Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Department of Economics

The cost-efficient abatement strategy for primary $PM_{2.5}$ emissions between sectors in Delhi to reach the national air quality standard

– A static model approach using the current legislation baseline scenario

Christoffer Karlsson

Independent project · 15 hec · Basic level
Agricultural Programme – Economics & Management
Degree thesis No 1157 · ISSN 1401-4084
Uppsala 2018

The cost-efficient abatement strategy for primary $PM_{2.5}$ emissions between sectors and surrounding states to reach the national air quality standard in Delhi

- A static model approach using the current legislation baseline scenario

Christoffer Karlsson

Supervisor: Franklin Amuakwa Mensah, Swedish University of
Agricultural Sciences,
Department of Economics

Examiner: Robert Hart Swedish University of
Agricultural Sciences,
Department of Economics

Credits: 15 hec
Level: G2E
Course title: Independent project in Economics
Course code: EX0808
Programme/education: Agricultural Programme – Economics & Management
Faculty: Faculty of Natural Resources and Agricultural Sciences

Place of publication: Uppsala
Year of publication: 2018
Name of series: Degree projects/SLU, Department of Economics
NO: 1157
ISSN: 1401-4084
Online publication: http://stud.epsilon.slu.se

Keywords: Air Pollution, Delhi, GAINS, India, MAC, Marginal Abatement Cost, Optimization, $PM_{2.5}$

Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Faculty of Natural Resources and Agricultural Sciences
Department of Economics

Acknowledgements

I would like to thank my supervisor Franklin Amuakwa Mensah for guiding me through the many uncertainties and obstacles in the process. I would also like to thank Robert Sander at the IIASA institute for granting me access to the GAINS South Asia model and helping me understand and use the framework.

Abstract

High level of ambient $PM_{2.5}$ concentration in cities have negative health implications for the population. Delhi have concentration levels above defined national standards as well as air quality guidelines defined by the WHO. The study estimates sector specific MAC functions for sectors in Delhi contributing to the primary $PM_{2.5}$ emissions, to find the cost-efficient strategy to reach the national air quality standard for annual population-weighted mean concentration. Different scenarios will be tested giving primary emissions from sectors in Delhi different levels of responsibility in the abatement strategy. The cost-minimization problem is conducted using economic programming with bottom up emission calculations and abatement data based on the GAINS model. Actual data from monitoring stations in Delhi is used to compare with the model estimations and used to derive a regression model with meteorological factors and seasonal dummy variables to further evaluate cost efficiency. For reaching the policy goal, most measures available must be implemented across the sectors giving primary emissions the share of the reduction it contributes. The regression model shows relationship between the concentration and the exogenic meteorological factors including the seasonal dummy variables. The results indicate that variation in activity rates or other seasonal dependent variables not included in the model effect the concentration between the seasons.

Sammanfattning

Höga nivåer av $PM_{2.5}$ koncentration i städer har en negativ inverkan på befolkningens hälsa. Delhi har koncentrationsnivåer som överskrider definierade nationella standarder samt riktlinjer för luftkvalitet som fastställts av WHO. I studien uppskattas sektorspecifika MAC-funktioner för sektorer i Delhi som bidrar till de primära $PM_{2.5}$ utsläppen, för att fastställa den kostnadseffektiva strategin för att nå den nationella luftkvalitetsstandarden för årlig befolkningsvägd medelkoncentration. Olika scenarier kommer att testas, vilket ger primära utsläpp från sektorer i Delhi olika ansvarsnivåer i minskningsstrategin. Kostnadsminimeringsproblemet genomförs med hjälp av ekonomisk programmering med nedifrån beräknade utsläpp och reduktionsdata baserat på GAINS-modellen. Faktiska data från övervakningsstationer i Delhi används för att jämföra med modellberäkningarna och estimera en regressionsmodell med meteorologiska faktorer och säsongsvariabler för att ytterligare utvärdera kostnadseffektiviteten. För att nå det politiska målet måste de flesta åtgärderna genomföras i strategin där de primära utsläppen har andelen av minskning som motsvarar andelen de bidrar med. Regressionsmodellen visar förhållandet mellan koncentrationen och de exogena meteorologiska faktorerna inklusive de säsongsmässiga dummyvariablerna. Modellen indikerar att variation i aktivitetsnivåer eller andra säsongsberoende variabler som inte är inkluderade i modellen påverkar koncentrationen mellan årstiderna.

Table of contents

List of Figures

List of Tables

$\mu g/m^3$ = micrograms per cubic meter
CPCB = Central Pollution Control Board
EEA = European Environmental Agency
EPA = United States Environmental Protection Agency
FOC = First-order conditions
GAINS = Greenhouse gas – Air pollution Interactions and Synergies
IIASA = International Institute for Applied Systems Analysis
MAC = Marginal Abatement Cost
NH_3 = Ammonia
NO_x = Nitrogen Oxide
PM = Particulate Matter
SO_x = Sulfur Oxide
VOCs = Volatile Organic Compounds
WHO = World Health Organization

1 Introduction

The paper sets out to apply the concept of economic efficiency in the development of abatement strategies tackling the issues of $PM_{2.5}$ pollution in Delhi. The policy interest concerning air pollution centers around current developments of cities failing to reach defined air quality targets and the underling health risks it implies for the population exposed to it. According to a report by the WHO (2016a), three million deaths were attributed to ambient air pollution globally for the year 2012. Air pollution is generated from various economic activities where emission rates are affected by the fuel and technology used for activities. From a report by the WHO (2016b) there is clear pattern where low- and middle-income countries are subject to a larger share of cities with more than 100 000 inhabitants exceeding defined air quality targets in comparison to high-income countries. This poses a great challenge for policy makers in low- and middle-income countries to both promote economic growth but also reduce the negative externalities generated by the economic activities.

Particulate matter (PM) is one of the pollutants carrying negative health effects for people exposed to it. PM emissions is a complex mixture of air-borne particles and liquids droplets composed of acids, ammonium, water, black or elemental carbon, organic chemicals, metals and soil materials (EPA, 2017). According to the WHO (2013) in a paper about the health effects generated from exposure of high PM concentration, there are both long term and short-term effects. Short term effects include reduced respiratory capacity while long term exposure can lead to asthma, hearth problems and death. The PM emissions is categorized by the size of its diameter, where $PM_{2.5}$ is the fine particulate matter with a diameter of less than 2.5 microns and PM_{10} is particulate matter with a diameter of less than 10 microns (EPA, 2017). Delhi has concentration levels of both $PM_{2.5}$ and PM_{10} that exceeds the WHO guidelines and defined national standards (CPCB, 2015).

The Indian national air quality standard for $PM_{2.5}$ defined by the Ministry of environment and forest (2009) is set at the acceptable 24 hours mean of 60 $\mu g/m^3$ and at the acceptable annual mean of 40 $\mu g/m^3$. The annual popuation-weighted mean concentration based on data from the WHO (2016c) was 122 $\mu g/m^3$ for the year 2013 which is above the defined standard. The need for improvement and policy intervention is well documented, and efforts are needed from government officials to lower the high concentration level of $PM_{2.5}$.

The paper seeks to find answers to the following research questions:

1) What is the cost-efficient distribution of abatement efforts for primary $PM_{2.5}$ emissions between contributing sectors in Delhi that will lower the $PM_{2.5}$ concentration to the acceptable annual mean of 40 $\mu g/m^3$?
2) How do the variation in the concentration level between seasons in Delhi effect the cost-efficiency of the derived abatement policy?

To evaluate the annual mean concentration for the whole Delhi, the annual population-weighted mean concentration will be used as the defined policy goal. This makes it possible to looking at policy implementation for a big area, taking into account local differences and weighing the local concentration levels according to the population share. Because the interest of policy makers centers around health implications from exposure of ambient $PM_{2.5}$ pollution, this gives the paper a policy relevant focus.

By looking at only the primary emissions from sectors in Delhi, two scenarios will be tested for reaching the defined concentration level. This is because the concentration level in Delhi is also affected by emissions from surrounding states and secondary emissions. Scenario one will assign the whole reduction of $PM_{2.5}$ emissions to the primary emissions from sectors in Delhi too test if these measures on their own can reach the defined annual population-weighted mean concentration. Scenario two will assign the share of the reduction equal to the share that the primary emissions from sectors in Delhi contributes to the annual population-weighted mean concentration. This scenario takes the perspective of an abatement strategy where emissions from surrounding states as well as secondary emissions are incorporated.

The focus on cost-effectiveness has not been the primary focus of previous research looking at Delhi and this paper aims to contribute to the understanding of specific sectors role in cost-efficient abatement strategies. In addition, the incorporation of seasonal variation in the analysis of cost-efficiency for $PM_{2.5}$ abatement strategies have not been applied in prior studies to the knowledge of the author.

The paper will continue with a presentation of current literature and theoretical framework. This will show application and methodology in similar studies as well as describe current findings in the subject of $PM_{2.5}$ emissions and policy strategy development. The methodology used for the paper will then be explained and data used in the study will be presented and described. Finally, the results, discussion and conclusion will be presented.

2 Theoretical perspective and literature review

Relevant literature and theoretical frameworks will be presented for both atmospheric science and environmental economics in the forthcoming sections.

