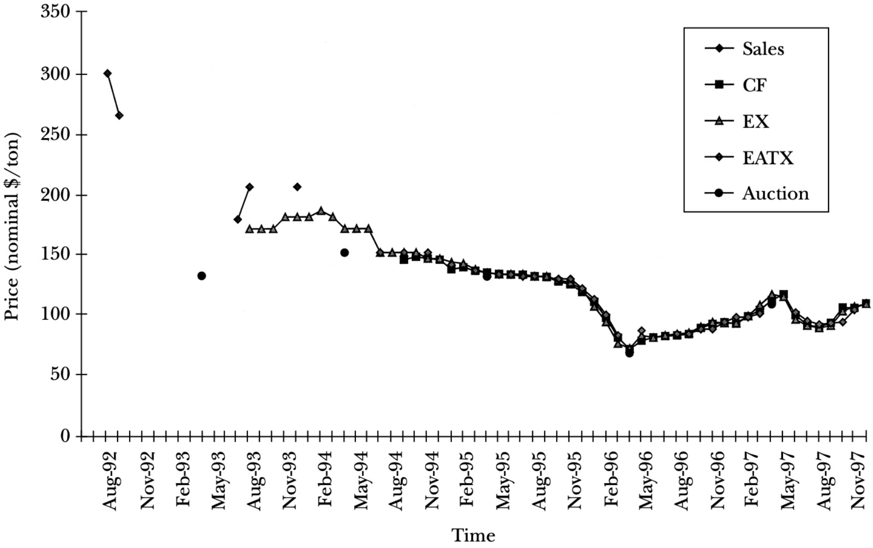
Contribution $\Rightarrow$ Estimates of the effects of emissions trading against a sharply defined experimental counterfactual.

Environmental economics.

- Landmark US environmental markets
  (Ellerman et al., 2000; Burtraw et al., 2005; Fowlie, Holland and Mansur, 2012)
- Used engineering estimates of costs
  (Burtraw et al., 2005)
- Developed econometric counterfactuals for emissions
  (Fowlie, Holland and Mansur, 2012; Martin, De Preux and Wagner, 2014; Borenstein et al., 2019; Martin, Mulls and Wagner, 2020)

Literature: Acid Rain program

Figure: Acid Rain Program (Schmalensee et al.)



Outline

Continuous Emissions Monitoring Systems

- Regulation and monitoring are an integrated system
  - Standards depend on what is measured
  - In the status quo: spot-checks of SPM concentration measured via manual samples taken with EPA reference method
- The Central Pollution Control Board (CPCB) led an effort to set PM CEMS standards
  - PIs participated in this effort
  - CPCB adopted national standards for PM CEMS in 2013
- CEMS enable changes in regulation
  - Can be based on load (kg) rather than concentration (mg/Nm^3)
  - Load = pollution emissions!

Manual sampling

- Climb the stack

- Install CEMS probe

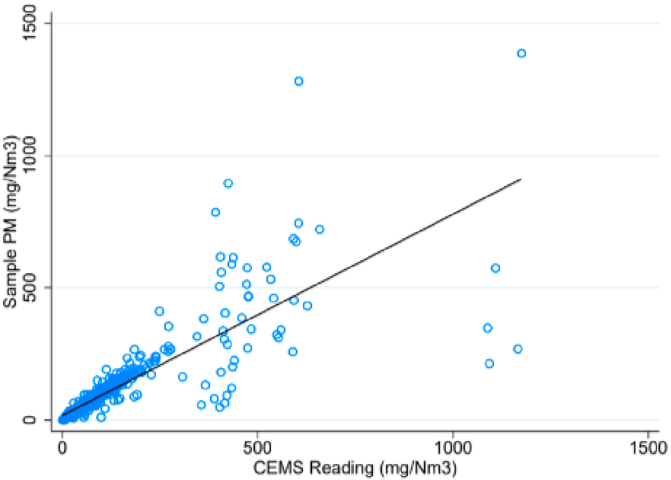
Manual sampling

- Sample for 30 minutes

- Return to lab
- Weigh emissions collected in thimble

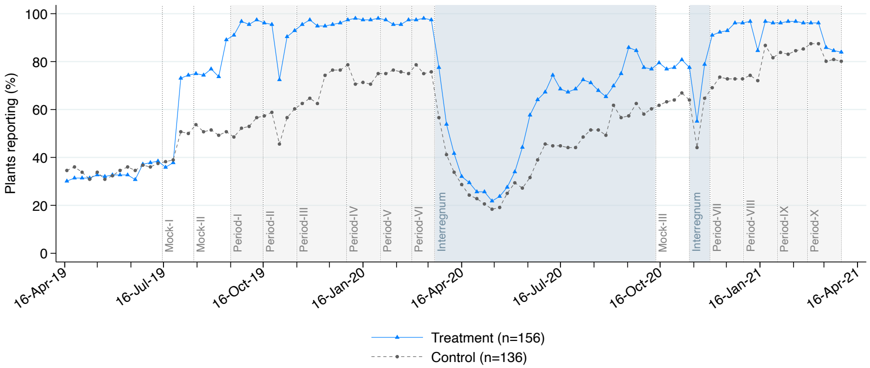
CEMS data calibrated to match manual samples

Figure: CEMS fit, initial calibration round



CEMS data reporting rate varied over the experiment and across treatment arms

Figure: Data availability from CEMS by treatment status



- Treatment firms incentivized to report more by imputation rules
- Control reporting converges slowly over time

Outline

Experimental design

- Sample of 342 plants in Surat, Gujarat region
  - Burning solid fuel (coal, lignite)
  - Stack diameter at least 25 cm
  - Boiler-equivalent thermal capacity ($\approx$ emissions potential) at least 0.8 tons per hour

- Two treatment arms
  1. **Control**: Command and control.
  2. **Treatment**: Emissions trading system.

- Plants assigned to treatment with $p = 0.5$, closures cause attrition.

