Michael Greenstone
Rohini Pande
Nicholas Ryan
Anant Sudarshan

# Continuous Emissions Monitoring Systems (CEMS) in India

March 2020

Impact Evaluation Report 111

Environment

International Initiative for Impact Evaluation

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## About this report

3ie accepted the final version of the report, *Continuous Emissions Monitoring Systems (CEMS) in India*, as partial fulfilment of requirements under grant DPW1.1067 awarded through Development Priorities Window 1. The report is technically sound and 3ie is making it available to the public in this final report version as it was received. No further work has been done.

The 3ie technical quality assurance team for this report comprises Rosaine Yegbemey, Kanika Jha Kingra, Deeksha Ahuja, Sayak Khatua, Marie Gaarder, an anonymous external impact evaluation design expert reviewer and an anonymous external sector expert reviewer, with overall technical supervision by Marie Gaarder. The 3ie editorial production team for this report comprises Anushruti Ganguly and Akarsh Gupta.

 Please direct any comments or queries to the corresponding author, Michael Greenstone, at: mgreenst@uchicago.edu.

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Michael Greenstone
University of Chicago

Rohini Pande
Yale University

Nicholas Ryan
Yale University

Anant Sudarshan
University of Chicago

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## Summary

The Emissions Trading Scheme pilot project for particulate matter is designing, implementing, and evaluating an innovative approach to pollution in India. As a regulatory instrument, emissions trading has the potential to eliminate the trade-off between environmental quality and growth by improving air quality through a mechanism that is transparent, predictable, and costs firms less to comply. A critical intermediate stage of this project involves the rollout of Continuous Emissions Monitoring Systems to monitor particulate matter emissions at the stack, which greatly improves the information and ability of regulators to monitor firms, allowing regulatory standards to be better targeted and enforced.

This article reports on the effect of implementing Continuous Emissions Monitoring Systems (CEMS) and reporting the data to the regulator in Surat, India. The goal was to help to reduce reliance on frequent manual monitoring, providing significant long-term cost and time savings, as well as increasing the reliability of readings.

Overall, it is unclear if the use of CEMS as an informative tool has had an impact on firms' emissions. This may be attributed to multiple factors, especially the absence of a structured methodology for regulators to use and act upon CEMS data.

We do not find any difference between treatment and control after the intervention was in place, which could be explained by different reasons. In the first place, treatment and control are installing CEMS devices, the main difference between treatment and control is that the treated group is reporting their data to the regulator. So even though the control group is not reporting data to the regulator, the fact that they have the device could be changing their behavior, attenuating our results. The second possibility is that as there is no change in the regulation yet, treated firms are not changing their behavior in answer to our treatment, as the regulator cannot enforce any punishment based on CEMS data.

We believe that the installation and connection of CEMS is a first step to changes in regulation as now the Gujarat Pollution Control Board has high frequency data that they could also use for future regulation. Market-based regulations would allow regulators to address many city and regional problems with water and air pollution at a lower cost than is possible today, and the installation of this devices is a necessary step to do this.

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# 1. Introduction

India today has the highest levels of air pollution in the world. Of the 20 cities in the world with the worst fine particulate air pollution, 13 are in India, including Delhi, the worst-ranked city (World Health Organization, 2013). Studies find that the average Indian loses about three years of his or her life due to the harm of this pollution (Greenstone et al., 2015). There is also growing evidence that high levels of pollution lower labor productivity and, therefore, potentially economic growth (Zivin and Neidell, 2013; Hanna and Oliva, 2015).

As the world identifies policies to address climate change, it is critical that the domestic concerns of emerging economies like India are addressed and potentially leveraged so as to reduce stark trade-offs between reducing emissions and lowering growth. While India's growth poses challenges, it also presents an opportunity to exemplify strategies that can be adopted elsewhere.

The way people of means cope with air pollution is to avoid it; to commute by car with the windows closed or sit in an air-conditioned office. These options are not available to the poor, who must often work outside, and so are differentially exposed to air pollution (Saksena et al., 2003). Thus while air pollution is a public harm, benefits from reducing air pollution may accrue more to poorer people due to their greater exposure. The pilots we propose may have immediate impacts on the local population of Surat in Gujarat (a city of over 4 million inhabitants).

If good information on who pollutes is available, then traditional environmental regulation can bring down emissions somewhat (Duflo et al., 2013), but regulators may lack the will or resources to penalize every polluter. What more can government due to contain such widespread damages?

In his canonical essay on "The Problem of Social Cost", Ronald Coase argued it should perhaps do nothing. His very first example "is that of a factory the smoke from which has harmful effects on those occupying neighbouring properties" (Coase, 1960). Coase argues that taxing the factory's emissions or holding the owner liable is not desirable or necessary, since if property rights are well-defined, and parties are well-informed, then the owner and other parties can work out the right level of pollution and compensation for the harm suffered. The United States and other countries have put this notion to work in "third wave" environmental regulations that require information disclosure, but have no formal enforcement provisions.

The current system of command-and-control approach to regulation is widely perceived as ineffective and imposing large burdens on polluting industries. Market-based instruments for environmental regulation have a successful track record (Stavins, 1998), but are seldom used in developing countries.

Present environmental regulations are seen as costly and unreliable. India is only likely to adopt more stringent regulations if they do not compromise economic growth. Policy-makers are keenly interested in innovative ways to reduce air pollution, as evidenced by the recent adoption of driving restrictions in New Delhi (the "odd-even" scheme). However, such short-term fixes can be costly for citizens, which may undermine support for regulation in the long-term. A proof-of-concept for market-based regulations would allow regulators to address many city and regional problems with water and air pollution at a lower cost than is possible today.

The Emissions Trading Scheme (ETS) pilot project for particulate matter (PM) is designing, implementing, and evaluating an innovative approach to pollution in India. As a regulatory instrument, emissions trading has the potential to eliminate the trade-off between environmental quality and growth by improving air quality through a mechanism that is transparent, predictable, and costs firms less to comply.

With a city population of 5 million and metropolitan population of 6.5 million, Surat is the second largest city in Gujarat and home to 15% of the state's small-scale industrial units, most of which are in the textile sector. All firms are located approximately 20 km from the city center, and thus their emissions were expected to affect ambient pollutant concentrations for a large sub-population. With a population density in the Surat Metropolitan Area (which encompasses the industrial clusters in the sample) of 4,065 persons/km$^2$, a crude estimate of the number of people in a 20 km radius affected by industrial emissions is 5.1 million. This rough calculation heightens the case for improved emissions monitoring and regulation by showing the substantial number of lives exposed to poor air quality and who would benefit from improved environmental regulation.

## 2. Intervention

### 2.1 Description

We are working with the Ministry of Environment, Forests and Climate Change, the Central Pollution Control Board (CPCB) and State Pollution Control Boards of Gujarat (GPCB), in setting up an ambitious pilot ETS for PM from industrial sources. A critical intermediate stage from implementing this project involves the rollout of Continuous Emissions Monitoring Systems (CEMS) to monitor PM emissions at the stack, which greatly improves the information and ability of regulators to monitor firms, allowing regulatory standards to be better targeted and enforced.

A regulatory action framework for treatment firms was designed which included CEMS installation and a list of criteria to characterize non-compliant behavior, along with the corresponding regulatory actions taken by GPCB.

For adopting CEMS, one of the first steps is to select a device (or combination of devices if flow meter is required) optimally suitable for the stack characteristics at the firm. Important considerations include stack diameter, flue gas temperature, and Air Pollution Control Devices (APCDs) installed, among others. In parallel, firms also need to select a CEMS vendor from which to purchase the equipment. The equipment has to be paid by the firm, and GPCB should check that each firm has installed CEMS according to their phase. Then, after installing the equipment, the Gujarat Pollution Control Board (GPCB) indicate whether the firm can proceed to calibration of the device and the test each CEMS device must pass to be in compliance with the ETS performance standards. Calibrating CEMS devices allowed the detection of device malfunctions and resolution of misreporting, thereby improving data accuracy. The steps for setting up the CEMS devices are described in table 1.

