Co-benefits of Effective Particulate Matter Regulation:

Health, Energy Efficiency and Climate Change Mitigation

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EXECUTIVE SUMMARY

Environmental policy can put costly restraints on growth. Echoing this view at the 11th Delhi Sustainable Development Summit, former Indian Prime Minister Manmohan Singh had said "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." Successful environmental policy, therefore, must not only place restrictions *on* industry, but work *with* industry, in order to raise buy-in and reduce the cost of compliance. Similarly, climate policy must not take place *in* developing countries, but *for* developing countries, by bringing co-benefits such as technology development, lower energy costs and lower local pollution. The only viable policy measures both carry climate benefits and serve immediate development priorities.

Against this backdrop, it is critical to consider for policymakers to consider two key questions. First, to what degree do these win-win opportunities exist within the space of conventional environmental opportunity? Second, given better information about the nature and magnitude of these co-benefits, how can policymakers use this knowledge to shape policies and institutions in ways that achieve both environmental and development goals in a harmonised manner?

The analysis in this report compares costs of abating Particulate Matter (PM) emissions from industries with the health benefits from these reductions. Using the Surat industrial cluster as a case study, the analysis finds that the health benefits of reduced air pollution far exceed the relatively modest abatement costs for industries. The report also underscores the potential for energy efficiency improvements in reducing fuel costs for the industries, while also reducing their greenhouse gas and PM emissions.

The chief objective and outcome of this study is to advance the understanding of the hypothesized co-benefits of environmental policies through rigorous empirical analysis to inform environmental policy making in India. In the long-run, such studies are intended to serve as the basis for sound policy decisions and informed choices by emission sources that result in the intended emissions reductions (of both local and global pollutants). Using an engineering economic model, the report estimates abatement costs for industries in response to different regulatory standards with command-and-control and cap-and-trade. The abatement model considers the case study of the Surat industrial cluster in Gujarat, takes as its inputs the current combustion source and air pollution control equipment installed at the plants as well as its current emission levels, to simulate plant behaviour to comply with alternative regulatory levels.

The results suggest that the increase in annual abatement costs to comply with the existing standards is relatively low, largely due to the existence of already efficient APCD equipment that are being poorly operated currently. In Surat, the average increase in annual costs is Rs. 30,000 (after amortization of any capital expenditure over the life of the equipment). For clusters with lower average emissions, the estimated increase in costs is even lower. However, there is significant heterogeneity of abatement costs for industries in each of the cluster based on their baseline emissions as well as their combustion source capacity.

While the abatement costs are relatively low, the health benefits are quite substantial. $PM_{2.5}$ is one of the most problematic pollutants in India, and most Indian cities have average ambient concentrations greater than the NAAQS standard, and several times the WHO standards. A reduction in $PM_{2.5}$ concentration by 10 $\mu g/m^3$ leads to an increase in average life expectancy by 0.6-1 year. We estimate the a 50% reduction in baseline emissions from the Surat cluster (leading to the load-weighted average concentration reaching existing regulatory standards) leads to an average increase in life expectancy by 0.12-0.34 years and in aggregate, 0.4-1.5 million person-years in Surat city. If monetized using estimates of Value of Statistical Life in India, the aggregate and marginal health benefits are 4-5 orders of magnitude greater than the corresponding costs to industries. The results strongly suggest that regulatory standards could be significantly more stringent than status quo.

Abatement measures related to energy efficiency improvements at the combustion source (e.g. boilers, thermic fluid heaters) could potentially have negative costs—due to fuel savings for the industry. Fuel savings and attendant PM and greenhouse gas emission reductions are estimated, using CO_2 in the stack as an indicator of excess air. We estimate that the average fuel savings is in the range of Rs. 2-3 lakh/ year. On average, about 10% reduction of baseline emissions could be achieved, and 500 tons of CO_2 emissions could be avoided. Aggregating over the cluster, fixing the excess air issue with energy efficiency retrofits could abate 160,000 tons of CO_2. The difficulty in realizing these fuel savings and the potential emission reductions is that the energy efficiency improvements involve many small measures, and can vary from one industry to another. In the absence of effective regulation, industries may not have sufficient motivation to explore these measures, despite high rates of return for such investments.

In this context, Continuous Emissions Monitoring Systems (CEMS) could play a critical role in improving regulatory oversight by providing real time, granular information on industrial emissions. CEMS would also allow for the regulatory parameter to change from the current concentration standards to load permits, which is the more relevant parameter for PM. To this end, JPAL South Asia has collaborated with the Central Pollution Control Board (CPCB) to publish the first standards for the use of Particulate Matter CEMS for Emissions Trading in India. Following the work, the CPCB has mandated the use of CEMS in 17 categories of industries for various air and water pollutants.

This shift to load permits paves the way for introducing emissions trading. Using the Surat industrial cluster as a case study, the model results indicate that cap-and-trade can reduce costs substantially over command-and-control. Data from a survey conducted by J-PAL South Asia in 2010-11 with about 500 industrial units in Gujarat suggest that 50% of the units had emission concentrations greater than the regulatory standard of 150 mg/Nm3. As a result, a cap equivalent to 100mg/Nm3 in the Surat cluster would result in a reduction of about 67% from current annual emissions. While the average increase in abatement costs from baseline with command-and-control is found to be close to Rs. 40,000/year, the average cost with trading is less than Rs. 19,000. In addition, the model substantiates these results by identifying the difference in abatement measures under the two regimes. While command-and-control will require a greater installation of new equipment, trading will utilize the existing equipment more effectively with improved maintenance and operations.

A combination of improved monitoring and market-based regulation could lead to a reduction in emissions at reduced costs of compliance. Effective regulation could push industries to realize energy efficiency gains or make low cost retrofits to existing poorly maintained equipment, and lead to cleaner air and better health in India’s over-polluted cities and industrial clusters.

1. INTRODUCTION

Particulate matter is by far the most problematic air pollutant on a national scale (CPCB, 2006). India's national average of 206.7 µg/m^3 of Suspended Particulate Matter (SPM) in 2007 is well above the old National Ambient Air Quality Standard (NAAQS) of 140 µg / m^3 for residential areas. Most Indian cities exceed, sometimes dramatically, the current NAAQS of 60µg / m^3 for Respirable Suspended Particulate Matter (RSPM). Average annual concentration of RSPM in Delhi is about 120 µg / m^3, as against a residential National Ambient Air Quality Standard of 60 µg / m^3 and World Health Organization (WHO) guidelines of 20 µg / m^3 (CPCB, 2006; WHO, 2008). Five of six cities covered in a recent report exceeded the standard in all years 2000-2006 (CPCB, 2011). Chronic exposure to fine particles raises the risk of cardiovascular disease and respiratory disease and the incidence of lung cancer (WHO, 2008) and has also been demonstrated to increase mortality (Chay and Greenstone, 2003; Chen et al., 2010). Indeed, the Global Burden of Disease ranked ambient and indoor pollution as two of the top five mortality risk factors in the world.

Yet the health impacts of particulate air pollution represent only one social cost they impose. Particulate matter from solid fuel combustion is also a dangerous short-lived climate pollutant. Black carbon particles from burning solid fuels are an important climate pollutant that has been linked to increased glacial melt in the Himalayas (Ramanathan and Carmichael, 2008). And beyond these direct climate effects, air pollution control has important secondary links to carbon abatement because one channel available to industry to reduce particulate emissions derives from the set of abatement actions that reduce fuel use (including actions to increase energy efficiency and improve combustion). On the flip side, many actions that may save industries money – principally energy efficiency measures – may also reduce particulate emissions.

A critical challenge in reducing PM emissions or for that matter, realizing private savings for industries with energy efficiency measures is ineffective monitoring and regulation of industrial emissions. Previous work by Duflo et al. (2012) shows a high non-compliance rate that was compounded by poor monitoring by third party auditors. We are working with Ministry of Environment, Forests and Climate Change, the Central Pollution Control Board and State Pollution Control Boards of Gujarat, Maharashtra and Tamil Nadu in setting up an ambitious pilot Emissions Trading Scheme for PM from industrial sources. A prerequisite for setting up the trading regime is improved monitoring of emissions among the participant industries, through Continuous Emissions Monitoring Systems (CEMS). CEMS will relay real-time information on emitted load to the regulators, and provide greater visibility of PM emissions to both the regulators and the industries themselves.

The principal objective of this analysis is to understand how industries that are currently emitting PM at higher than the regulatory standard can reduce their emissions. The model simulates the abatement actions of industries in response to regulatory changes about the particulate matter emissions, and estimates the costs of these actions to the industries. As part of the baseline surveys for this project, we have collected detailed information regarding the emission sources in these industries and the air pollution control devices (APCDs) installed to reduce PM emissions. The surveys include gravimetric stack sampling by environmental laboratories to measure the concentration of PM emissions in the stacks (chimneys) of these industries.

We then juxtapose these costs with an estimation of the health benefits from PM reduction. This analysis focuses on the Surat industrial cluster, which is adjacent to the relatively populous city of

Surat. The Surat cluster is one of the industrial clusters where the ETS is being rolled out and is ahead of the other clusters in terms of installation of CEMS devices.

We use a bottom-up engineering economic model, where the firm is minimizing the costs of emissions abatement in order to comply with regulatory standards. The firm has to choose from among a suite of options that are appropriate for the specific characteristics of this firm (emission source capacity, existing APCDs, and current emission behaviour). Abatement measures can include improved maintenance of existing components in the chain, retrofits to the equipment, or installation of new air pollution control devices.

The two alternative regulatory regimes we consider are load permits (in kg/ year) without trading, and a cluster-wise cap and trade. Economic theory as well as previous experiences with cap-and-trade programs suggests that trading reduces costs of compliance to industries. The objective of the model is to simulate the industries' behavior, as cost-minimizing agents, and estimate the reduction in costs, if any, as a result of trading. This would set up the economic case for introducing the Emissions Trading Scheme in India in the identified clusters in Gujarat, Maharashtra and Tamil Nadu. The simulations also help us understand the distributional impact of the two alternative regimes on industries—costs and abatement actions for industries of different sizes and current emissions.

In sum, this analysis will look to answer the following questions.

- What abatement measures can industries take to become compliant to command and control regulation? What would be the costs of these measures?
- What are the savings to industries due to cap and trade?
- How does abatement behavior change as the standards becomes more stringent? Does this differ between the cap-and-trade and command and control cases?
- What health gains can be expected from the reduction in industrial emissions in Surat? How do the monetized health benefits compare with the abatement costs?
- What is the potential for win-win-win energy efficiency solutions in terms of reducing fuel savings, greenhouse gas and PM reductions?

2. REGULATORY REGIMES

This analysis considers two alternative regulatory regimes— command and control, and cap and trade. Both regimes here involve assignment of load permits based on combustion source capacity and a cluster level cap of emissions. The load permits in the command and control case departs from business-as-usual where the regulatory parameter is emissions concentration. However, this comparison ensures that the two regimes are analogous and are more appropriate in the presence of Continuous Emissions Monitoring Systems (CEMS). CEMS devices in this case have been designed to measure load, not concentration.

The permit allocation in both regimes is identical, and in our model we compare the costs for different levels of emissions caps. The major difference between the two regimes then is the ability of industries to trade permits in one case. Allocation of load permits without trading is similar to concentration standards, except that the industry does not have an instantaneous standard; they can choose to turn off their air pollution control equipment over certain periods of time while still emitting at a level equal to or lower than the permits they hold. As a result, industries have a little more flexibility in being compliant with the non-tradable load permits case than with concentration standards.

Load permits are allocated using the following steps:

1. The total current emissions (in tons/ year), and the load weighted average PM concentration (in mg/Nm^3) are estimated as reference
2. For a desired concentration standards level, the emissions cap is estimated as

$$Emissions\ cap = \frac{Target\ concentration\ standard}{Mean\ baseline\ concentration}\ X\ Baseline\ emissions\ load$$

3. The emissions cap is then distributed as permits among the regulated industries, in proportion to their combustion source capacity

In the case of command and control, industries need to ensure that their annual load is within the permits allotted to them. With trading, industries can trade permits and for compliance, they need to ensure that their annual emissions are less than the permits they hold. The permit price is established in the market while trading. The market price will only be regulated through a market floor and ceiling, set by the SPCB.

The central idea for why trading is preferable over command and control is that abatement measures with the lowest marginal costs in the cluster, as opposed to the individual industry, are used. As a result, aggregate costs of compliance for the cluster as a group reduces.