	Treatment	Control	Total
Sample	168	174	342
Closed	11	10	21
Final	157	164	321

Experimental design

Status quo regulation

- **Command:** install air pollution control devices (APCD)
- **Control:** Sanctions if emissions exceed concentration standard
    - Infrequent samples and inaccurate information on emissions (Duflo et al., 2013; 2018)
    - Sanctions in practice only applied for high concentration levels beyond *de jure* standard

Theoretical ideal to measure cost differences:

- Set **load** standards for all plants
- Allow trade only in one treatment arm

Treatment regulation departs from control in at least **three** ways

1. Control standards not tradeable [theoretical ideal]
2. Control regulation based on concentration readings
3. Stringency of regulation in treatment may differ

Market design

- **Cap** set at 280 tons of SPM per month based on incomplete initial data, later revised downwards to 170 tons
- **Allocation** 80% of permits given to plants *pro rata* with respect to boiler capacity. 20% auctioned by GPCB each compliance period.
- **Trade** Double-sided multi-unit auctions with uniform clearing price held weekly. OTC trade permitted but only at auction clearing price from the prior week.
- **Price collar** Minimum (Rs 5/kg) and maximum (Rs 100/kg) prices
  → Floor price set to make it worthwhile to run most APCDs
- **Compliance**
  - All plants had to post a bond (Environmental Damage Compensation Deposit) at the start of the market
  - Plants subject to a fine at 2× ceiling price for emissions in excess at permit holdings at the end of the period

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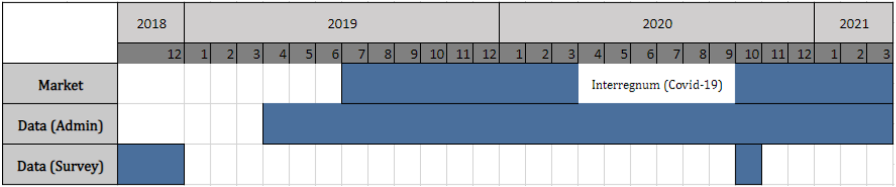
Timeline: Report on ten compliance periods over about one and a half years

Figure: Intervention timeline

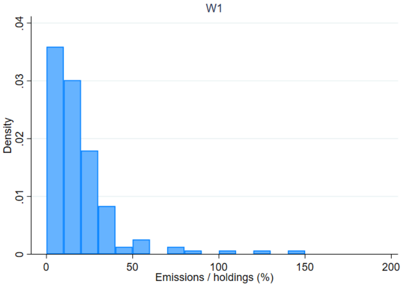


- Market started in July, 2019
- Each compliance period from 4-6 weeks
- Interruption for first Covid-19 wave (lockdown)
- End sample period at second Covid-19 wave (delta)

Would plants comply?

Figure: Emissions/permit holdings

A. Period 1, week 1

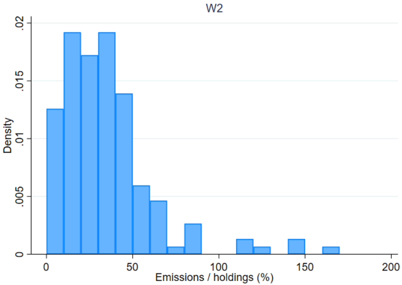


B. Period 10

Would plants comply?

Figure: Emissions/permit holdings

A. Period 1, week 2

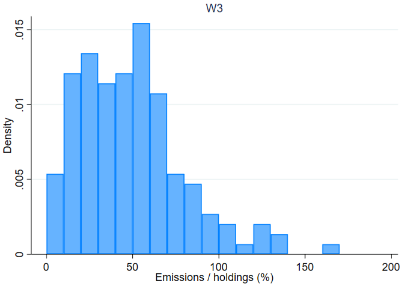


B. Period 10

Would plants comply?

Figure: Emissions/permit holdings

A. Period 1, week 3

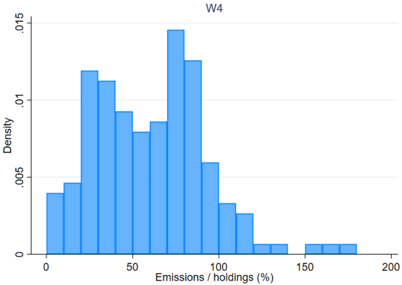


B. Period 10

Would plants comply?

Figure: Emissions/permit holdings

A. Period 1, week 4

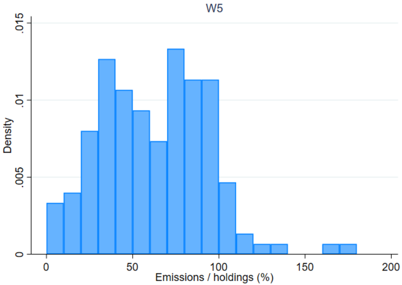


B. Period 10

Would plants comply?

Figure: Emissions/permit holdings

A. Period 1, week 5

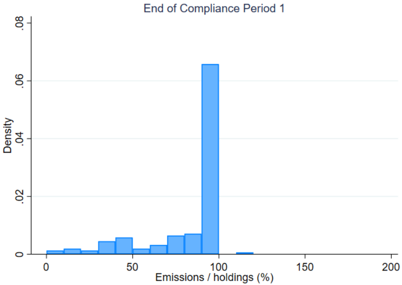


B. Period 10

Would plants comply?

Figure: Emissions/permit holdings

A. Period 1, End



B. Period 10

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Figure: Emissions/permit holdings

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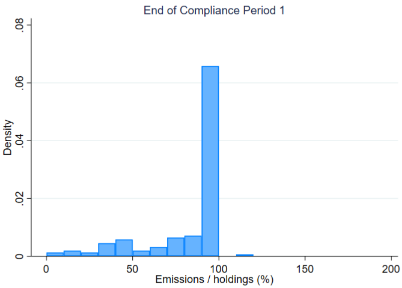
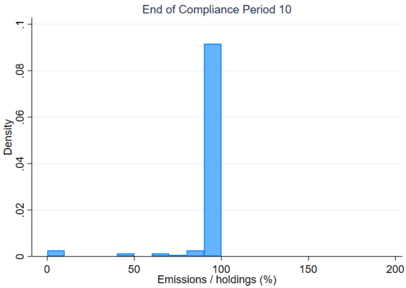


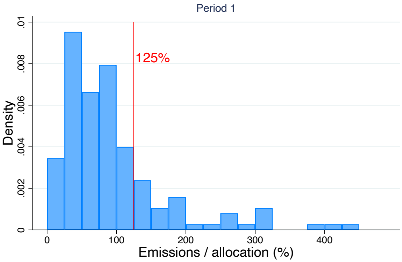
B. Period 10, End



Did allocations determine emissions?