**Table 1: Steps in setting up the CEMS devices**

| Step | Responsibility of |
|---|---|
| Submission of the User-ID form | Firm |
| Creating firm user-ID | GPCB |
| Firm placing the Purchase Order (PO) for procuring the CEMS device | Firm |
| Delivery of the CEMS device | Vendor |
| Installation of the CEMS device | Vendor, firm |
| Connection of the CEMS device (un-calibrated raw readings from device to the server) | Vendor, firm |
| Conducting iso-kinetic sampling (standard reference method) for calibration of the PM CEMS device | Environment lab, vendor, firm |
| Calculation of calibration factors and accuracy of the device by the software | GPCB |
| Calibrated PM emissions readings sent from device to the server | Firm, vendor |

The action framework is designed to target worst-performing firms on two criteria, PM performance and data performance, with the aim of eventually fine-tuning performance criteria as variance across the sample reduces over time. A key feature of the framework is that it actively works against the natural tendency of command-and-control regulation, where severe punishment is meted out at any instance of non-compliance. Instead, the framework offers a graded set of actions, which escalate in severity with the level of non-compliance. Further, a graded set of actions targeted at a specific section of plants enables efficient use of the regulator's limited capacity, allowing for this system to be absorbed into the status quo. Tables 2 and 3 describe the specifics of GPCB regulatory actions for non-compliance as per the Action Framework.

**Table 2: Regulatory Action Framework for PM performance non-compliance**

| Action | List of Firms | Detailed Criteria |
|---|---|---|
| Regional office sends an autogenerated SMS and email to the firm | As per weekly report | Firm is one of five with worst PM performance in the past week and exceedance was reported |
| Regional office sends an autogenerated email and letter to the firm | As per weekly report | Firm is one of five with worst PM performance in each of the past 2 weeks and exceedance was reported |
| Regional office meets with the firm | As per weekly report | Firm is one of five with worst PM performance in each of the past 3 weeks and exceedance was reported |
| Regional office conducts site visit and collects stack sample | As per weekly report | Firm is one of five with worst PM performance in each of the past 4 weeks and exceedance was reported |
| Regional office issues show case notice | As per weekly report | Sample results indicate that firm's emissions are higher than the legal standard |

**Table 3: Regulatory Action Framework for data availability non-compliance**

| Action | List of Firms | Detailed Criteria |
|---|---|---|
| Regional office sends an autogenerated SMS and email to the firm | As per weekly report | Firm is one of five with lowest positive data availability and mean data availability is <85% in the past week or the firm has zero data availability in last week |
| Regional office sends an autogenerated email and letter to the firm | As per weekly report | Firm is one of five with lowest positive data availability and mean data availability is <85% in each of the past 2 weeks or the firm has zero data availability in each of the last 2 weeks |
| Regional office meets with the firm | As per weekly report | Firm is one of five with lowest positive data availability and mean data availability is <85% in each of the past 3 weeks or the firm has zero data availability in each of the last 3 weeks |
| Regional office conducts site visit and collects stack sample | As per weekly report | Firm is one of five with lowest positive data availability and mean data availability is <85% in each of the past 4 weeks or the firm has zero data availability in each of the last 4 weeks |
| Regional office issues show case notice | As per weekly report | Sample results indicate that firm's emissions are higher than the legal standard |

In April 2018, GPCB formalized rules for using CEMS data to regulate firm PM emissions. Two workshops were held in Surat, where regulators and firms were trained on the use of CEMS weekly reports and its grading across the Framework's set of actions. At the workshop, firms were trained on the web portal through which they could monitor their Data Availability and Emissions to avoid featuring under weekly worse performers in the GPCB generated performance reports.

Implemented in a staggered manner, GPCB initially started in March 2018 by sending auto-generated SMS/emails to firms that did not achieve the PM requirements or the data availability requirements shown in table 2 and 3. The exceedance is calculated as a moving average within a 15 minutes period. The letters were sent since May 2018. The meetings started in July 2018 and the site-visits and sample collection started in September 2018.

Even though GPCB cannot enforce any punishment based on CEMS data, the structure of the treatment allows GPCB to inspect a firm if they do not comply with the treatment for 4 weeks in a row, as is shown in table 2 and 3. During the inspection GPCB collects a PM sample, if the sample indicate that the firm is violating the industrial emissions, the regulator must take actions that could lead to the closure of the firm.

## 2.2 Theory of Change

A critical challenge in reducing PM emissions is ineffective monitoring and regulation of industrial emissions. Previous work by Duflo et al. (2013) shows a high non-compliance rate that was compounded by poor monitoring by third party auditors. The ETS program is a pilot emissions trading scheme for particulate matter air pollution in 350 highly-polluting industries in Surat, Gujarat. In this program, treatment industries will receive particulate matter load permits that they can choose to trade over the course of a regulatory compliance period. Our theory of change is that a cap-and-trade market will be more effective at reducing emissions than a command-and-control system because a cap-and-trade has reliable monitoring, the requirement to hold permits is transparent and market-based systems have lower costs of compliance, making it easier to reduce emissions. Actual emissions will be monitored through CEMS installed in all industry smokestacks. If industries have emitted in exceedance of the permits they hold at the end of any particular compliance period, they will be penalized by the environmental regulator, the Gujarat Pollution Control Board. A prerequisite for setting up the trading regime is improved monitoring of emissions among the participant firms, through CEMS.

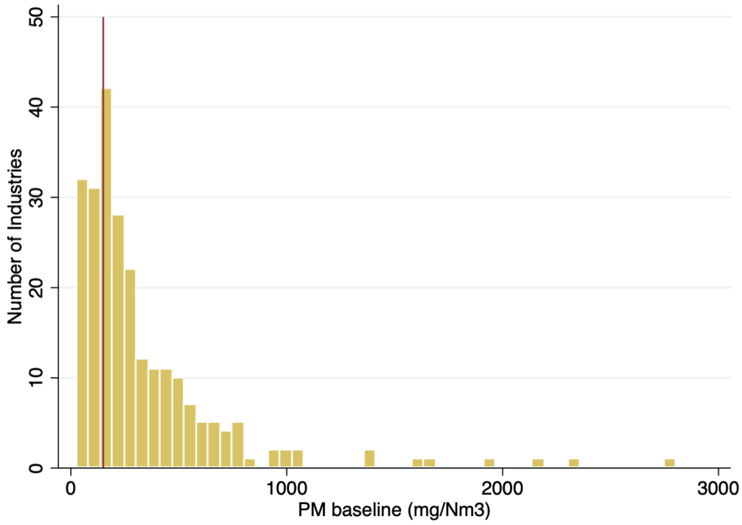
Using CEMS, it is possible to estimate the total mass of pollutants released into the atmosphere over any time period, a quantity that is more directly relevant to pollution health impacts than the instantaneous concentration. Because CEMS devices supply real-time data on emissions from the industrial stack, they dramatically improve the frequency and quantity of particulate emissions data available to regulators and the firms themselves. Currently, plant emissions are measured in terms of concentration of pollutants over a short period of time. Thus, plants reporting under CEMS are expected to display greater incentive to conserve kilograms of fuel burned relative to the status quo. Hence, we expect to see lower overall PM emissions for industries in the treatment group (with PM CEMS devices) than those in the control group (without PM CEMS devices).

A CEMS regime helps reduce reliance on frequent manual monitoring, providing significant long-term cost and time savings, as well as great potential for increasing the reliability of readings. It also enables policy partners to generate a rigorous and comprehensive database of pollution data from the major pollutants across any given region. Real time emissions data would enable better-informed decisions and policymaking related to air pollution. In addition, continuous monitoring enables a highly transparent regulatory system and opens up options such as public release of emissions information in real time.

The primary outcomes of interest for this evaluation are the level and variance of pollution emissions in the treatment group, as well as level of pollution and compliance costs of treatment relative to control plants. The former will be measured through real-time CEMS data over the course of the evaluation, and the latter will be measured through detailed firm surveys.

Baseline data for sample plants has been collected through a detailed technical survey that collected information on plant configurations and conducted PM stack sampling. The survey shows that more than 70 percent of the firms are not complying with the regulatory standard of 150 mg/Nm$^3$ for particulates. Figure 1 shows the distribution of PM samples collected, with the red line representing the regulatory standard of 150 mg/$Nm^3$ for particulates.

**Figure 1: Distribution of PM Sample Baseline**




## 2.3 Monitoring plan

The outcomes we are interested to evaluate with this project are the level and variance of pollution emissions in the treatment relative to control plants, as well as the compliance costs of treatment plants relative to control plants. Actual emissions will be monitored through Continuous Emissions Monitoring Systems (CEMS) installed in all treated firms' smokestacks.

Over the course of the CEMS installation, we collected records on when firms have completed all of the intermediate steps of installation, from placing a purchase order, to passing a postcalibration test. This data helps us to identify bottlenecks and make recommendations for further process improvements.