3. ABATEMENT COST MODEL

3.1 OVERVIEW

We have developed an industry -level abatement cost function based on engineering estimates, where costs are a function of firm characteristics and the status quo abatement strategy. We have collected detailed information on firm characteristics, the status quo abatement strategy, such as the installed pollution control equipment, the quality and disrepair status of the equipment, and usage and maintenance practices. We use the survey data to predict abatement costs for each firm.

In the model, the industry selects abatement technologies and operating practices by minimizing expected abatement costs, to comply with the regulatory standards. We consider two alternative regulatory systems— command-and-control, and cap-and-trade.

In an industrial plant, combustion equipment (emission source) burns fuel to generate usable energy (in form of steam/thermic fluid heat), generating emissions as a by-product. The emissions are passed through a series of Air Pollution Control Devices (APCDs) that together compose an APCD system. The APCD system captures some emissions and the remaining emissions are released though the chimney/stack. A 'parallel chain' would be an emission source followed by a group of APCDs. Often, more than one parallel chain is connected to the stack.

The regulated quantity, final emissions from the stack, is a function of several factors. The efficiency of the combustion equipment determines the quantity of emissions created as a byproduct. The efficiency of the APCD system determines the quantity of emissions captured. The firm can choose to not operate the APCD system and instead directly pass emissions from the combustion source to the smoke stack. The firm can also change the type of fuel used for combustion (some fuels are more polluting than others), and could cut down on production of the final product (e.g. textiles) to reduce emissions.

In the model we have developed, the firm can implement various discrete actions that improve the efficiency of the combustion equipment and individual APCDs. Each distinct and feasible combination of discrete actions is called a 'technology'. The choice of technology determines the overall efficiency of the system. In the model, the firm has a single operating choice: whether or not to operate the APCD system. Thus, currently, the firm optimizes over two variables: technology choice, and operation of the APCD system.

A firm can have several smoke stacks. As all regulations are at the stack level, the firm must separately select a cost-minimizing strategy for each stack in the factory. Thus the model of a firm's constrained optimization is set-up at the stack level.

3.2 MODEL INPUTS

In this section, we describe the inputs for the model from the baseline survey and from expert inputs on abatement methods for industries received previously from FICCI. We sought inputs from FICCI to develop a methodology to automate analysis of abatement options based on baseline data. The baseline questionnaire was designed specifically to enable this analysis.

3.2.1 INPUTS ON APCD COSTS AND OPERATIONS FROM FICCI

FICCI experts were consulted to prepare detailed energy audits for eight example industries, and then help in providing a detailed methodology to enable automating the audit analysis for the baseline industries. FICCI provide inputs on capital, operations and maintenance costs for APCDs, their best collection efficiencies and typical lifetimes. A summary of these is provided in Tables 1 and 2.

Table 1 Capital costs of APCDs by boiler capacity (in Rs. Lakh)

Boiler Capacity (TPH)	Bag Filter	Cyclone	Scrubber	Boiler
2	7.1	1.2	2.8	35
5	10.3	1.7	3.3	82
10	14.7	2.1	4.3	136

Table 2 Lifetime and collection efficiency assumptions for the three APCD types

	Lifetime (years)	Efficiency
Cyclone	13	80%
Scrubber	10	94%
Bag Filter	20	99%

As Electrostatic Precipitators (ESPs) are very expensive, and scrubbers and bag filters are already in use, we do not consider upgrades to existing ESPs or installation of new ESPs in the current version of the model.

Table 3 Inputs to the model from FICCI data

Input	Variable description	Role in the model
APCD capital costs as per boiler size	Interpolated capital costs from FICCI inputs	APCD capital costs estimated for each boiler size. Intermediate input in the case of retrofits.
Operations and maintenance costs	Constant fraction of capital costs	Annual O&M costs are part of the cost function that is minimized for each industry.
Equipment lifetime	Lifetime of APCD type with sufficient maintenance	To annualize capital costs of equipment.
Maximum efficiencies	Maximum achievable efficiency for each APCD type	Intermediate input to estimate APCD efficient efficiencies for each industry empirically.

3.2.2 INPUTS FROM THE BASELINE SURVEYS

The baseline surveys provide a rich dataset to enable a systematic appraisal of their current PM emissions, and the reduction potential and costs of abatement measures at their disposal. The baseline survey questionnaire included questions on the fuel consumption and combustion sources, the parallel chain configurations attached to each stack, the technical specifications of each APCD, and most importantly, included a measurement of emissions concentration by gravimetric stack sampling.

From these data, the following variables are being used in the model.

Table 4 Inputs to the model from baseline data

Input	Variable description	Role in the model
Parallel chain configuration	Type of combustion source and the APCD types attached	Industries are grouped by their parallel chain configuration, to estimate APCD efficiencies empirically
Combustion source capacity	Boiler or thermopack capacity in TPH	Costs of new APCD equipment are estimated such for the combustion source capacity Combustion capacity also used to determine flow rate in each chain if there are multiple chains Permits are allocated as per combustion source capacity

Outlet concentration	Measured outlet PM concentration in mg/Nm3	To compute baseline load (in kg/ year) To compute APCD efficiency
Gas flow rate in the stack	Measured flow rate during sampling	To compute load (in kg/ year) at baseline and with alternative regulatory levels

3.2.3 INDUSTRY-WISE APCD EFFICIENCY- EMPIRICALLY DETERMINED

The efficiencies of the current APCDs are empirically determined using the baseline stack sampling results and the known theoretical maximum efficiencies of each APCD type. The combined APCD chain efficiency can be estimated as a multiplicative function of individual APCD efficiencies. The chain efficiency given the efficiency of three individual APCDs is determined as below.

$$(1 - Eff_{chain}) = (1 - Eff_{APCD1})(1 - Eff_{APCD2})(1 - Eff_{APCD3})$$

And hence,

$$Eff_{chain} = 1 - (1 - Eff_{APCD1})(1 - Eff_{APCD2})(1 - Eff_{APCD3})$$

However, it is difficult to measure individual APCD efficiencies. We have attempted to estimate the APCD efficiencies empirically based on baseline data on configurations of the emission source- APCD chains attached to the stacks, and the PM concentrations at the stack.

Estimating baseline chain efficiency

All the industries are grouped by the parallel chain configurations attached to the stack. Among each group of industries with a common configuration, the following process is followed to determine efficiencies of each APCD chain.

1. For each group of industries with the same configuration, the industry with the lowest outlet PM concentration, "best performer", is assumed to have a chain efficiency equal to the theoretical efficiency
2. The chain efficiencies of the all other industries with the same configuration are estimated relative to the best performer.
    a. The inlet concentration of the best performer is estimated based on the outlet concentration and the theoretical maximum efficiency.
    b. The inlet concentration of all the other industries are estimated to be the same as that of the best performer
    c. Using this empirically determined inlet concentration and the measured outlet concentration, the chain efficiencies of all the industries are estimated
    d. If industries have multiple chains, each chain is assigned the same inlet concentration and chain efficiency, but flow rates are allowed to differ based on the capacity of the emission source within that chain

For industries, that do not have a common APCD configuration, an inlet concentration of 2000 mg/Nm^3 is assumed. The average inlet concentration as determined by the inlet sampling from the baseline surveys was found to be 1750 mg/Nm^3, justifying this choice. The chain efficiency is then estimated as (2000 – $Conc_{outlet}$)/ 2000

Estimating baseline APCD efficiencies

Although we know the maximum efficiency possible with each APCD type, it is difficult to estimate the efficiency of the individual APCD in every baseline industry. As a result, we need to make a few assumptions in apportioning the chain efficiency among its constituent APCDs. As a general assumption we assume that each constituent APCD in a given chain has the same efficiency, bound above by the theoretical maximum for its type. As the efficiencies are multiplicative, the common APCD efficiency would equal $1- (1- Eff_{chain})^{1/n}$, where n is the number of APCDs in the parallel chain.

If the efficiency determined above exceeds the maximum theoretical efficiency of the APCD type, the efficiency for that APCD is set at the maximum and the efficiencies of the other APCDs are adjusted accordingly.

3.2.4 INDUSTRY-WISE ABATEMENT COSTS

We combine the FICCI cost inputs with the empirically determined efficiencies to estimate the cost of the equipment.

For new equipment: The costs of installing new APCDs to complement existing pollution control measures are estimated based on combustion source capacity in the industry. Using the FICCI cost inputs in Table 1, we interpolate to estimate capital costs of new equipment for each industry. The capital costs are then annualized over the lifetime of the equipment. The annual operations and maintenance costs of the equipment are taken to be 3% and 6% of the upfront capital costs.

To retrofit equipment: Capital costs of retrofitting equipment are computed in a similar manner as for the new equipment. However, instead of the full capital costs, retrofit cost is estimated as a function of the relative increase in efficiency from baseline to ideal.

$$CC_{retro,ik} = \frac{Eff_{i,max} - Eff_{ik,baseline}}{Eff_{i,max}} . CC_{ik}$$

Increase in operations and maintenance cost are estimated as 3% and 6% respectively for the retrofit costs.

3.3 MODEL DESCRIPTION

The abatement cost model is built in the software package MATLAB. In addition, the inputs to the model, including the empirical estimation of industry-wise APCD efficiencies and costs, are prepared using the statistical package STATA.

Each stack k must choose a technology *t* out of T_k choices (t=1, 2…T_k) and must choose Fr_k , the fraction of time the APCD system operates (Fr_k is a fraction between 0 and 1). A technology *t* here refers to some combination of abatement measures that is available to the stack *k*.

The T_k choices for stack k depend on the existing stack configuration, provided by the baseline data. The model organizes this by letting every industry have any combination of APCDs for up to two chains attached to each stack. Given baseline data on the existing parallel chain configuration and their efficiencies, the model estimates the costs of every combination of installing new APCDs or retrofitting existing APCDs to achieve maximum efficiency, and chooses the least expensive one that allows the industry to meet the standards.

Chain 1	Combustion source	Cyclone 1	Cyclone 2	Scrubber	Bag Filter	ESP	Stack
Chain 2	Combustion source	Cyclone 1	Cyclone 2	Scrubber	Bag Filter	ESP	

For each stack k, the firm minimizes expected costs

$$C_{kt}(Fr_k) = CC_{kt} + MC_{kt}(Fr_k) + OC_{kt}(Fr_k)$$

where CC_{kt} is the expected annualized capital costs of technology option t, $MC_{kt}(Fr_k)$ is the expected annual maintenance costs of technology t given Fr_k, and $OC_{kt}(Fr_k)$ is the expected annual operations costs of technology t given Fr_k.

The engineering estimates and baseline survey data can be used to estimate CC_{kt} (expected annualized capital costs of technology t, in Rs/year), $MC|Fr = 0_{kt}$ and $MC|Fr = 1_{kt}$ (expected annual maintenance costs of the technology t when Fr_k=0 or 1 respectively, in Rs/year), $OC|Fr = 0_{kt}$ and $OC|Fr = 1_{kt}$ (expected annual operations costs of the technology t when Fr_k=0 or 1 respectively, in Rs/year).

The maintenance costs are assumed to be the same irrespective of how often the APCDs are used. On the other hand, the operations costs are assumed to be linear with hours of usage. The industries have the option of switching off or bypassing the APCD system such that their emissions can be exactly equal to the number of permits they hold.

The baseline survey is also used to estimate firm emissions. For the function descriptions that follow, let

- E_{kt} be the annual emissions with technology t when the APCD system is being used, in kg/year.
- Eb_{kt} be the annual emissions with technology t when the APCD system is not operational, in kg/year.
- Ec_{kt} be the emissions concentration with technology t when the APCD system is operational, in mg/Nm3, which is fixed given technology type.

Firm's Optimization under Load Permits without trading:

Under a load standard regime, each stack k is allocated emissions permits $\bar{E}_k$, in kg/year. Emissions are not allowed to exceed the allocated amount. Each firm's stack-level optimization problem is:

$$Min_{t,Fr_k,Workinghours_k}\ C_{kt}(Fr_k, Workinghours_k)$$
$$subject\ to$$
$$1)\ \ AnnualEmissions_{kt}(Fr_k, Workinghours_k) \le \overline{E_k}$$

Firm's Optimization under an Emissions Trading Scheme:

Under an emissions trading scheme, each stack k is allocated emissions permits $\bar{E}_k$, in kg/year. Stacks can buy and sell permits at the permit price Pr, and must ultimately hold permits equal to emissions. Each firm's stack-level optimization problem is:

$$\begin{aligned} Min_{t,Fr_k,Workinghours_k}\ & C_{kt}(Fr_k, Workinghours_k) \\ & + [AnnualEmissions_{kt}(Fr_k, Workinghours_k) - \bar{E}_k] \times Pr \end{aligned}$$

The aggregate emissions cap is $\sum_k^K \bar{E}_k$, where K is the number of stacks in the market. For each stack $[(Fr_k \times E_{kt} + (1 - Fr_k) \times Eb_{kt}) - \bar{E}_k]$ is the number of permits purchased, that is, it is the quantity of emissions produced less the initial permit allocation.