Figure: Emissions/permit allocations

A. Period 1, End



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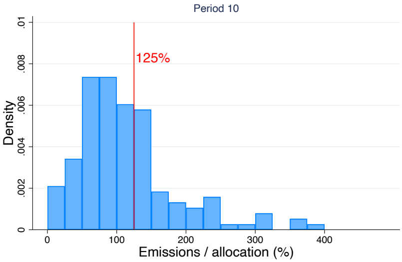
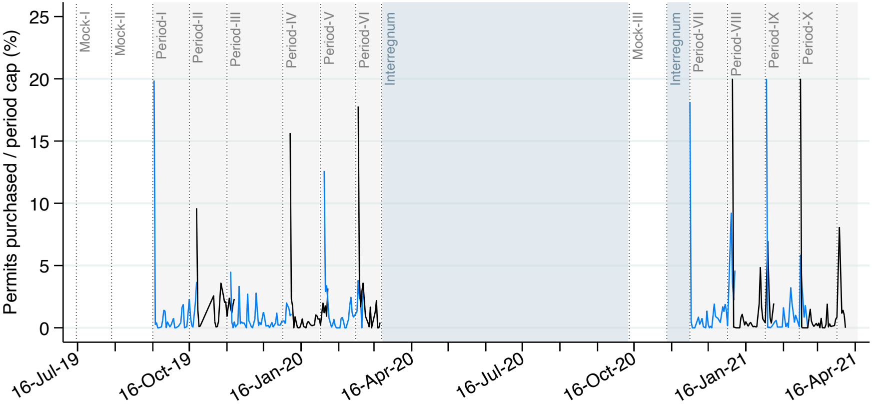


Market design emphasized early liquidity

Figure: Permit quantities purchased



- Regulator sold off 20% of the cap in permits at floor price (INR 5 per kg) in the first auction of each period
- This gives firms an incentive to anticipate emissions and purchase early. Later auctions can incorporate new information.

Outline

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1. **Monitoring**
2. **Experimental design and market functioning**
3. **Treatment effects analysis**
   - Plants have abatement capital
   - Non-compliance common
   - Treatment reduces pollution
   - No increase in abatement capital
4. **Model of abatement costs**
   - Abatement Cost Function Estimation
   - Pollution Market Cost Curve
   - Counterfactual Command and Control Price Curve
5. **Conclusion**

Balance of baseline plant characteristics

Table: Balance of plant abatement and investment cost by treatment status

	Treatment	Control	Difference
Boiler house employment	36.8	31.7	5.13
	[32.5]	[30.0]	(3.59)
Boiler house capital expenditure (1,000 USD)	198.3	164.2	34.0
	[398.6]	[190.9]	(36.7)
Boiler house operating cost (1,000 USD)	138.1	111.0	27.1
	[202.6]	[84.9]	(17.6)
APCD: Cyclone present	0.98	0.97	0.0081
	[0.14]	[0.16]	(0.017)
APCD: Bag filter present	0.80	0.86	-0.055
	[0.40]	[0.35]	(0.043)
APCD: Scrubber present	0.64	0.61	0.032
	[0.48]	[0.49]	(0.056)
APCD: ESP present	0.11	0.082	0.033
	[0.32]	[0.27]	(0.034)
Number of plants	162	156	

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Balance of plant characteristics

Table: Balance of plant pollution measures by treatment status

	Treatment	Control	Difference
Plant total PM mass rate (kg/hr)	3.62	3.51	0.11
	[4.86]	[3.76]	(0.50)
Plant mean PM concentration (mg/Nm^3)	177.9	168.5	9.37
	[153.6]	[151.5]	(17.5)
Plant mean Ringelmann score (1 to 5)	1.36	1.35	0.0090
	[0.42]	[0.37]	(0.045)
Above regulatory standard at ETS baseline (=1)	0.33	0.28	0.052
	[0.47]	[0.45]	(0.053)
Number of plants	162	156	

Balance of plant characteristics

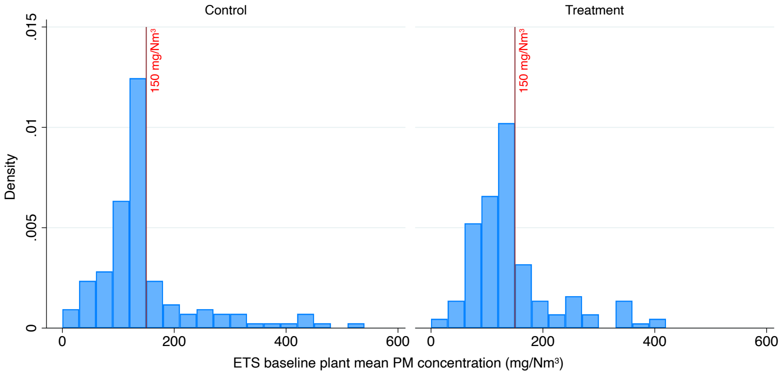

Figure: Distribution of PM concentration before the experiment

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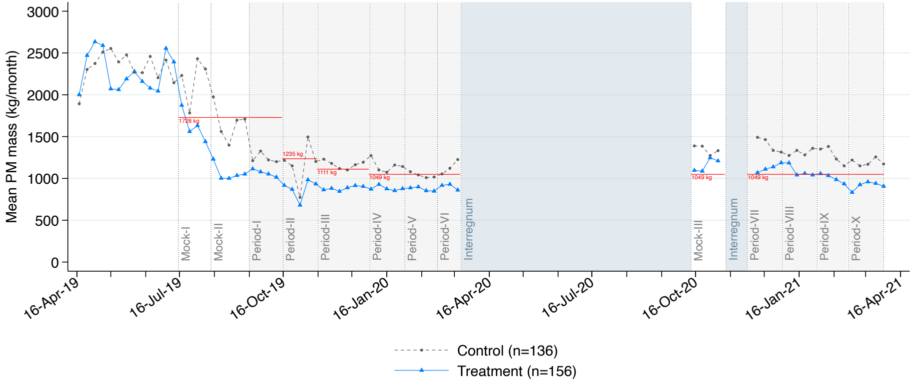
Treatment reduces pollution