2.1 $PM_{2.5}$ emissions and concentration

$PM_{2.5}$ pollution is of interest for both environmental economics as well as air pollution science. Hill, Marshall & Tessum (2017) describes in their paper the properties of the primary and secondary $PM_{2.5}$ emissions. The primary emissions are directly emitted through anthropogenic activities while the secondary is formed in the atmosphere by natural processes from VOCs, SO_x, NO_x and NH_3. The spatial distribution of both the primary and secondary emissions can be intercontinental but also variable around the emission source. The relationship between emissions and concentration is therefore complex and highly variable. This is further discussed in a report by the European Environmental Agency (EEA) (2013) describing important exogenic variables affecting the concentration level such as meteorological factors and other geographical characteristics. The relationship is investigated in a report submitted to the Delhi Pollution Control Committee by Sharma (2016) focusing on air pollution and greenhouse gas emissions where seasonal variation in meteorological factors are examined in Delhi. Factors that are evaluated are wind speed, wind direction, temperature and precipitation. These factors are shown to affect the concentration level by its impact on the dispersion of the emissions. In another paper by Gurjar & Guttikunda (2012) the subject is further evaluated, where the meteorological conditions are described to be important for places like Delhi that is characterized by flat terrain and therefore have higher impact on the dispersion of the emissions. The modeling aspect of PM concentration is explained in a paper by Lind et al. (2015) where a regression model is estimated with the incorporation of a lag for the concentration by including the previous day’s observation. The result showed higher explanatory power to the model and can be linked to the fact that PM emissions can be active in the atmosphere for multiple days.

2.2 Source contribution

The source contribution of $PM_{2.5}$ emissions is necessary for being able to put abatement efforts where the desirable effect can be reached. There are multiple methods for estimating source contribution of $PM_{2.5}$ emissions. One method is to analyze data from monitoring stations measuring the concentration levels and applying receptor modeling. In a paper by Jeong et al. (2017) the methodology is described for a case study in South Korea for $PM_{2.5}$. It is a mathematical procedure that uses data on chemical and meteorological characteristics on PM measures from the monitoring site to estimate source contribution. This method is also applied in the report by Sharma (2016) at multiple monitoring stations in Delhi.

The bottom up emission calculation is an alternative method using emission factors and corresponding activity data. The emission factor describes how much a unit of a given activity emits of a specific pollutant. The emission factors are in most cases averages of available data and is described by the United State Environmental Protection Agency (EPA) (2016) as representative factors for long-term averages for the specific source category. It could be argued that the bottom up method is preferred regarding the usability and lower cost for applying in research purposes. The method also creates a heterogenic framework that can be applied and developed on multiple scales, while losing some of the accuracy that the receptor modeling method captures. The bottom up emission calculation method is used for the Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model (IIASA, 2017). The GAINS model is a web-based tool for developing and testing policy strategies. It is created by the International Institute for Applied Systems Analysis (IIASA) and contains cost estimations for end-of-pipe abatement measures, emission factors and yearly activity estimations. The end-of-pipe abatement measures are measures applied at the end of the line in the activity chain and only affects the emissions, not the activity rate itself. The GAINS model has been developed for different spatial scales, where global as well as regional perspectives can be investigated, and area specific conditions are applied for given spatial scales. The methodology for the GAINS model is presented in a report by Amann et al. (2008). The model applies different scenarios that are assuming different pathways for policy implementation while also considering population growth and changes in activities over time. The model incorporates the chemistry transportation model TM5 to describe and capture the changes in air quality indicators in response to implementation of abatement measures or activity changes by incorporating external factors such as meteorological conditions and topographic characteristics. The relationship is used to capture the source contribution relationship and describes the connection between the emissions and the concentration.

The GAINS model has been applied in multiple studies, including a study about the effectiveness of policy strategies concerning $PM_{2.5}$ emissions in Delhi by Amann et al. (2017). The focus of the paper was to evaluate pre-defined strategies for reaching the national air quality standard of annual mean concentration by the year 2030. The advanced technology scenario sets limits for emissions in the different technologies used in the industrial sector and the Delhi clean air strategy applies limits for non-industrial activities. The paper reaches the conclusion that for a strategy to be able to reach the national air quality target, secondary emissions and surrounding states need to be incorporated. The primary emissions from sectors in Delhi are estimated to only stand for 40% of the contribution to the annual population-weighted mean concentration. The study fails to address the economic aspect of policy development but shows the need for policy strategies that incorporates emissions from outside the city boundaries. Similar studies have been conducted in other regions and countries, including a study focusing on Italy by Ciucci et al. (2016) for reaching the European directive on ambient air quality and cleaner air for Europe by the year 2030. The paper concludes that the approach of focusing on areas with lower MAC has its shortcomings in relation to the alternative where absolute limits for concentration levels are set at each local area in Italy. This has to do with the possible variation of $PM_{2.5}$ concentration between local areas and therefore implying health risks for parts of the population.

2.3 Modeling cost-efficient abatement strategies

There are multiple ways of estimating the cost-efficient abatement strategy of a specific policy goal. Based on environmental economic theory the efficient distribution between agents should be where the MAC is equal between all included agents. Common et al. (2003) writes in the book Natural Resources and Environmental Economics about optimization problems surrounding agents and firms concerning cost-minimizing abatement distribution. In the cost-minimizing optimization problem a Lagrangian function is constructed with the abatement cost function defined as the objective function and the constrains are related to the abatement policy goal and the abatement potential of the included agents. The first-order conditions (FOC) are then used to solve for the cost-efficient solution. For optimization problems, the cost function may be derived and applied, or the MAC function could be used directly. In a review paper by Chou, Huang & Kuo (2016) different approaches are described for estimating the MAC functions. The paper divides the approaches into three categories: bottom up, hybrid model and top-down. Based on the review paper, most of the examined papers use the bottom up approach. This involves a step-wise MAC curve that ranks each abatement effort by its MAC, and then the potential abatement size for the given measure. They are ranked from lowest to highest MAC where the next best measure is applied after the previous abatement potential is finished.

The bottom up MAC approach has been applied in a study for the abatement of $PM_{2.5}$ in a paper by Johansson et al. (2007) concerning Finland. The paper uses estimations for emissions, available data on abatement technologies and factors from multiple sources including the RAINS model. The RAINS model is a predecessor to the GAINS model and has a similar structure as the current framework. The paper includes only primary $PM_{2.5}$ emissions and the graphical solution is represented by sector specific stepwise MAC curves where limits for emissions as well as the baseline abatement efforts are indicated. Similar methodology have been applied by Ball et al. (2010) looking at greenhouse gas abatement strategies for the agricultural sector in the UK and in another paper by Alsalam et al. (2015) looking at global greenhouse gas abatement strategies by constructing sector specific MAC curves.

For economic optimization programing, functional forms can be derived and applied. DeCarolis, Srivastava & Vijay (2010) estimates a functional form in their paper by OLS regression for the constructed bottom up MAC curve representing coal-fired utility boilers with NO_x abatement measures. The methodology behind it is to minimize the abatement cost for each boiler, and then combining them to create the MAC function for the entire sector. The cost-minimization problem using economic optimization has further been applied to pollution policy studies, evaluating allocation of abatement measures between agents with the goal of reaching defined ambient concentration targets. In a study by Faichney et al. (1999) a Lagrangian minimizing problem is constructed with the goal of reaching a water quality target in Forth Estuary. The optimization problem consists of the abatement cost function from contributing sources to reduce emissions. To create the optimization problem focusing on the water quality the emissions are relate to the ambient water concentration by the inclusion of the transfer coefficient that takes into account necessary exogenic variables effect on the dispersion of the emissions.

2.4 End-of-pipe abatement measures in Delhi

Available end-of-pipe abatement measures varies between sector and activity type. Based on estimations from the GAINS model (IIASA, 2017) the sectors mobile sources, industrial combustion, residential combustion, industrial processes and energy have large impact on the $PM_{2.5}$ emissions in Delhi.

Mobile sources have abatement possibilities by switching to vehicles with higher European Emission Standard classification (IIASA, 2017). The standard sets limits for allowed emissions per unit activity for vehicles (European Commission, 2018). The classification ranges between 1-6 with the EURO 6 standard being the most recent and restrictive (Colsa, et al., 2016).

In the energy sector, high efficiency dedusters can be implemented to lower emissions. These dedusters are described in a paper by Komarova & Valdberg (2011) to remove suspended particles from gases released in the processes for stationary combustion. There are different types of dedusters including cyclones, scrubbers and wet scrubbers. Dedusters are also available to implement in the residential and industrial combustion sector for boilers. In the residential combustion sector, other available abatement measures include switching from kerosene lamps to LED lamps, using different fuel types and implementing new less emitting stoves in the sector (IIASA, 2017).

In the industrial processes sector, brick production is a central activity (IIASA, 2017). The available measure vertical shaft brick kiln with basic dust control is described by Andimuthu et al. (2015) to have the potential of both lowering the energy use, which could imply lower overall cost, but also reduce the emissions for the activity up to 40%. Other potential abatement measures in the sector includes efforts in aluminum- and briquette production with implementation of dedusters and good practice implementation in handling of bulk products.

Other activities that contribute to the emissions in Delhi is trash burning and the agriculture sector (IIASA, 2017). Trash burning has in previous papers by Hodzic et al. (2012) and Bergin et al. (2016) been shown to be highly associated with areas of low economic status and have high impact on the population exposure of $PM_{2.5}$. Measures available would be to ban open burning to have a less emitting management. For the agriculture sector available measures include feed modification for animals (IIASA, 2017).

3 Method

The methodology section will describe the implementation of the GAINS model, the structure of the optimization problem and the estimation of the seasonal variation for the concentration level.

3.1 Optimization problem

3.1.1 GAINS South Asia

The GAINS model will be used to derive the baseline scenario for the optimization problem. This consist of implemented abatement measures and activity rates for the different activities for the base year 2015. The model used is the GAINS South Asia model (IIASA, 2018), which takes into account regional specific characteristics regarding activities and fuel use in South Asia. The baseline scenario that will be applied in the paper is the predefined scenario ECLIPSE v.5a CLE (IIASA, 2016). The CLE scenario considers the current legislation and defines abatement implementation at given years depending on legislation and current policy strategies.

The activities and corresponding abatement measures are categorized into sectors for the optimization problem in similar manner as the GAINS sector categorization (IIASA, 2017). The sectors consist of; mobile sources, industrial processes, residential combustion, industrial combustion, energy, agriculture and other.