When the market is in equilibrium, aggregate supply of permits should equal aggregate demand for permits. Thus the net sum of permits purchased by all stacks should equal zero (given that it is a closed market and some stacks are sellers). Ideally in equilibrium

$$\textstyle\sum_k^K [(Fr_k \times E_{kt} + (1 - Fr_k) \times Eb_{kt}) - \bar{E}_k] = 0.$$

In order to ensure that aggregate emissions are below the cap, it must be the case that net sum of purchases is negative, i.e. that there are more permits sold than bought.

Due to discontinuities in the cost curves for market participants, the condition that aggregate supply of permits equals aggregate demand is rarely empirically satisfied, and thus the equilibrium permit price is defined as the minimum permit price such that net sum of permit purchases is negative. It is the solution to the following minimization problem.

$$Min_{Pr}\ Pr\ s.t. \sum_k^K [(Fr_k \times E_{kt} + (1 - Fr_k) \times Eb_{kt}) - \bar{E}_k] \leq 0$$

Thus the equilibrium conditions for an emissions trading scheme are

- $Pr = Pr^*$, the solution to the above minimization problem
- $t_k = t_k^*, Fr_k = Fr_k^*\ for\ \forall k$, i.e. each firm is optimizing given the equilibrium permit price
- $\sum_k^K (Fr_k \times E_{kt} + (1 - Fr_k) \times Eb_{kt}) \leq \sum_k^K \bar{E}_k$, i.e. aggregate emissions are below the aggregate emissions cap.

3.3.1 FUNCTIONS IN THE MODEL

The functions are set up on the premise that stacks have up to two parallel chains, Chain 1 and Chain 2.

$$\begin{aligned} \boldsymbol{AnnualEmissions_{kt}} & \\ & = Workinghours_k \\ & * (Fr_k * HourlyEmissionsControlled_{kt} + (1 - Fr_k) \\ & * HourlyEmissionsGenerated_k) \end{aligned}$$

*HourlyEmissionsControlled**kt*** is the hourly emissions (kg/hour) from the smoke stack if the APCD system is operational that hour, i.e. if Fr_k = 1

$$HourlyEmissionsControlled_{kt} = HourlyEmissionsGenerated_k Chain1 * (1 - APCDefficiency_{kt} Chain1) + HourlyEmissionsGenerated_k Chain2 * (1 - APCDefficiency_{kt} Chain2)$$

Where $APCDefficiency_{kt}Chaini$ is the net efficiency of the APCD system in Chain i for stack k with technology t.

$$\boldsymbol{HourlyEmissionsGenerated_k} = HourlyEmissionsGenerated_k Chain1 + HourlyEmissionsGenerated_k Chain2$$

Flow Rate and Concentration Functions:

$Flowrate_k = Flowrate_{k,Chain1} + Flowrate_{k,Chain2}$

$Flowrate_k$, $Flowrate_{k,Chain1}$, $Flowrate_{k,Chain2}$ are all in Nm^3/hour. $Flowrate_k$ is the overall flow rate for the stack, as measured during the stack sampling. The flow rates in the chains are determined by distributing the overall flow rate by combustion source capacity in each chain.

$EmissionConcentrations_{kt}$ is the concentration (mg/Nm3) when the APCD system is operational, i.e. $Fr_k = 1$

$$EmissionConcentrations_{kt} = \frac{AnnualEmissions_{kt}(Fr_k, Workinghours_k | Fr_k = 1) * 10^6}{Flowrate_k * Workinghours_k}$$

$$EmissionConcentrations_{kt} = \frac{(Workinghours_k * (Fr_k * HourlyEmissionsControlled_{kt} + (1 - Fr_k) * HourlyEmissionsGenerated_k) | Fr_k = 1) * 10^6}{Flowrate_k * Workinghours_k}$$

$$\therefore EmissionConcentrations_{kt} = \frac{HourlyEmissionsControlled_{kt} * 10^6}{Flowrate_k}$$

Cost Functions

The firm minimizes expected costs:

$$\boldsymbol{C_{kt}(Fr_k, Workinghours_k)} = CC_{kt} + MC_{kt}(Fr_k, Workinghours_k) + OC_{kt}(Fr_k, Workinghours_k)$$

CC_{kt} is the expected annualized capital costs of technology option *t* for stack *k*. Engineering estimates and baseline survey data is used to estimate the capital costs for each stack k for each technology *t*, i.e., each combination of discrete actions such as installing a new scrubber, retrofitting a cyclone, etc.

MC_{kt} is the expected annual maintenance costs (Rs./year). The rationale for this function is that if equipment is used at all, then the full maintenance expenses must be incurred to prevent rapid depreciation of the capital equipment.

OC_{kt} is the expected annual operations costs given technology t as a function of Fr_k and $Workinghours_k$

3.4. MODEL RESULTS

3.4.1 SIMULATION RESULTS FOR TWO EXAMPLE INDUSTRIES

We include below the model results for two example industries to elucidate the workings of the model. For the sake of simplicity, we consider two industries with a single parallel chain, i.e. with a single boiler and a series of APCDs connected to a stack. The objective of this section is to describe the model's working in detail to give perspective to the aggregate analysis in subsequent section.

Example industry 1: Abatement action for an industry with baseline concentration exceeding the current regulatory standard

The first example is an industry, with a chain comprising a boiler, cyclone and bag filter, attached to the stack. Table 5 lists all the major inputs. PM concentration was found to be 238 mg/Nm^3 for the industry. Using the best performer with the same parallel chain configuration, the inlet concentration was found to be 4260 mg/Nm^3. The collection efficiency for the chain was estimated using the outlet and estimated inlet concentrations. The collection efficiencies of the APCDs were assumed to be equal, and both were set at 76%.

The retrofits costs were estimated using this empirically determined efficiency, the best achievable efficiency, and the estimated capital costs of new cyclones and bag filters for this boiler capacity. Increase in annual operation costs were estimated to be 3% of the upfront retrofit costs, and this was divided by the annual working hours from baseline data to get an hourly operations cost.

Increase in annual maintenance cost was determined as 6% of the upfront costs. The capital costs themselves were annualized using a discount rate of 15%. This would be equivalent to leasing the equipment for a period of the APCD's lifetime paying an equal amount every year.

Table 5 Model inputs for the first example industry

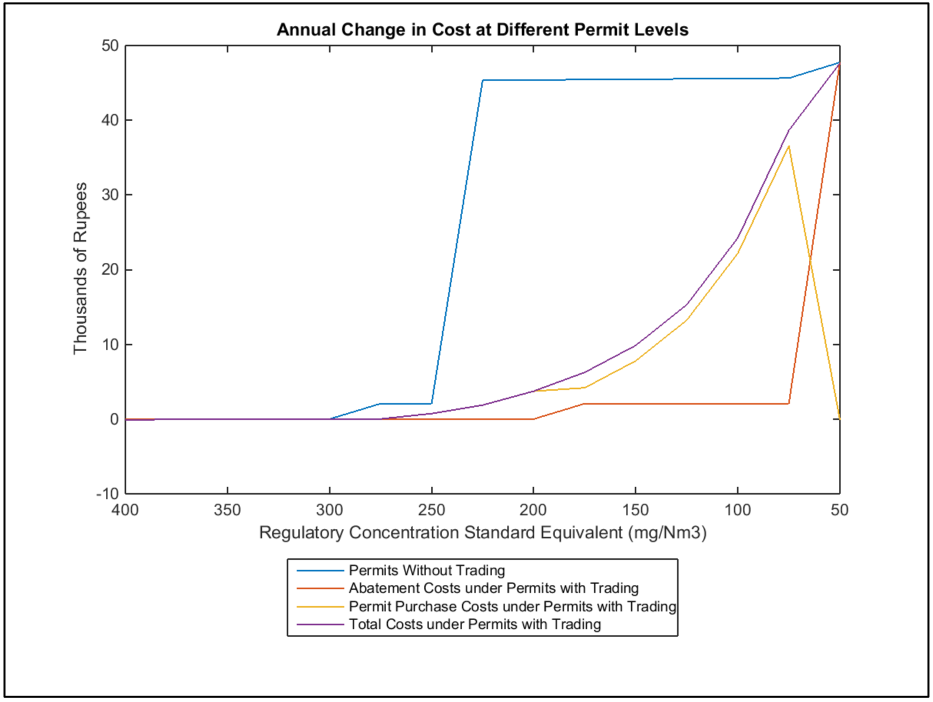
Inputs from baseline survey	Emission Source	Boiler
	APCDs attached	Cyclone and Bag Filter
	Baseline PM concentration	238 mg/Nm3
	Flow rate	12197 Nm3/hour
	Estimated load	22 tons/ year
Empirically estimated inputs	Inlet concentration	4260 mg/Nm3
	Efficiency of individual APCDs	Cyclone- 76% Bag Filter- 76%
	Costs of retrofitting equipment	Cyclone- Rs. 7,700 one time; Rs. 1300/ year Bag Filter- Rs. 2.5 lakhs one-time; 40,000/ year
	Additional operations and maintenance costs	Cyclone- Rs. 230/year maintenance; Rs. 0.06/ hour of operation Bag Filter- Rs. 7,500/ year maintenance; Rs. 2/ hour of operation

Based on these inputs, the model estimates abatement costs for different regulatory levels as shown in Figure 1.

With the load permits without trading case, there are two bumps in costs. The smaller bump is for the retrofit to cyclones, and the larger one is for bag filters. Note that although the baseline concentration is 238 mg/Nm^3 the load permit allocation also depends on boiler capacity and the resultant concentration equivalent may be higher or lower; in this case, it seems to be higher necessitating abatement action at around 300 mg/Nm^3 itself, and the second one at 250 mg/Nm^3. The more gradual slopes are due to operations costs.

With trading, the industry chooses to initially purchase permits to meet compliance. At about 200 mg/Nm^3, the industry retrofits its cyclone. This does not suffice, and the industry continues to purchase permits in the market up to less than 100 mg/Nm^3, when it becomes more economical to retrofit the bag filter instead, and sell excess permits in the market. In this way, there is a reduction in costs from the command and control case.

Figure 1 Abatement costs for the industry with increasingly stringent standards for command-and-control (blue) and cap-and-trade (purple). Cap-and-trade costs are broken down into permit purchase (yellow) and abatement (orange) costs



Example industry 2: Abatement actions for an industry with baseline concentration lower than the current regulatory standard

The second example industry has a baseline concentration of 76 mg/Nm^3 and is already meeting the regulatory standard. This industry has boiler followed by a cyclone and scrubber. Using the best performer for this configuration, the inlet concentration is found to be 2200 mg/Nm^3. Based on this, the baseline efficiencies are found to be 80% for the cyclone (equal to its best achievable) and 82% for the scrubber. The costs are computed as described for the first industry.