In 2017 the GPCB undertook a careful auditing exercise of plants installing CEMS devices following a regulatory mandate. Typically these monitors are installed by technology vendors and calibrated on site, with payments made by firms. The accuracy of this calibration underlies the accuracy of the CEMS architecture—if the calibration coefficients are falsified, CEMS reported readings will also be under-estimates. Thanks to a careful data collection regime, the GPCB was able to document that when calibration was carried out by plants, CEMS measurements were consistently lower than prior manual inspections had suggested they should be. The devices were therefore audited and independent calibrations were carried out. The true calibration factors were found to be very different from those initially reported, and consequently true emissions much higher.

Once firms have established connectivity, we also maintain records on why the devices go offline, categorize any hardware and software problems, and track firm grievances and vendor responses. Data Acquisition and Handling Center coordinators additionally make intermittent site visits to troubleshoot and resolve firm's issues.

The CEMS data availability provides an account of minute-wise emissions data generated by CEMS devices throughout an entire day. Through daily interactions with firms and follow-ups with hardware and vendors, we have been able to synthesize proactive and sustainable solutions to ensure high and accurate data availability from CEMS.

# 3. Evaluation

## 3.1 Primary and secondary questions

The primary question is, does CEMS intervention affect the level and variance of the plant's pollution emissions? For measuring this we will evaluate how the emissions measured by CEMS in the treatment group vary after the implementation. Also we will compare the level and variance of pollution in the treatment relative to control plants, given by the PM samples taken in the baseline and endline. The secondary question is, does CEMS intervention affect the abatement costs of treatment plants relative to control plants? We will measure the abatement cost through detailed firm surveys.

## 3.2 Design and methods

The evaluation design is a randomized-control trial at the level of the industrial plant, where the main outcomes are plant pollution and abatement costs. The main problem with past studies of the effects of emissions markets on pollution and abatement costs is the absence of a clear counter-factual for what plants would have emitted under another regulatory regime, such as command-and-control regulation. Our design solves this problem by having a control group that remains subject to status quo, command-and-control regulation as the treatment group is brought under an emissions market.

CEMS rollout is divided into 4 phases for logistic reasons. As CEMS calibration and connection involves heavy coordination with the firms, CEMS vendors and environmental laboratories, CEMS rollout is divided into various phases to smoothly run the operations. Although all firms in the CEMS sample will eventually install continuous monitoring devices as part of the ETS evaluation, the design has randomly assigned approximately half of these firms (called Phase-II firms) to install their devices prior to the rest (called Phase-IV). Hence during the period between the completion of Phase-II installations and beginning of Phase IV installations, Phase II firms will have been treated with CEMS, while Phase IV firms will continue to face status quo manual sample monitoring by GPCB.

The main outcomes of interest are plant pollution and abatement costs. Pollution will be measured using CEMS devices that record, at very high frequency, the mass of pollution being emitted from each stack. Even though some control firms will have installed CEMS devices, the data connectivity for them is very low, so we would just have CEMS data for the treatment group. Pollution levels could be compared between the treatment and control group through samples taken during the baseline and endline. Costs will be measured using detailed plant-level surveys on capital, maintenance and operating expenditures for abatement equipment.

### 3.3 Ethics

This study does not involve human subjects, and we do not anticipate any risks to respondents in this evaluation. Participating firms are required by environmental regulators to install additional equipment.

### 3.4 Sampling and data collection

The sample of industrial plants was drawn to comprise all the largest point sources of emissions in the Surat metropolitan area. This industrial cluster was selected due to having a large number of heavily polluting plants in close proximity to an urban center.

The sample was drawn using administrative data from GPCB on fuel type and stack diameter, cross-checked against field visits. To be eligible, a source had to use solid or liquid fossil fuels and to have a stack (chimney) suitable for the installation of CEMS devices. Amongst the list of eligible sources, the GPCB, with the advice of our team, selected the largest 350, in terms of fuel consumption, in order to include the major sources of particulate emissions.

We use data from the endline survey of Duflo et al. (2013) on pollution levels and abatement costs as inputs. We restrict the sample to industrial plants in Surat with PM emissions and a stack diameter of 0.25 meters, which are the rough sample selection criteria for the evaluation. The below table presents the calculation inputs. The mean level of PM is 194 mg/Nm3, above the regulatory standard of 150 mg/Nm3. Assuming the correlation between baseline and endline concentration readings is 0.60, achieving a power of about 80% against the null of no chance in emissions concentration yields an effect size of 19.5% reduction in PM emissions concentration.

**Table 4: Assumptions for Power Calculation**

| | (1) |
|---|---|
| Outcome variable | PM concentration (mg/Nm$^3$) |
| Mean | 193.90 mg/Nm$^3$ |
| Standard deviation | 84.79 mg/Nm$^3$ |
| Correlation with baseline | 0.60 |
| Sample size | 350 |
| Power | 0.795 |
| Effect size (percent) | 19.5% |

sample of 373 industrial plants have 765 eligible stacks, because some plants have multiple stacks. Sample plants are located in highly-polluted industrial clusters and had high pollution potential. These plants are predominantly (94%) in the textile industry. They most often burn coal (37%) or lignite (27%) but a fair number also use liquid fuel such as diesel (14%).

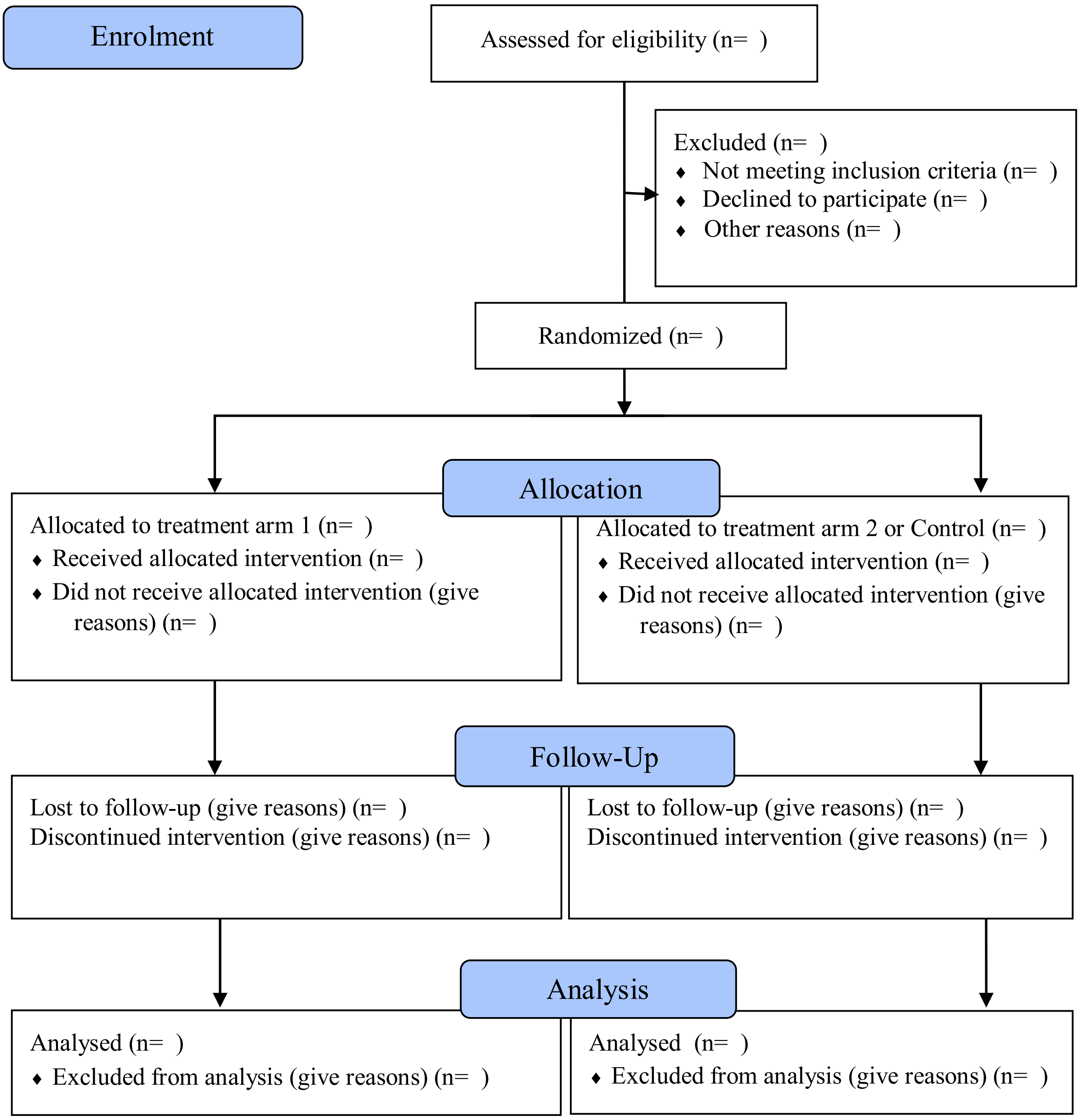
The study uses a randomised phase-in design for the evaluation of the new CEMS monitoring regime in the Surat industrial cluster in Gujarat. The evaluation initially began with a small group of pilot installations (Phase I roll-out) which are firms that are representative of the sample and are non-random. This phase is followed by random assignment of the remaining sample of plants to one of three experimental treatment groups. The randomization was done in a stratified manner, within groups of firms on the basis of geographical area, which we call industrial-cluster from now on, and baseline PM emissions, for more statistical power. Each treatment group of firms was mandated to install PM CEMS and begin sending CEMS data to the regulator in a staggered manner across three phases, numbered II, III, and IV. In this phase-in design, plants without CEMS connections who were assigned to later phases, would serve as a control group for the plants in Phase I and II who installed CEMS first. Table 5 lists the number of firms in each treatment assignment group, and Figure 2 shows the timeline for the CEMS installation in each of the phases.