3.1.2 Emissions and abatement potential

The emission function describes how much each sector emits in tons $PM_{2.5}$. These are estimates of yearly emissions for each sector, given the corresponding activity data, emission factor and abatement measures currently applied. The approach used is the bottom up emission calculation method described in Equation 1 and will show how many tons $PM_{2.5}$ is emitted for the baseline scenario.

$$E_i = \sum_{kym=1}^{n} A_{ky} EF_{ky} \left(1 - e_{ff_m}\right) x_{km} \qquad \text{Eq.1}$$

$E =$ Emissions in tons $PM_{2.5}$
$A =$ Activity rate
$EF =$ Emission factor
$eff =$ Removal efficiency in %
$x =$ Implementation rate
$i, k, y, m =$ Sector, fuel, activity, abatement measure

The abatement possibility for each sector is dependent on the activity rate, abatement technology and removal efficiency for available measures shown in

Equation 2. The abatement potential of the sector is the cumulative abatement potential for all included activities.

$$z_i^{max} = \sum_{kym=1}^{n} A_{ky} EF_{ky} eff_m \qquad \text{Eq.2}$$

z^{max} = Maximum abatement potential

If there are multiple measures available for a specific activity, the abatement possibility for the higher efficiency measures will be the difference between the higher efficiency measure and the previous measures applied. The same methodology is used if measures at the initial point of the CLE scenario are already implemented and there are higher efficiency measures available.

3.1.3 Transfer coefficient

The concentration level is not only dependent on the emissions from the different sources but also external factors such as meteorological conditions affecting the dispersion of the emissions. To find the relationship between a ton $PM_{2.5}$ emitted from a sector and the contribution to the concentration level, the contributed share from each sector to the annual population-weighted mean concentration is divided with the corresponding emissions from the sector using Equation 3.

$$t_i = \frac{C_{PM_{2.5}}^{POP} S_i}{E_i} \qquad \text{Eq.3}$$

$C_{PM_{2.5}}^{POP}$ = Annual population-weighted mean concentration

t = Transfer coefficient

S = Contributed share to the annual population-weighted mean concentration

The transfer coefficient will capture the properties of the TM5 model that is incorporated in the GAINS models estimated annual population-weighted concentration. Because of the structure for the optimization problem, the transfer coefficients will represent the average effect of each ton of $PM_{2.5}$ emitted from each sector on the annual population-weighted mean concentration. This transfer coefficient will capture the exogenous factors effecting the dispersion of the emissions and the impact of the sectors emissions on the populations exposure of $PM_{2.5}$.

3.1.4 Bottom-up MAC functions

The MAC function describes the MAC for each sector at different levels of abatement. It consists of multiple abatement measures that are available in each sector and will be constructed using the bottom up approach. The unit cost per unit activity for each measure for the different activities in the sector will be used to create the sector specific MAC function. These unit costs per unit activity is converted to the unit cost of each ton $PM_{2.5}$ abated using Equation 4. This will make it possible to use the unit cost for the MAC calculations.

$$uc_{PM_{2.5}} = \frac{uc_{iky}}{EF_{iky}eff_m} \qquad \text{Eq.4}$$

$uc_{PM_{2.5}} =$ Unit cost per $PM_{2.5}$ abated
$uc_{iky} =$ Unit cost per unit activity

In the case of multiple available abatement measures for a specific activity, the MAC can be derived by comparing the less effective measure with the higher efficiency measure. This is done by looking at that additional cost for applying the measure with the extra removal potential it carries shown in Equation 5.

$$MAC_{ikym} = \frac{uc_{PM_{2.5}m}eff_m - uc_{PM_{2.5}m-1}eff_{m-1}}{eff_m - eff_{m-1}} \qquad \text{Eq.5}$$

$MAC =$ Marginal abatement cost

In the case of only one available abatement measure for a specific activity, the unit cost per $PM_{2.5}$ reduction equals the MAC. The calculated MACs, including respective measures abatement possibility, will be used to construct the MAC functions for each sector. This is done by using the bottom up approach ordering the MAC from lowest to highest and using the cumulative abatement for each sector. The MAC function is estimated by OLS-regression analysis with available abatement measures for MAC greater than zero described in Equation 6. The abatement measures that have a MAC less or equal to zero are excluded from the functions and applied prior to the optimization problem. This is partially because of the immediate economic gains and efficiency improvements the measures bring, but also for the functional form of the sector specific MAC functions. The functional form that is used is semi-log, where the MAC values are defined in natural logarithmic form. The abatement factor is raised to the power of a, where the sector specific MAC values and abatement potential will determine the appropriate value. The advantages of using the semi-log function is that it can be displayed in a graphical form where the data is more compressed and the functions are more easily estimated using the OLS approach.

$$LN(MAC_i) = b_0 + b_1 z^a + \varepsilon_i \qquad \text{Eq.6}$$

$a =$ Power of the variable z

3.1.5 Objective function and constrains

The optimization problem will be carried out using economic programing by applying the FOC and defined constrains. For adding up the sector specific semi-log MAC functions from Equation 6, the functions are inverted to make the abatement factor *z* the dependent variable. The inverse total abatement function with the MAC as the independent variable is the sum of the sector specific inverse MAC functions described in Equation 7.

$$Z = \sum_{i=1}^{n} \left(\frac{LN(MAC_i) - b_{i0}}{b_{i1}}\right)^{\frac{1}{a_i}} \qquad \text{Eq.7}$$

$Z =$ Total abatement between sectors

For relating the abatement to the reduction of the annual population-weighted mean concentration, the sector specific transfer coefficient from Equation 3 is multiplied with each respective inverted MAC function from Equation 6 represented by Equation 8.

$$C_{PM_{2.5}}^{r-pop} = \sum_{i=1}^{n} \left(\frac{LN(MAC_i) - b_{i0}}{b_{i1}}\right)^{\frac{1}{a_i}} t_i \qquad \text{Eq.8}$$

$C_{PM_{2.5}}^{r-pop} =$ Reduction of the population-weighted $PM_{2.5}$ annual mean concentration

For describing the ambient concentration level, Equation 8 is combined with the sectors emission function from Equation 1, to create the objective function in Equation 9 describing the primary emissions from sectors in Delhi's contribution to the annual population-weighted mean concentration.

$$C_{PM_{2.5}}^{POP} = \sum_{i=1}^{n} (E_i - \left(\frac{LN(MAC_i) - b_{i0}}{b_{i1}}\right)^{\frac{1}{a_i}}) t_i \qquad \text{Eq.9}$$

The constrains for the optimization problem will be the maximum abatement each sector can accomplish and the defined policy goal of $PM_{2.5}$ concentration including the contribution from the other emission categories not included in this paper. The constrains are presented in Equation 10-11 and are based on Equation 2 and Equation 9 with the acceptable annual population-weighted mean $PM_{2.5}$ concentration depending on the scenario.

$$\sum_{i=1}^{n} z_i = Z \leq \sum_{i=1}^{n} z_i^{max} = Z^{max} \qquad \text{Eq.10}$$

$$C_{PM_{2.5}q}^{POP} + \sum_{i=1}^{n} (E_i - z_i) t_i = \bar{C}_{PM_{2.5}}^{POP} \qquad \text{Eq.11}$$

$\bar{C}_{PM_{2.5}}^{POP} =$ Acceptable annual population-weighted mean $PM_{2.5}$ concentration

$C_{PM_{2.5}q}^{POP} =$ Contribution to the annual population-weighted mean concentration from surrounding states, secondary emissions and non-anthropogenic emissions

The objective function and the constrains are combined to find the cost-minimizing distribution between included sectors by using economic programing.

3.1.6 Population-weighted concentration

The observed annual population-weighted mean concentration will be calculated to compare with the GAINS model estimation to evaluate the feasibility of the model estimations. This is done by weighing different monitoring stations observed concentration levels based on the population in the district the station it is located, applying Equation 12.

$$C_{PM_{2.5}}^{pop} = \sum_{d=1}^{n} \frac{\sum_{o=1}^{n} c_{PM_{2.5do}}}{o_d} P_d \qquad \text{Eq.12}$$

$C_{PM_{2.5}}^{pop} =$ Annual population-weighted mean PM$_{2.5}$ concentration
$P =$ Population share
$d =$ District
$o =$ Number of observations for concentration level

If there are multiple monitoring stations located in the same district, each monitoring stations observed concentration level will be given the same share representing the district in the annual population-weighted mean concentration.

3.2 External factors and seasonal variation of PM$_{2.5}$ concentration

To evaluate the external factors and the seasonal variations impact on the concentration of PM$_{2.5}$, a panel data fixed-effect regression model will be estimated using Equation 13. This is done with available data for daily observations of PM$_{2.5}$ concentration, meteorological data for corresponding period and seasonal dummy variables. The seasonal dummy variables categorization will be defined based on a report by Attri et al. (2013) where the seasons included are; Winter (Dec-Feb), Summer (Mar-May), Monsoon (Jun-Sep) and Post Monsoon (Oct-Nov). By using the panel data fixed effect regression model, the cross-sectional categorization will capture the local characteristics of the monitoring stations including geographical and other area specific characteristics. The previous days observation of concentration level will also be included as a lag for the dependent variable. This is included to consider the fact that PM$_{2.5}$ particles can be active in the atmosphere for multiple days and therefore affect the current days concentration. By including the variable there could be issues with endogeneity. This will be valued in comparison with the benefits to include the variable in the regression model.

$$C_{PM_{2.5}l} = b_0 + C_{PM_{2.5t-1}l} + \lambda_l + \sum_{e=1}^{n} b_{el} x_{el} + \sum_{s}^{n} D_{sl} + \epsilon_{esl} \qquad \text{Eq.13}$$

$C_{PM_{2.5}} =$ Observed daily concentration
$b_0 =$ Constant
$b =$ Coefficient
$\lambda =$ Monitoring stations fixed-effect
$D =$ Dummy variable
$x =$ External factor
$\epsilon =$ Error term
$t, e, s, l =$ Time, meteorological factor, season, monitoring station

4 Data collection

The data that is used for the study is presented including economic, meteorological and $PM_{2.5}$ specific.

