

Technical Synergies and Trade-Offs Between Abatement of Global and Local Air Pollution

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Accepted: 1 February 2017 / Published online: 16 February 2017
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Abstract In this paper, we explore the synergies and tradeoffs between abatement of global and local pollution. We build a unique dataset of Swedish combined heat and power plants with detailed boiler-level data 2001–2009 on not only production and inputs but also on emissions of CO₂ and NO_x. Both pollutants are regulated by strict policies in Sweden. CO₂ is subject to the European Union Emission Trading Scheme and Swedish carbon taxes; NO_x—as a precursor of acid rain and eutrophication—is regulated by a heavy fee. Using a quadratic directional output distance function, we characterize changes in technical efficiency as well as patterns of substitutability in response to the policies mentioned. The fact that generating units face a trade-off between the pollutants indicates the need for policy coordination.

Keywords Environmental policies · Shadow pricing · Directional distance function · Climate change · Local pollution · Policy interactions

JEL Classification H23 · L51 · L94 · L98 · Q48

1 Introduction

Climate policy is affected by multiple decision makers at local, national, and international levels. Usually these decision makers are not fully coordinated in terms of goals and methods, and the existence of several layers of governance may encourage strategic behavior from powerful local actors trying to enhance their own positions (Caillaud et al. 1996). Multi-level climate policy governance is also related to governance of local air pollutants since production processes often involve emitting several air pollutants simultaneously and most emission control measures affect more than one pollutant. Environmental policies aiming

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at reducing CO₂ emissions might therefore create spillovers, i.e., reductions or increases in emissions of other pollutants by firms changing or modifying their production processes in response to climate policy. For example, a common strategy to reduce CO₂ emissions is switching the fuel mix from fuel oil to biofuels, which are counted as having zero carbon. However, although such a transition may make CO₂ emissions fall dramatically, biofuels often imply an increase in nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and volatile organic compound (VOC) emissions (Brännlund and Kriström 2001).

Spillovers from climate policy have important implications for policy design since they affect the cost of climate regulations. Theory shows that one critical factor determining whether an increased stringency of climate policies leads to increased emission of local pollutants is the elasticity of substitution (e.g., Ambec and Coria 2013). If pollutants are substitutes, CO₂ emissions will be reduced at the expense of increased emissions of local pollutants. If they are complements, climate policies might lead to ancillary benefits since local pollutants will then be reduced alongside CO₂ emissions. There is also the effect of technological development, which generally decreases the emissions of all pollutants. Therefore, emissions of pollutants that are substitutes to CO₂ can still fall with climate policy if technological development outweighs the substitution effect. In this paper, we characterize changes in the relative performance of Swedish combined heat and power plants with respect to CO₂ and NO_x emissions in response to variations in the level of stringency of CO₂ and NO_x policies and multiple layers of regulation. In particular, we study the effects of the interaction between the European Union Emissions Trading System (EU ETS) and the Swedish CO₂ tax and refundable charge on NO_x emissions with the goal of determining whether multi-level climate policy governance has generated ancillary benefits or costs in terms of NO_x emissions. To this end, we built a unique dataset of Swedish combined heat and power plants for the period 2001–2009 consisting of detailed boiler-level data on not only production and inputs but also CO₂ and NO_x emissions. We estimate a quadratic directional output distance function to study and compare patterns of technical progress, substitution between CO₂ and NO_x, and shadow prices of these pollutants in the period 2001–2004 (before introduction of the EU ETS) and 2005–2009 (post-implementation).

To the best of our knowledge, this is the first study analyzing and quantifying the effects of the multi-governance of climate change policy and its interaction with the other national policy instruments aimed to reduce local pollutants. However, some previous studies have employed directional output distance functions to analyze the shadow cost of environmental regulations (see e.g., Färe et al. 2005; Marklund and Samakovlis 2007; Wei et al. 2013; Du et al. 2015a, b) and the technological non-separability and substitutability among air and water pollutants (see e.g., Murty et al. 2007; Kumar and Managi 2011; Färe et al. 2012). Notably, Agee et al. (2014) estimate a multiple-input, multiple-output directional output distance function to analyze the technological non-separability in the control of CO₂ and NO_x emissions of the U.S. electric utilities' sector and its implications for the design of a CO₂ emissions cap and trade system. They find that controlling one pollutant also controls the other, and hence there are ancillary benefits from policies targeted at reducing one of them. Their results are consistent with those of Burtraw et al. (2003), who employ an electricity market equilibrium model to simulate changes in emissions resulting from different climate policy scenarios and find considerable (health-related) ancillary benefits due to reduced NO_x emissions.

Our work differs from previous studies in two important ways. First, we focus on policy-induced substitutability across pollutants and the changes in relative shadow prices of emissions introduced by environmental multi-level governance. Second, we analyze the case of Sweden who has been at the forefront of CO₂ emission reduction for a long time, and it

is one of the few countries whose present level of emissions is below the level recorded in 1990. This accomplishment is mainly explained by the remarkable expansion of biofuel use, which has the potential negative side effect of increasing NO_x emissions. Hence, compared with the U.S., where switching from high-carbon fuels (like coal and oil) to reduced-carbon ones such as natural gas is still an option, in Sweden most emission reductions have already been undertaken. Our results indicate that there are limits to the positive spillovers (i.e., ancillary benefits) from climate policy as countries approach the goal of a carbon-free economy. Furthermore, the existence of spillovers indicates the need for better coordination across policymakers at different levels of governance, and policy coordination becomes even more important under substitutability since the unintended costs of climate policy on local pollution can make it less acceptable to the public and policymakers. This is particularly the case since the benefits from reduced climate change mostly accrue in the long term and on a global scale, while any ancillary costs of climate policy would tend to accrue in the near term, affecting the countries undertaking mitigation action.

This paper is organized as follows. Section 2 briefly describes the climate and NO_x policy in Sweden and the changes in the relative price of CO_2/NO_x over the period 2001–2009. Section 3 presents the theoretical and empirical framework of the joint production of heat and power, CO_2 and NO_x emissions. Section 4 discusses the data and empirical results and analyzes the sensitivity of our results to different directional vectors. Section 5 discusses some policy implications and Sect. 6 concludes the paper.

2 Climate and NO_x Policy for Combined Heat and Power Plants in Sweden: Carbon Taxation, EU ETS, and the Refundable NO_x Charge

Combined heat and power (hereinafter CHP) is the simultaneous generation of useful heat and power from a single fuel or energy source at or close to the point of use. As in all combustion processes, CO_2 emissions produced by CHP depend mainly on the carbon content of the fuel, while NO_x emissions and the interactions between measures to control CO_2 and NO_x emissions vary according to the design characteristics of the individual plants. For instance, compression-ignition engines generally operate with lower air-to-fuel ratios and higher combustion temperatures, which results in higher NO_x emissions per unit of power generated. Alternatively, the use of spark-ignition gas engines operated on natural gas would enable CHP to reduce NO_x emissions, albeit with a small increase in CO_2 emissions. Moreover, NO_x is produced largely from an unintended chemical reaction between nitrogen and oxygen in the combustion chamber. The process is quite non-linear in temperature and other parameters of the combustion process, which implies that there is a large scope for NO_x reduction through various technical measures. For example, it is possible to reduce NO_x emissions by operating at lower engine efficiency or through the investment in post-combustion technologies (PCTs) that clean up NO_x once it has been formed. However, such technologies usually require energy and thus will increase CO_2 emissions (at least relative to output). It is also possible to invest in combustion technologies (CTs) involving the optimal control of combustion parameters (temperature, pressure, stoichiometry, flame stability and homogeneity, and flue gas residence time) to inhibit the formation of thermal and prompt NO_x . The adoption of these technologies clearly depends on the investment costs, which have shown to be boiler and plant specific and vary with boiler capacity (Linn 2008). Moreover,

some technologies are not commercially available below certain size thresholds (Sterner and Turnheim 2009).¹

Since most emission control measures employed by CHP plants affect both CO₂ and NO_x emissions, one should observe some changes in pollutants' substitutability in response to the variations in the level of stringency of CO₂ and NO_x policies and multiple layers of regulations.² Therefore, in order to develop a hypothesis regarding the relative incentives to reduce CO₂ and NO_x emissions, respectively, we start by briefly describing climate and NO_x policies in Sweden and the evolution of the relative cost of CO₂/NO_x per unit of output over the period 2001–2009 (for a detailed description of Swedish environmental policy see SEPA 2007).

In 1991, Sweden introduced a carbon tax that is directly connected to the carbon content of the fuel. Initially, the tax was equivalent to 25 €/metric ton of CO₂. After increasing steadily over the last decade, it currently corresponds to 105 €/ton.³ Since the tax is very high and Sweden is a small open economy, there has been concern for the competitiveness of some energy-intensive industries. Thus, a number of deductions and exemptions have been created in those sectors that are open to competition, and a series of reduced tax rates have been introduced. In the case of the heat and power sector, the carbon tax varies according to the type of generation, i.e., whether the generating unit is a CHP boiler or an only-heat boiler. From 2005 to June 2008, the carbon tax and the EU ETS overlapped. At that point, the tax was essentially replaced with the EU ETS, and CHP plants were granted a tax reduction of 85%. Since the level of the price of CO₂ allowances is much lower than the Swedish tax level, this harmonization with the EU actually has implied a sizeable fall in the price of carbon emissions for most CHP plants.