Table 6 Model inputs for the second example industry

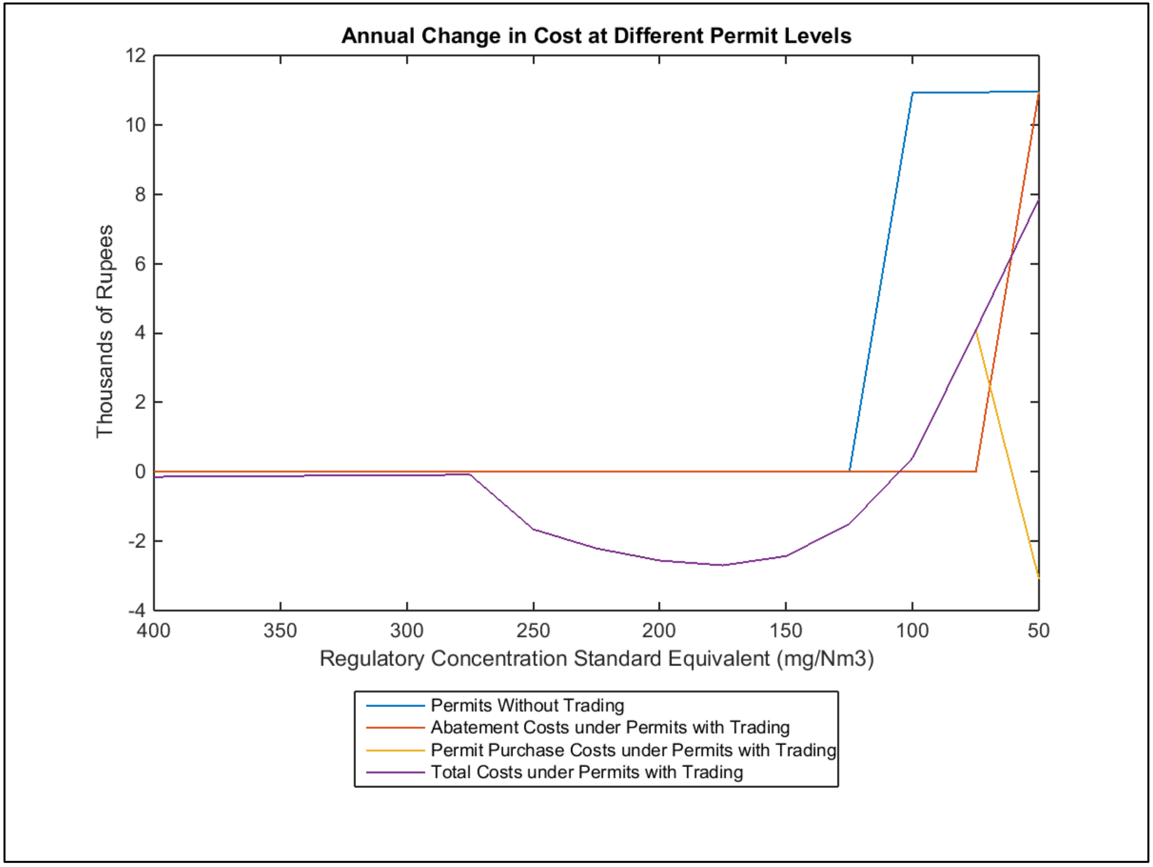
Baseline inputs	Emission Source	Boiler
	APCDs attached	Cyclone and Scrubber
	Baseline PM concentration	76 mg/Nm3
	Flow rate	12197 Nm3/hour
	Estimated load	5.1 tons/ year
Empirically estimated inputs	Inlet concentration	2200 mg/Nm3
	Efficiency of individual APCDs	Cyclone- 80% Scrubber- 82%
	Costs of retrofitting equipment	Cyclone- NIL Scrubber- Rs. 38000 one-time; Rs. 7,500/ year annualized
	Additional operations and maintenance costs	Cyclone- NIL Scrubber- Maintenance: Rs. 1,140/year; Operations: Rs.0.3/hour

The abatement costs with and without trading are shown in Figure 2. For the command and control case, the industry has to retrofit the scrubber at about 125 mgNm^3. Note once again, that the permit allocation by capacity leads to these changes between baseline concentration and concentration standard- equivalent

With the trading case, we find that abatement is not required for the industry till almost 75 mg/Nm^3. The net cost of compliance curve (purple) is the same as the permit purchase curve (yellow), till the point at which the industry retrofits the scrubber. Initially, as the market price is low, revenues from permit sales are low. This increases, till a maximum at about 175 mg/Nm^3, after which permit sales revenues drop again as the number of excess permits held by the industry drop faster than the increase in market price. Eventually, at about 100 mg/Nm^3, the industry must purchase permits till the point at which retrofitting the scrubber has lower marginal costs. As there is once again an excess in permits, the net costs are lower than the costs of the scrubber.

In this manner, there is a reduction in costs for both low and high polluters under trading. The model is successful at incorporating the nuances of command-and-control as well as cap-and-trade, and simulating the behaviour of the industries, within the limits imposed by the assumptions used while preparing the inputs and the limitations posed by data availability.

Figure 2 Abatement costs for the industry with increasingly stringent standards for command-and-control (blue) and cap-and-trade (purple). Cap-and-trade costs are broken down into permit purchase (yellow) and abatement (orange) costs



3.4.2 ABATEMENT COSTS OF INDUSTRIES WITH COMMAND AND CONTROL

Figure 2 shows the PM emissions level in ~500 industrial units in Gujarat from studies previously conducted by JPAL South Asia. The red line corresponds to 150 mg/Nm^3 on the x-axis, which is the stack-level concentration limit for PM emissions for industries. Note first that 50% of the plants in this sample had concentrations higher than 150 mg/Nm^3.

Using data collected more recently for a group of about 300 industries in the Surat cluster, Figure 3 shows a histogram of the abatement costs to reach 150 mg/ Nm^3 for the command and control case. In Gujarat, for about 40% of the industries, these additional costs are lower than Rs. 10,000/ year, and for about 15 % they exceed Rs. 70,000/ year. For the other clusters, many industries could not be modeled because of one of the reasons mentioned above. Based on the emissions concentration levels, it would seem that the emissions are lower in general than in Surat, and therefore additional abatement costs would either be negligible or low.

Figure 3: Variation in SPM Emissions of SME Units

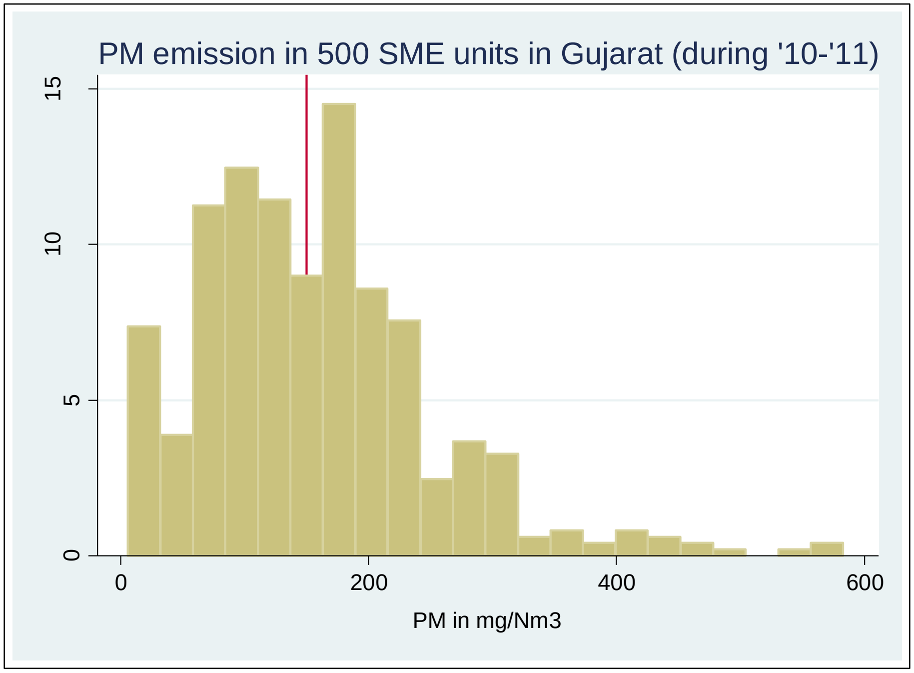
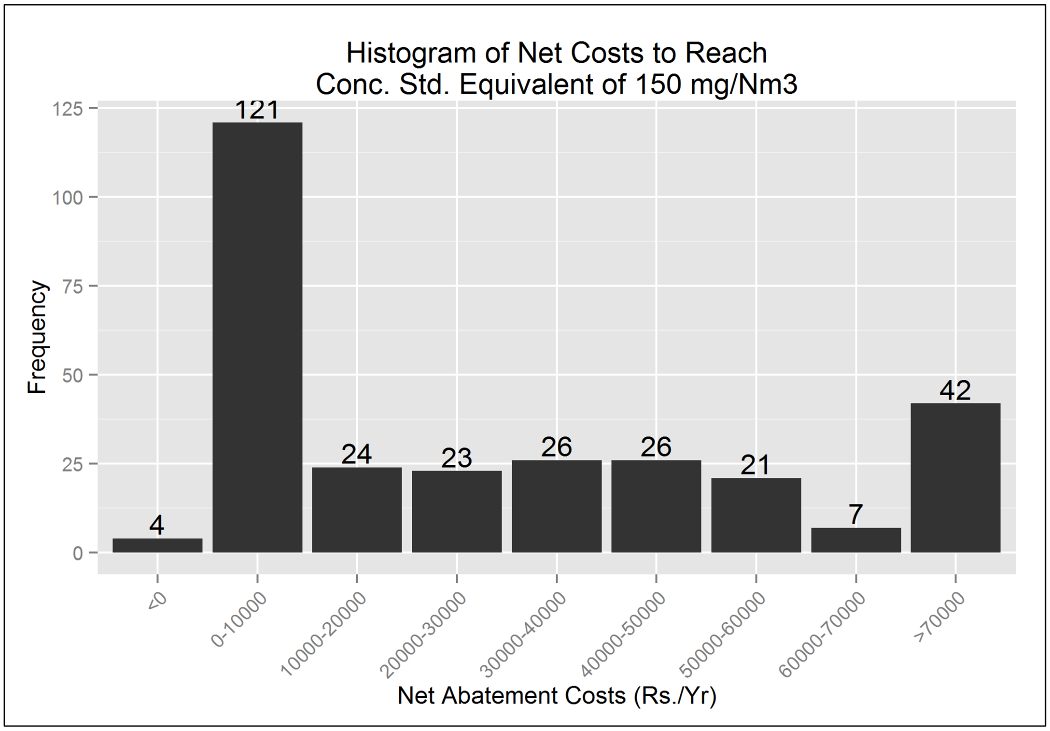


Figure 4 Additional abatement costs to meet 150 mg/ Nm3 in the command and control case for the Surat cluster



3.4.3 AGGREGATE ABATEMENT COSTS WITH AND WITHOUT TRADING

Figure 5 compares the average abatement costs of industries in the Surat cluster with and without trading. As expected from theory, costs of compliance reduce with trading. The estimated average increase in annual abatement costs with load permits without trading is about Rs. 28,000 at a cap that is equivalent to 150 mg/Nm^3. With trading, this is about Rs. 7000. The gap narrows as the standards become more stringent, but even at 100 mg/Nm^3 equivalent, the costs with trading is less than 50% of costs with command and control.

Figure 5 Comparison of average net additional costs to industries with load permits with and without trading.