4.1 Economic, emission and abatement data

The economic data is taken from the GAINS model (IIASA, 2017) in unit cost format per unit activity for the different abatement measures. In a guidance document for the GAINS abatement cost methodology by Kelly, King & Redmond (2010) the cost is explained to be estimated on a production cost level rather than a consumption level. This leaves out mark-ups as well at taxes applied. The unit cost is incorporating investment cost, variable operational cost and fixed operational cost. The investment cost is annualized for the technical lifetime of the technology and the fixed operational cost includes maintenance and repairs which is represented as a percentage of the investment cost. All the unit cost is expressed in 2005 euros and shows the yearly cost for the measures. The abatement cost values are common data applicable for global analysis while sector size and fuel use consider national differences. For activities containing multiple abatement measures, only cost-efficient options will be considered. This implies measures with higher unit cost per ton $PM_{2.5}$ abated and lower removal efficiency than other available measures will be excluded from the optimization problem.

Data on available abatement technologies, corresponding removal efficiency, emission factors and estimations on activity rates for 2015 are taken from the GAINS modeling framework (IIASA, 2017). These are in the GAINS model adapted to correspond with local variation in size and applicability depending on fuel and sector activity. Data on current implementation for 2015 is also taken to correspond with current legislation for the baseline scenario. The activity trash burning is treated as a separate activity and will not be included in one of the sectors. In the cost-minimizing solution, the measure will be represented as a constant MAC for the available abatement measure. The agricultural sector and the remaining activities in the sector “other” will be excluded from the optimization problem because of low abatement potential and high MAC for the few available measures.

4.2 Concentration data of PM$_{2.5}$ from monitoring stations in Delhi

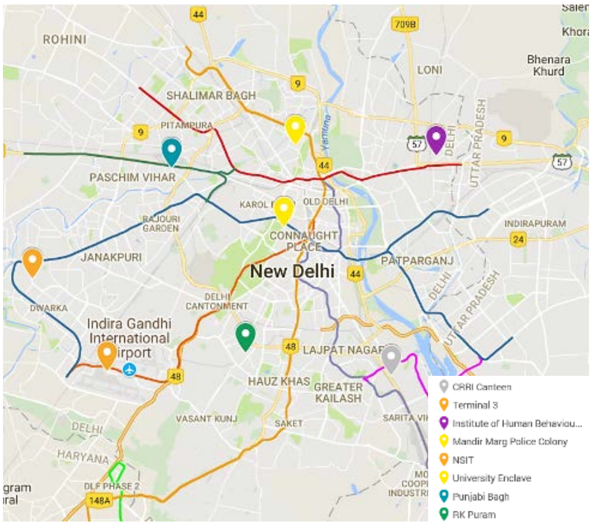

Figure 1: Map of Delhi with indicators for monitoring stations

The data for the concentration levels of PM$_{2.5}$ is taken from the Central Pollution Control Board (CPSB) (2015). It consists of daily monitoring data from eight monitoring stations for the year 2015. The data varies regarding availability for specific days and seasons. Total number of observations between the eight stations for 2015 is 726. Figure 1 shows the location of each of the eight monitoring stations.

Information about the characteristics of each station is taken from CPCB in a document about ambient air quality data (2017). The classification is in four categories; residential, industrial, commercial and traffic which shows the heterogeneity of the locations. The monitoring stations available for the year 2015 do not include a monitoring site with the traffic characteristics.

4.3 Meteorological data

The meteorological data is taken from Urban Emissions (2016) which is a website dedicated to the subject of air pollution, providing data and research surrounding the subject. The dataset is based on data from the National Centers for Environmental Prediction (NCEP) by using WRF meteorological model for the year 2015. The meteorological variables available is precipitation (mm/hour), mixing height (m), temperature (°C), wind speed (m/sec) and wind direction (degrees). The data consist of the hourly measurements for each of the variables in the different districts in Delhi. These will be converted to daily mean values for respective district. The district categorization is; Central, East, New Delhi, North, North West, South, South West and West.

4.4 Population data

Data for the population in the different districts in Delhi described in section 4.3 is taken from the latest available census report by the Indian Administrative Service (2011). The population for the year 2015 is the predicted population (Census Population , 2015). The share for the population distribution between districts from the latest available Census report is used and assumed to correspond the population distribution between the districts for the year 2015.

4.6 Contribution to the annual population-weighted mean concentration between sources

The contribution to the annual population-weighted mean concentration for the year 2015 from the primary emissions in Delhi is taken from a paper by Amann et al. (2017). The paper uses the annual population-weighted mean concentration as the measurement and shows the contribution from surrounding states, secondary emissions, natural emissions and emissions from inside Delhi. The paper looks at the year 2015 as the base year and applies the GAINS model corresponding with the methodology of this paper. The primary emissions based on data from the paper by Amann et al. (2017) stands for 40% of the annual population-weighted mean concentration. The mobile sources have the biggest share of the contribution to the annual population-weighted mean concentration with 41% of the primary emissions contribution from sectors in Delhi. The lowest contribution between the primary emissions from sectors in Delhi is the industrial combustion which stands for 2.15% of the contribution. Based on the paper by Amann et al. (2017), the annual population-weighted mean concentration from the GAINS model for the year 2015 was 121.1 µg/m^3.

5 Results

In the upcoming sections, the results will be presented. First, respective sectors MAC function is described, followed by the results from the optimization problem. Finally, the regression model showing the relationship between external factors, the concentration and the comparison between actual observations and the model is presented.

5.1 Sector specific MAC functions

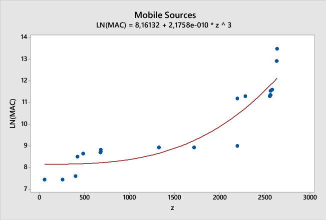

Figure 2*:* Mobile sources

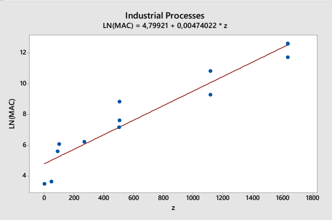

Figure 3: Industrial processes

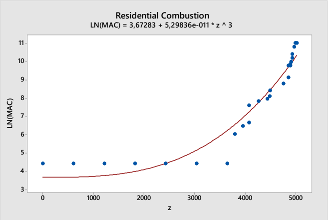

Figure 4: Residential Combustion

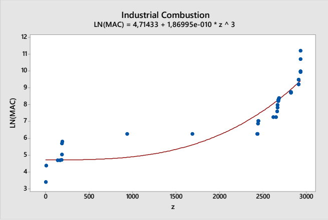

Figure 5*:* Industrial combustion

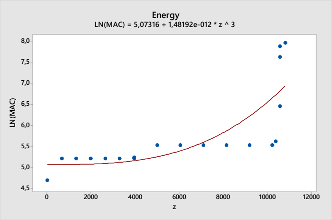

Figure 6*:* Energy

The sector specific MAC functions with abatement potential in tons $PM_{2.5}$ is presented in Figure 2-6 with each semi-log functions graphical representation. The semi-log function is used to derive the growth of the MAC with the increasing abatement responsibility for each sector. For the industrial processes the semi-log function is linear and indicates a growth for the MAC of 0.47 percent for each additional ton $PM_{2.5}$ abated. For the other semi-log functions, the abatement factor is raised to the power of three which indicates a quadratic MAC growth dependent on the level abated. The functions show heterogeneity between the sectors.

A summary of the function is presented in Table 2 containing each functions coefficients and respective p-values as well as R-square and F-value for each function. Table 2 also displace the abatement potential for both measures included in the functional estimations and the measures that had MAC ≤ 0. *Appendix 1* contains further details for the different measures and the data used in the estimations of the functions. The functions show high explanatory power based on the data for the cumulative abatement potential and MAC for respective sector. The estimated p-values for the coefficient are all under the 1% significance level.

Table 1*:* Summary of respective sectors MAC function
P-values are represented in the brackets for coefficients and F-value: *** < 1%, ** < 5%, * < 10%

Sector	Const.	b_1	a	R-squared	F-value (p-value)	Increase of MAC per ton $PM_{2.5}$ abated (%)	Abatement potential MAC > 0 (tons $PM_{2.5}$)	Abatement potential MAC$\leq$ 0 (tons $PM_{2.5}$)
Mobile sources	8.16132 (***)	$2.17580e^{-10}$ (***)	3	0.85965	123.5002 ($9.37e^{-10}$)	$6.5274e^{-8}\, z^2$	2 632.9	1 276.48
Industrial processes	4.79921 (***)	0.00474022 (***)	1	0.91589	131.6722 ($1.84e^{-7}$)	0.474022	1 632.9	2 142.05
Residential combustion	3.67283 (***)	$5.29836e^{-11}$ (***)	3	0.93656	370.0573 ($4.32e^{-16}$)	$1.59e^{-8}\, z^2$	5 015.95	1 719.54
Industrial combustion	4.71433 (***)	$1.86995e^{-10}$ (***)	3	0.86192	225.7097 ($7.85e^{-17}$)	$5.61e^{-8}\, z^2$	2 929.18	
Energy	5.07316 (***)	$1.48192e^{-12}$ (***)	3	0.60117	28.13223 (0.000058)	$4.45e^{-10}\, z^2$	10 805.53	5 356.18

5.2 Transfer coefficients

By using the data on the population-weighted annual mean concentration, the share each sector contributes and the calculated emissions from each sector the transfer coefficient for the annual population-weighted mean concentration for each sector can be derived. The transfer coefficients for each sector including the calculated emissions for each sector and the source contribution from each sector that was used in the estimation of the coefficient is summarized in Table 2.