The tax reform of 1991 introduced not only a carbon tax but also other taxes including a high fee on NO_x. The fee was initially confined to NO_x emissions from electricity and heat-producing boilers, stationary combustion engines, and gas turbines with a useful energy production⁴ of at least 50 gigawatt hours (GWh) per year (approx. 182 boilers). However, because of its effectiveness in reducing emissions and simultaneously falling monitoring costs, in 1996 the charge system was extended to include all boilers producing at least 40 GWh of useful energy per year, and in 1997 the limit was again lowered to 25 GWh.

¹ PCTs consist of flue gas treatments designed to clean up NO_x once it has been formed, usually through conversion to benign chemical species. Examples include: (1) SCR (selective catalytic reduction), which is rather costly to install but achieves highly efficient reduction levels, and (2) SNCR (selective non-catalytic reduction of chemicals, e.g., ammonia, urea, and sodium bicarbonate), which is less costly than SCR in both capital and operating costs but also less effective.

² The adoption of CO₂ and NO_x emission control technologies does not necessarily imply a change in the relative technical efficiency of the generating units because the efficiency scores are computed relative to the performance of a best-practice frontier, but the fact that multiple regulations are into play motivate us also to explore this as an empirical question in Sect. 5.1.

³ This is by all accounts a very high carbon tax. To put it in context, the carbon dioxide permits on U.S. markets such as the Regional Greenhouse Gas Initiative (RGGI) and Chicago are trading at around 4 €/ton; the EU ETS has varied around a mean of 15–20 €/ton; and France has tried to introduce a carbon tax of 17 €/ton—but has failed because of fears that such a level would be detrimental to the economy.

⁴ “Useful energy” is the output variable of the NO_x charge system that measures the total energy production from the heterogeneous group of regulated industries (heat and power, waste, wood, pulp and paper, chemical, metal, and food industry). For CHP plants and only-heat plants “useful energy” is the energy sold in the form of heat or electricity. For other industries, “useful energy” is the energy in the form of steam, hot water or electricity produced in the boiler and used in production processes or heating of factory buildings (see Sterner and Höglund 2006 for details).

The total fees are refunded to the participating plants⁵ in proportion to their production of useful energy. Hence, the system encourages plants to reduce NO_x emissions per unit of energy to the largest possible extent, since plants with lower emissions relative to energy output are net receivers of the refund. The fee was originally set at 4.3 €/kg, which is an extremely high level compared to other countries.⁶

The Swedish NO_x fee has been evaluated extensively (see e.g., Höglund 2005; Sterner and Höglund 2006; Sterner and Turnheim 2009; Bonilla et al. 2015). It has been shown to be very effective in lowering emissions. Empirical findings suggest that extensive emission reductions have taken place due to learning and technological development in abatement. Nevertheless, emissions fell mostly in the early years. The decrease has continued since then, but at a reduced pace. Hence, as the impact of the charge seemed to diminish, in 2008 the Swedish government decided to raise the fee to 5.3 €/kg to foster further adoption of more effective treatment techniques (SEPA 2003, 2007, 2009).

How have the regulations described above affected the relative cost of CO₂/NO_x emissions? To assess the overall picture is not altogether easy. Although large industrial plants in the energy sector can to some extent adjust their technology in response to short-run price variations (e.g., through fuel switching), many features of their design take a decade to build and are adapted to expected price trends over a longer time horizon (e.g., the ability to switch fuels may well be one such feature). Furthermore, the carbon tax paid and allowances used depend on the type of fuel being burned, which is endogenous to the stringency of CO₂ policies in previous years.⁷ To provide an indication of the relative stringency of CO₂ and NO_x policies, we compute the relative cost of CO₂ and NO_x emissions per unit of output for the CHP plants in our data (see Fig. 1). The cost of CO₂ emissions is calculated as the sum of the CO₂ tax plus the EU ETS price, while the cost of NO_x emissions corresponds to the fee on NO_x. As shown in Fig. 1, it seems clear that over the period 2001–2009, policy signals in Sweden told power companies to avoid fossil fuels. The cost of emitting CO₂ is much higher than the cost of emitting NO_x. For example, in 2003, an average CHP plant emitted 0.082 tons of CO₂ and 0.248 kg of NO_x to produce 1 MWh of useful energy. Given the magnitude of the carbon tax and NO_x fee at that time, this implied a cost of 6.116 and 0.936 €/MWh for CO₂ and NO_x emissions, respectively. This is to say that the cost of CO₂ emissions per unit of output was over six times the cost of NO_x emissions.

The variation observed in Fig. 1 suggests that CO₂ policy did become less stringent (relative to NO_x) due to the carbon tax phase-out. Indeed, the reduction began already in 2004 when CHP plants were granted a significant carbon tax reduction.⁸ Furthermore, Sweden

⁵ With the exception of 0.7% that is kept for administration costs. The refund varies from year to year, but in recent years it has been around 0.9 €/megawatt hour (MWh) of useful energy while the average NO_x emissions per unit of energy has been 0.23 kg of NO_x per MWh.

⁶ This number corresponds to 4300 €/ton, which can be compared with the Taxe Parafiscale in France of 40.85 €/ton and the Norwegian fee of 525 €/ton.

⁷ As described by Färe et al. (2016), in a given period the opportunity costs of abatement depends on the choice of inputs and technology available at that point in time. Figure 1 plots the relative cost of CO₂/NO_x emissions per MWh. We calculated the relative cost per boiler per year (as each boiler uses a different combination of inputs and technology, which determines the opportunity cost) and then averaged the relative cost of CO₂/NO_x emissions per MWh across boilers. Thus, we compute the average value of the relative cost across boilers.

⁸ Specifically, CHP plants about to be regulated by the EU ETS were only required to pay 21% of the CO₂ tax. We acknowledge that in terms of measuring the effect of variations in the CO₂/NO_x, the periods 2001–2003 and 2004–2009 can be interesting. Nevertheless, the objective of this paper is to analyze the effect of multi-governance and overlapping of policies, and therefore, we focus on the comparison of the periods 2001–2004 and 2005–2009.

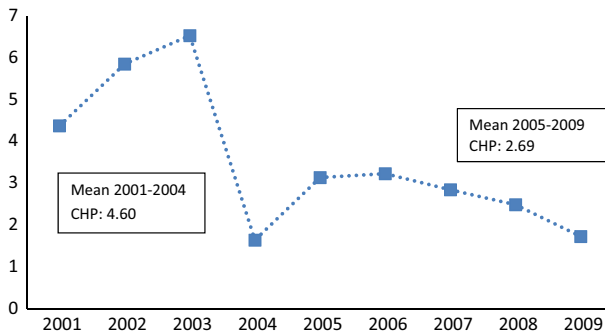


Fig. 1 Relative cost of CO₂/NO_x emissions per MWh for CHP plants. *Note* The cost of CO₂ emissions is calculated as the sum of the carbon tax plus the CO₂ EU ETS price (mean of forward contracts 2007–2013). We compute the relative cost of CO₂/NO_x emissions per MWh per boiler and average the values across boilers

increased the fee on NO_x for all regulated boilers in 2008, adding to the effect of the reduced carbon tax on the relative cost of CO₂/NO_x.

A clear hypothesis to be derived from the analysis above is that firms should direct most abatement efforts to reducing CO₂ emissions as the economic effect of CO₂ regulations on firms' profitability (taking into account both abatement costs and abatement benefits through reduced pollution payments) is much higher than that of NO_x regulations. Moreover, the variations in the relative cost of CO₂/NO_x emissions should have induced some variations in the relative CO₂/NO_x abatement efforts if generating units were to minimize the cost of compliance with environmental regulations. The magnitude and direction of the changes in the optimal mix of CO₂/NO_x emissions would depend, however, on a series of factors such as technological development and whether CO₂ and NO_x are substitutes or complements in abatement. For instance, in the absence of technological development, one would expect emissions of NO_x from CHPs to decrease relatively more in 2005–2009 than 2001–2004 if pollutants are substitutes, while the reverse holds if pollutants are complements. On the other hand, the high relative cost of reducing CO₂ emissions should have also triggered technological fixes and fuel switching aiming to reduce them. Hence, given the relative stringency of CO₂/NO_x regulations, we would expect technological efforts to be overall biased towards CO₂ emission reductions. In the next sections, we use a quadratic directional output distance function to derive the relative shadow prices of emissions for each generating unit and analyze the changes on technical efficiency and abatement efforts induced by the regulatory changes, but first we will describe the estimation strategy.