Figure: PM emissions by treatment status



- Treatment emissions below cap (at cap, with imputed emissions)
- Gap between treatment and control emissions opens during first mock trading period and stays open

Regression specification

$$log(PM_{it}) = \beta_1 Treatment_i + \alpha_t + \epsilon_{it}$$

PM_{it}	SPM emissions in kg per month
$Treatment_i$	dummy for plant being assigned to treatment
α_t	Year-month fixed effects.

- Standard errors clustered at the plant level.

Treatment reduces pollution

Table: Treatment effects on PM emissions (log(PM mass/month))

	No Imputation		With Imputation	
	(1)	(2)	(3)	(4)
ETS Treatment=1	-0.193**	-0.194**	-0.282***	-0.316***
	(0.0763)	(0.0751)	(0.0745)	(0.0568)
Month FE	Yes	Yes	Yes	Yes
Imputation rule			Rule A	Rule B
Reweighted		Yes		
Mean dep. var (control)	6.67	6.66	6.80	6.88
R^2	0.17	0.17	0.22	0.25
Plants	292	292	292	292
Observations	3235	3235	3796	3796

Stack-Experiment Treatment-Month

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No increase in abatement capital

Table: Treatment effects on abatement capital using survey data (1000's of USD)

	Total Costs	All APCDs	Components			
			Cyclone	Bag	Scrubber	ESP
	(1)	(2)	(3)	(4)	(5)	(6)
ETS Treatment=1	11.26	-3.467	0.602**	0.530*	-0.222	-4.281
	(26.31)	(3.089)	(0.266)	(0.318)	(0.407)	(3.344)
R^2	0.93	0.90	0.85	0.83	0.84	0.89
Control mean	578.8	44.04	7.80	9.85	9.69	16.70
Plants	185	276	276	276	276	276

Outline

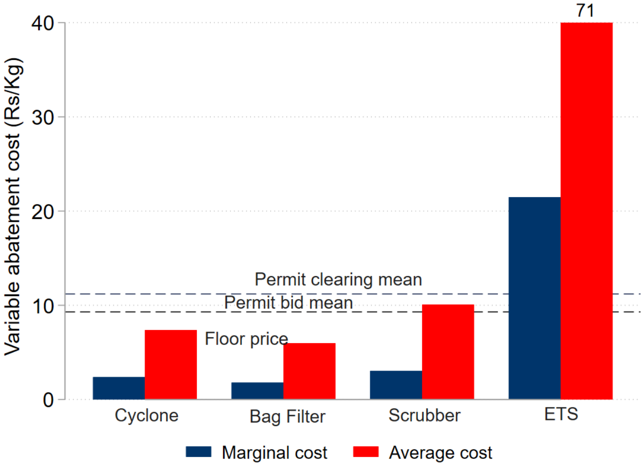
Model of abatement costs: Motivation

Why use a model?

1. **Counterfactual questions**.
   - Treatment was a bundle of {trade,load,level}
   - What is the effect on variable costs, holding pollution load constant? How does this vary with regulatory stringency?
2. **Measurement**.
   - Permit bids are informative about marginal abatement costs
   - Use permit bids in treatment to characterize abatement cost function and variable costs in both regimes

Engineering estimates of MAC are similar to Bids

Figure: Engineering estimates of abatement costs (INR/kg)



Outline

Abatement Cost Function and FOCs

- Firm's FOC is that at the chosen level of emissions, marginal abatement costs equal the permit price.
- Assume abatement cost function:

$$Z_{it}(E_{it}) = e^{\xi_{it}} \left(\frac{1}{\beta_1 + 1} \right) \left(\overline{E}_i^{\beta_1+1} - E_{it}^{\beta_1+1} \right), \quad \beta_1 \in (-1, 0)$$

  - E_{it} is emissions of plant i in period t
  - $\overline{E}_i$ is emissions of plant i with no abatement investment (calculated from measured flowrates and assumed concentrations)
  - ξ_{it} consists of a full set of plant-period fixed-effects
- This yields marginal abatement cost:

$$MAC(E_{it}) = -\frac{\partial Z_{it}(E_{it})}{\partial E_{it}} \implies \log MAC(E_{it}) = \beta_1 \log E_{it} + \xi_{it}$$

Estimating Abatement Cost Parameters

- Estimate abatement cost function by assuming plants bid their MAC plus an additively separable in logs error term (forecast error)

$$\log MAC(E_{it}) = \beta_1 \log E_{it} + \xi_{it}$$

$$\downarrow \quad \text{(estimated by)}$$

$$\log b_{itk} = \beta_1 \log E_{itk} + \xi_{it} + \epsilon_{itk}, \quad \mathbb{E}[\epsilon_{itk} | E_{itk}, \xi_{it}] = 0,$$

  where b_{itk} is the price of the bid k by plant i at period t, and E_{itk} are emissions (permit holdings) if this bid were executed.