The variation in transfer coefficient can be explained by the variation in the sectors relationship to the population. Because it is the annual population-weighted mean concentration that is evaluated, this means that activities present at areas where the population share is lower or where atmospheric dispersion of the emissions is higher will have a lower transfer coefficient. This indicates that the emissions from sectors with a lower transfer coefficient has a lower impact on the annual population-weighted mean concentration per ton $PM_{2.5}$ emitted.

Table 2*:* Transfer coefficients for each sector including relevant data
*Source: (Amann, et al., 2017)

Sector	Emissions in baseline scenario (tons $PM_{2.5}$)	Contribution to the annual population-weighted mean concentration (%)*	Transfer coefficient
Mobile	4762	40.75773	0.003865
Industrial Processes	3834	2.781902	0.000772
Residential Combustion	9454	25.24274	0.001206
Industrial Combustion	2929	2.155889	0.000315
Energy	17837	12.43615	0.000315
Trash Burning	1529.5	5.313557	0.001657

5.3 Cost-minimizing abatement strategy between sectors

Two scenarios are tested in the optimization problem. The objective function is defined using the estimated MAC functions from section 5.1, the emissions for the baseline scenario and the transfer coefficients from Table 2 in section 5.2. The constrain for the abatement possibility for each sector is shown in Table 1 in section 5.1 with the abatement measures for MAC > 0. The constrain for allowed concentration level will vary depending on the scenario. The first scenario sets the constrain at 40 µg/m^3 while scenario two sets the constrain so the share of the reduction equals the share that the included sectors contributes to the annual population-weighted mean concentration. For the baseline scenario the annual population-weighted mean concentration is 121.1 µg/m^3, with primary emissions from sectors in Delhi contributing 40%, which equals 48.44 µg/m^3. Based on the policy goal of 40 µg/m^3 this implies a total needed reduction of 81.1 µg/m^3. The share of the reduction for primary emissions from sectors in Delhi for scenario two is than 32.44 µg/m^3. That implies an allowed contribution by the primary emissions from sectors in Delhi of 16 µg/m^3 and a constrain for the annual population-weighted mean concentration in Delhi of 88.66 µg/m^3.

Applying measures that have a MAC less or equal to zero reduces the emissions with 10 494.25 tons of PM$_{2.5}$ which leaves the population-weighted concentration at 109.17 µg/m^3 and 36.51 µg/m^3 for primary emissions from sources in Delhi. The measures whit a negative MAC are therefore not enough to reach the defined policy goals in either scenario one or scenario two.

In scenario one, the available measures for the primary emissions from sources in Delhi are not enough. By implementing all the available measures, the annual population-weighted mean concentration is 84.84 µg/m^3 and the remaining contribution from the primary emission from sectors in Delhi is 12.18 µg/m^3.

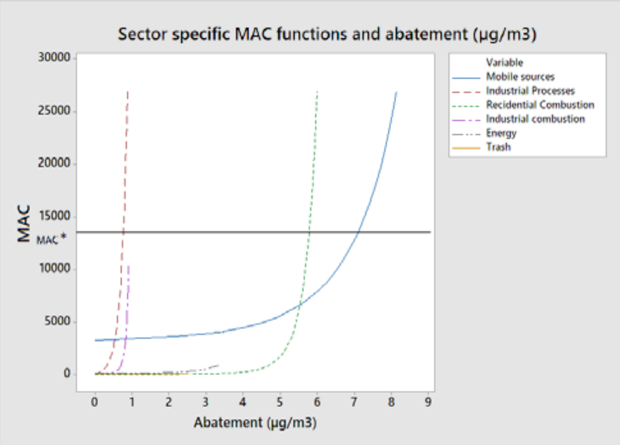

Figure 7*:* Cost-minimizing solution for abatement strategies between sectors for scenario two where MAC > 0
MAC* = cost-minimizing level of MAC

For the second scenario, a feasible result could be established. The graphical solution is represented by Figure 7 with the cost-minimizing MAC level indicated. The graphical solution shows the reduction in µg/m^3 and displays the reduction between the sectors to reach the defined concentration level for scenario two. Table 3 presents the results for each sector with reduction in both tons PM$_{2.5}$ and in µg/m^3. For the cost-minimizing solution, the MAC equals 13 510.2 euros (2005 exchange rate) across the sectors. The results show full use of available abatement measures in the sectors industrial combustion, energy and trash burning. The mobile sources have the highest impact on the reduction of the annual population-weighted mean concentration but has the lowest share of applied abatement measures of the ones available in the sector. The high impact on the population-weighted concentration creates the high impact from the measures applied for the mobile sources. The energy sector takes the biggest responsibility in the reduction of $PM_{2.5}$ measured in tons. Though, because of the relatively low impact on the population-weighted exposure, the impact on the reduction in µg/m^3 is not as impactful as the sectors residential combustion and mobile sources.

Table 3: Summary of cost-minimizing abatement strategy for scenario two

Sector	Abatement (MAC > 0) tons	Abatement (MAC ≤ 0) tons	Abatement (MAC > 0) µg/m3	Abatement (MAC ≤ 0) µg/m3	% of potential applied
Mobile Sources	1837.492	1276.477421	7.102704338	4.934140106	79.65383823
Industrial Processes	994.0446	2142.053708	0.767018887	1.652839001	83.07638206
Residential Combustion	4794.206	1719.538133	5.781164845	2.073530593	96.70783009
Industrial Combustion	2929.178		0.922332816		100
Energy	10805.53	5356.182069	3.402420562	1.686542354	100
Trash Burning	1529.5		2.534400684		100

5.4 Population-weighted concentration from actual observations

The population-weighted annual mean concentration in Delhi for year 2015 based on observed concentration levels from CPCB (2015) is 131.47 µg/m^3. In comparison to the model estimates of 121.1 µg/m^3 the actual data shows an annual population-weighted mean concentration of 10.37 µg/m^3 higher than the model estimates.

5.5 Meteorological factors and seasonal variation

The fixed effect panel data regression model that is derived for the external factors effect on the concentration level is summarized in Table 4. The model is ordered by station with eight cross-sectional units, in panel data form with date of observation as the time index variable for 279 periods. This will make it possible to find the effect of the included external variables despite local variation in characteristics between the monitoring stations. The panel data regression will estimate the fixed effect on the incorporated variables.

Table 4: Fixed-effect panel data regression model summary

Variable	Coefficient	P-value	Std. error
Const	90.0505	***	13.0583
Previous Day Observation	0.564947	***	0.0310267
Mixing Height (m)	0.00841313	0.3600	0.00918580
Wind Speed (m/sec)	−5.25020	***	1.55482
Wind Direction (degrees)	0.0553063	***	0.0180583
Temperature (Celsius)	−0.655995	0.1566	0.462547
Precipitation (mm/h)	−11.0681	0.2711	10.0489
Winter	−7.10095	0.2886	6.68671
Summer	−30.9186	***	6.27433
Monsoon	−27.8348	***	5.90617
Model Summary	LSDV R-squared 0.614923	LSDV F-value 69.86360 (4.1e-133)	Durbin Watson 1.923172

The model shows an explanatory power of 60%. Most of the included variables show significance under the 5% limit, apart from mixing height, precipitation, temperature and winter showing significance greater than 10%. The seasonal dummy variables show variation between seasons, where summer and the monsoon season has the highest negative effect on the concentration. The post monsoon season is acting as the reference variable for the model. The model shows negative effect for the meteorological factors wind speed, temperature and precipitation, while mixing height and wind direction has a positive effect on the concentration. The time-lag for the observed concentration shows a positive effect on the concentration corresponding with the fact that $PM_{2.5}$ can be active in the atmosphere for multiple days. The Durbin-Watson value is 1.92 which indicates that the model does not suffer from autocorrelation.

Based on the dataset of the meteorological factors (UrbanEmissions, 2016), the seasons winter and post monsoon exhibit on average non-favorable meteorological conditions for dispersion of emissions in comparison to the summer and monsoon seasons. This means factors contributing to high dispersion of the particles are on average less present during the winter and post monsoon seasons, and one of the reasons for higher overall concentration during these periods. The other seasonal dependent effects are captured in the seasonal dummy variables.

6 Discussion

Discussion surrounding the results and comparison with previous research will be carried out to put the findings in the relevant context. Subject of interest for further research and limitations of findings in the paper are also deliberated on.

6.1 Abatement strategies and possible external benefits

The result for the optimization problem corresponds with previous research, including the paper by Amman et al. (2017) which points out the importance of policy strategies that goes over city boundaries and that incorporates strategies for secondary $PM_{2.5}$ emissions. The feasible result where an abatement strategy that considers the need for incorporating of other non-local sources was established showing that most of the available end-of-pipe measures had to be implemented to reach the policy goal. This could indicate a need to not only focus on abatement measures but also behavioral changes for consumers and companies. As shown in the abatement potential for the mobile sources, the contribution to the annual population-weighted mean concentration is the highest per ton emitted and could be a target for such strategies.

The measures implemented in the established abatement strategy could have further benefits in the reduction of other pollutants. In addition, there could be further reduction when looking at secondary emissions which could lead to lower annual population-weighted mean concentration of $PM_{2.5}$ in Delhi for the measures applied. These effects are not looked at in this paper but could lead to further improvements for both the relevant ambient concentration indicator and other air quality targets, both in Delhi and for surrounding states.

6.2 Population-weighted concentration levels between observations and the model

When comparing the population-weighted concentration in the GAINS model and the calculated value based on data from CPCB (2015) the observed value is 10.37 $\mu g/m^3$ higher than the GAINS estimations. The difference could partially depend on the scale of the data, where the actual observations are based on eight monitoring stations, while the GAINS model estimates the concentration for the whole Delhi. This could indicate an overestimation for the actual annual population-weighted mean concentration because the monitoring stations are centered around policy relevant areas. The modeling framework is therefore assumed to be corresponding well with actual observations.