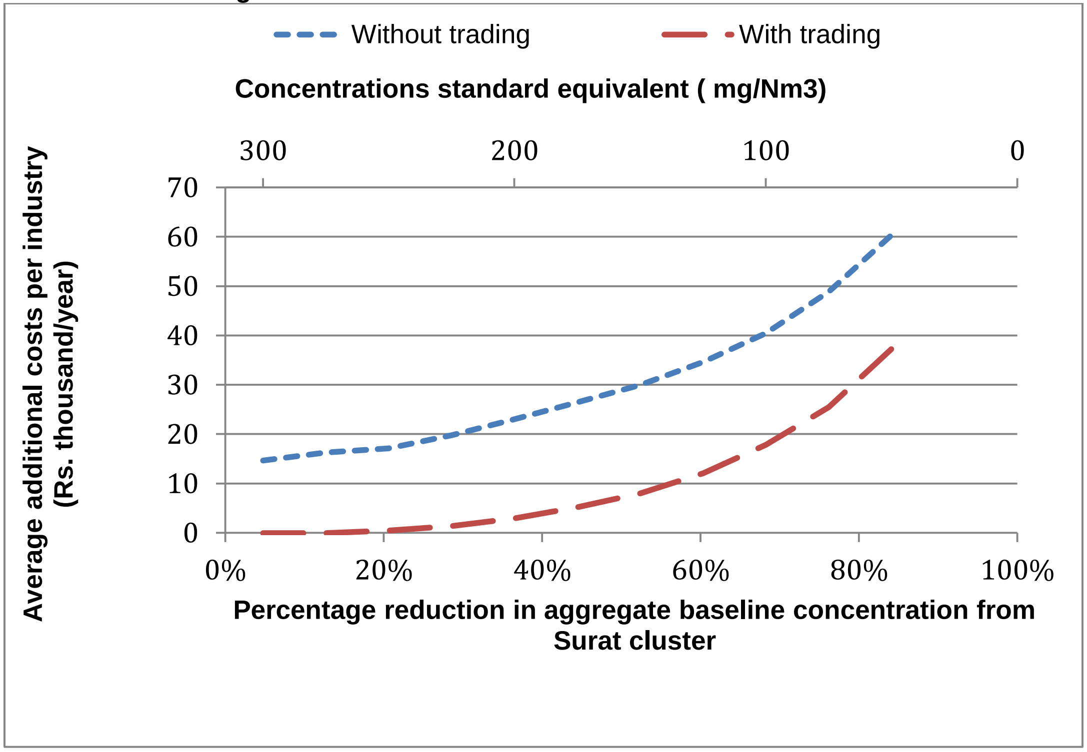


Figure 6 Equilibrium market price at alternative emissions cap levels in Surat

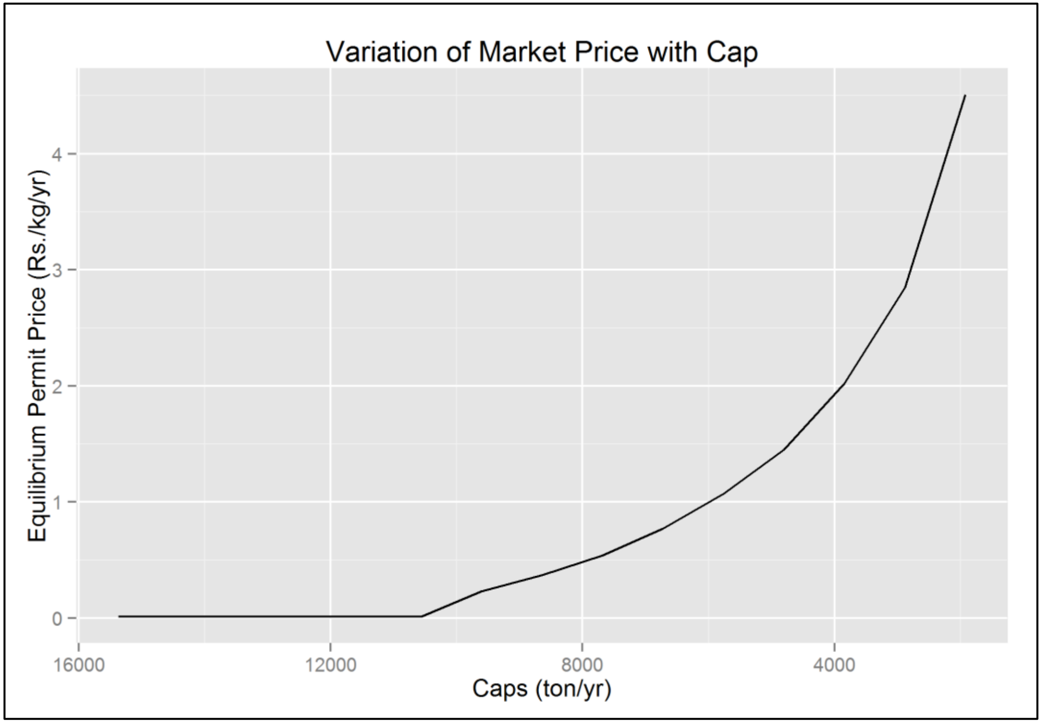


Figure 6 shows the estimated equilibrium market price with different levels of emissions cap. The market price at the 150 mg/Nm^3 level is Rs. 1/kg/year, and at 100 mg/Nm^3 this increases to Rs. 2/kg/year.

Figure 7 Number of new APCDs installed in response to alternative regulatory levels with command and control

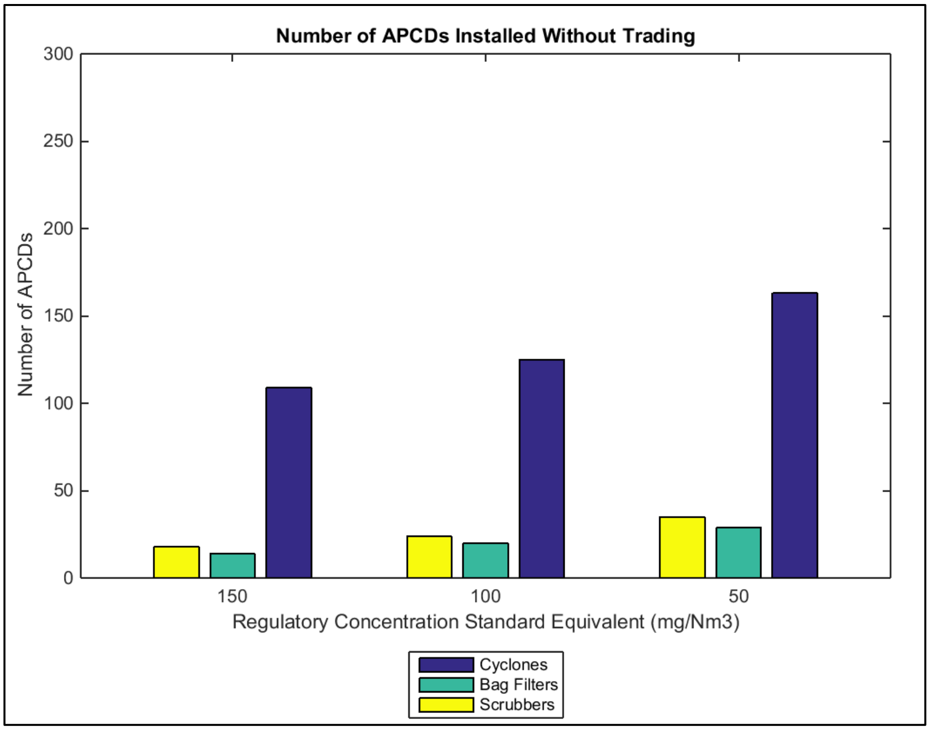
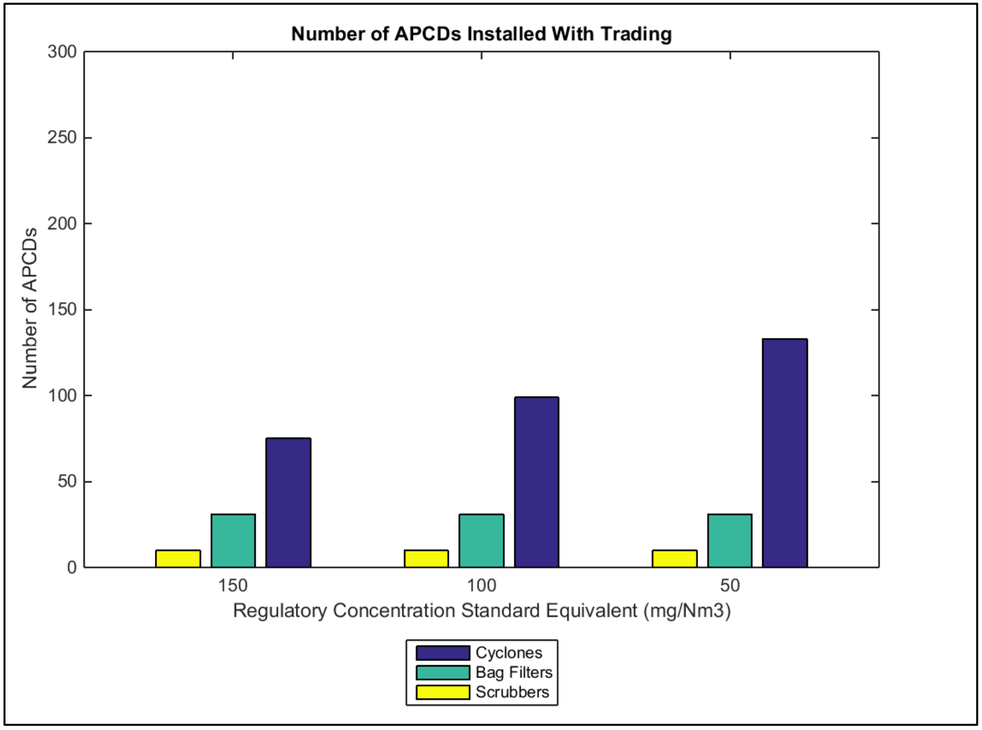


Figure 8 Number of new APCDs installed in response to alternative regulatory levels with cap and trade



Figures 7-10 demonstrate how there is a reduction in costs with trading. The difference between command-and-control and trading is that in the former, each industry must comply with the standard. This includes industries for which abatement would be very expensive. Conversely, industries with emissions lower than the standard have no incentive to further abate emissions even if the marginal costs for abatement are low. As a result, the costs of abatement increase. As figures 10 and 11 demonstrate, the number of newly installed APCDs reduces with trading. On the contrary, as figures 12 and 13 show, retrofits increase with trading. As figure 13 indicates, industries retrofit the cyclones to the extent possible.

Figure 9 Number of retrofits to existing APCDs in response to alternative regulatory levels with command and control

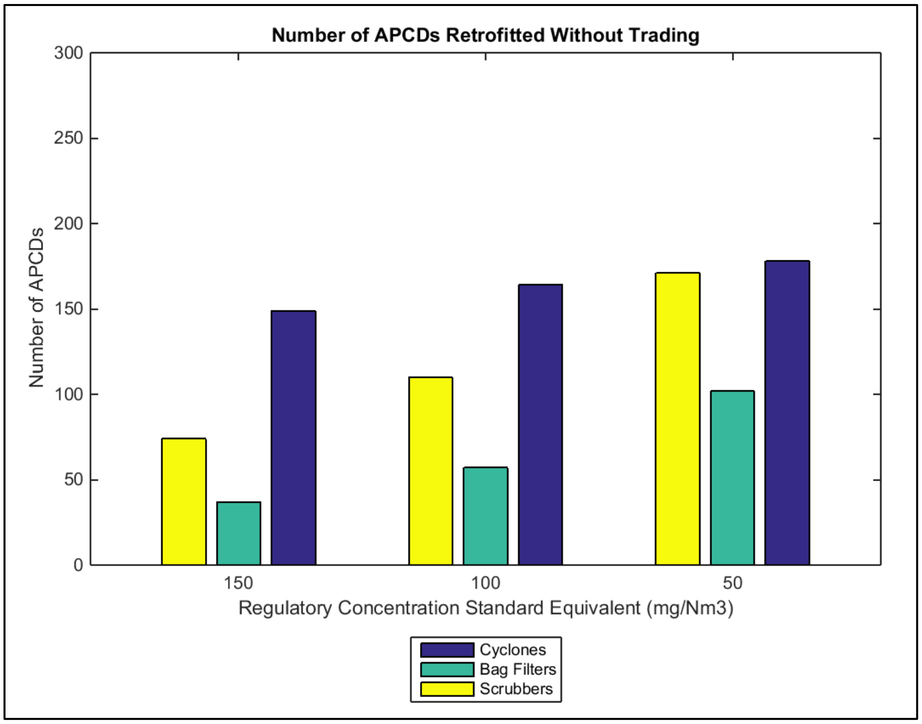


Figure 10 Number of retrofits to existing APCDs in response to alternative regulatory levels with cap and trade

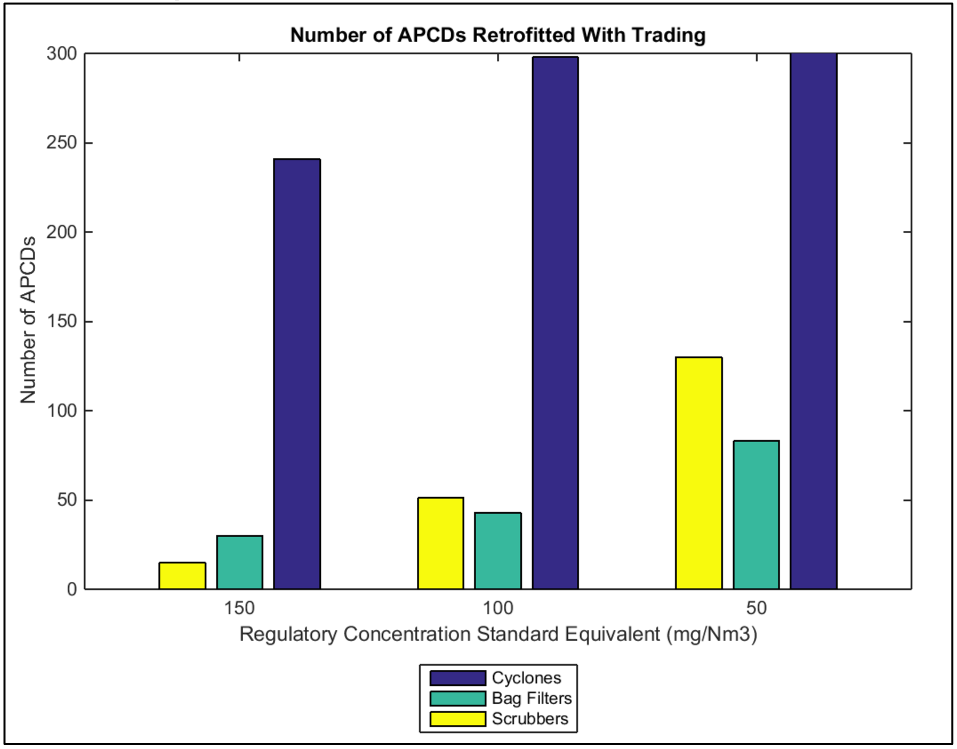


Figure 3 Number of APCDs retrofitted by industries by industries of different baseline concentrations