- Typical problem is endogeneity of emissions to shocks:
  - Allow plant $\times$ period heterogeneity in abatement cost shocks (ξ_{it})
  - Unbiased if firms do not anticipate emissions shocks at high frequency within a period

▸ Model Details

Estimating Abatement Cost Parameters

Table: Elasticity of marginal cost with respect to emissions

	log(Bid price)	
	(1)	(2)
log(Emissions as bid)	-0.269***	-0.609***
	(0.0836)	(0.0872)
Period FE	Yes	
Plant FE	Yes	
Plant × Period FE		Yes
R^2	0.26	0.46
Plants	138	127
Observations	3112	2775

Outline

Pollution Market Equilibrium Prices

- Main result is the familiar one that in pollution markets, firms choose emissions to set expected MAC equal to permit price (P_t)

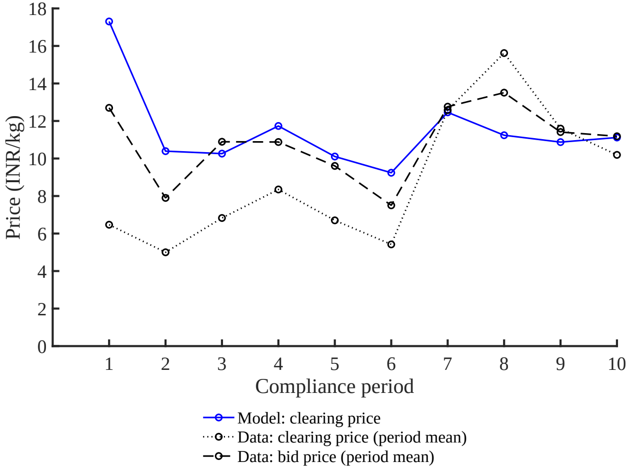
$$P_t = \mathbb{E}[MAC(E_{it})] = e^{\hat{\xi}_{it}} E_{it}^{\hat{\beta}_1} \implies E_{it}(P_t) = P_t^{1/\hat{\beta}_1} e^{-\hat{\xi}_{it}/\hat{\beta}_1}.$$

- Summing emissions over industries gives total emissions $\bar{Q}_t$. Equilibrium price (P_t^*) can thus be derived from total emissions:

$$E_t(P_t^*) = \sum_i E_{it}(P_t^*) = \bar{Q}_t \implies P_t^*(\bar{Q}_t) = E_t^{-1}(\bar{Q}_t).$$

  - $\hat{\beta}_1 < 0$, thus $E_t(P_t)$ is monotonically decreasing and thus invertible
- Thus, we can determine the equilibrium market price for each potential cap.

Model Fits Market Prices Reasonably Well

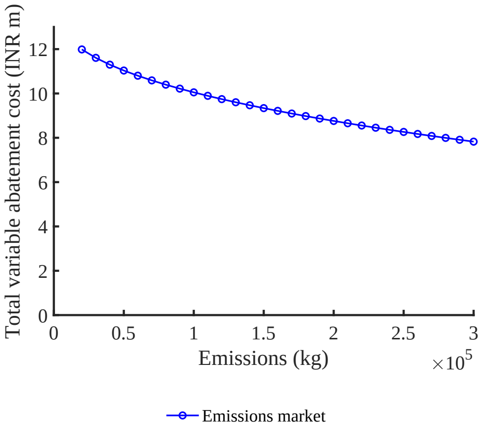


- Predicted prices too high in early periods, because early firm bids were also higher than clearing prices

Cost Curve in Pollution Market

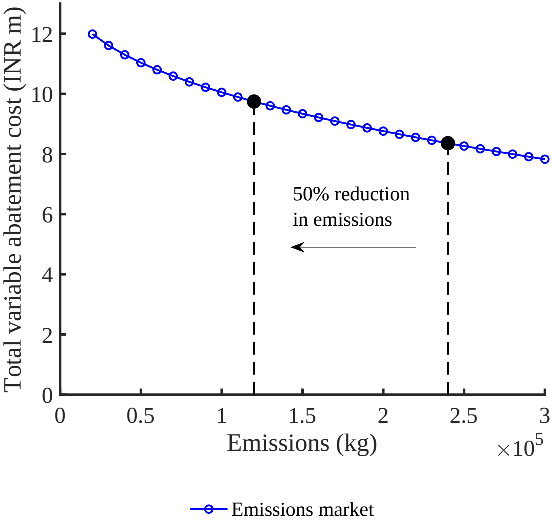
Using market cap to pin down permit price, can also estimate total abatement costs as function of market cap (total emissions):

$$\sum_i Z_{it}(E_{it}) = \sum_i e^{\hat{\xi}_{it}} \left(\frac{1}{\hat{\beta}_1 + 1} \right) \left(\overline{E}_i^{\hat{\beta}_1 + 1} - E_{it}(P_t^*(\bar{Q}_t))^{\hat{\beta}_1 + 1} \right)$$



Cost Curve in Pollution Market

Figure: Total variable abatement costs under ETS



Cost Curve in Pollution Market

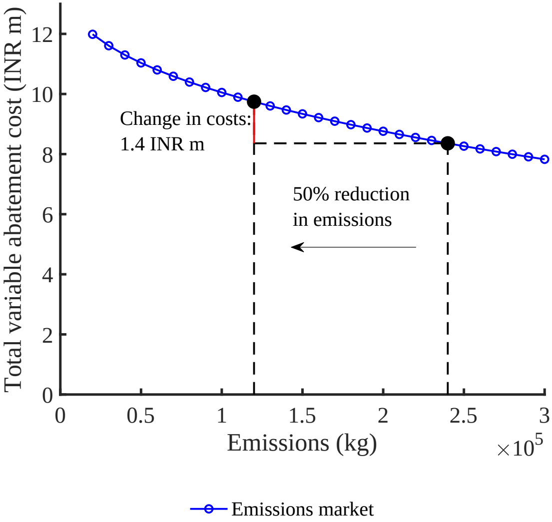


Figure: Total variable abatement costs under ETS

Outline

1. **Monitoring**
2. **Experimental design and market functioning**
3. **Treatment effects analysis**
   - Plants have abatement capital
   - Non-compliance common
   - Treatment reduces pollution
   - No increase in abatement capital
4. **Model of abatement costs**
   - Abatement Cost Function Estimation
   - Pollution Market Cost Curve
   - Counterfactual Command and Control Price Curve
5. **Conclusion**