3 Estimation Strategy

One of the main objectives of this paper is to quantitatively characterize the degree of substitutability or complementarity between reductions of CO₂ and NO_x emissions. The technical efficiency literature provides a variety of methods to evaluate the performance of the generating units, including nonparametric and parametric approaches. Since substitutability is associated with the curvature along the output possibilities set (see Färe et al. 2005), in our approach we employ a parametric directional output distance function that is twice differentiable to derive estimates of elasticities of substitution output/pollutants and between

pollutants.⁹ We also estimate technical efficiencies and absolute and relative shadow prices of CO₂/NO_x.

In the past, researchers have first estimated a production function frontier and then the distances of individual plants from the frontier. The function used here seeks the simultaneous expansion of good outputs and contraction of bad outputs, which is very suitable to our case. Modeling the technology in this manner allows for the adoption of abatement measures in order to reduce the bad outputs (emissions) and still increase, or hold constant, the production of heat and power.

Following Färe et al. (2005), we treat emissions as bad or undesirable outputs generated in the boilers' combustion process and model jointly the production of heat and power and emissions. Let the set of output possibilities $P(x) = \{(y, b): x \text{ can produce } (y, b)\}$ represent all feasible input–output possibilities of boilers that jointly generate heat and power (y) and a vector of emissions $b = (b_1, b_2)$ (where b_1 represents emissions of CO₂ and b_2 represents emissions of NO_x) using an input vector $x = (x_1, x_2, x_3)$ containing installed capacity, fuel consumption (as input energy) and labor, respectively. We assume that inputs are strongly disposable, which implies that the output set is not shrinking if the inputs are expanding. Furthermore, we assume null-jointness, implying that no good output is produced without a positive amount of at least one of the bad outputs. Moreover, all outputs are assumed to be jointly weakly disposable, implying that bad outputs are not freely disposable and cannot be reduced without affecting the production of good outputs, i.e., through the diversion of inputs into pollution reduction. Finally, we consider that the good output is strongly disposable, implying that if an observed good and bad output vector is feasible, then any output vector with less of the good output is also feasible (i.e., good outputs are freely disposable since they have a nonnegative value). The directional output distance function is characterized as

$$\bar{D}_0(x, y, b; g) = \max \left\{ \gamma : (y + \gamma g_y, b_1 - \gamma g_{b_1}, b_2 - \gamma g_{b_2}) \in P(x) \right\}. \quad (1)$$

Equation (1) is a functional representation of the technology that is consistent with $P(x)$ and its associated properties. The solution $\gamma^* = \bar{D}_0(x, y, b; g)$ corresponds to the maximum expansion and contraction of good and bad outputs, respectively. The directional vector $g = (g_y, g_{b_1}, g_{b_2})$ specifies in which direction the good and bad outputs are scaled so as to reach the boundary of the output set at $(b_1 - \gamma^* g_{b_1}, b_2 - \gamma^* g_{b_2}, y + \gamma^* g_y)$.

The directional output distance function has several properties listed below (see Färe et al. 2005):

- (1) $\bar{D}_0(x, y, b; g) \geq 0$ if and only if (y, b) is an element of $P(x)$
- (2) $\bar{D}_0(x, y', b; g) \geq \bar{D}_0(x, y, b; g)$ for $(y', b) \leq (y, b) \in P(x)$
- (3) $\bar{D}_0(x, y, b'; g) \geq \bar{D}_0(x, y, b; g)$ for $(y, b') \geq (y, b) \in P(x)$
- (4) $\bar{D}_0(x', y, b; g) \geq \bar{D}_0(x, y, b; g)$ for $x' \geq x \in P(x)$
- (5) $\bar{D}_0(x, y, b; g)$ is concave in $(y, b) \in P(x)$
- (6) $\bar{D}_0(x, \lambda y, \lambda b; g) \geq 0$ for $(y, b) \in P(x)$ and $0 \leq \lambda \leq 1$
- (7) If $\bar{D}_0(x, y, 0; g) < 0$ for $y > 0$, then $(y, 0) \notin P(x)$
- (8) $\bar{D}_0(x, y + \rho g_y, b_1 - \rho g_{b_1}, b_2 - \rho g_{b_2}; g) = \bar{D}_0(x, y, b; g) - \rho, \rho \in \Re,$

Property (1) points out that $\bar{D}_0(x, y, b; g)$ is non-negative for feasible output vectors. Thus, the function takes the value of zero for generating units with efficient output vectors on the

⁹ An advantage of a nonparametric method such as Data Envelopment Analysis (DEA) is that it does not restrict the directional distance function to any particular functional form (Førsund et al. 2007; Hjalmarsson et al. 1996). However, as discussed by Førsund and Hjalmarsson (1983) a piecewise linear frontier is not differentiable, not being suited for computing elasticities of substitution between pollutants.

boundary of $P(x)$ or takes positive values for generating units operating inefficiently below the boundary. Higher values of $\bar{D}_o(x, y, b; g)$ indicate higher inefficiency. $\bar{D}_o(x, y, b; g)$ also satisfies monotonicity: (2) indicates that it is non-increasing in good output, (3) states that it is non-decreasing in undesirable outputs, and (4) points out that it is non-decreasing in inputs. Property (5) indicates that the output set frontier is concave in good and bad outputs. $\bar{D}_o(x, y, b; g)$ also satisfies (6) weak disposability of good output and bad outputs, and (7) null jointness. Additionally, the directional output distance function satisfies the translation property. Under this property, which corresponds to expression (8), the inefficiency can decrease by the amount of ρ if bad outputs are contracted by ρg_{b_1} and ρg_{b_2} , and the good output is expanded by ρg_y .

We specify our directional output distance function with a quadratic form to ensure that the frontier is a twice differentiable function.¹⁰ For a generating unit k operating at period t , the directional output distance function corresponds to

$$\begin{aligned} \bar{D}_o^t(x_k^t, y_k^t, b_k^t; g) &= \alpha + \sum_{n=1}^3 \alpha_n x_{nk}^t + \beta_1 y_k^t + \sum_{i=1}^2 \theta_i b_{ik}^t + \frac{1}{2} \sum_{n=1}^3 \sum_{n'=1}^3 \alpha_{nn'} x_{nk}^t x_{n'k}^t + \frac{1}{2} \beta_2 [y_k^t]^2 \\ &+ \frac{1}{2} \sum_{i=1}^2 \sum_{i'=1}^2 \theta_{ii'} b_{ik}^t b_{i'k}^t + \sum_{n=1}^3 \sum_{i=1}^2 \eta_{ni} x_{nk}^t b_{ik}^t + \sum_{i=1}^2 \mu_i y_k^t b_{ik}^t \\ &+ \sum_{n=1}^3 \delta_n x_{nk}^t y_k^t + \tau_t + \zeta_f, \end{aligned} \tag{2}$$

where $k = 1, 2, \dots, K$; $t = 1, 2, \dots, T$; τ_t are fixed effects per year and ζ_f are fixed effects per firm. In order to estimate the directional output distance function in (2), we minimize the sum of the deviations of the estimated distance function from the efficient value of zero, subject to the constraints (1)–(9). That is,

$\min \sum_{t=1}^T \sum_{k=1}^K [\bar{D}_o^t(x_k^t, y_k^t, b_k^t; g) - 0]$, subject to

- (1) $\bar{D}_o^t(x_k^t, y_k^t, b_k^t; g) \geq 0, \forall k, t.$
- (2) $\partial \bar{D}_o^t(x_k^t, y_k^t, b_k^t; g) / \partial b_i = \theta_i + \theta_{ii} b_{ik}^t + \frac{1}{2} (\theta_{ii'} + \theta_{i'i}) b_{i'k}^t + \sum_{n=1}^3 \eta_{ni} x_{nk}^t + \mu_i y_k^t \geq 0 \forall i, k, t.$
- (3) $\partial \bar{D}_o^t(x_k^t, y_k^t, b_k^t; g) / \partial y = \beta_1 + \beta_2 y_k^t + \sum_{i=1}^2 \mu_i b_{ik}^t + \sum_{n=1}^3 \delta_n x_{nk}^t \leq 0, \forall k, t.$
- (4) $\partial \bar{D}_o^t(\bar{x}, \bar{y}, \bar{b}; g) / \partial x_n = \alpha_n + \alpha_{nn} x_{nk}^t + \frac{1}{2} \sum_{n' \neq n} (\alpha_{nn'} + \alpha_{n'n}) x_{n'k}^t + \sum_{i=1}^2 \eta_{ni} b_{ik}^t + \delta_n y_k^t \geq 0, n = 1, 2, 3$
- (5) $\frac{\partial^2 \bar{D}_o^t(x_k^t, y_k^t, b_k^t; g)}{\partial y^2} = \beta_2 \leq 0, \forall k, t.$
 $\frac{\partial^2 \bar{D}_o^t(x_k^t, y_k^t, b_k^t; g)}{\partial b_i^2} = \theta_{ii} \leq 0, \forall i, k, t.$
- (6) $\frac{\partial^2 \bar{D}_o^t(x_k^t, y_k^t, b_k^t; g)}{\partial b_i \partial y} = \mu_i \leq 0, \forall i, k, t.$
- (7) $\bar{D}_o^t(x_k^t, y_k^t, 0; g) < 0, \forall k, t$
- (8) $\beta_1 g_y - \sum_{i=1}^2 \theta_i g_{b_i} = -1, \beta_2 g_y - \sum_{i=1}^2 \mu_i g_{b_i} = 0, \mu_i g_y - \sum_{i'=1}^2 \theta_{ii'} g_{b_{i'}} = 0$ and $\delta_n g_y - \sum_{i=1}^2 \eta_{ni} g_{b_i} = 0, \forall i, n.$
- (9) $\alpha_{nn'} = \alpha_{n'n}$ with $n, n' = 1, 2, 3$ and $n \neq n'$. $\theta_{ii'} = \theta_{i'i}$ for $i, i' = 1, 2$ and $i \neq i'$.