6.3 Indication of seasonal variation and possible implications for policy strategies

For the relationship between the concentration and the exogenic variables, the estimated panel data fixed-effect regression model showed that wind speed, wind direction, the previous days observed concentration, summer and monsoon had an established significant effect on the concentration. The meteorological factors have been shown to be of importance in multiple prior studies (Gurjar & Guttikunda, 2012; Sharma, 2016; Lind, et al., 2015). By using the panel data fixed effect model, the station specific characteristics of the local area are captured in the monitoring stations cross-sectional classification and other factors of interest can be evaluated. The central part of the model is the integration of the seasonal dummy variables which are incorporated to try to estimate variation in concentration between the seasons from other factors than the meteorological factors and area specific characteristics of the monitoring station incorporated in the model. The estimations show that the fall and winter period have the highest impact on the concentration and the summer and monsoon periods has the lowest. The model could indicate activity changes between the seasons because of the incorporation of important exogenic factors in the model. The subject could be of further interest for policy makers in developing cost-efficient policy strategies. Activities more central in seasons where natural dispersion is high depending on favorable meteorological factors could be shown to be less effective than focusing on activities with higher presence in seasons where natural dispersion of the $PM_{2.5}$ emissions is low.

6.4 Limitations of the paper

As been indicated in reports by the WHO (2016b; 2013) the policy goal is centered around the health benefits of lower ambient $PM_{2.5}$ concentration levels. By doing the analysis on a city scale using the population-weighted concentration, this implies weighing the areas depending on the population. This suggest policy strategies where the focus is set on areas where the population carries a larger share and therefore local points in Delhi could experience concentration levels exceeding the defined policy goal as was indicated in the paper by Ciucci et al. (2016).

The unit cost estimations used in the paper are defined on a production side rather than a consumption side described in the guidance document for the GAINS cost methodology by Kelly, King & Redmond (2010). The consumption cost is hard to define because of additional factors such as market structures, availability and taxes that effect the price which may additionally vary between time and place. The use of the production cost may imply variation from the modelling results for both actual cost of implementing the measures but also in the abatement distribution between sectors. Because the paper only looks at the primary emissions from Delhi, there is still uncertainties how in comparison to efforts in surrounding states as well as effort in lowering the secondary emissions compares in cost-efficiency to the measures looked at in the paper. It can be assumed that the activities are similar in the surrounding states, but where the cost-efficiency is depending on current implementation of efforts and the activity size in the surrounding states.

The fixed-effect regression model for the external factors and seasonal variation shows that there are other factors centred around the different seasons than the variables included in the model that effects the concentration. Because the data available for activity frequency for each sector is only for yearly values, it is hard to say if the seasonal variation is due to activity changes or other external factors not incorporated in the model. For determining the relationship, data on emissions and activity per season need to be incorporated.

7 Conclusion

In the study a static model approach was used to evaluate cost-minimizing policy strategies between sectors in Delhi contributing to the $PM_{2.5}$ emissions. The results show similarly to previous research that policy strategies on city levels need to incorporate measures for surrounding states and secondary emissions for reaching national air quality standards. When evaluating the cost-efficient distribution between sectors in Delhi in the scenario where primary emissions takes the reduction share equal to the share it contributes, mobile sources stands the biggest reduction in $\mu g/m^3$. For reaching the defined policy goal high share of the available measures for all sectors need to be implemented. The sector specific semi-log MAC functions show structural variations where both linear and functions where abatement factor is raised to the power of three could be established. This shows heterogeneity between sectors. The regression model is incorporated to further evaluate exogenic factors effect on the concentration, where meteorological factors were shown to affect the concentration of $PM_{2.5}$ in Delhi. Seasonal variation could further be determined with uncertainty in what factors are captured in the dummy variables. The seasonal impact on concentration levels concerning variation in activity rates could be of interest for further studies focusing on cost-efficient abatement strategies.

References

Ahmed, B. et al., 2017. PM2.5 footprint of household energy consumption. *Applied Energy*.

Alsalam, J. et al., 2015. Global mitigation of non-CO2 greenhouse gases: marginal abatement costs curves and abatement potential through 2030. *Journal of IntegratIve envIronmental ScIenceS,* Volume 12.

Amann, M. et al., 2017. Managing future air quality in megacities: A case study for Delhi. *Atmospheric Environment,* Volume 161.

Amann, M. et al., 2008. *GAINS Asia: a tool to combat air pollution and climate change simultaneously*: IIASA.

Andimuthu, R. et al., 2015. Assessment of Population Exposure to Coarse and Fine Particulate Matter in the Urban Areas of Chennai, India. *The Scientific World Journal,* Volume 2015.

Attri, S., Jaswal, A. & Rathore, L., 2013. *STATE LEVEL CLIMATE CHANGE TRENDS IN INDIA,* New Delhi: India Meteorological Department.

Ball, B. et al., 2010. Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. *Agricultural Systems,* Volume 103.

Bergin, M. et al., 2016. Chemical characterization and toxicity of particulate matter emissions from roadside trash combustion in urban India. *Atmospheric Environment,* Volume 147.

Census Population , 2015. *Delhi Population Census Data 2011 - Delhi 2018 Population.* [Online]
Available at: https://www.census2011.co.in/census/state/delhi.html
[Accessed 13 April 2018].

Chou, K., Huang, S. K. & Kuo, L., 2016. The applicability of marginal abatement cost approach: A comprehensive review. *Journal of Cleaner Production,* Volume 127.

Ciucci, A. et al., 2016. Cost-effective reduction of PM2.5 concentration and exposure in Italy. *Atmospheric Environment,* Volume 140.

Colsa, A. et al., 2016 . *Comparative study on the differences between the EU and US legislation on emissions in the automotive sector*.

Common, M., Ma, Y., McGilvray, J. & Perman, R., 2003. *Natural Resources and Environmental Economics.* 3rd ed. Harlow: Pearson Education.

CPCB, 2015. *Manual Monotoring Data.* [Online]
Available at: http://cpcb.nic.in/manual-monitoring/
[Accessed 19 March 2018].

CPCB, 2017. *Ambient Air Quality Data of Delhi-NCR.* [Online]
Available at: http://cpcb.nic.in/NGT/Air_Quality_data_Delhi-NCR_December_2017.pdf
[Accessed 27 April 2018].

DeCarolis, J. F., Srivastava, R. K. & Vijay, S., 2010. A bottom-up method to develop pollution abatement cost curves for coal-fired utility boilers. *Energy Policy,* Volume 38.

Dube, R., 2009. *Indian National Air Quality Standard.* [Online]
Available at: http://www.indiaenvironmentportal.org.in/files/826.pdf
[Accessed 23 03 2018].

EEA, 2013. *Air quality in Europe — 2013 report,* Copenhagen: EEA.

EPA, 2016. *Basic Information of Air Emissions Factors and Quantification.* [Online]
Available at: https://www.epa.gov/air-emissions-factors-and-quantification/basic-information-air-emissions-factors-and-quantification
[Accessed 24 April 2018].

EPA, 2017. *What is PM?.* [Online]
Available at: https://www3.epa.gov/region1/airquality/pm-what-is.html
[Accessed 23 March 2018].

European Commission, 2018. *Emissions in the automotive sector.* [Online]
Available at: https://ec.europa.eu/growth/sectors/automotive/environment-protection/emissions_en
[Accessed 4 May 2018].

Faichney, R., Hanley, N., Munro, A. & Shortle, J. S., 1999. Least-cost pollution allocations for probalistic water quality targets to protect salmon on the Forth Estuary. In: *Pollution for Sale: Emissions Trading and Joint Implementation.* Cheltenham: Edwars Elgar Publishing Limited, pp. 211-230.

Gurjar, B. R. & Guttikunda, S. K., 2012. Role of meteorology in seasonality of air pollution in megacity Delhi, India. *Environ Monit Assess* , Volume 184.

Hill, J. D. M. J. D. &. T. C. W., 2017. InMAP: A model for air pollution interventions.. *PLoS ONE* , 12(4).

Hodzic, A., Jimenez, J., Sacedo, D. & Wiedinmyer, C., 2012. Impact of Trash Burning on Air Quality in Mexico City. *Environ. Sci. Technol,* 46(9).

IIASA, 2016. *ECLIPSE V5a global emission fields.* [Online]
Available at:
www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5a.html
[Accessed 27 April 2018].

IIASA, 2017. *Global emission fields of air pollutants and GHGs.* [Online]
Available at:
http://www.iiasa.ac.at/web/home/research/researchPrograms/air/Global_emissions.html
[Accessed 15 03 2018].

IIASA, 2018. *GAINS South Asia.* [Online]
Available at: https://gains.iiasa.ac.at/gains/INN/index.login?logout=1
[Accessed 2018].

Indian Administrative Service, 2011. *Census of India 2011: Primary Census Abstract: Data Highlights NCT of Delhi.* [Online]
Available at:
http://censusindia.gov.in/2011census/PCA/PCA_Highlights/pca_highlights_file/Delhi/DATA_SHEET_PCA_DISTRICTS_NCT_OF_DELHI.pdf
[Accessed 12 April 2018].

Jeong, J. K. M. H. K. S. Z., 2017. Comparison of source apportionment of PM2.5 using receptor models in the main hub port city of East Asia: Busan. *Atmospheric Environment,* 148(1).

Johansson, M., Karvosenoja, N., Klimont, Z. & Tohka, A., 2007. Cost-effective reduction of fine primary. *Environmental Research Letters,* Volume 2.

Kelly, A., King, F. & Redmond, L., 2010. *GAINS Abatement Cost Guide,* Dublin: AP EnvEcon IMP.

Komarova, N. G. & Valdberg, A. Y., 2011. Analysis of the disperse composition of dust in a gas flow at the outlet from a deduster. *Chemical and Petroleum Engineering,* Volume 46.

Lind, P. G. et al., 2015. Neural network forecast of daily pollution concentration using optimal meteorological data at synoptic and local scales. *Atmospheric Pollution Research,* 6(3).