Command & Control Counterfactual

- Let $R_{it} = E_{it}/H_i$. We fit the following model for the control group in each period to estimate command/control emissions decisions:

$$\log R_{it} = \gamma_{0t} + \gamma_{1t} \log H_i + \epsilon_{it}.$$

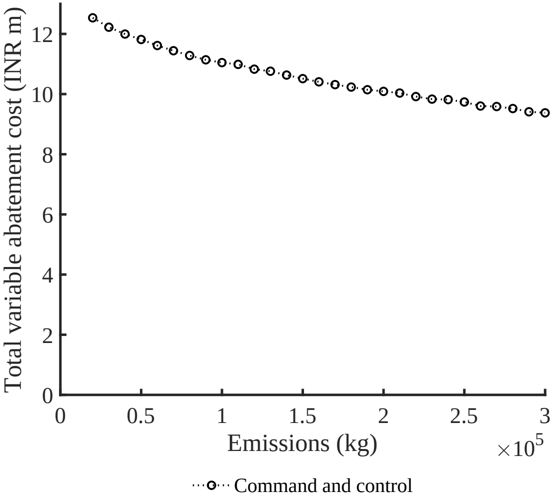
- Using fitted model, obtain counterfactual (command/control) emissions for each treatment plant and period: $\hat{E}_{it} = \exp(\widehat{\log R}_{it}) H_i$
- To obtain counterfactual abatement costs for total emissions $\overline{Q}_t$
  1. Scale plants' counterfactual emissions so they sum to $\overline{Q}_t$: $\tilde{E}_{it}(\bar{Q}_t) = \frac{\bar{Q}_t}{\sum_i \hat{E}_{its}} \cdot \hat{E}_{it}$
  2. Sum abatement costs corresponding to these scaled emissions:

$$\sum_i Z_{it}(\tilde{E}_{it}) = \sum_i e^{\hat{\xi}_{it}} \left(\frac{1}{\hat{\beta}_1 + 1} \right) \left(\overline{E}_i^{\hat{\beta}_1 + 1} - \tilde{E}_{it}(\bar{Q}_t)^{\hat{\beta}_1 + 1} \right)$$

Further Details

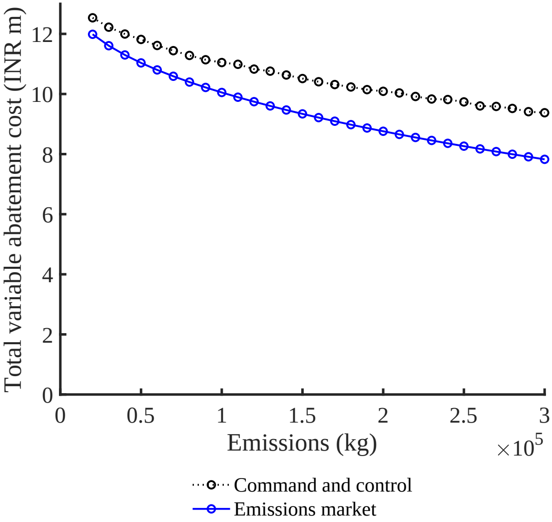
Cost Curve in Command & Control

Figure: Total variable abatement costs under command & control



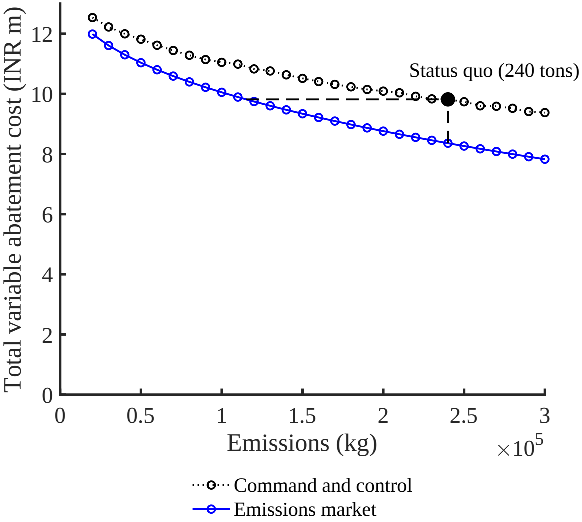
Cost Curves in Both Regimes

Figure: Total variable abatement costs by regime



Cost Curves in Both Regimes

Figure: Total variable abatement costs by regime



Emissions market cuts costs 8-13% at emissions of 170 tons per month

Table: Variable abatement costs under alternative regulatory regimes

	Emissions = 170 tons			Emissions = 240 tons		
	Price (INR/kg) (1)	Cost (INR m) (2)	ΔCost (%) (3)	Price (INR/kg) (4)	Cost (INR m) (5)	ΔCost (%) (6)
ETS	12.23	10.08	0			
CER		10.89	8.04			
CER, with error		11.19	11.01			
CBR		11.01	9.23			
CBR, with error		11.31	12.2			
CBR, corr. error		11.39	13			

CER = Constant Emissions Rate. CBR = Capacity-Based Rate

Emissions market cuts costs 10-16% at status quo emissions of 240 tons per month

Table: Variable abatement costs under alternative regulatory regimes

	Emissions = 170 tons			Emissions = 240 tons		
	Price (INR/kg) (1)	Cost (INR m) (2)	ΔCost (%) (3)	Price (INR/kg) (4)	Cost (INR m) (5)	ΔCost (%) (6)
ETS	12.23	10.08	0	9.91	9.31	0
CER		10.89	8.04		10.24	9.99
CER, with error		11.19	11.01		10.58	13.64
CBR		11.01	9.23		10.37	11.39
CBR, with error		11.31	12.2		10.7	14.93
CBR, corr. error		11.39	13		10.82	16.22

CER = Constant Emissions Rate. CBR = Capacity-Based Rate

Outline

Conclusion

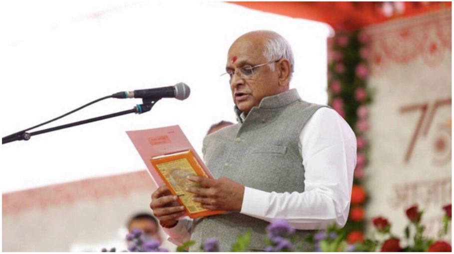
- This paper gives the results of a decade-long effort to start a market to regulate particulate matter air pollution in India
- The main takeaway from the results is that most of the costs of pollution abatement appear to be social: in making firms abate pollution, rather than in the physical abatement itself
  - Echoes finding of Shapiro and Walker (2018) that transformative reductions in US industrial pollution were achieved through changes in "technique"
  - Not possible for all pollutants (CO_2), but could make progress on particulates
- The process is as important as the results
  - Proof-of-concept for environmental markets
  - New monitoring framework and standards via CEMS
  - New regulatory framework and portable market rules

Conclusion: Research into policy

Gujarat inks MoU to develop India's first carbon market

The MoU was signed in the presence of Chief Minister Bhupendra Patel and officials from climate change and mines and industries department.