¹⁰ We chose the generalized quadratic function as it also has additional suitable properties from the econometric and economic point of view. Besides including both first and second order terms (which allows twice differentiability) this specification is linear in the parameters and it is the only specification that yields a second-order Taylor's series approximation to arbitrary functions consistent with the translation property of the directional distance function (Chambers et al. 2013; Färe et al. 2010; Hailu and Chambers 2012).

In this parametric specification we have also imposed through expression (9) cross-output and cross-input symmetry conditions. In Tables 5 and 6 in the ‘‘Appendix’’ we assess the monotonicity conditions, null-jointness property and concavity of the output set frontier.

3.1 Shadow Prices

When pollutants are considered as bad outputs, it is usual to interpret the values of the directional output distance function as a measure of the combined environmental and technical efficiency. The reason for this is that given the level of inputs, the function besides allowing increases in the good output, it also accounts for environmental efficiency as it enables simultaneous decreases in pollutants (see Färe et al. 2005). The directional output distance function approach allows us, however, to not only account for technical and environmental efficiency, but also calculate the shadow prices of CO₂ and NO_x emissions and the elasticity of substitution between these pollutants. Indeed, since the directional output distance function $\bar{D}_o(x, y, b; g)$ describes the technology, the revenue function can be written as

$$R(x, p, q) = \max_{y, b_1, b_2} \left\{ py - q_1 b_1 - q_2 b_2 : \bar{D}_o(x, y, b; g) \geq 0 \right\}$$

where $q = (q_1, q_2)$ denotes the emissions price vector containing CO₂ and NO_x shadow prices, respectively, and p denotes the output price. Chambers et al. (1998) show that the Lagrange multiplier associated with the maximization of revenues corresponds to $\lambda = pg_y + q_1 g_{b_1} + q_2 g_{b_2}$. Hence, the revenue function can be characterized as

$$R(x, p, q) = \max_{y, b_1, b_2} \left\{ py - q_1 b_1 - q_2 b_2 + (pg_y + q_1 g_{b_1} + q_2 g_{b_2}) \bar{D}_o(x, y, b; g) \right\}.$$

The corresponding first order conditions with regard to y, b_1 and b_2 are

$$(pg_y + q_1 g_{b_1} + q_2 g_{b_2}) D_y = -p, \tag{3}$$

$$(pg_y + q_1 g_{b_1} + q_2 g_{b_2}) D_{b_1} = q_1, \tag{4}$$

$$(pg_y + q_1 g_{b_1} + q_2 g_{b_2}) D_{b_2} = q_2, \tag{5}$$

where D_y and D_{b_i} are the first order derivatives of $\bar{D}_o(x, y, b; g)$ with respect to good output and pollutant b_i , respectively.

The ratio between Eqs. (4) and (5) provides us with the relative shadow price of pollution, which represents the trade-off between these two pollutants, i.e., the shadow marginal rate of transformation.¹¹

$$\frac{q_1}{q_2} = \frac{D_{b_1}}{D_{b_2}} \geq 0. \tag{6}$$

Moreover, we can obtain the absolute shadow prices of pollution (i.e., the marginal loss in CHP production necessary to reduce CO₂ or NO_x emissions) from the ratio between Eqs. (4) and (3) and (5) and (3):

$$q_i = -p \frac{D_{b_i}}{D_y}. \tag{7}$$

¹¹ For a detailed explanation of the shadow prices approach in the context of the output distance function, see Färe et al. (1993). For applications in the case of directional output distance functions, see Färe et al. (2001, 2005).

3.2 Morishima Elasticities of Substitution

The Morishima elasticity of substitution provides us with information on how much the relative shadow prices of outputs will change in response to changes in emission intensities (see Blackorby and Russell 1981, 1989). In the context of the technology described by the directional output distance function, the indirect Morishima elasticity of substitution between pollutants b_1 and b_2 can be expressed as (see Kumar and Managi 2011)

$$M_{b_1b_2} = \frac{\partial \ln (q_1/q_2)}{\partial \ln (b_2/b_1)} = b_2^* \left(\frac{D_{b_1b_2}}{D_{b_1}} - \frac{D_{b_2b_2}}{D_{b_2}} \right), \tag{8}$$

and between pollutant b_i and good output as

$$M_{b_iy} = \frac{\partial \ln (q_i/p)}{\partial \ln (y/b_i)} = y^* \left(\frac{D_{b_iy}}{D_{b_i}} - \frac{D_{yy}}{D_y} \right), \tag{9}$$

where $D_{b_1b_2}$, $D_{b_2b_2}$, D_{b_iy} , and D_{yy} are second order derivatives of the directional output distance function, $y^* = y + \bar{D}_o(x, y, b; g) g_y$ and $b_i^* = b_i - \bar{D}_o(x, y, b; g) g_{b_i}$. If $M_{b_1b_2} > 0$, then b_1 and b_2 are Morishima substitutes. That is, the pollutants are substitutes if the emission intensity (b_2/b_1) increases when the relative shadow price (q_2/q_1) decreases; emission reductions in b_1 are accompanied by increased emissions in b_2 . Conversely, b_1 and b_2 are complements when $M_{b_1b_2} < 0$.

Note that $M_{b_iy} \leq 0$ since $\bar{D}_o(x, y, b; g)$ satisfies monotonicity and concavity properties.¹² Moreover, in terms of the quadratic directional distance function we can write the elasticity $M_{b_1b_2}$ as

$$M_{b_1b_2} = b_2^* \left(\frac{\theta_{12}}{\theta_1 + \theta_{11}b'_{1k} + \theta_{12}b'_{2k} + \sum_{n=1}^3 \eta_{n1}x'_{nk} + \mu_1y'_k} - \frac{\theta_{22}}{\theta_2 + \theta_{22}b'_{2k} + \theta_{21}b'_{1k} + \sum_{n=1}^3 \eta_{n2}x'_{nk} + \mu_2y'_k} \right), \tag{10}$$

where the sign of $M_{b_1b_2} = b_2^* \left[\frac{+}{+} - \frac{-}{+} \right]$ depends critically on the sign and magnitude of θ_{12} . In particular, for $b_2^* > 0$, it holds that b_1 and b_2 are Morishima substitutes if

- $\theta_{12} > 0$ or
- $\theta_{12} < 0$ and $\left| \frac{\theta_{12}}{\theta_1 + \theta_{11}b'_{1k} + \theta_{12}b'_{2k} + \sum_{n=1}^3 \eta_{n1}x'_{nk} + \mu_1y'_k} \right| < \left| \frac{\theta_{22}}{\theta_2 + \theta_{22}b'_{2k} + \theta_{21}b'_{1k} + \sum_{n=1}^3 \eta_{n2}x'_{nk} + \mu_2y'_k} \right|$.

By analogy, the elasticity $M_{b_2b_1}$ corresponds to

$$M_{b_2b_1} = b_1^* \left(\frac{\theta_{21}}{\theta_2 + \theta_{22}b'_{2k} + \theta_{21}b'_{1k} + \sum_{n=1}^3 \eta_{n2}x'_{nk} + \mu_2y'_k} - \frac{\theta_{11}}{\theta_1 + \theta_{11}b'_{1k} + \theta_{12}b'_{2k} + \sum_{n=1}^3 \eta_{n1}x'_{nk} + \mu_1y'_k} \right). \tag{11}$$

The Morishima elasticities of substitution show that a percentage change in the price ratio q_1/q_2 (motivated for instance by an increase in q_1) has two effects on the quantity ratio: the first term shows the effect on b_1 while the second term shows the effect on b_2 . Therefore, despite the fact that symmetry conditions for cross-output ensure that $\theta_{12} = \theta_{21}$, the

¹² $sign M_{b_iy} = y^* \left[\frac{-}{+} - \frac{-}{+} \right] \leq 0$ for $y^* > 0$.

Morishima elasticities are inherently asymmetric ($M_{b_1b_2} \neq M_{b_2b_1}$) since they represent the difference between two elasticities: a cross elasticity and own price elasticity. In terms of the analysis, the asymmetric substitutability tells us which pollutant is easier to substitute for another pollutant for a fixed amount of output. Note that a lower value of the Morishima elasticities of substitution indicates greater substitution possibilities between pollutants. The intuition behind this is that to generate the same change in the emission intensity (b_2/b_1), a smaller change in the prices (q_1/q_2) is required when the pollutants are close substitutes. Likewise, lower pollution-good output elasticities in absolute value indicate greater substitution possibilities.