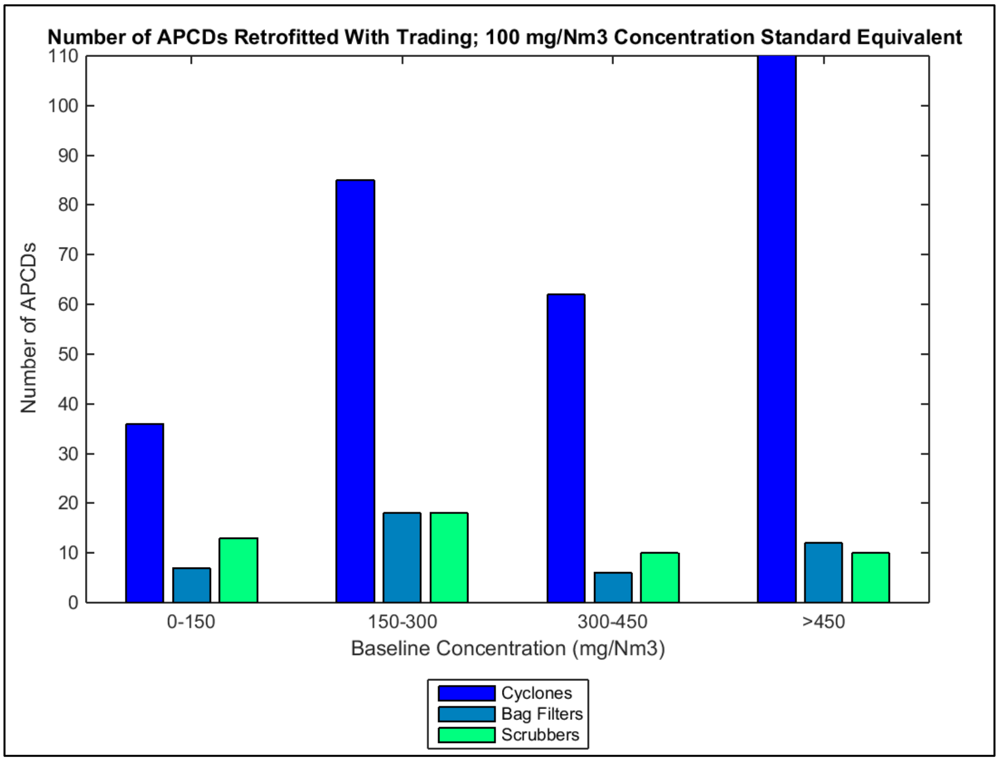
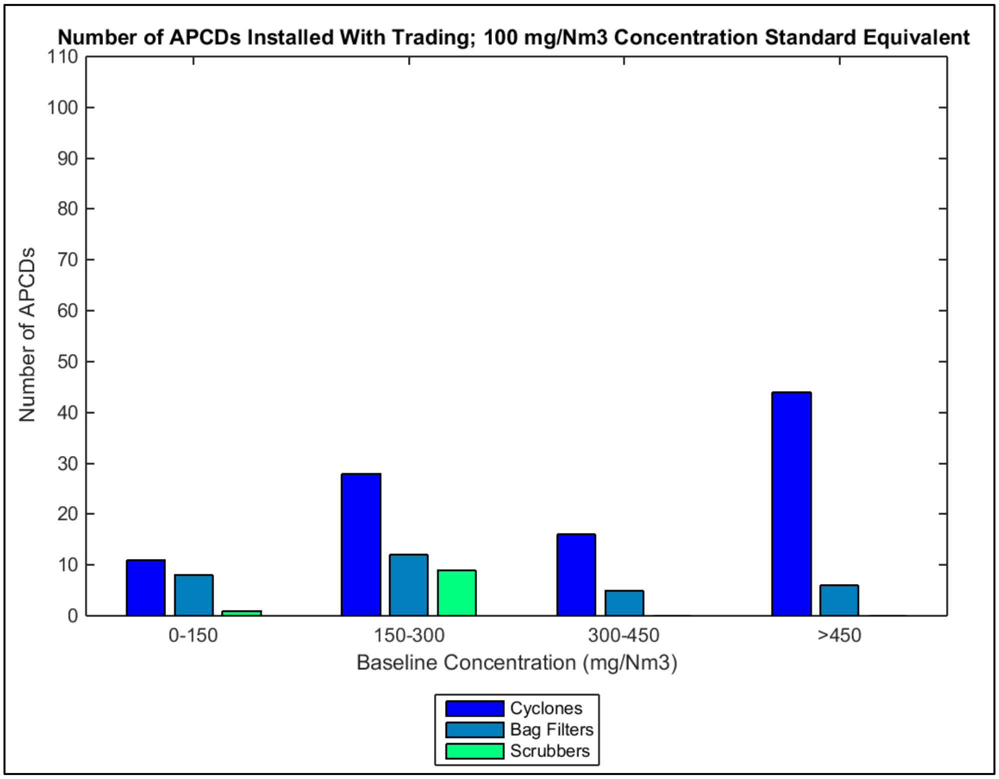


Figure 12 Number of APCDs installed by industries of different baseline concentrations

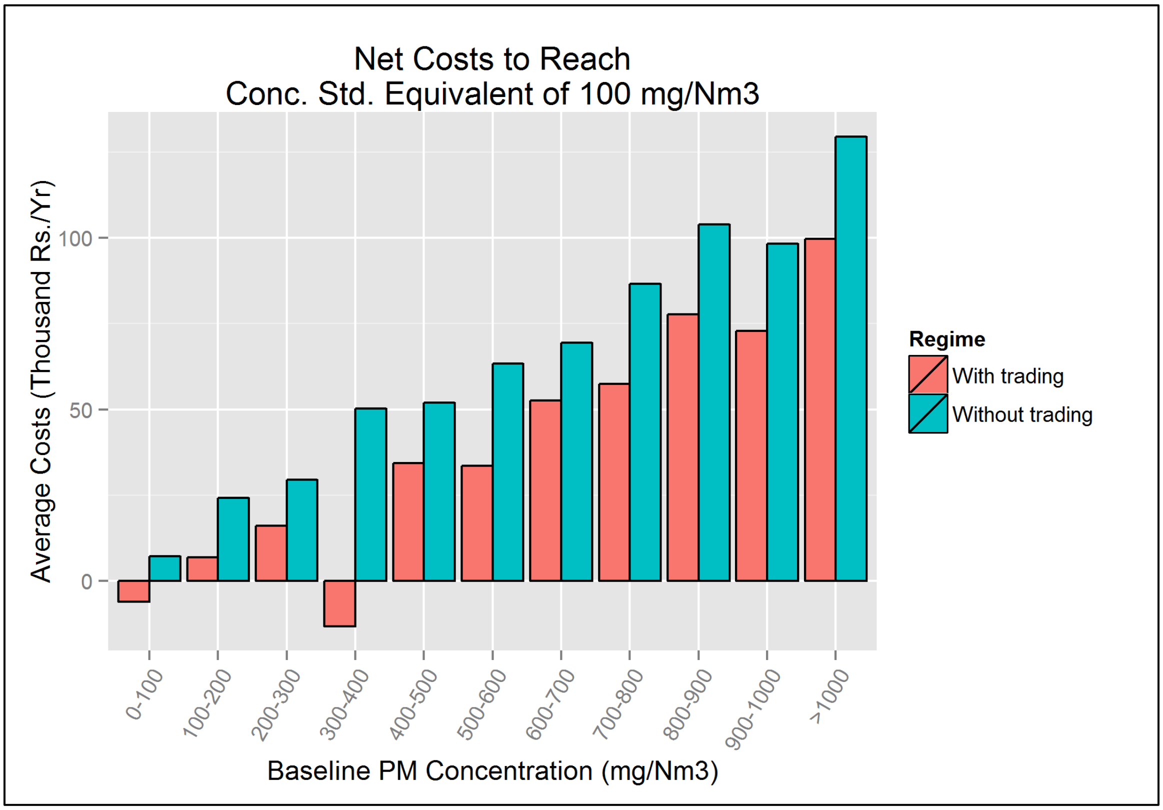


3.4.4 DISTRIBUTION OF ABATEMENT COSTS ACROSS INDUSTRIES

Figures 15 and 16 show the differences in abatement actions among these groups of industries, with an emissions cap that corresponds to 100 mg/Nm^3. As would be expected, the number of installations and retrofits are proportionally higher for industries with higher baseline concentrations. It is worth noticing that industries with low emissions are also installing and retrofitting their APCD equipment with trading.

Figure 17 compares the abatement costs for industries with different baseline concentrations for the command-and-control and cap-and-trade regimes. In general the costs are lower with trading, as would be expected. For industries in the lowest concentration level, cap-and-trade leads to revenues from permit sales.

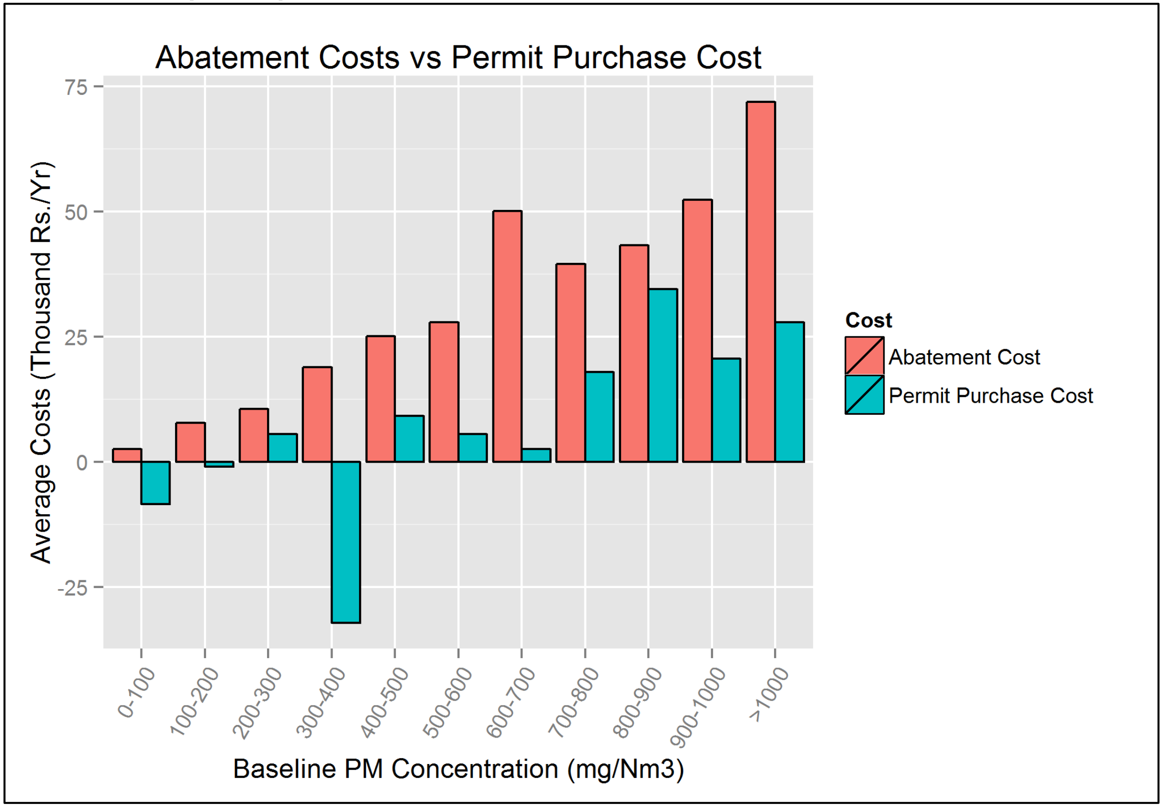
Figure 43 Average abatement costs for industries under command and control and cap-and-trade



Interestingly, it looks like some industries with relative high baseline concentrations (300-400 mg/Nm^3) also have net positive revenues with trading. Figure 14 explores the net abatement costs further by separating the new abatement measures undertaken with permit purchase costs. It would seem that some industries between 300-400 mg/Nm^3 have especially low marginal costs of abatement, which would make such a situation possible.

Figures 13 and 14 show that the abatement costs is not linear on average with baseline concentration. This should not be surprising as permit allocation is dependent on boiler capacity, and there is significant heterogeneity among industries with the same APCD configurations.