By: Express News Service | Ahmedabad |
May 24, 2022 5:42:04 am

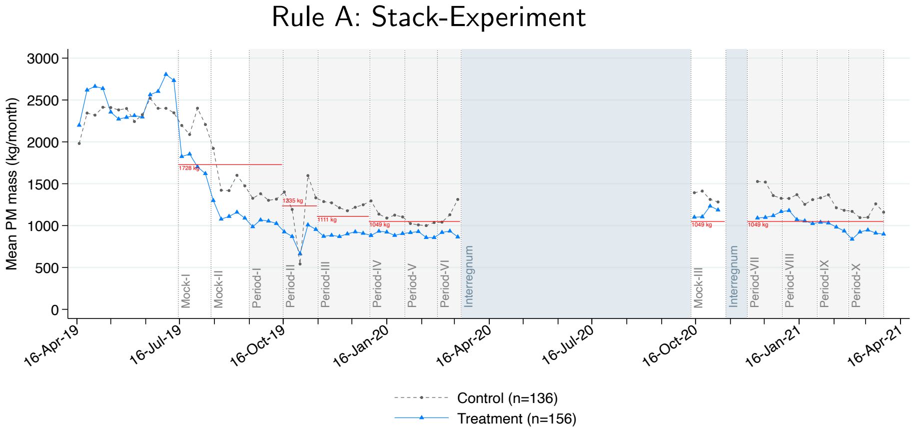


Source: Indian Express

1. **Control group**. Being moved into emissions market in Surat.
2. **Other cities**. Ahmedabad plants and surrounding industrial estates installing CEMS to join a separate PM market.
3. **Other pollutants**. Government of Gujarat has announced their intention to start a market for carbon dioxide emissions.

Annex

Pollution with stack-level imputation



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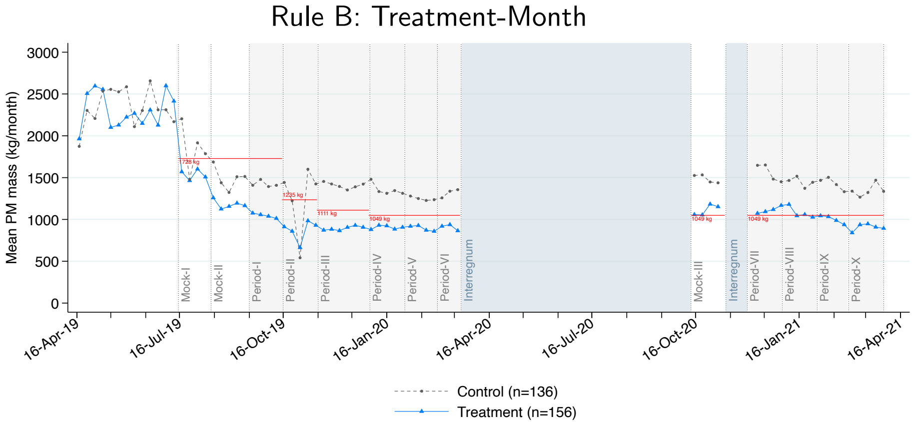
Pollution with arm-month imputation



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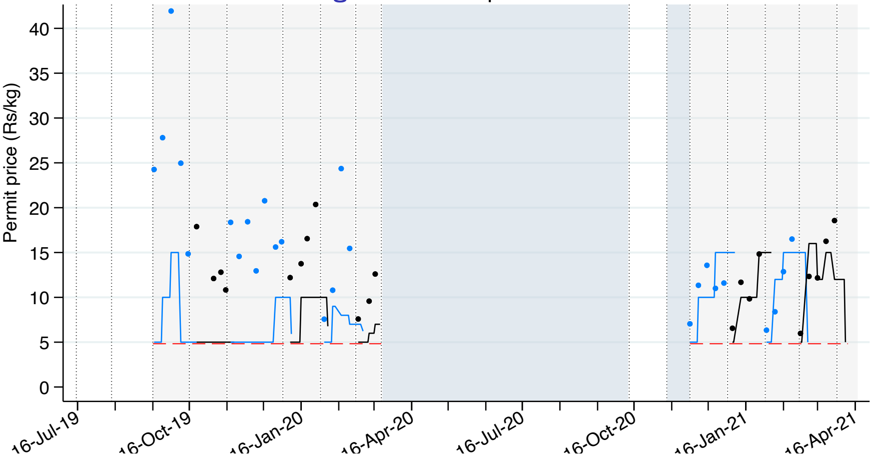
Clearing mechanism dampens price volatility

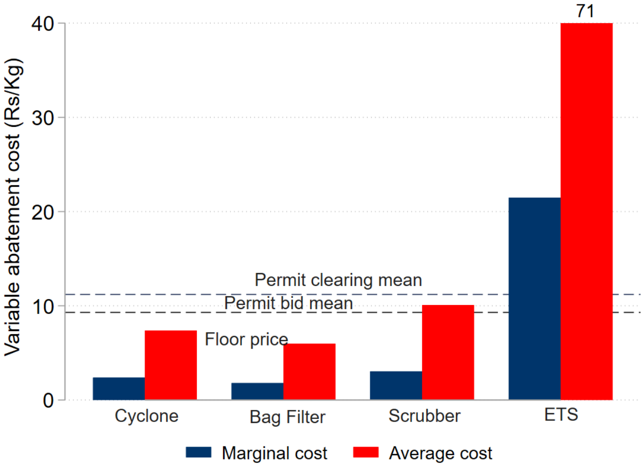
Figure: Permit prices



- Weekly auctions set over-the-counter price for next week
- Cap tightened after initial low clearing prices
- Early bids suggest high abatement cost expectations