We estimate the directional output distance function using a deterministic method, i.e., parametric linear programming (PLP) that allows us to impose parametric restrictions that are a result of the underlying technology such as monotonicity in good or bad outputs. We follow Aigner and Chu's (1968) procedure of minimizing the sum of the distance between the frontier technology and the actual observations of the generating units in each period. Hence, the method chooses the parameters that make the generating units as efficient as possible subject to a set of restrictions associated with the technology properties already described (see Färe et al. 2001, 2005, 2006).

Note that the choice of directional vector $g = (g_y, g_{b_1}, g_{b_2})$ affects the magnitude of the first and second order derivatives of the directional distance function through the constraints (8). As in Färe et al. (2006), our choice of directional vector is $g = (1, 1, 1)$, i.e., the component of the good output and the components of the two pollutants are equal to one, making the model parsimonious. In Sect. 5.5 we develop a sensitivity analysis estimating the directional distance function in Eq. (2) for two additional direction sets.

We derive estimates of the coefficients for pre- (2001–2004) and post- (2005–2009) EU ETS implementation. We wrote the code to solve the optimization problem in Matlab. In order to avoid convergence problems in the algorithm, all variables are expressed in normalized values, i.e., each output and input is divided by its own sample mean.¹³ Year and firm fixed effects (τ_t and ζ_f) are estimated using a set of yearly and firm dummy variables. These variables take the value of one if the observation belongs to year t or firm f , accordingly; and zero otherwise. In the case of the yearly dummies, the reference year corresponds to the first year for each period of analysis (e.g., 2001 for pre-EU ETS and 2005 for post-EU ETS). Regarding the firm dummies, we chose arbitrarily a firm as the reference firm for both periods.¹⁴ All the dummy variables (except those representing the reference cases) are included in the objective function of the minimization problem to carry out the estimations. Using the estimated coefficients of the directional output distance function, we compute the technical and environmental efficiencies and the Morishima elasticities of substitution between pollutants and between pollutants and output according to Eqs. (8) and (9), respectively. The relative and absolute shadow prices are obtained by applying Eqs. (6) and (7). To identify changes in efficiencies, elasticities, and relative shadow prices before and after the implementation of the EU ETS, we compare the density functions of these measures between periods. To this end, we employ kernel-based methods to statistically test the difference between distributions. Our

¹³ Note that the choice of a unit vector g is equivalent to set the direction equal to the sample average of inputs, good and bad outputs when the data is normalized by the sample mean.

¹⁴ Given that the regressions are estimated with intercept, our model included 34 firm dummies. The purpose of including those variables is to control for unobserved factors at the firm level that are constant over time (either 2001–2004 or 2005–2009) which may affect the technical and environmental efficiency.

tests are conducted by computing the nonparametric T_n -statistic of Li et al. (2009)¹⁵ which assesses the equality between two density functions. Let $f(x)$ and $g(x)$ denote the density functions of a random variable x . We test the null hypothesis that $f(x) = g(x)$ against the alternative hypothesis that $f(x) \neq g(x)$. Following Hayfield and Racine (2008, 2011), we implement this procedure in the software R with 500 bootstrap repetitions and estimate the T_n -statistic using a standard normal kernel. The empirical p values of the consistent density equality test are computed after bootstrapping.

4 Data

Our analysis models production and emissions at the boiler level in the heat and power sector using data for the Swedish CHP plants during 2001–2009. We focus on CHP plants since approximately 75% of the plants in the heat and power sector belong to this group. Moreover, CHP plants have been promoted within the European Union as an effective means to increase the overall energy efficiency (EU Directive 2004/8/EC).¹⁶ In Sweden approximately 30–50% of the total input energy of a CHP is converted to electricity and the rest to heat (Svensk Fjärrvärme 2011). Though we would have liked to develop the analysis by disaggregating production into heat and power, the information available at the boiler level only allows us to analyze the joint production. Hence, our measure of good output is the amount of useful energy (MWh) commercially sold. This is the sum of electrical energy and process heat in those cases where this heat is sold (generally for district heating¹⁷) or used in industrial processes. The two undesirable outputs, CO₂ and NO_x emissions, are expressed in metric tons, and as stated above, the inputs consist of installed capacity (MW),¹⁸ fuel consumption (MWh),¹⁹ and labor (number of employees). NO_x emissions and useful energy are taken from the Swedish Environmental Protection Agency's (SEPA) NO_x charge database. These two variables are measured and reported to the SEPA directly by the generating units along with information about energy fuel shares, installed capacity, and the available NO_x combustion and post-combustion technologies (CTs and PCTs, respectively), which makes this dataset unique in the sense that it is the most detailed longitudinal database at the boiler level of the Swedish heat and power sector. Installed capacity is used as a proxy for capital in physical units. With regard to labor, the data at company level were gathered from Retriever Bolagsinfo. For multi-unit plants, we allocated labor to generating units according to their generating capacity ratio.²⁰

¹⁵ The T_n -statistic of Li et al. (2009) can be used in a broader perspective to test equality of distributions with mixed and continuous data. The test of equality of two density functions is just a particular case of it. Unlike the T -statistic of Li (1996, 1999), the T -statistic of Li et al. (2009) is not sensitive to the ordering of the data.

¹⁶ A high-efficiency CHP can use 10% less fuel than that required to produce the same quantities of heat and electricity separately (Swedish Energy Agency 2009).

¹⁷ District heating is an energy network that supplies and spreads heat to homes and other facilities. Heat is produced by a group of boilers in a central plant burning a range of different fuels, and then distributed through pipelines to customers.

¹⁸ Although our variable of installed capacity does not account directly for the capital invested to abate NO_x emissions, this variable partially and indirectly considers the likelihood of carrying out abatement investments since PCTs and CTs are strongly dependent on boiler size.

¹⁹ A vast literature reports the heat content in the fuel in Btu units; however for simplicity we have expressed fuel input in MWh since the NO_x charge system makes use of MWh as its fundamental unit of data analysis.

²⁰ Assuming that labor is proportional to generating capacity is common in the literature (see e.g., Färe et al. 2005; Agee et al. 2014). The motivation for including labor as an input in the production process is that the

Although we have CO₂ values accessed from the SEPA's EU ETS database, their aggregation at installation level prevents us from recovering the emissions for each boiler. Instead, CO₂ emissions are estimated based on available data on the boilers' energy fuel shares and emission factors per fuel type. Hence, we can recover the total input energy that corresponds to the amount of fuel consumed per boiler. In addition, our dataset comprises a wide range of fuel types, i.e., gas, oil, coal, peat, biofuel, and waste. We use emission factors for each fuel classification.²¹ However, this method only considers emissions derived from fuel use for combustion and excludes emissions coming from raw materials,²² which—unlike other industries—are not significant in the case of the heat and power generation.²³

We focus on boilers that operate every year. This group of generating units represents the operation of the sector under normal or standard conditions, i.e., we exclude boilers that may only be switched on under certain circumstances (e.g., as backup during episodes of very cold winters). Two boilers for which information on fuel shares is missing are dropped. One boiler that uses a combination of mixed refinery gas and gas converted during the process is also excluded due to the complexity of the fuel and its extremely high emissions. Finally, our sample consists of a panel of 82 boilers distributed across 35 firms (738 observations, of which 328 are for the period 2001–2004 and 410 are for 2005–2009).

Descriptive statistics of the variables are presented in Table 1. As we can see, there is large variation in emission rates among boilers. CO₂ emission rates vary from zero to 428.5 tons/GWh, while NO_x emission rates vary almost 20-fold from 0.03 to 0.68 tons/GWh. This reflects differences within the sector in fuel mix, fuel usage, boiler size, and availability of NO_x abatement technologies.

5 Results

In this section, we describe and analyze the results of our estimates of technical efficiencies, elasticities of substitution, and shadow prices.

5.1 Technical Efficiency and Technical Progress

The estimated coefficients of the quadratic directional output distance function are shown in Table 2, and Tables 5 and 6 in the “Appendix” verify that the coefficients are consistent with monotonicity, concavity, and null-jointness constraints.

Footnote 20 continued

implementation of NO_x abatement measures requires qualified human capital. Moreover, as pointed out by Sterner and Turnheim (2009), direct real-time measurement of NO_x emissions is very important as simple rules of thumb are not useful, and not even the engineers themselves know the emissions levels unless they are continuously monitored.

²¹ Each type of fuel has some sub-classifications. For instance, gas may include natural gas, LPG, and biogas, oil may include no. 1 and no. 5 fuel oil as well as bio-oil, and biofuel may include several kinds of residues from the forest and other types of biomass. Specific emission factors for every sub-classification have been considered to develop the estimations (see emission factors in SEPA 2009).