Sharma, M., 2016. *Comprehensive Study on Air Pollution and Green House Gases (GHGs) in Delhi* , Delhi: Department of Environment, Government of National Capital Territory of Delhi and Delhi Pollution Control Committee.

UrbanEmissions, 2016. *About.* [Online]
Available at: http://www.urbanemissions.info/about/
[Accessed 15 April 2018].

UrbanEmissions, 2016. *India – Summary of 2015 Meteorology by District.* [Online]
Available at: http://www.urbanemissions.info/india-air-quality/india-2015meterology-bydistrict/
[Accessed 12 April 2018].

WHO, 2013. *Health effects of particulate matter,* Denmark: WHO.

WHO, 2016a. *Ambient Air Pollution: A global assessment of exposure and burden of disease,* Geneva: WHO Documented Production Services.

WHO, 2016b. *WHO Global Urban Ambient Air Pollution Database (update 2016).* [Online]
Available at: http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/
[Accessed 24 March 2018].

WHO, 2016c. *AAP database*: WHO.

Appendix

Appendix A: Abatement data by sector

Sector	Activity	Fuel activity	Measure	MAC (2005-euros)	Possible Abatement (tons $PM_{2.5}$)	Cumulative Abatement (tons $PM_{2.5}$)
Energy	Modern power plants (coal: ultra & supercritical; gas: CCGT)	Hard coal, grade 2	High efficiency deduster - power plants + S,N meas.	-1058.73	1704.632	1704.632
	Power & district heat plants - new coal (>50 MWth)	Hard coal, grade 2	High efficiency deduster - power plants + S,N meas.	-1058.73	1444.711	3149.343
	Modern power plants (coal: ultra & supercritical; gas: CCGT)	Brown coal/lignite grade 1	High efficiency deduster - power plants + S,N meas.	-816.664	333.43	3482.773
	Power & district heat plants - new coal (>50 MWth)	Brown coal/lignite grade 1	High efficiency deduster - power plants + S,N meas.	-816.664	63.23382	3546.007
	Power & district heat plants - new coal (>50 MWth)	Brown coal/lignite grade 1	High efficiency deduster - power plants + S,N meas.	-39.8933	1056.908	4602.915
	Power & district heat plants - existing coal (>50 MWth)	Brown coal/lignite grade 1	High efficiency deduster - power plants + S,N meas.	-5.83595	753.1846	5356.1
	Generator sets	Gaseous fuels	EURO 6	0	0.08232	5356.182
	Power & district heat plants - existing coal (<50 MWth)	Brown coal/lignite grade 1	High efficiency deduster - power plants + S,N meas.	110.0062	15.32759	5371.51
	Power & district heat plants - existing coal (>50 MWth)	Hard coal, grade 2	High efficiency deduster - power plants + S,N meas.	183.8652	1313.377	6684.887
	Power & district heat plants - existing coal (>50 MWth)	Hard coal, grade 2	High efficiency deduster - power plants + S,N meas.	183.8652	1313.377	7998.264
	Power & district heat plants - existing coal (>50 MWth)	Hard coal, grade 2	High efficiency deduster - power plants + S,N meas.	183.8652	1313.377	9311.641
	Generator sets	Heavy fuel oil	Stage 3B	188.8723	2.03312	9313.674
	Power & district heat plants - new coal (>50 MWth)	Hard coal, grade 2	High efficiency deduster - power plants + S,N meas.	252.9314	2086.805	11400.48
	Power & district heat plants - new coal (>50 MWth)	Hard coal, grade 2	High efficiency deduster - power plants + S,N meas.	252.9314	2086.805	13487.28
	Power & district heat plants - new coal (>50 MWth)	Hard coal, grade 2	High efficiency deduster - power plants + S,N meas.	252.9314	2086.805	15574.09
	Power & district heat plants - existing coal (<50 MWth)	Hard coal, grade 2	High efficiency deduster - power plants + S,N meas.	275.965	141.9251	15716.01
	Generator sets	Diesel	Stage 3B	637.7551	196.0839	15912.1
	Power & district heat plants - new (excl. coal)	Biomass fuels	High efficiency deduster	2056.157	0.4403	15912.54
	Power & district heat plants - new (excl. coal)	Biomass fuels	Electrostatic precipitator: 2 fields	2642.342	0.3774	15912.91
	Generator sets	Diesel	Stage 3B	2878.007	244.3003	16157.21
	Generator sets	Heavy fuel oil	Stage 5	117366.4	0.016768	16157.23
	Generator sets	Diesel	Stage 5	252604.2	4.47744	16161.71
Mobile sources	Cars	Gasoline	EURO 6	-3.7E-11	3.107093	3.107093
	Light duty vehicles	Diesel	EURO 5	-5.2E-12	31.03967	34.14677
	Light duty vehicles	Diesel	EURO 5	-5E-12	21.13499	55.28175
	Mopeds	Gasoline	Stage 3 (2-stroke)	-1.9E-12	10.9214	66.20315
	Mopeds	Gasoline	Stage 3 (2-stroke)	-9.3E-13	19.79926	86.00241
	Agriculture	Diesel	Stage 3B	0	0.724973	86.72738
	Construction machinery	Liquefied petroleum gas	EURO 6	0	0.25872	86.9861
	Construction machinery	Diesel	Stage 3B	0	32.83139	119.8175
	Buses	Gaseous fuels	Stage 3	0	0.015861	119.8334
	Cars	Gaseous fuels	EURO 6	0	2.051715	121.8851
	Cars	Gasoline	EURO 6	0	31.34408	153.2291
	Cars	Gasoline	EURO 6	0	6.243952	159.4731
	Cars	Gasoline	EURO 6	0	9.420208	168.8933
	Cars	Liquefied petroleum gas	EURO 6	0	0.018307	168.9116
	Cars	Diesel	EURO 5	0	109.8155	278.7271
	Cars	Diesel	EURO 5	0	91.7948	370.5219
	Cars	Diesel	EURO 5	0	134.8135	505.3354
	Light duty vehicles	Gaseous fuels	EURO 6	0	0.184412	505.5198
	Light duty vehicles	Gasoline	EURO 6	0	1.271124	506.7909
	Light duty vehicles	Gasoline	EURO 6	0	12.82299	519.6139
	Light duty vehicles	Gasoline	EURO 6	0	2.554426	522.1683
	Light duty vehicles	Gasoline	EURO 6	0	3.853845	526.0222
	Light duty vehicles	Diesel	EURO 5	0	25.2841	551.3063
	Motorcycles	Gasoline	Stage 3 (4-stroke)	0	18.91997	570.2262
	Motorcycles	Gasoline	Stage 3 (4-stroke)	0	10.27041	580.4966
	Buses	Diesel	EURO IV	2.62E-12	62.25317	642.7498
	Heavy duty vehicles	Diesel	EURO IV	2.62E-12	307.3785	950.1283
	Buses	Diesel	EURO IV	4.97E-12	21.81469	971.943
	Heavy duty vehicles	Diesel	EURO IV	4.97E-12	304.5344	1276.477
	Buses	Diesel	EURO IV	1704.325	58.32704	1334.804
	Heavy duty vehicles	Diesel	EURO IV	1704.325	195.9753	1530.78
	Mopeds	Gasoline	Stage 3 (2-stroke)	1997.405	146.6385	1677.418
	Cars	Diesel	EURO 5	4897.978	19.17344	1696.592
	Agriculture	Diesel	Stage 3B	5696.62	62.74444	1759.336
	Construction machinery	Diesel	Stage 3B	5994.205	192.9392	1952.275
	Light duty vehicles	Diesel	EURO 5	6204.105	4.414525	1956.69
	Other non-road machinery	Diesel	EURO IV	6743.025	0.111972	1956.802
	Buses	Diesel	EURO IV	7562.271	643.5396	2600.341
	Heavy duty vehicles	Diesel	EURO IV	7562.271	390.9783	2991.32
	Railways	Diesel	Stage 3B	8108.14	478.5437	3469.863
	Other non-road machinery	Diesel	EURO VI	72167.32	0.00762	3469.871
	Buses	Diesel	EURO VI	80935.32	88.68181	3558.553
	Heavy duty vehicles	Diesel	EURO VI	80935.32	271.5014	3830.054
	Cars	Gasoline	EURO 6	84770.83	3.30933	3833.364
	Light duty vehicles	Gasoline	EURO 6	84770.83	1.35386	3834.717
	Agriculture	Diesel	Stage 5	102634.4	2.818308	3837.536
	Construction machinery	Diesel	Stage 5	107995.9	14.18122	3851.717
	Construction machinery	Gasoline	EURO 6	108991.1	0.49392	3852.211
	Motorcycles	Gasoline	Stage 3 (4-stroke)	406900	44.81989	3897.031
	Railways	Diesel	Stage 5	716035.2	3.946752	3900.978
Industrial Processes	Brick production	No fuel use	Vertical Shaft Brick Kiln with basic dust control	-12081.3	7.247252	7.247252
	Brick production	No fuel use	Vertical Shaft Brick Kiln with basic dust control	-4106.05	502.0048	509.252