**Table 5: CEMS Phased Roll-out Treatment Assignment**

| Phase | Number of Firms | Percent | Rollout Timeline |
|---|---|---|---|
| I | 11 | 2.95 | Jan 2014 |
| II | 141 | 37.80 | July 2014 |
| III | 82 | 21.98 | Sep 2018 |
| IV | 139 | 37.27 | Feb 2019 |

The purpose of the pilot phase was to field-test the CEMS installation and calibration protocol stipulated in the Central Pollution Control Board CEMS specifications. A batch size of 11 firms from Surat cluster was selected, and 4 vendors supplied 9 DC triboelectric-based (measures PM mass flow) and 2 electrodynamic-based (measures PM mass concentration) devices. The 11 firms were chosen based on the representativeness of the sample in terms of the size of the firms and the air pollution control devices installed, and the willingness of the firms to participate in the pilot.

## Appendix B: Example of evaluation design




Source:

### *3.4.1 Plant survey*

We have developed a detailed firm quantitative survey to measure key outcomes of interest, which will be administered at baseline and endline. The survey instrument has a general section to collect data regarding the firms' fuel consumption, production and revenues to understand the scale of operations within the firm, and a technical section to collect information on all emission sources and installed abatement measures installed. The technical section can be customized based on the number of stacks within a firm, the number of parallel chains within each stack, and the number and type of installed equipment in each parallel chain. It captures detailed information about each piece of equipment, including the year of installation, the technical design, and the operations and maintenance costs

The first round of firm surveys was conducted in late 2014. The second round was conducted in 2016, previous to the treatment implementation, and the endline survey was conducted between December 2018 and March 2019.

### *3.4.2 CEMS*

Pollution is measured using Continuous Emissions Monitoring Systems (CEMS) that record, at very high frequency, the mass of pollution being emitted from each stack. Also, over the course of the CEMS installation, we have collected records on when firms have completed all of the intermediate steps of installation, from placing a purchase order, to passing a post calibration test.

Calibration process of CEMS devices involve comparing CEMS readings against manual sample measurements. In figure 3 we plot the correlation between CEMS readings and the manual samples in standard deviations. There is a high correlation among CEMS reading and PM samples. Table 6 measures the correlation between manual samples and CEMS readings in standard deviations, with firm fixed effects. The correlation is as expected, positive and significant, which validates CEMS reading as a way to measure pollution.

**Figure 2: Correlation between CEMS reading and PM sample**

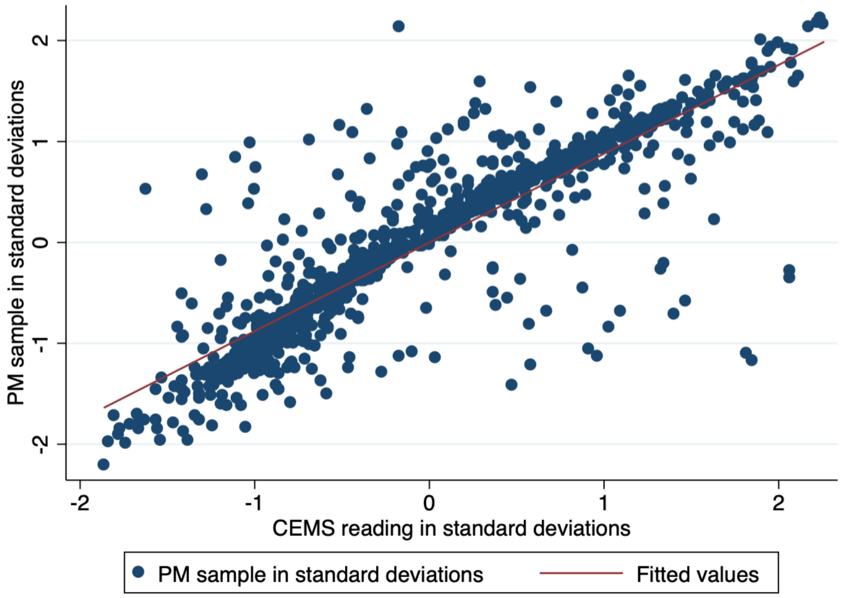



**Table 6: Correlation between CEMS reading and PM sample**

| | (1) |
|---|---|
| | PM sample |
| CEMS reading | 0.88*** |
| | (0.03) |
| Firm FE | Yes |
| No. of Obs. | 967 |
| R-Squared | 0.77 |

Notes: Regressions include firm FE. * p<.10, **p<.05, ***p<.01

#### *3.4.3 Ringelmann*

The Ringelmann test consists on a measure of the apparent density or opacity of smoke, based on its color. We hired and trained a group of surveyors to observe each firm stack from the outside for intervals of half an hour. The training of all Ringelmann surveyors is standardized. Surveyors are trained for 3 days of practical field exercises before they begin surveying. The training consists of the following protocol:

1. Surveyor stands 45-100-meter distance from stack. 2
2. Mark position of surveyor, the stack, the sun, and the direction of flue gas using standardized clock notation.
3. Begin the survey; smoke ratings are assigned from 0-5 (using standard Ringelmann Chart) everyone minute, for 30 minutes. 30 observations, along with one photo each minute, comprise the completed Ringelmann Survey.

The surveyor will be given a smoke chart, which has five different shades of gray scaled from 1 to 5, and she will have to compare the color of the smoke for the 30 minutes period, reporting which number better represents the color of the firm smoke every minute. The average of these 30 observations will give us the Ringelmann score. Surveyors are required to upload pictures of the stack at start of the survey and at the end of the survey for each firm. Each stack has the firm name mentioned on it, we are able track whether the surveyors are covering respective industries or not.

The advantage of Ringelmann data is that is very easy and cheap to get, so we could have many observations for each firm over time. The problem is that it could be not as highly correlated with air pollution as PM samples or CEMS data. For that reason, we will be using PM sampling data, CEMS data and Ringelmann data for the pollution analysis.

Each Ringelmann round consists on a period of approximately two weeks where surveyors are visiting firms. Four rounds were conducted before the treatment started and nine rounds were conducted after the implementation of the treatment.