²² Raw materials in this context are primary substances or goods, different than fuels, used as feedstocks in the production process to be transformed and generate industrial products, e.g., chemicals or metals. We acknowledge that the carbon content in those substances may not be negligible.

²³ For comparison purposes, we also estimated the CO₂ emissions using the total output per boiler, adjusting it by boiler efficiency to obtain the input energy and distributing it across fuels by means of the energy fuel shares. Another check involved the comparison of the sum of the estimated emissions per installation and the corresponding aggregated emissions in the SEPA's EU ETS database for some installations where such aggregation was possible. In both cases, our estimations were in a similar order of magnitude.

Table 1 Descriptive statistics

Variable	Description	Mean	Standard Deviation	Min.	Max.
2001–2004					
Y	Useful energy (MWh)	239,286	227,590	26,119	1,292,804
b_1	CO ₂ (tons)	25,098	53,406	6.5	350,320
b_2	NO _x (tons)	46.7	33.9	4.4	185.8
b_1/Y	CO ₂ (tons)/GWh	81.4	120.7	0.2	428.5
b_2/Y	NO _x (tons)/GWh	0.25	0.09	0.03	0.56
x_1	Installed capacity (MW)	72.3	80.2	6	600
x_2	Fuel consumption (MWh)	253,096	237,637	23,642	1,247,052
x_3	Labor (no. of employees)	36.6	41.5	1	200
2005–2009					
Y	Useful energy (MWh)	242,729	253,471	25,091	1,232,591
b_1	CO ₂ (tons)	20,575	56,114	0	382,960
b_2	NO _x (tons)	42.5	32.0	5.0	192.2
b_1/Y	CO ₂ (tons)/GWh	69.7	119.0	0	427.3
b_2/Y	NO _x (tons)/GWh	0.23	0.10	0.03	0.68
x_1	Installed capacity (MW)	70.7	77.5	6	600
x_2	Fuel consumption (MWh)	255,025	266,095	23,726	1,334,877
x_3	Labor (no. of employees)	44.4	43.0	2	211

Stringent environmental regulations have a positive effect not only on environmental quality but also possibly on firms' absolute performance if they induce development of new technologies and a more efficient use of resources. Compliance costs due to stricter environmental regulations make environmentally friendlier technological development relatively less costly. This should be represented by an outward shift of the production possibility curve or an inward shift in the input coefficient space, which means that with a given set of resources it is now possible to produce more goods and services without worsening the environmental quality (Xepapadeas and Zeeuw 1999).

Our results from the Swedish CHP plants are a case in point and indicate the existence of significant technical progress. We compute the frontier for the years 2001 and 2009 (the initial and final years in our sample) using our PLP coefficient estimates. The frontiers are obtained for a generating unit using the mean values of inputs in both periods. The normalized values of inputs of this generating unit are substituted into the directional output distance function leading to an expression that only depends on the good and bad outputs. We solve this equation for values of the good output that make the directional output distance function equal to zero (i.e., no technical inefficiency). The frontiers are plotted allowing for a grid of values of both pollutants. As shown in Fig. 2, technological progress drives a significant movement of the frontier towards reduced emissions of both pollutants, though as expected the overall reduction is biased towards CO₂ emission reduction. The movement of the frontier itself is consistent with the fact that the amount of heat and power generation per unit of emissions increases for both pollutants between periods, but the efficiency increase is greater in the case of CO₂. We could thus say that the technical change is "carbon saving" in much the same

Table 2 Parameter estimates of the quadratic directional output distance function using the parametric linear programming approach ($g = 1, 1, 1$)

Coefficients	Variable	Before EU ETS 2001–2004	After EU ETS 2005–2009
α_0	Intercept	0.005	0.008
α_1	x_1	-0.127	-0.039
α_2	x_2	0.737	0.610
α_3	x_3	0.060	-0.016
β_1	y	-0.777	-0.745
θ_1	b_1	0.020	0.012
θ_2	b_2	0.221	0.243
α_{11}	x_1^2	-0.027	-0.073
α_{12}	x_1x_2	-0.178	-0.204
α_{13}	x_1x_3	0.126	0.131
α_{22}	x_2^2	-0.112	-0.227
α_{23}	x_2x_3	-0.039	0.025
α_{33}	x_3^2	-0.117	-0.071
β_2	y^2	-0.159	-0.129
θ_{11}	b_1^2	-0.003	-0.0001
θ_{22}	b_2^2	-0.158	-0.129
η_{11}	x_1b_1	-0.0004	0.004
η_{21}	x_2b_1	0.011	-0.007
η_{31}	x_3b_1	-0.001	0.011
η_{12}	x_1b_2	0.103	0.089
η_{22}	x_2b_2	0.178	0.248
η_{32}	x_3b_2	0.029	-0.046
μ_1	yb_1	-0.002	0.000
μ_2	yb_2	-0.157	-0.129
θ_{12}	b_1b_2	0.001	0.0001
δ_1	x_1y	0.102	0.093
δ_2	x_2y	0.189	0.241
δ_3	x_3y	0.028	-0.035
τ_2	2002	-0.010	
τ_3	2003	-0.008	
τ_4	2004	-0.009	
τ_6	2006		-0.009
τ_7	2007		-0.016
τ_8	2008		-0.009
τ_9	2009		-0.007
Number of observations		328	410
Satisfy concavity in (y, b_1, b_2)		Yes	Yes

x_1 = installed capacity, x_2 = fuel consumption, x_3 = labor, y = useful energy, b_1 = CO₂, and b_2 = NO_x. Years 2001 and 2005 are the reference cases for each estimation period respectively, so that τ_1 and τ_5 coefficients are absorbed by the intercept α_0 . Estimations include firm fixed effects, but their coefficients are not shown in the table

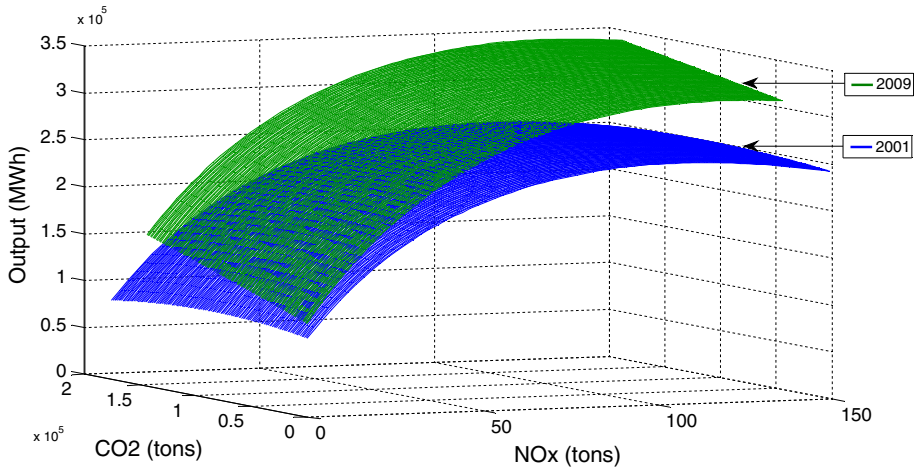


Fig. 2 Frontiers in 2001 and 2009. *Note* The frontiers are obtained for a generating unit using the mean values of inputs in both periods. The normalized values of inputs of this generating unit are substituted into the directional output distance function leading to an expression that only depends on the good and bad outputs. The plots are expressed in original units multiplying the normalized values by the corresponding means of good and bad outputs

way as traditionally technical changes often have been characterized as “labor saving.”²⁴ On average, CO₂ emissions per GWh by CHP plants decreased by 15% between the periods (from 81.4 in 2001–2004 to 69.7 ton/GWh in 2005–2009) and by approximately 5% for NO_x (from 0.245 to 0.232 ton/GWh).

Thus far we have analyzed technical progress at the frontier. We are also interested in the performance of all firms, which is conveniently measured by studying technical efficiency relative to each respective frontier: We find that out of 82 boilers of the sample, 45 were found to operate at least once on the frontier during 2001–2004 and 44 at least once on the frontier during 2005–2009. Thirty-three boilers were found to operate on the frontier at least one of the years in each of the two periods.

The estimations of technical and environmental efficiency yield mean inefficiency values of 14.86 and 17.68% for the pre- and post-introduction periods of the EU ETS, respectively.²⁵ This indicates that during 2001–2004, boilers on average could have expanded heat and power generation by 35.56 GWh (i.e., $239.3 \times 14.86\%$) and contracted CO₂ emissions by 3730 tons ($25,098 \times 14.86\%$) and NO_x emissions by 6.94 tons ($46.7 \times 14.86\%$) if they would have adopted the best practice of frontier-generating units. Similarly, in 2005–2009 boilers on average could have increased their production by 42.91 GWh and decreased CO₂ and NO_x emissions by 3638 and 7.51 tons, respectively, if the generating units were to operate efficiently.²⁶ Given these results, the amount of possible reduction in emissions and increase

²⁴ We mean by “carbon saving” the same as “reducing net system emissions of CO₂”. We assume that the biomass is sustainably grown and leads to no (or low) CO₂ emissions. Thus, reducing carbon emissions is here largely synonymous with “fossil-fuel saving” or “biomass using”.