Engineering estimates of abatement costs

Figure: Engineering estimates of abatement costs (INR/kg)



Model: Specification in detail

- Plants i chooses the level of variable abatement expenditures Z_{it} in compliance period $t = 1, 2, ...10$.
  - Plants differ in total heat output H_i and in other characteristics such as their abatement capital stock.
  - The plant spends a fixed cost Z_{i0} to maintain its abatement capital
- Abatement cost function
  - Let $E_{it}(Z_{it}), E' < 0, E'' > 0$ be the level of emissions as a function of expenditures.
  - Let $Z_{it}(E_{it})$ be the inverse, total abatement costs as a function of emissions

Model: Specification in detail

- The plant seeks to minimize the total cost of compliance:

$$\min_{Z_{it}} Z_{i0} + Z_{it} + P_t(E_{it}(Z_{it}) - A_{it}). \quad (1)$$

  - A_{it} permit allocation
  - P_t clearing price

First-order condition

$$-\frac{\partial Z_{it}(E_{it})}{\partial E_{it}} \equiv MAC(E_{it}) = P_t.$$

The marginal cost of abatement is equal to the permit price

Model: Specification in detail

- We assume the abatement cost function:

$$Z_{it}(E_{it}) = e^{\beta_0 + \tilde{\xi}_{it}} H^{\beta_2} \left(\frac{1}{\beta_1 + 1} \right) \left(\overline{E}_i^{\beta_1+1} - E_{it}^{\beta_1+1} \right), \qquad \beta_1 \in (-1, 0).$$

  - $\tilde{\xi}_{it}$ plant-period specific marginal cost shock
  - $\overline{E}_i$ uncontrolled emissions

- Implied log of marginal abatement cost:

$$\log MAC(E_{it}) = \beta_0 + \beta_1 \log E_{it} + \beta_2 \log H_i + \tilde{\xi}_{it}.$$

- Emissions endogenous: $\mathbb{E}[\tilde{\xi}_{it} | E_{it}, H_i] \neq 0$.
  - Expect upward bias: $\beta_1 < 0$, $\hat{\beta}_1 > \beta_1$.

Model: Specification in detail

- Our approach to estimation is to use within plant-period variation in plant bids to estimate the marginal abatement cost function

- Assume firms **expect** emissions of $\widetilde{E}_{itk} = E_{it}\nu_{itk}$ with $\nu_{itk} \perp E_{itk}, \xi_{it}$ and $\mathbb{E}[\log \nu_{itk}] = 0$.

- This expectation yields an estimating equation

$$\log b_{itk} \quad = \quad \beta_0 + \beta_1 \log E_{itk} + \xi_{it} + \epsilon_{itk}, \qquad \mathbb{E}[\epsilon_{itk}|E_{itk}, \xi_{it}] = 0.$$

  - Cost shifter $\xi_{it} = \beta_2 \log H_i + \tilde{\xi}_{it}$
  - Residual $\epsilon_{itk} = \beta_1 \log \nu_{itk}$. Exogenous because it is based on the forecast error.

- Firms know their own abatement costs, in general, but do not know if they will get a big order in 3 weeks Back

Command & Control Counterfactual Details

- As above we fit $\log R_{it} = \gamma_{0t} + \gamma_{1t} \log H_i + \epsilon_{it}$ for control plants in each period.
- We draw 20 error terms $(\epsilon_{its}, s = 1, ..., 20)$ with distribution $\mathcal{N}(0, \text{Var}[log(R_{i \in \text{control}, t})])$
- Using fitted model above, for each period and plant in the treatment group we obtain

$$\hat{E}_{its} = R_{its} H_i = \exp(\widehat{\log R_{it}} + \epsilon_{its}) H_i, \quad s = 1, ..., 20$$

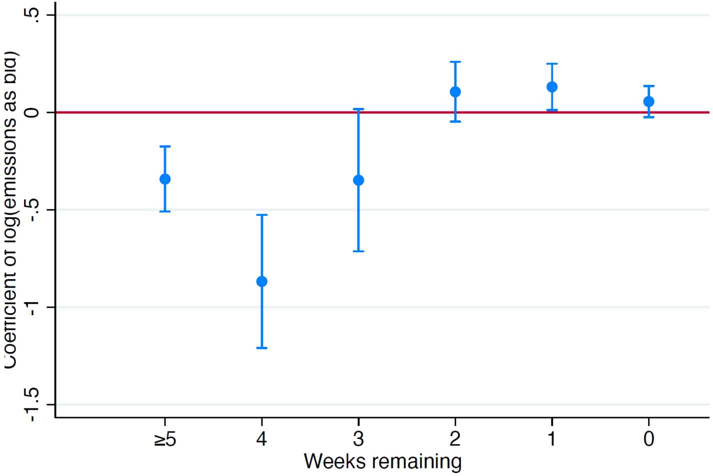
- To obtain counterfactual abatement costs at total emissions $\overline{Q}_t$:
  1. Scale $\hat{E}_{its}$ values so they sum to $\overline{Q}_t$: $\tilde{E}_{its}(\bar{Q}_t) = \frac{\bar{Q}_t}{\sum_i \hat{E}_{its}} \cdot \hat{E}_{its}$
  2. Take average across error term draws for each plant: $\tilde{E}_{it} = \frac{1}{20} \sum_s \tilde{E}_{its}$
  3. Sum abatement costs corresponding to these scaled plant emissions:

$$\sum_i Z_{it}(\tilde{E}_{it}) = \sum_i e^{\hat{\xi}_{it}} \left(\frac{1}{\hat{\beta}_1 + 1} \right) \left(\overline{E}_i^{\hat{\beta}_1 + 1} - \tilde{E}_{it}(\bar{Q}_t)^{\hat{\beta}_1 + 1} \right)$$

Back

Plants cannot make trade-offs when emissions sunk

Figure: Elasticity estimate by weeks remaining in the order period



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