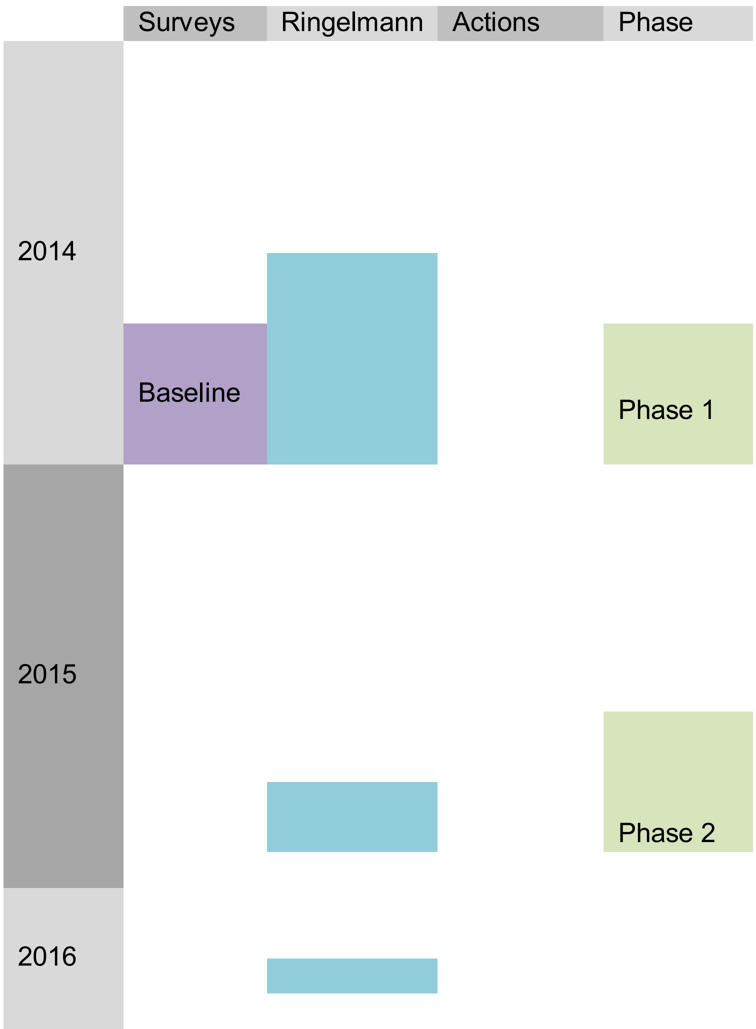
We evaluate the correlation observed between the stack sampling (in logs) in each survey and the Ringelmann values. Table 7 shows the correlation for the stack sampling and the Ringelmann values, controlling for variables that could be affecting the outcome variable. Specifically in column 1 we are controlling for sun position, plume position, Ringlemann round, approximate distance to the stack and weather. In column 2 we add lab fixed effects. All of the point estimates calculated in the tables are positive and significant, which validates Ringelmann data as a way to measure pollution.

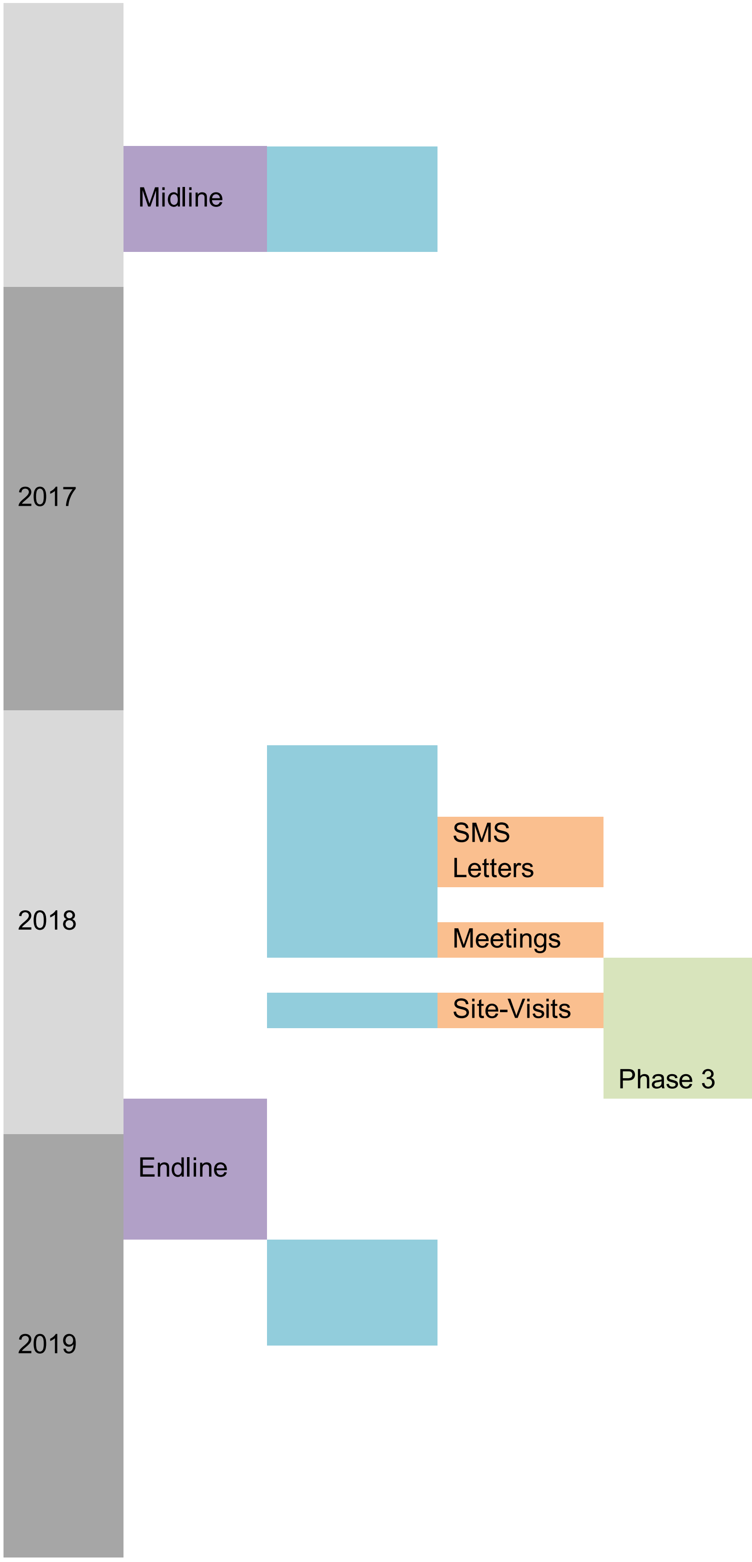
**Table 7: Correlation between PM Emissions and Ringelmann all surveys**

| | (1) | (2) |
|---|---|---|
| | Log PM | Log PM |
| Ringelmann mean | 0.17*** | 0.19*** |
| | (0.06) | (0.05) |
| Weather Controls | Yes | Yes |
| Industrial-cluster FE | Yes | Yes |
| Round FE | Yes | Yes |
| Lab FE | No | Yes |
| No. of Obs. | 586 | 586 |
| R-Squared | 0.16 | 0.19 |

Notes: Regressions include firm FE, industrial-cluster FE, sun position, plume position, Ringelmann round, approximate distance to the stack and weather controls. Column (2) adds lab FE. Each PM sample is associated with the Ringelmann Round that was more close in time to the sample collection. * p<.10, **p<.05, ***p<.01

**Figure 3: Timeline**




Midline
2017
SMS
Letters
2018
Meetings
Site-Visits
Phase 3
Endline
2019

# 4. Findings

## 4.1 Intervention implementation fidelity

Table 7 shows firm operational status, CEMS purchase orders, installation and calibration at the time of the endline, and a mean-comparison test between treatment (phase II firms) and control (phase IV firms). We have the operational status for all treatment and control firms, but the rest of the variables are only for operational firms, with some missing values. Almost all firms were still operating by the time of the endline, but there is a small and significant difference among treatment and control in the operational status, with the treatment group having more permanently closed firms. At the time of the survey, almost all treatment firms had their purchase orders and installation of CEMS devices done. At the same time, 40 percent of the firms in the control group also had installed CEMS. As CEMS is a new technology, it is expected that some of the control group firms will be willing to install the devices. We are not worried about contamination of the treatment to the control group measured by the installation, as the main outcome of interest of our treatment is observing how firms behave when they know that the regulator has access to high frequency data on their air pollution, given by CEMS. Table 8 shows that 76 percent of treatment firms had their devices calibrated, compared to only 8 percent of the control group. The most relevant outcome for the implementation fidelity is the data connectivity, as that is the way the regulator could observed the firm pollution, which was 97 percent for treatment firms and 0 for the control group.