²⁵ The firm fixed-effect coefficients were in general different from zero; i.e., on average, a set of CHP units belonging to specific firms tend to be much closer or farther to the best-practice frontier than the group of CHP units of the reference firm.

²⁶ We also analyzed the sensitivity of our estimations to the heterogeneity in the number of plants per firm. In our dataset we have firms with one, two, or seven plants. We estimated Eq. (2) adding two dummy variables:

in heat and power generation that could have been achieved between periods following the practice of the most efficient generating units is of considerable magnitude. The bootstrapped Li et al. (2009) T_n -statistic allows us to compare the inefficiency distributions between periods and conclude that the boilers are statistically equally efficient in the two periods at the 10% significance level.

If we compare inefficiencies by fuel type, we find that the highest technical and environmental efficiencies are reached by boilers using mainly biofuel while the highest inefficiencies are found for boilers burning mainly fossil fuels. For instance, average inefficiencies for boilers with biofuel shares exceeding 80% are 9.64% for 2001–2004 and 13.60% for 2005–2009 whereas the corresponding numbers for boilers with fossil fuel shares exceeding 80% are 36.37 and 33.42%, respectively. In the case of fossil fuels, the bootstrapped Li et al. (2009) test indicates that the differences between periods are not statistically significant, while in the case of biofuels the test indicates that inefficiencies tend to increase in the period 2005–2009 (p value = 0.056).

When it comes to the availability of NO_x abatement technologies, we find that the inefficiencies are larger for boilers that use only PCTs (22.27% in 2001–2004 vs. 27.37% in 2005–2009) compared with boilers that use only CTs (11.11% in 2001–2004 vs. 15.21% in 2005–2009). As discussed in Sect. 2, PCTs usually require energy that might lead to increased CO_2 emissions. Nevertheless, as shown in Table 3, we find a significant correlation between the type of NO_x technology installed and the boiler size. Indeed, if we classify boilers according to size, we observe that the incidence of CTs (whose investment cost is lower) is greater among small boilers compared with PCTs, which are more expensive and mostly adopted by large boilers (alone or in combination with CTs).²⁷ The incidence of biofuel use is also greater among small boilers. Moreover, these boilers tend to minimize the use of fossil fuels to the largest possible extent by using alternative fuels such as peat and waste, which were exempt from CO_2 taxation at certain times during the period 2001–2009. Overall, these findings suggest that smaller boilers substitute pollutants by means of the choice of fuel while larger boilers substitute by adopting NO_x -reducing technologies, which is a reflection of the fact that the production process of large boilers is relatively more inflexible and—as discussed in the following section—less sensitive to variations in the relative price of CO_2/NO_x .

5.2 Output- CO_2 and Output- NO_x Elasticities

With regard to the pollution-good output elasticities, Fig. 3a, b illustrate the kernel distributions between the two periods (and report the mean values, standard deviation, and p -value of the nonparametric test). As expected, the pollution-good output elasticities are negative, implying that the emission intensity decreases when the relative shadow price of emissions to output increases. When it comes to CO_2 , the mean CO_2 -output elasticity changed from -0.420 to -0.176 between the periods. That is, substitution increased since lower pollution-

Footnote 26 continued

a dummy that takes the value of one for firms with seven plants (and zero otherwise); and a dummy that takes the value of one for firms with one plant (and zero otherwise). The group of firms with two plants is the reference case. We then compared the density functions of the inefficiency scores of the models with and without dummy variables for the number of plants per firm. For both periods (2001–2004 and 2005–2009) we were not able to reject the null hypothesis that the inefficiency-scores density functions are equal at the 10% significance level. This suggests that controlling for the number of plants per firm does not have a statistically significant impact on the results.

²⁷ Size is proxied by installed capacity. Generating units with installed capacity below the median are classified as small boilers and boilers with installed capacity above the median are classified as large boilers.

Table 3 CO₂ and NO_x emissions, fuel use, and availability of abatement technology by boiler size

Period/size ^a	Emission intensity (tons/GWh) ^b		Fuel shares mean (SD) ^b		% of boilers according to fuel type ^c		% boilers with NO _x technology				
	CO ₂	NO _x	Biofuel	Fossil fuel	Biofuel (>80%)	Fossil fuel (>80%)	None	Only PCT	Only CT	PCT and CT	
2001–2004											
Small	52.4 (101.7)	0.286 (0.089)	82.7 (30.6)	0.4 (1.3)	16.9 (30.6)	70.7	0	31.7	13.4	48.8	6.1
Large	110.4 (131.1)	0.203 (0.078)	62.8 (42.5)	31.6 (42.2)	5.6 (13.0)	48.8	24.4	9.8	24.4	33.5	32.3
Overall	81.4 (120.7)	0.245 (0.093)	72.7 (38.3)	16.0 (33.6)	11.3 (24.1)	59.8	12.2	20.7	18.9	41.2	19.2
2005–2009											
Small	40.6 (87.8)	0.270 (0.093)	85.4 (29.1)	1.5 (8.9)	13.2 (28.3)	74.8	0	29.4	10.3	43.9	16.4
Large	101.4 (139.1)	0.191 (0.085)	66.6 (43.3)	26.6 (41.5)	6.8 (17.8)	51.0	23.0	3.6	23.0	34.7	38.8
Overall	69.7 (119.0)	0.232 (0.098)	76.4 (37.7)	13.5 (31.9)	10.1 (24.0)	63.4	11.0	17.1	16.3	39.5	27.1

^a To classify firms according to size we use the median of the variable installed capacity (equal to 50MW). Small firms correspond to firms that are smaller than the median while the reverse holds for firms denoted as large

^b Standard deviations (SD) are reported in parentheses

^c Biofuel and fossil fuel (>80%) include all boilers with the respective fuel share greater than or equal to 80% in each year within the respective time period

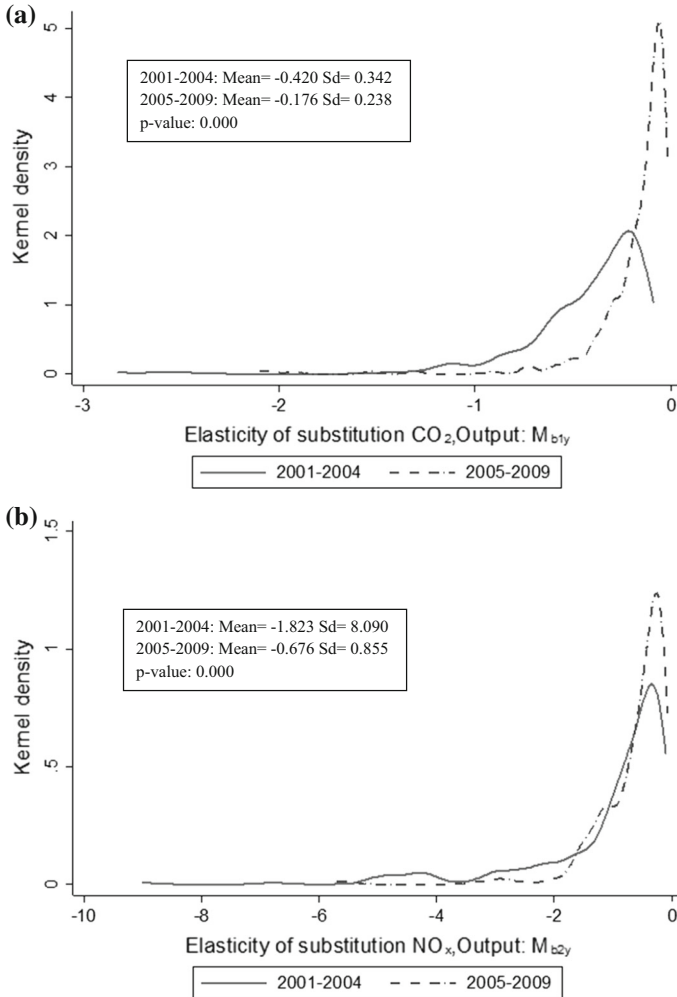


Fig. 3 **a** Kernel distribution of CO₂-output elasticities. **b** kernel distribution of NO_x-output elasticities. *Note* Elasticities lower than -8.5 are not shown for convenience of presentation

good output elasticities in absolute values indicate greater substitution possibilities. Using the Li et al. (2009) test, we are able to reject the null hypothesis of equality between the density functions of the pollution-good output elasticities pre- and post-introduction of the EU ETS for CO₂. An explanation for the increased substitution is technological development. Indeed, the results in the previous section indicate that several technical measures were implemented in order to reduce CO₂ emissions. The trend towards phasing out of fossil fuels in Sweden has been quite stable over the sampled period and most firms in the sector have already switched to “carbon-free” fuels. For instance, during the period 2005–2009 the fraction of boilers with biofuel shares greater than or equal to 80% was approximately 63%, while the fraction of boilers using mainly fossil fuels was around 11% (see Table 3). As discussed before, there are clear differences between small and large boilers; the Morishima elasticities of substitution indicate greater substitution among small boilers (e.g., a CO₂-output elasticity of -0.243

and -0.076 for the first and second period versus -0.634 and -0.309 for large boilers). Consequently, the CO_2 emission intensity of small boilers is lower than that of large boilers.