	Brick production	No fuel use	Vertical Shaft Brick Kiln with basic dust control	-462.02	12.02796	521.28
	Brick production	No fuel use	Vertical Shaft Brick Kiln with basic dust control	-393.854	1527.679	2048.959
	Brick production	No fuel use	Vertical Shaft Brick Kiln with basic dust control	-24.1793	57.45789	2106.417
	Brick production	No fuel use	Vertical Shaft Brick Kiln with basic dust control	-19.4923	35.6369	2142.054
	Electric arc furnace	No fuel use	Cyclone	32.7138	0.407484	2142.461
	Electric arc furnace	No fuel use	High efficiency deduster	38.22609	46.86066	2189.322
	Cast iron (grey iron foundries)	No fuel use	Electrostatic precipitator: 2 fields	268.3829	42.3126	2231.634
	Aluminum production - secondary	No fuel use	Cyclone	435.3845	9.584775	2241.219
	Aluminum production - secondary	No fuel use	High efficiency deduster	501.8809	169.0115	2410.231
	Brick production	No fuel use	Hoffman Kilns	1314.982	234.6468	2644.878
	Cast iron (grey iron foundries)	No fuel use	High efficiency deduster	2058.405	1.9233	2646.801
	Briquettes production	No fuel use	Electrostatic precipitator: 2 fields	6896.866	0.00858	2646.809
	Brick production	No fuel use	Tunnel Kilns burning other fuels than coal	10755.64	609.525	3256.334
	Briquettes production	No fuel use	High efficiency deduster	50397.4	0.00039	3256.335
	Small industrial and business facilities - fugitive	No fuel use	Good practice: ind.process - stage 2 (fugitive)	123721.8	517.776	3774.111
	Storage & handling of other industrial bulk products	No fuel use	Good practice: storage and handling	295771.7	0.4828	3774.594
	Storage & handling of coal	No fuel use	Good practice: storage and handling	304685.3	0.3642	3774.958
Residential Combustion	Cooking stoves	Fuelwood	New stove - biomass	-40670.4	4.299717	4.299717
	Residential - kerosene lamps	Gasoline	LED lamp	-5471.21	26.8416	31.14132
	Residential - kerosene lamps	Gasoline	LED lamp	-4114.85	12.91808	44.0594
	Heating stoves	Fuelwood	New stove - biomass	-2918.15	0.98952	45.04892
	Cooking stoves	Fuelwood	New stove - biomass	-2561.32	1240.136	1285.185
	Heating stoves	Fuelwood	New stove - biomass	-1693.23	94.99392	1380.179
	Cooking stoves	Agricultural residues	Improved stove - biomass	-887.673	339.3596	1719.538
	Medium boilers (<50MW) - automatic	Hard coal, grade 2	High efficiency deduster	83.4522	1214.374	2933.912
	Medium boilers (<50MW) - automatic	Hard coal, grade 2	High efficiency deduster	83.4522	1214.374	4148.286
	Medium boilers (<50MW) - automatic	Hard coal, grade 2	High efficiency deduster	83.4522	1214.374	5362.66
	Cooking stoves	Dung	Improved stove - biomass	418.1644	145.2764	5507.937
	Meat frying, food preparation, BBQ	No fuel use	Filters in households (kitchen)	648.2667	161.805	5669.742
	Cooking stoves	Agricultural residues	New stove - biomass	791.4343	117.8332	5787.575
	Cooking stoves	Brown coal/lignite grade 1	Briquette stove	2023.508	3.400186	5790.975
	Medium boilers (<1MW) - manual	Fuelwood	Pellet boiler	2556.076	189.554	5980.529
	Medium boilers (<50MW) - automatic	Fuelwood	Pellet boiler	2871.995	169.8601	6150.389
	Cooking stoves	Dung	New stove - biomass	3344.614	50.4432	6200.832
	Cooking stoves	Brown coal/lignite grade 1	Improved stove - coal	4622.202	1.728	6202.56
	Cooking stoves	Fuelwood	Fan assisted cooking stove	6627.214	269.2774	6471.838
	Cooking stoves	Agricultural residues	Fan assisted cooking stove	9247.796	95.39776	6567.235
	Heating stoves	Hard coal, grade 2	New stove - coal	17714.86	1.2375	6568.473
	Cooking stoves	Dung	Fan assisted cooking stove	18009.71	35.07568	6603.549
	Heating stoves	Hard coal, grade 2	Briquette stove	19383.4	0.974259	6604.523
	Medium boilers (<50MW) - automatic	Fuelwood	High efficiency deduster	22038.85	19.0854	6623.608
	Heating stoves	Fuelwood	New stove with electrostatic precipitator	27336.5	19.45025	6643.059
	Residential-commercial	Heavy fuel oil	Good housekeeping: domestic oil boilers	33587.12	0.119475	6643.178
	Cooking stoves	Hard coal, grade 2	New stove - coal	49964.98	41.769	6684.947
	Medium boilers (<1MW) - manual	Fuelwood	High efficiency deduster	60976.67	21.2982	6706.245
	Cooking stoves	Hard coal, grade 2	Briquette stove	61487.29	29.2383	6735.484
	Heating stoves	Fuelwood	Pellet stove with electrostatic precipitator	749914.8	4.360073	6739.844
Industrial Combustion	Other industry (large coal boilers; > 50 MWth)	Brown coal/lignite grade 1	Electrostatic precipitator: 1 field	29.6444	0.372884	0.372884
	Other industry (large coal boilers; > 50 MWth)	Hard coal, grade 2	Electrostatic precipitator: 1 field	79.5786	6.48675	6.859634
	Trash burning	No fuel use	Ban on open burning	92.2534	509.8333	516.693
	Trash burning	No fuel use	Ban on open burning	92.2534	509.8333	1026.526
	Trash burning	No fuel use	Ban on open burning	92.2534	509.8333	1536.36
	Transformation sector (boilers)	Hard coal, grade 1	Electrostatic precipitator: 1 field	107.7531	131.4525	1667.812
	Paper & pulp (boilers)	Hard coal, grade 1	Electrostatic precipitator: 1 field	107.7531	26.04879	1693.861
	Industry: Other combustion, pulverized	Hard coal, grade 2	Electrostatic precipitator: 1 field	111.6125	16.03501	1709.896
	Industry: Other combustion, pulverized	Hard coal, grade 1	Electrostatic precipitator: 1 field	151.9018	6.245694	1716.142
	Other industry (large coal boilers; > 50 MWth)	Brown coal/lignite grade 1	High efficiency deduster - industrial combustion + S,N meas.	294.8654	0.48114	1716.623
	Industrial furnaces	Biomass fuels	Electrostatic precipitator: 1 field	330.7669	3.85392	1720.477
	Other industry (boilers; liquid and gaseous fuels)	Biomass fuels	Electrostatic precipitator: 1 field	514.3666	746.7888	2467.265
	Other industry (boilers; liquid and gaseous fuels)	Biomass fuels	Electrostatic precipitator: 1 field	514.3666	746.7888	3214.054
	Other industry (boilers; liquid and gaseous fuels)	Biomass fuels	Electrostatic precipitator: 1 field	514.3666	746.7888	3960.843
	Paper & pulp (boilers)	Biomass fuels	Electrostatic precipitator: 1 field	514.3666	1.3764	3962.219
	Other industry (large coal boilers; > 50 MWth)	Hard coal, grade 2	High efficiency deduster - industrial combustion + S,N meas.	959.2283	8.37	3970.589
	Paper & pulp (boilers)	Other biomass and waste fuels	Electrostatic precipitator: 1 field	1115.036	0.6324	3971.222
	Chemical industry (boilers)	Biomass fuels	Electrostatic precipitator: 1 field	1115.036	3.02808	3974.25
	Transformation sector (boilers)	Hard coal, grade 1	High efficiency deduster - industrial combustion + S,N meas.	1403.8	169.6162	4143.866
	Paper & pulp (boilers)	Hard coal, grade 1	High efficiency deduster - industrial combustion + S,N meas.	1403.8	33.61134	4177.477
	Industry: Other combustion, pulverized	Hard coal, grade 2	High efficiency deduster	1967.911	10.34517	4187.823
	Industry: Other combustion, pulverized	Hard coal, grade 1	High efficiency deduster	2461.648	4.02948	4191.852
	Industrial furnaces	Derived coal (coke, briquettes)	Electrostatic precipitator: 1 field	2888.206	0.019656	4191.872
	Industry: Other combustion, pulverized	Hard coal, grade 2	Electrostatic precipitator: 2 fields	3636.813	10.34517	4202.217
	Industrial furnaces	Biomass fuels	High efficiency deduster	3814.103	0.1554	4202.372
	Industrial furnaces	Derived coal (coke, briquettes)	Electrostatic precipitator: 1 field	3918.352	0.01116	4202.383
	Other industry (boilers; liquid and gaseous fuels)	Heavy fuel oil	Good housekeeping: industrial oil boilers	4222.364	4.518	4206.901
	Industry: Other combustion, pulverized	Hard coal, grade 1	Electrostatic precipitator: 2 fields	4362.619	4.02948	4210.931
	Other industry (boilers; liquid and gaseous fuels)	Biomass fuels	High efficiency deduster	6004.482	136.0623	4346.993
	Paper & pulp (boilers)	Biomass fuels	High efficiency deduster	6004.482	0.0555	4347.049
	Industrial furnaces	Biomass fuels	Electrostatic precipitator: 2 fields	6252.86	0.1554	4347.204
	Other industry (boilers; liquid and gaseous fuels)	Biomass fuels	Electrostatic precipitator: 2 fields	9884.405	90.33735	4437.541
	Paper & pulp (boilers)	Biomass fuels	Electrostatic precipitator: 2 fields	9884.405	0.0555	4437.597
	Paper & pulp (boilers)	Other biomass and waste fuels	High efficiency deduster	12978.47	0.0255	4437.622
	Chemical industry (boilers)	Biomass fuels	High efficiency deduster	12978.47	0.1221	4437.745
	Other industry (boilers; liquid and gaseous fuels)	Heavy fuel oil	High efficiency deduster	20317.06	20.7828	4458.527
	Chemical industry (boilers)	Biomass fuels	Electrostatic precipitator: 2 fields	21337.8	0.1221	4458.649
	Paper & pulp (boilers)	Other biomass and waste fuels	Electrostatic precipitator: 2 fields	21337.81	0.0255	4458.675
	Industrial furnaces	Derived coal (coke, briquettes)	High efficiency deduster	44751.51	0.00144	4458.676
	Industrial furnaces	Derived coal (coke, briquettes)	Electrostatic precipitator: 2 fields	73038.17	0.00144	4458.678