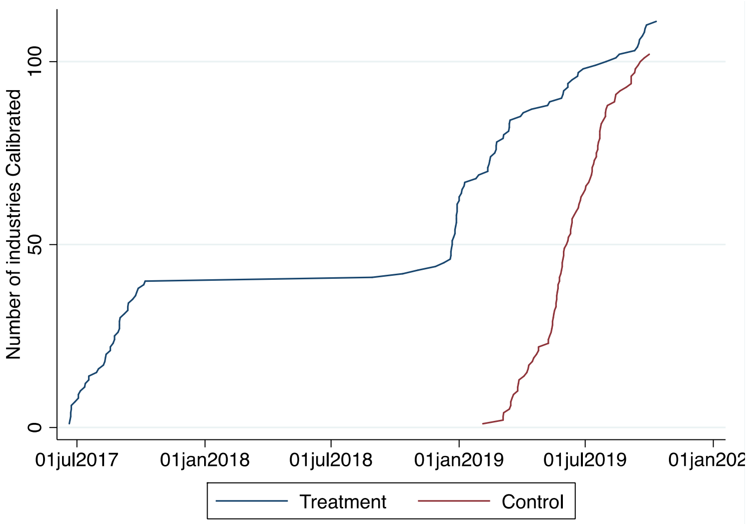
**Table 8: CEMS Intervention fidelity**

| | Treatment Mean | Control Mean | Difference | p value |
|---|---|---|---|---|
| Operational status | 0.79 | 0.88 | -0.09** | 0.04 |
| Observations | 141 | 139 | 280 | |
| Purchase Orders | 1.00 | 0.50 | 0.50*** | 0.00 |
| Observations | 109 | 88 | 197 | |
| Installation Done | 0.99 | 0.40 | 0.59*** | 0.00 |
| Observations | 111 | 95 | 206 | |
| Calibration | 0.76 | 0.08 | 0.68*** | 0.00 |
| Observations | 111 | 101 | 212 | |
| Data Connectivity | 0.97 | 0.00 | 0.97*** | 0.00 |
| Observations | 117 | 126 | 243 | |

Notes: The table reports purchase orders, installation and calibration by the time when the endline finished (March 2019), and operational status and data connectivity by June 2019. * p<.10, **p<.05, ***p<.01

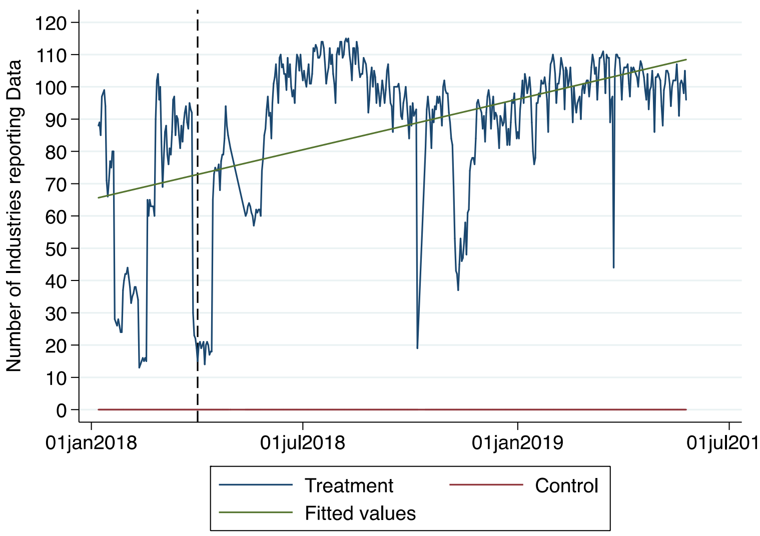
Figure 4 shows the timing and the number of firms that passed the calibration of the CEMS devices by treatment group. The blue line represents the treatment group, and as it can be seen, firms from the treatment started calibrated their devices on July 2017, opposed to control firms, represented by the red line, which began to calibrate their devices in January 2019.

**Figure 4: Calibration by Treatment**




We plot the number of firms reporting data over time in figure 5. The blue line represents the treatment group and the red line represents the control. The dashed line shows the date when the actions began to be implemented. As it can be noticed, the number of treated firms reporting data over time is increasing, while the number of control firms reporting data is zero, during the whole period analyzed.

**Figure 5: CEMS Reporting Over Time**




## 4.2 Impact analysis

### *4.2.1 Descriptive statistics and balance tables*

Table 9 presents a randomization check using baseline characteristics of plants in the study sample, showing that plant characteristics are balanced by treatment assignment. Of all of the baseline measures reported, there is just two variables that has a significant difference between the treatment and the control group at the 10% level. In Panel A we consider plant economic characteristics that could be related with pollution and their boiler and thermopack capacity. The control group has a bigger boiler capacity on average but a lower thermopack capacity, with none of these differences being significant.  In panel B we consider characteristics of the plants associated with the APCDs they have in the baseline. The most common APCD is the Cyclon, and on average control and treatment firms have around 4. Panel C shows all the plant characteristics related to pollution, measured at the baseline. It appears that on average, treatment plants have a higher concentration of PM given by the PM sample, but this difference is not significant. Table A1 presents the balance check for the firms in the baseline which were also interviewed at the endline.

**Table 9: Balance Check Baseline**

| **Panel A** | Control Mean | Treatment Mean | Difference | p-value |
|---|---|---|---|---|
| Asset Value (Excluding Land) | 802.81 | 626.69 | 176.12 | 0.40 |
| Gross Sales Revenue Annually | 4182.33 | 2933.72 | 1248.61 | 0.28 |
| Employment | 261.63 | 235.21 | 26.42 | 0.39 |
| Boiler Capacity | 11.48 | 6.17 | 5.30 | 0.26 |
| Thermopack Capacity | 17.64 | 32.81 | -15.17 | 0.60 |
| Observations | 128 | 130 | 258 | |
| **Panel B** | Control Mean | Treatment Mean | Difference | p-value |
| Operating Cost | 7.20 | 7.24 | -0.04 | 0.97 |
| Maintenance Cost | 2.25 | 2.15 | 0.09 | 0.77 |
| Capital Cost | 25.85 | 25.12 | 0.73 | 0.92 |
| Recent Modifications Cost | 0.07 | 0.40 | -0.32* | 0.06 |
| Number of Cyclon | 4.16 | 4.11 | 0.05 | 0.81 |
| Number of Bag Filter | 2.53 | 2.69 | -0.16 | 0.59 |
| Number of ESP | 0.27 | 0.16 | 0.10 | 0.55 |
| Number of Scrubber | 3.12 | 2.70 | 0.42 | 0.14 |
| Observations | 128 | 130 | 258 | |
| **Panel C** | Control Mean | Treatment Mean | Difference | p-value |
| Ringelmann Mean Score | 1.62 | 1.72 | -0.09* | 0.10 |
| PM Concentration | 335.10 | 368.10 | -33.00 | 0.50 |
| Observations | 128 | 130 | 258 | |

Notes: Columns (1) and (2) show means. Column (3) shows the difference among the means, and column (4) shows the p value. . *p<.10, **p<.05, ***p<.01.

### *4.2.2 Results*

Table 10 shows the treatment effects on PM samples and compliance at the endline. The observations are less than the initial sample because some of the firms closed during the treatment. In the first column we ran an OLS where we regress the endline PM concentration with the treatment status, controlling by the PM concentration at the baseline. In column 2 we add a fixed effects for the lab taking the sample. Column 3 and 4 have the same regressions as the previous two columns, but now regressing the log of the PM samples. Column 5 and 6 regress a dummy that takes the value of one if the firm is complying to the norm of PM of less than 150 mg/Nm$^3$. The average PM concentration at the endline is 185 mg/Nm$^3$ with a standard deviation of 211, and at the baseline the average was 338 mg/Nm$^3$ with a standard deviation of 374. Columns 7 and 8 regress a probit and a logit respectively, finding also not significant effects. The treatment effect calculated in every specification is insignificant, showing that there is no significant difference between the treatment and the pollution at the endline measured by PM samples.

**Table 10: Treatment effects on PM samples**

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|---|---|---|---|---|---|---|---|---|
| | PM Endline | PM Endline | Log PM | Log PM | Compliance | Compliance | Compliance | Compliance |
| Treatment | -19.81 | -24.23 | 0.05 | 0.03 | -0.05 | -0.05 | -0.13 | -0.22 |
| | (28.76) | (28.32) | (0.10) | (0.09) | (0.06) | (0.05) | (0.16) | (0.27) |
| PM Baseline | -0.04 | -0.01 | | | | | | |
| | (0.03) | (0.03) | | | | | | |
| Log PM Baseline | | | -0.04 | -0.03 | -0.01 | -0.00 | -0.04 | -0.07 |
| | | | (0.06) | (0.06) | (0.03) | (0.03) | (0.09) | (0.15) |
| Lab FE | No | Yes | No | Yes | No | Yes | No | No |
| Industrial-Cluster FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| No. of Obs. | 240.00 | 239.00 | 240.00 | 239.00 | 264.00 | 239.00 | 264.00 | 264.00 |
| R-Squared | 0.05 | 0.18 | 0.06 | 0.13 | 0.05 | 0.36 | | |

Notes: Regressions include industrial-cluster FE. Columns (2), (4) and (6) add lab FE. Standard errors clustered at the plant level in parenthesis. * p<.10, **p<.05, ***p<.01

Table 11 shows the effect of being treated on the Ringelmann data. The average Ringelmann score was 1.58 with a standard deviation of 0.76. In column 1 we control by sun position, plume position, Ringelmann round, approximate distance to the stack and weather. In column 2 we add pre-treatment readings as controls. The results from table 10 show that the treatment was not significant at the 10% level, measured by the Ringelmann data.