Figure 54 Breakdown of net abatement costs with trading into costs of abatement measures and permit purchase



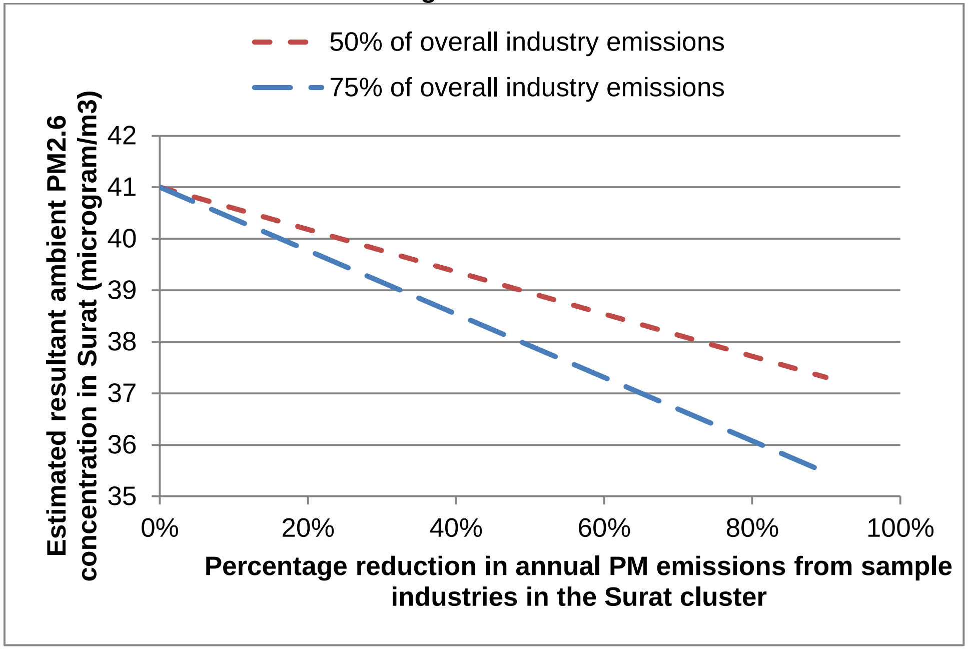
4. HEALTH BENEFITS FROM REDUCED POLLUTION

Particulate matter becomes more dangerous as the diameter of the PM particles decreases. With the air pollution control equipment installed at the industries, most of the PM released from industrial stacks tends to be smaller than 10 µm in diameter (designated as PM_{10}). A fraction of these particulates are smaller than 2.5 µm in diameter (designated as $PM_{2.5}$). The smaller the particles, the greater the risk of their entering human lungs; and hence, the greater their impact on health. Jawahar and Guttikunda (2014) estimate that the industrial contribution to ambient $PM_{2.5}$ concentrations in cities in Gujarat tends to be between 4% (Ahmedabad) and 36% (Rajkot). In the case of Surat, they estimate this proportion to be about 20%. Industrial contributions to ambient PM_{10} is lower at 12%; in contrast, larger road dust particles accounts for a third of PM_{10}, and only about 8% of $PM_{2.5}$.

Ambient $PM_{2.5}$ concentration in Surat 41.5 $\mu g/m^3$ (CPCB, 2012), just over the national NAAQS standard of 40 $\mu g/m^3$, and four times over the WHO prescribed standard of 10 $\mu g/m^3$. It should be noted here that Surat is a relatively populous industrial city with 4.5 million people (Census, 2011). As a result, we should expect to see a large beneficial impact on health with the reduction of PM emissions from Surat's industries.

Our sample of industries includes the top 350 emitters of PM from the Surat industrial cluster. In other words, PM emissions from among the industries will account for most of the industrial emissions in and around Surat city. Assuming that a reduction of PM emissions has a proportionate reduction in the industrial component of Surat's PM 2.5 emissions, and assuming that the sample industries account for (a conservative) 50% or 75% of overall industry emissions in the region, Figure 15 gives the estimated ambient concentration in Surat. The results suggest that a 50% reduction in baseline industrial emissions could lead to a reduction by 2-3 $\mu g/m^3$. 50% reduction in aggregate baseline emissions would correspond to the load weighted average emissions from the industries being equal to the current regulatory standards.

Figure 15 Estimated ambient concentrations in Surat with alternative levels of emissions reduction in the Surat cluster with surveyed industries accounting for 50% and 75% of all industrial PM emissions in the region



There are not many estimates for life expectancy gains with PM reduction in the Indian context. Most estimates (e.g. Pope et al., 2009; Correa et al., 2013) are for the American context where the ambient concentrations tend to be significantly lower. A more comparable estimate can be derived from Chen et al. (2013) for China, where ambient concentrations are similar to what they are in India. However the estimates are for Suspended Particulate Matter (less than 100 µm in diameter), and would need to be adapted for the $PM_{2.5}$ case. We follow the estimates from Greenstone et al. (2015), which was coauthored by all the Principal Investigators on this grant. Table 7 reports alternative estimates for life expectancy gains due to $PM_{2.5}$ reduction.

Table 7 Summary of Estimates of Marginal Impacts of PM2.5 on Life Expectancy and Infant Mortality Rates (*- Life expectancy interpretations from Pope and Dockery (2013) (as reported in Greenstone et al, 2015)

Source:	**Increase in Life Expectancy per 10 µg/m3 decrease in PM2.5 (years)**
Chen, Ebenstein, Greenstone, and Li (2013)	1.00
Pope, Ezzati, and Dockery (200)9	0.61
Correia, Pope, Dockery, Wang, Ezzati, and Dominici (2013)	0.35
Pope et al. (2002) *	0.73
Laden, Schwartz, Speizer, and Dockery (2006)*	1.80
Hoek et al. (2013)*	0.73

Based on these estimates, we can estimate what the life expectancy gains could be expected from a reduction of industry emissions by 50% or alternatively, a reduction in $PM_{2.5}$ concentrations by 2-3 μg/m^3. Based on the life expectancy improvement estimates above, this would lead to an average increase of 0.1- 0.3 years. With a population of 4.5 million in Surat, this would lead to increase in aggregate of 5.5- 14 lakh person years. The estimates have been summarized in

We will now proceed to monetize the health benefits using Value of Statistical Life estimates for India. It must be noted that there is limited literature for VSL in the Indian context, and in general, monetizing health benefits is difficult. However, we are interested in understanding the order of magnitude of the health benefits in light of the abatement costs estimated in the previous section. From an economic standpoint, the optimal level of regulatory standards is the point where the marginal private abatement cost is equal to the marginal monetized social benefit. While in practice regulatory standards may be set keeping other factors in mind, monetized health benefits provide perspective on the current standards.

For value of statistical life, we use two estimates: Rs. 1.3 million (Bhattacharya et al, 2006) and Rs. 15 million (Madheswaran, 2007). Both of these estimates are used in Cropper et al. (2015), where they study emissions from coal-based thermal power plants. Based on these estimates, we get aggregate benefits of Rs. 7 million lakhs to 200 million lakhs. The marginal benefit will be a constant number and estimated as the aggregate benefit divided by reduction of emissions in kg/year. This number is of the order of 1-30 lakhs/kg/year. These large numbers should not be surprising if we consider that Surat is a fairly populous city and a significant fraction of its air pollution is due to the nearby industrial cluster.

Table 8 Major assumptions in estimating health benefits with 50% reduction of aggregate emissions from the Surat industries

	Lower bound	**Upper bound**
Reduction in ambient concentration of $PM_{2.5}$ (μg/m^3)	2	3
Increase in life expectancy factor (years/ reduction by 10 μg/m^3 of $PM_{2.5}$)	0.6	1
Expected increase in life expectancy (years)	0.12	0.31
Overall increase in life expectancy (person-years)	5.5×10^5	1.4×10^6
VSL in India (Rs. million)	1.3×10^6	1.5×10^7
Aggregate health benefits (Rs. million)	7×10^5	2×10^7
Marginal health benefit (Rs./kg/year)	1×10^5	3×10^6

The marginal costs seen in the previous section were of the order of less than Rs. 5/kg/year, even at a third of the current concentration level (see figure 6). As the standards become stringent, the costs go up quite steeply. If the marginal health benefits are actively considered, we should be able to justify significantly more stringent standards in Surat. With a less populous city close to the industrial cluster, or if industrial emissions formed a smaller chunk of the existing ambient air pollution, or if the air pollution levels were lower to begin with, the health benefits of reduced pollution may not be quite as large.

5. BOILER EFFICIENCY IMPROVEMENTS

The discussion so far suggests that while the health benefits from reduced pollution are quite large, abatement costs are quite modest. The latter in particular would suggest that compliance rates are low not because abatement costs are prohibitive but because of largely ineffectual regulation. On the other hand, the health benefits underscore the magnitude of the problem and suggest that the regulatory standards could be tightened significantly.

In this section, we discuss the potential for “win-win-win” solutions: abatement measures that could reduce PM emissions as well as greenhouse gas emissions, while also leading to fuel savings for the industry. The marginal costs for such abatement measures would be negative. In reality, improving combustion source efficiency is not one abatement action but several small ones. With these “win-win-win” scenarios in mind, the Government of India has launched a National Mission on Enhanced Energy Efficiency, and international organizations including US AID, through the ECO III project, JICA and GIZ have supported industrial energy-efficiency measures in Indian manufacturing firms. However, energy inefficiency remains a common problem, especially among the small and medium industries like those that make up more than 90% of Surat’s industries.

A useful indicator of energy inefficiency in industries is the percentage of CO_2 in the flue gas in the stack. While in the atmosphere, CO_2 occupies only 0.039% of the volume of dry air, in the stack this percentage should be about 12% with an optimal fuel:air ratio. If CO_2 percentage is lower, it would suggest excess air being sent into the boiler. For complete combustion, industries would need to have air 20% in excess. However, any more than that is just deadweight loss as extra fuel would need to be combusted to take this air from room temperature to the higher temperatures of the flue gas. The excess air problem is symptomatic of general boiler efficiency and could be fixed with automatic fuel inputs and other mechanized controls. One problem in small and medium enterprises in Surat is that the boiler is often fed manually and supervised by operators who are usually short-term contracted labor and are not usually well trained. Furthermore, managers running the industrial plants have limited visibility in the boiler operations. The combination of these results in sub-optimal operations and high inefficiency losses.

In the analysis that follows, we estimate fuel savings, and GHG and PM reductions after fixing the excess air problem. Volume of excess air is determined using the proportional deviation of CO_2% in the stack from the ideal 12%, and the measured volume flow rate in the stack. We then compute the additional fuel needed to heat this excess air from room temperature to the temperature in the stack. Knowing the typical calorific value of bituminous coal, we can estimate the fuel saved; this can then be expressed in terms of saved fuel expenditure. Reduction in GHG emissions is estimated using GHG emissions factor for a ton of bituminous coal. Similarly, reduction in PM emissions is estimated using the PM emissions factor recommended by the EPA for bituminous coals with known ash content. The assumptions used are summarized in Table 9 below.

Table 9 Assumptions made while estimating energy efficiency gains

Ideal outlet CO_2 percentage	12	%
Recommended excess air	20	%
Specific heat capacity of air	1.01	kJ/kg-K
Density of air	1.20	kg/m3
Calorific value of coal	20125	kJ/kg

Air room temperature	20	degree C
Ash content in bituminous coal	15	%
PM emissions factor (per pound)	150	g/lb of coal
PM emissions factor (kg/ton)	68	kg/ton
Fly ash percentage	70	%
Price of coal	1400	Rs./ton
CO_2 emissions factor	2.15	ton CO2/ton coal
Social cost of carbon	40	USD
Exchange rate	62	Rs./USD

Figure 16 plots the estimated fuel savings with the percentage reduction of PM emissions from baseline levels. As would be expected, these are positively correlated; in general, the greater the scope for fuel savings, the greater the reduction of PM emissions. Fuel savings and GHG reduction would be exactly linear, as GHG reductions would be linearly proportional with fuel reduction. On the other hand, with PM we will have air pollution control equipment of varying levels of efficiency.