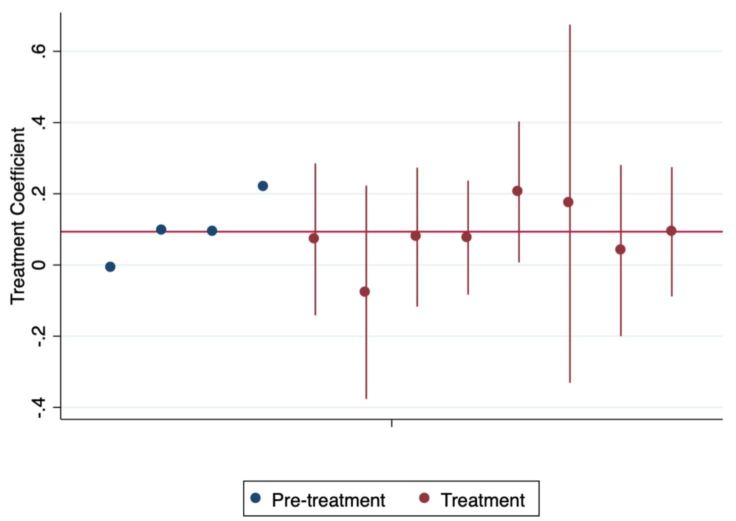
**Table 11: Treatment effects on Ringelmann data**

| | (1) | (2) |
|---|---|---|
| | Ringelmann Mean Score | Ringelmann Mean Score |
| Treatment | 0.08 | 0.03 |
| | (0.06) | (0.06) |
| Pre-treatment Ringelmann | | 0.45*** |
| | | (0.06) |
| Weather Controls | Yes | Yes |
| Industrial-Cluster FE | Yes | Yes |
| Round FE | Yes | Yes |
| No. of Readings | 1582 | 1574 |
| No. of Plants | 253 | 250 |
| R-Squared | 0.12 | 0.18 |

Notes: Regressions include industrial-cluster FE. Columns (2) includes Pre-treatment Ringelmann which is an average of the four Ringelmann Rounds conducted before the treatment began. Standard errors clustered at the plant level in parenthesis. * p<.10, **p<.05, ***p<.01

Figure 6 shows the coefficients for regressions for each Ringelmann round by treatment status. The blue dots represent treatment coefficients for the rounds applied before the treatment. The red line represents the average of the pre-treatment coefficient. The red dots represent the coefficient obtained in the regressions from the rounds surveyed after the treatment started. As it can be seen, no coefficient is statistically different from the average of the pre-treatment period.

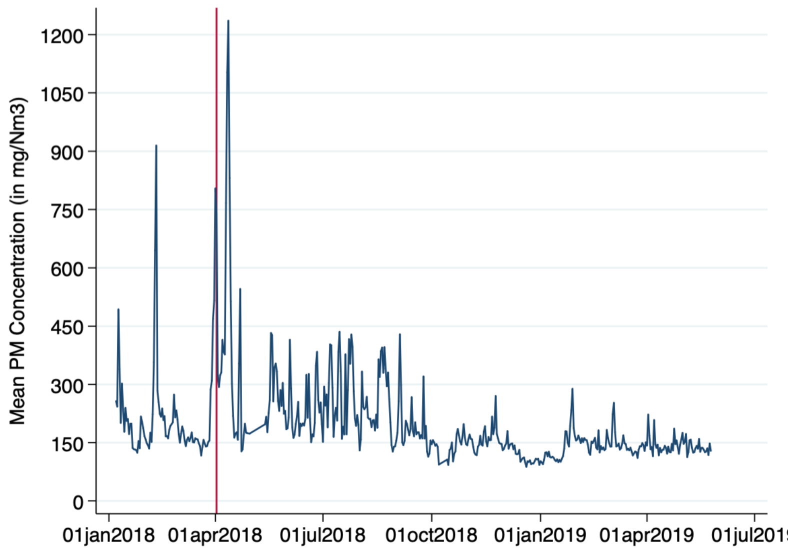
**Figure 6: Treatment coefficients by Ringelmann Round**




Note: The lines represent 95% confidence interval for the treatment coefficients applied in the Ringelmann rounds after the treatment started. All regressions include controls for sun position, plume position, distance, weather and industrial-cluster FE. Standard errors clustered at the plant level.

Using the CEMS reading from the devices that are reporting data, we could measure the mean daily PM concentration among treated firms over time. This measure is reported on figure 7. The red line shows when the actions started. The PM concentration is calculated as the mean of the daily average concentration of each firm that is reporting data for at least one minute during that day. As it can be noticed on figure 7, the PM concentration does not seem to be changing too much over time, but the variance of the concentration is clearly decreasing overtime, with a big decrease after the treatment started

**Figure 7: CEMS PM Concentration Over Time**




Note: PM concentration is calculated as the mean of the daily average concentration of each firm that is reporting data for at least one minute during that day.

Table 12 shows an OLS for the treatment effect on APCDs, the capital cost and, operation and maintenance costs of the APCDs each firm has at the endline. The first column shows an OLS regression for estimating the treatment effect on the number of APCDs a firm has at the endline, controlling by the number of APCD the firm had at the baseline. Column 2 has a similar regression, with the dependent variable being a dummy that takes the value of one if the firm increased the number of APCDs they had with respect to the baseline. The point estimates of the number and the dummy of increasing the number of APCDs is positive, as we expected, but the effect is not significant. As the number of APCDs does not exactly matches investments firms could be doing for reducing their pollution, we evaluate if the capital cost of APCDs for firms in the treatment compared to the control group have increased. The point estimate has the sign we expected, as we expected that the treatment would increase the investments firms do on APCDs, but still the effect is not significant.

The maintenance cost consists in annual testing cost, cost of repairs and small replacements, and cleaning costs per month. The operations costs consist on electricity cost, labor cost and inputs (water and chemicals). Column 4 has an OLS regression estimating the treatment effect on the operation and maintenance cost. The point estimate for the treatment effect on the sum of these costs are negative, but also not significant.

**Table 12: APCDs per firm by treatment status**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Number of APCDs | Dummy APCDs | Capital Cost | Op and Maintenance |
| Treatment | 0.24 | 0.24 | 4.59 | -2.25 |
| | (0.18) | (0.18) | (8.02) | (5.29) |
| Number APCDs Baseline | 0.85*** | | | |
| | (0.12) | | | |
| Capital Baseline | | | 0.11** | |
| | | | (0.05) | |
| Op and Maint Baseline | | | | 1.30*** |
| | | | | (0.33) |
| Industrial-Cluster FE | Yes | Yes | Yes | Yes |
| No. of Obs. | 229.00 | 229.00 | 234.00 | 234.00 |
| R-Squared | 0.52 | 0.06 | 0.04 | 0.16 |
| Mean | 4.84 | 0.4 | 35.60 | 26.05 |

Notes: Regressions include industrial-cluster FE. Standard errors clustered at the plant level in parenthesis. * p<.10, **p<.05, ***p<.01

### *4.2.3 Heterogeneity of impacts*

Finally, we explore if there is a heterogeneous response to the treatment based on the initial type of APCDs each firm had. We construct four dummies, one for each type of APCD. Each dummy takes the value of 1 if the firm had that type of APCD by the time of the baseline. We interact those dummies with the treatment and regress these variables against pollution level in the endline sample controlling for initial number of APCDs, and Table 13 shows the results. There is only one APCD, the gravity settling chamber, that is not included in the regression because only one firm has it. We find that the presence of Bag Filters and ESP is correlated with the plant having less pollution by the end line. Despite that, we do not find evidence that having those APCDs made the firm more responsive to the treatment, as we do not find evidence of any heterogeneous response.