Figure 16 Estimated savings in fuel expenditure with corresponding reduction of PM emissions from baseline

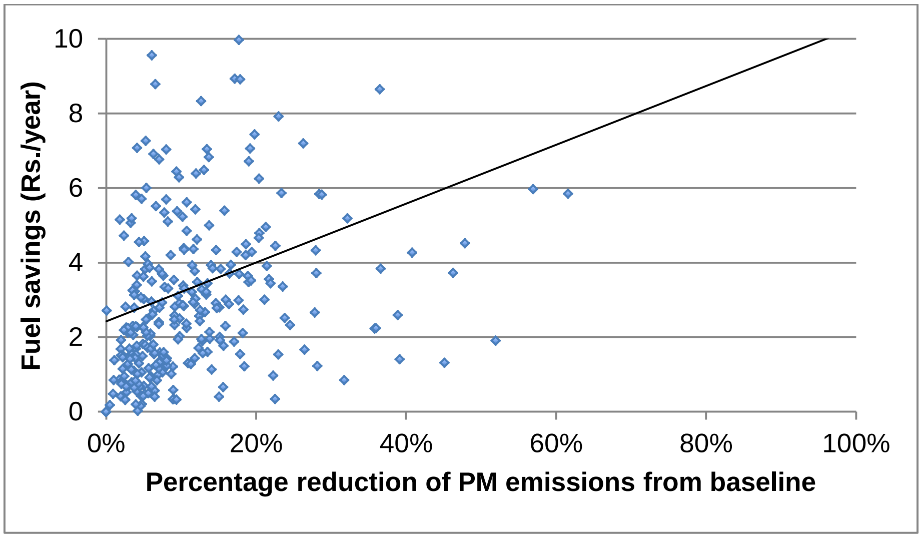
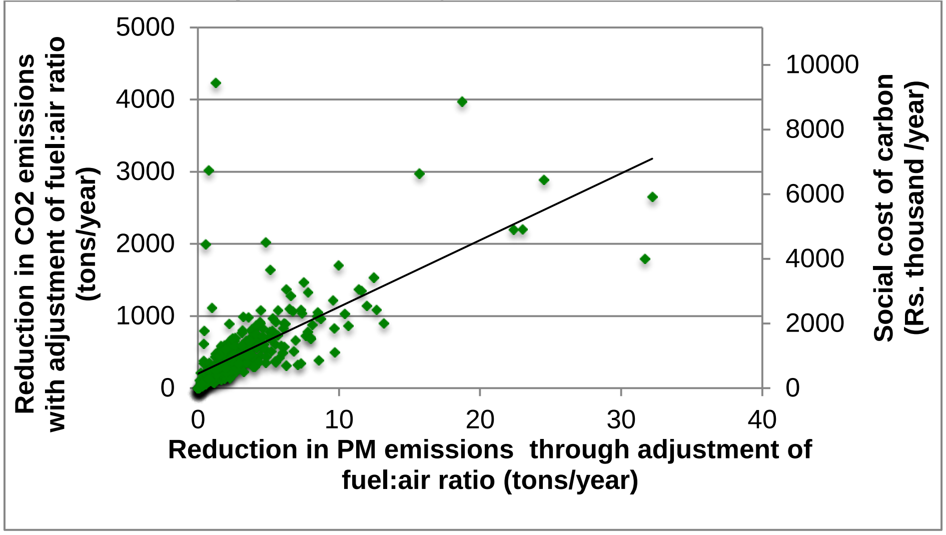


Figure 17 plots the reduction in the two pollutants. If monetized using EPA's Social Cost of Carbon estimates, aggregate greenhouse gas emission reductions from Surat industries due to improved efficiency could exceed Rs. 400 million/year.

Figure 17 Correlation between reduction in greenhouse gas and particulate matter emissions with improved efficiency



One of our own research team members, Nicholas Ryan, has conducted a large-scale randomized-controlled trial amongst energy-intensive textile and chemical plants in Gujarat to understand the reasons for low levels of efficient technology adoption. The main finding of the study, for which analysis is still in progress, is that adoption of technology and energy savings were low despite very high projected returns. The median projected return on measures recommended to sample plants was 104% per year, yet treatment plants were estimated to have invested only several hundred dollars more than control plants on efficient capital, a trivial fraction of their overall capital stock. Boiler efficiency improved modestly but there was no reduction seen in energy consumption. A leading explanation for this result is that, while projected returns are high, many measures are small, and firms do not wish to spend the time and expertise required to pick up all these small returns. That is, it may be economically efficient to leave one's plant somewhat energy *inefficient,* in the absence of any external incentive such as pollution regulation.

6. DISCUSSION

In summary, the major takeaways of this study are as follows.

- Costs of abatement for the industries are modest, with most abatement actions involving upgrades to and improved maintenance of existing equipment.
- Social health benefits vastly exceed private abatement costs, and justify a very stringent standard.
- Energy efficiency improvements exist that lead to private benefits and reduce PM and GHG emissions, but these savings are rarely realized.
- Low cost abatement actions and efficiency improvements may be undertaken only if regulation was more effectively monitored.
- A combination of continuous emissions monitoring to improve regulatory oversight, and emissions trading to reduce costs of compliance to industries could provide the missing stick and carrot, respectively, for industries to reduce emissions.

The abatement cost analysis indicates that most industries are able to meet the standards by retrofitting existing equipment. In Surat, although there is a high fraction of industries with baseline concentration exceeding the regulatory standard, 64% of industries have scrubbers in their APCD chain and 59% have bag filters. Scrubbers and bag filters have high collection efficiencies and if maintained and operated well, no additional abatement measures are needed to comply.

The second major result of the abatement modeling is that cap and trade reduces costs of compliance, relative to command and control. At an emissions cap equivalent to 100 mg/ Nm^3 in the Surat cluster, average costs of compliance with trading are less than 50% of the costs of compliance without trading. The model results provide a strong argument to allow industries to trade permits among themselves to reduce overall emissions at low costs. The reduction in overall costs can be attributed to

- One, industries, that are polluting at lower than assigned permits, have an incentive to retrofit their existing equipment if their costs are lower than the cost of selling permits
- Two, industries that are polluting in excess of their permits may prefer to buy permits than purchase new abatement equipment

As a result, with trading, there are more retrofits to existing equipment than in the command and control case, and fewer new installations of equipment. The analysis of the model results substantiates these. We also find that cyclones are retrofit more often, as they are relatively less expensive and industries could purchase permits instead of making more expensive retrofits or purchase.

While the abatement costs are relatively low, the health benefits are quite substantial. $PM_{2.5}$ is one of the most problematic pollutants in India, and most Indian cities have average ambient concentrations greater than the NAAQS standard, and several times the WHO standards. A reduction in $PM_{2.5}$ concentration by 10 $\mu g/m^3$ leads to an increase in average life expectancy by 0.6-1 year. We estimate the a 50% reduction in baseline emissions from the Surat cluster (leading to the load-weighted average concentration reaching existing regulatory standards) leads to an average increase in life expectancy by 0.12-0.34 years and in aggregate, 0.4-1.5 million person-years in Surat city. If monetized using estimates of Value of Statistical Life in India, the aggregate and marginal health benefits are 4-5 orders of magnitude greater than the corresponding costs. The results suggest that regulatory standards could be significantly more stringent than they currently are.

While abatement costs in general are low, there is one set of abatement measures related to energy efficiency improvements at the combustion source (e.g. boilers, thermic fluid heaters) that could potentially have negative costs—due to fuel savings for the industry. Fuel savings and attendant PM and greenhouse gas emission reductions are estimated, using CO_2 in the stack as an indicator of excess air. We estimate that the average fuel savings is in the range of Rs. 2-3 lakh/ year. On average, about 10% reduction of baseline emissions could be achieved, and 500 tons of CO_2 emissions could be avoided. Aggregating over the cluster, fixing the excess air issue with energy efficiency retrofits could abate 160,000 tons of CO_2. The difficulty in realizing these fuel savings and the potential emission reductions is that the energy efficiency improvements involve many small measures, and can vary from one industry to another. In the absence of effective regulation, industries may not have sufficient motivation to explore these measures, despite high rates of return for such investments.

In this context, CEMS could play a critical role in improving regulatory oversight by providing real time, granular information on industrial emissions. CEMS would also allow for the regulatory parameter to change from the current concentration standards to load permits, which is the more relevant parameter for PM. This shift to load permits paves the way for introducing emissions trading. A combination of improved monitoring and market-based regulation could lead a reduction in emissions, and at reduced costs of compliance. Effective regulation could push industries to realize energy efficiency gains or make low cost retrofits to existing poorly maintained equipment, and lead to cleaner air and better health in India’s over-polluted cities and industrial clusters.

REFERENCES

Bhattacharya, S., Alberini, A., & Cropper, M. L. (2007). The value of mortality risk reductions in Delhi, India. *Journal of Risk and Uncertainty, 34*(1), 21-47.

Chay, K. Y., & Greenstone, M. (2003). The Impact of Air Pollution on Infant Mortality: Evidence from Geographic Variation in Pollution Shocks Induced by a Recession. *The Quarterly Journal of Economics, 118*(3), 1121-1167.

Chen, Y., Ebenstein, A., Greenstone, M., & Li, H. (2013). Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. *Proceedings of the National Academy of Sciences, 110*(32), 12936-12941.

Correia, A. W., Pope, C. A., 3rd, Dockery, D. W., Wang, Y., Ezzati, M., & Dominici, F. (2013). Effect of air pollution control on life expectancy in the United States: an analysis of 545 U.S. counties for the period from 2000 to 2007. *Epidemiology, 24*(1), 23-31.

CPCB. (2006). Air Quality Trends and Action Plan for Control of Air Pollution from Seventeen Cities. Central Pollution Control Board, Government of India. *Available at http://www.cpcb.nic.in/upload/NewItems/NewItem_104_airquality17cities-package-.pdf*.

CPCB. (2009a). Ambient Air Quality Standards. Central Pollution Control Board, Government of India. *Available at http://cpcbenvis.nic.in/airpollution/standard.htm*.

CPCB. (2009b). Comprehensive Environmental Assessment of Industrial Clusters. Central Pollution Control Board, Government of India. *Available at http://www.cpcb.nic.in/upload/NewItems/NewItem_152_Final-Book_2.pdf*.

CPCB. (2010). National Air Quality Monitoring Program. Central Pollution Control Board, Government of India. *Available at http://cpcbenvis.nic.in/airpollution/finding.htm*.

CPCB. (2011). Air Quality Monitoring, Emission Inventory and Source Apportionment Study for Indian Cities: National Summary Report. Central Pollution Control Board, Government of India. *Available at http://cpcb.nic.in/FinalNationalSummary.pdf*.

CPCB. (2013). Specifications and Guidelines for Con- tinuous Emissions Monitoring Systems (CEMS) for PM Measurement with Special Reference to Emission Trading Programmes. Central Pollution Control Board, Government of India*. Available at http://cpcb.nic.in/upload/NewItems/New-Item_202_CEMS_Specs_v21-11-13v_cpcb.pdf*

Cropper, M., Gamkhar, S., Malik, K., Limonov, A., & Partridge, I. (2012). The Health Effects of Coal Electricity Generation in India. Resources for the Future Discussion Paper.

Duflo, E., Greenstone, M., Pande, R., & Ryan, N. (2013). Truth-telling by Third-party Auditors and the Response of Polluting Firms: Experimental Evidence from India. *The Quarterly Journal of Economics, 128*(4), 1499–1545.

EPA. (2015). Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. Environmental Protection Agency, USA.

Greenstone, M., Nilekani, J., Pande, R., Ryan, N., Sudarshan, A., & Sugathan, A. (2015). Lower pollution, longer lives life expectancy gains if India reduced particulate matter pollution. *Economics and Political Weekly, 8*, 40-46.

Hoek, G., Krishnan, R. M., Beelen, R., Peters, A., Ostro, B., Brunekreef, B., & Kaufman, J. D. (2013). Long-term air pollution exposure and cardio-respiratory mortality: a review. *Environmental Health, 12*(1), 43.

Jawahar, P., & Guttikunda, S. (2011). Urban Air Pollution Analysis in India. *SIM-AIR Working Paper Series. Available at urban-emissions.info*.

Laden, F., Schwartz, J., Speizer, F. E., & Dockery, D. W. (2006). Reduction in Fine Particulate Air Pollution and Mortality. *American Journal of Respiratory and Critical Care Medicine, 173*(6), 667-672.

Madheswaran, S. (2007). Measuring the value of statistical life: estimating compensating wage differentials among workers in India. *Social Indicators Research, 84*(1), 83-96.

Pope, C. A., & Dockery, D. W. (2013). Air pollution and life expectancy in China and beyond. *Proceedings of the National Academy of Sciences, 110*(32), 12861-12862.

Pope, C. A., Ezzati, M., & Dockery, D. W. (2009). Fine-particulate air pollution and life expectancy in the United States. *The New England journal of medicine, 360*(4), 376-386.

Pope, I. C., Burnett, R. T., Thun, M. J., & et al. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA, 287*(9), 1132-1141.

Ramanathan, V., & Carmichael, G. (2008). Global and regional climate changes due to black carbon. *Nature Geoscience, 1*(4), 221-227.