**Table 13: Heterogeneous Treatment Effects**

| | (1) |
|---|---|
| | Number APCDs Endline |
| ESP*Treatment | 1.75 |
| | (3.17) |
| Cyclon*Treatment | -3.02 |
| | (4.32) |
| Bag Filter*Treatment | 0.50 |
| | (0.91) |
| Scrubber*Treatment | 0.61 |
| | (0.95) |
| Treatment | 2.42 |
| | (4.28) |
| ESP | -3.19** |
| | (1.46) |
| Cyclon | 0.86 |
| | (1.50) |
| Bag Filter | -3.31*** |
| | (0.65) |
| Scrubber | -0.67 |
| | (0.79) |
| Number APCDs Baseline | 0.57*** |
| | (0.18) |
| Industrial-Cluster FE | Yes |
| No. of Obs. | 234.00 |
| R-Squared | 0.25 |

Notes: Regressions include industrial-cluster FE. Standard errors clustered at the plant level in parenthesis. * p<.10, **p<.05, ***p<.01

## 5. Cost analysis

The first step for adopting CEMS is to select a device (or combination of devices if flow meter is required) optimally suitable for the stack characteristics at the firm. The two most affordable PM CEMS technologies are DC and AC Tribos and almost all the firms in Surat have installed them. The prices of CEMS Tribos ranges from 200,000 to 300,000 rupees (2798 to 4198 US dollars).

Even though the intervention does not seem to be effective as we are unable to find a difference in behavior between the treatment and the control, the installation and data connectivity is a first step to implement regulation and policies based on high frequency data.

CEMS is the total equipment necessary to determine concentration or emission rate of a gas or particulate matter. The system of CEMS was introduced with a promise of more efficient pollution regulation and lower costs of compliance. The underlying assumption is that regulators will utilize high-quality industrial pollution information to make effective decisions. However, for this to be true, the technology needs to be seamlessly integrated into the industrial pollution reporting system.

# 6. Discussion

## 6.1 Introduction

Like many industrial clusters in India, the majority of firms in Surat burn solid fuel and are noncompliant with current environmental regulation.

This project has already generated widespread interest among Indian policymakers to use CEMS for pollution monitoring and has huge and immediate potential for scale up. In fact, CPCB has already mandated that 17 categories of large, highly polluting firms nationwide install CEMS for various air and water pollutants. Since this mandate was issued, these installations have proceeded with fits and starts across states and sectors.

The limitations of this study are two. In the first place, as it can be noticed in table 7, CEMS devices are being installed by the treatment and the control group, so if there is an effect of installing the device in the polluting behavior of the firm, the coefficients would be attenuated. In the second place, even though now GPCB has high frequency data on pollution, the current regulation is based on PM samples that the regulator has to take during inspections to the firms. Given that, we expect that the regulator is using CEMS data to target better the inspections and take samples on firms that they know are violating the regulation. In order to evaluate this, future research is needed with data on inspections from GPCB.

## 6.2 Policy and programme relevance: evidence uptake and use

The project is being conducted jointly with all of the concerned environmental regulators in order to building policy influence from the start. These regulators include the Ministry of Environment, Forests and Climate Change (MoEF&CC), the Central Pollution Control Board (CPCB) and the Gujarat Pollution Control Board (GPCB).

Present environmental regulations are seen as costly and unreliable. The regulation is based on samples that GPCB has to take while they are inspecting a firm. CEMS helps reducing reliance on frequent manual monitoring, providing significant long-term cost and time savings, as well as great potential for increasing the reliability of readings. It also enables policy partners to generate a rigorous and comprehensive database of pollution data from the major pollutants across any given region. Real time emissions data would enable better informed decisions and policymaking related to air pollution. In addition, continuous monitoring enables a highly transparent regulatory system and opens up options such as public release of emissions information in real time.

### 6.3 Challenges and lessons

The main challenge about CEMS monitoring regime is whether the data is reliable. This issue is important because like any other metering device, CEMS also require calibration and auditing. These tasks must be carried out by trained regulatory staff, or accredited third-party regulators. In prior work, Duflo et al (2013) have documented how regular plant monitoring can lead to falsified results because plants may be required to hire and pay the environmental labs that are responsible for testing them. In Section 3.4 we used additional pollution outcome measures to test the reliability of CEMS and found strong correlates with these measures.

## 7. Conclusions and recommendations

This article reports on the effect of implementing Continuous Emissions Monitoring Systems and reporting the data to the regulator in Surat, India. The goal was to help to reduce reliance on frequent manual monitoring, providing significant long-term cost and time savings, as well as increasing the reliability of readings. In addition, continuous monitoring enables a highly transparent regulatory system and opens up options such as public release of emissions information in real time.

Before our intervention, the levels of pollution of the firms in the sample were high, and the compliance with the regulation was low. Our analysis studies the effect of installing CEMS and reporting data to GPCB, with an intervention were firms were notified if they were among the worst firms in terms of pollution or data availability.

In Section 3.4 we showed that data from CEMS is reliable, as it strongly correlates with other measures of pollution, so despite CEMS could be subject to manipulation through their calibration, this does not seem to be the case as the devices installed in this intervention are working and reporting accurate data.

Overall, it is unclear if the use of CEMS as an informative tool has had an impact on firms' emissions. This may be attributed to multiple factors, especially the absence of a structured methodology for regulators to use and act upon CEMS data. Having said this, CEMS may achieve its intended purpose of lowering emissions if it is supplemented by a robust system which ensures accountability of all stakeholders and consequently galvanizes them into committing to high quality data transfer.

Despite we do not find any difference between treatment and control after the intervention was in place, this could be explained by different reasons. In the first place, it could be the case that our estimations are lacking enough power. Even though that is a possibility, because our sample is not very big and our variables are noisy, we find very consistently over our study a not significant effect in all of the outcomes we measured. A second possibility is that treatment and control are installing CEMS devices as we show in Section 4.1, so even though the control group is not reporting data, the fact that they have the device could be changing their behavior as well, so it could be the case that treatment and control are reacting to the intervention, attenuating our results. The third possibility is that as there is no change in the regulation yet, firms are not changing their behavior. We believe that the installation and connection of CEMS is a first step to changes in regulation as now GPCB has high frequency data that they could use to target better their inspections, but that they could also use in the future for regulation. Market-based regulations would allow regulators to address many city and regional problems with water and air pollution at a lower cost than is possible today, and the installation of this devices is a necessary step to do this.

# Appendix

**Table A1: Balance check baseline**

| **Panel A** | Control Mean | Treatment Mean | Difference | p-value |
|---|---|---|---|---|
| Asset Value (Excluding Land) | 1120.22 | 702.71 | 417.51 | 0.12 |
| Gross Sales Revenue Annually | 5342.27 | 3984.86 | 1357.41 | 0.37 |
| Employment | 282.03 | 250.03 | 32.00 | 0.33 |
| Boiler Capacity | 13.69 | 6.80 | 6.90 | 0.17 |
| Thermopack Capacity | 18.73 | 35.20 | -16.46 | 0.59 |
| Observations | 125 | 121 | 246 | |
| **Panel B** | Control Mean | Treatment Mean | Difference | p-value |
| Operating Cost | 8.80 | 8.51 | 0.29 | 0.86 |
| Maintenance Cost | 2.35 | 2.34 | 0.01 | 0.98 |
| Capital Cost | 41.37 | 26.07 | 15.31 | 0.21 |
| Recent Modifications Cost | 0.07 | 0.48 | -0.41** | 0.03 |
| Number of Cyclon | 4.22 | 4.13 | 0.08 | 0.71 |
| Number of Bag Filter | 2.54 | 2.82 | -0.27 | 0.37 |
| Number of ESP | 0.41 | 0.17 | 0.23 | 0.25 |
| Number of Scrubber | 3.22 | 2.74 | 0.49* | 0.10 |
| Observations | 125 | 121 | 246 | |
| **Panel C** | Control Mean | Treatment Mean | Difference | p-value |
| Ringelmann Mean Score | 1.61 | 1.74 | -0.12** | 0.03 |
| PM Concentration | 323.48 | 355.20 | -31.72 | 0.51 |
| Observations | 125 | 121 | 246 | |

Notes: Columns (1) and (2) show means. Column (3) shows the difference among the means, and column (4) shows the p value. . *p<.10, **p<.05, ***p<.01.

# Online appendixes

## Online Appendix A: Baseline Survey Summary

https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1067-India-Pollution-Online-appendix-A.pdf

## Online appendix B: Survey Instruments

B1: ETS CEMS Endline Survey (General Section)

https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1067-India-Pollution-Online-appendix-B1.pdf

B2: ETS CEMS Endline Survey (Technical Section)

https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1067-India-Pollution-Online-appendix-B2.pdf

B3: Monitoring Data from Stack Sampling

https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1067-India-Pollution-Online-appendix-B3.pdf

## Online appendix C: Ringelmann Smoke Chart

https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1067-India-Pollution-Online-appendix-C.pdf

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