The mean absolute value of the NO_x -output elasticity also decreased between the pre- and post-EU ETS periods (from -1.823 to -0.676), indicating greater substitution. The test that compares the density functions of the elasticities before and after the introduction of the EU ETS indicates that there is a statistically significant difference between the two distributions at the 1% significance level. This result might be explained by the fact that the fraction of generating units without any NO_x abatement measure declined between the periods from 21 to 17% and also that the simultaneous adoption of more than one NO_x reduction technology increased from 19 to 27% (see Table 3). The decrease in absolute value of these elasticities for the period 2005–2009 would suggest that the easiest emission reductions have already been undertaken. Therefore further reductions of NO_x per unit of output will only be supported by much higher charges for NO_x emissions. NO_x emission reductions have certainly been achieved since the NO_x charge was implemented yet the slow pace of these reductions relative to CO_2 during the last decade also reflects an inclination to rather favor CO_2 than NO_x emission reductions.

When it comes to NO_x -output elasticity by size, our results indicate greater substitution among small boilers than among large boilers. For small boilers, the NO_x -output elasticity is -0.564 and -0.360 for the first and second period, respectively, versus -3.348 and -1.100 for large boilers.

5.3 CO_2 - NO_x Substitution

One main purpose of this study is to assess the existence of substitutability between CO_2 and NO_x . Our results indicate that CO_2 and NO_x are substitutes. Like in the case of pollution-good output elasticities, lower absolute values of the Morishima elasticities of substitution indicate greater substitution possibilities between pollutants. Hence, substitution increased during the period 2005–2009. For instance, the mean estimates of the Morishima CO_2 - NO_x elasticity correspond to 1.706 for 2001–2004 and 0.472 for 2005–2009. The mean estimates of the corresponding NO_x - CO_2 elasticity are 0.446 for 2001–2004 and 0.004 for 2005–2009.

The asymmetry of the elasticities indicates that it is easier to substitute CO_2 with NO_x than NO_x with CO_2 . In other words, firms are much more sensitive to variations in CO_2 prices and therefore more willing to decrease CO_2 emissions at the expense of increasing NO_x emissions rather than the other way around. Clearly, this is linked to the fact that CO_2 emissions have a much higher opportunity cost than NO_x emissions. As mentioned before, a policy implication that could be derived from here is that—given the high opportunity costs of CO_2 emissions—the NO_x fee would have to be increased to a higher level than its current value in order to achieve large NO_x emission reductions. An alternative implication has to do with the choice of policy instruments as the effects of climate policy on NO_x emissions depend crucially on the environmental regulation of NO_x . In particular, NO_x emissions change in response to climate policy since NO_x is subject to price regulation. If NO_x instead would be subject to, for instance, an emissions cap-and-trade system, then climate policy would not change NO_x emissions but would change the price of permits in the NO_x market.

Kernel distributions of the elasticities between pollutants are depicted in Fig. 4a, b. Using the bootstrapped Li et al. (2009) T_n -statistics, we tested the null hypothesis of equal density functions between the pre- and post-implementation period of the EU ETS. We reject this null hypothesis; the elasticity of CO_2 - NO_x substitution does tend to shift towards the left-hand side of the distribution, indicating greater substitution in 2005–2009 than in 2001–2004. In the case of the NO_x - CO_2 elasticity, we also observe that for many generating units the

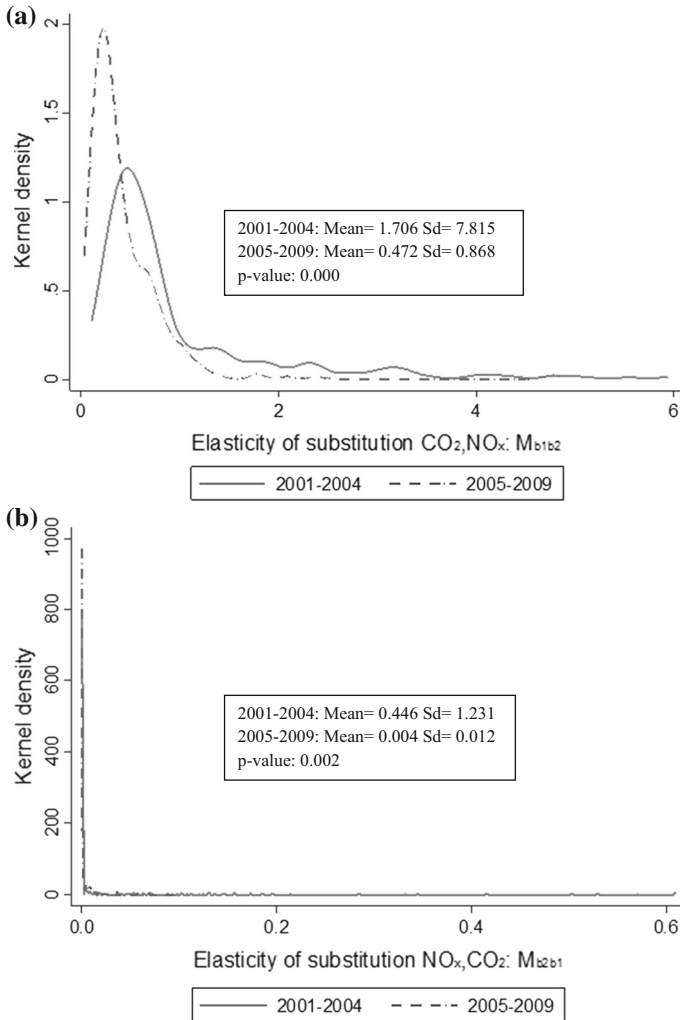


Fig. 4 **a** Kernel distribution of CO_2 – NO_x elasticities. *Note* Elasticities greater than 6 are not shown for convenience of presentation, **b** kernel distribution of elasticities NO_x – CO_2 . *Note* Elasticities greater than 0.6 are not shown for convenience of presentation

estimates are concentrated around zero. Further CO_2 – NO_x substitution has increased because most firms have implemented technical measures to allow for this substitution to take place (they have in fact undertaken a complete transition to biofuels).

The asymmetric substitution is also observed when classifying by boiler size. Among small boilers, it is easier to substitute NO_x for CO_2 than CO_2 for NO_x , e.g., the value of the CO_2 – NO_x elasticity for small boilers is 0.699 and 0.340 for the first and second period, respectively, versus 0.172 and 0.001 for the NO_x – CO_2 elasticity. Similar evidence is found for large boilers; the value of the CO_2 – NO_x elasticity is 2.926 and 0.648 for the first and second period versus 0.777 and 0.008 for the NO_x – CO_2 elasticity. Moreover, in line with the results described in the previous section, in the case of both the CO_2 – NO_x and the NO_x –

CO₂ elasticity, we observe that substitution is greater among small boilers than large boilers, which might be explained by a more inflexible production process for large boilers.

5.4 Shadow Prices

Finally, we compute the absolute and relative shadow prices. When it comes to the absolute shadow prices, we follow Färe et al.'s (2005) approach and assume that the price of heat and power is known (and equal to its shadow price). We proxy the price of heat and power through the annual price of district heating reported by the Swedish Energy Agency. The average price corresponds to 56.6 €/MWh for the period 2001–2004 and 61.7 €/MWh for the period 2005–2009.²⁸ Based on our estimates of the derivatives D_y and D_{b_i} , the shadow prices of CO₂ and NO_x for the period 2001–2004 correspond to 5.33 and 80,136 €/ton, respectively. The shadow prices for the period 2005–2009 are significantly higher (which supports the claim that the easiest emission reductions have already been undertaken) at 19.23 and 129,556 €/ton, respectively. Furthermore, there is a very small (though statistically significant) increase in the shadow price of CO₂/NO_x from a mean of 0.00018 in 2001–2004 to a mean of 0.00019 in 2005–2009²⁹ (Fig. 5.).

The sum of the CO₂ tax (net of deductions) plus the EU ETS price corresponded to 52 €/ton in 2001–2004 and 33.4 €/ton in 2005–2009. The price of the NO_x charge corresponded to 3766.5 and 4143.1 €/ton, respectively. Hence, in terms of €/ton, the regulatory relative prices of CO₂/NO_x decreased from a mean of 0.014 to a mean of 0.008. Overall, these estimates suggest that, in relative terms, the relative shadow price of CO₂/NO_x emissions is lower than the regulatory relative price. The comparison of absolute prices indicates that with regard to the prices of the regulations, CO₂ has been cheaper to reduce while the reverse holds for NO_x. This is consistent with our previous claim that in order to achieve further NO_x reductions, the NO_x fee has to be increased to a greater extent.

5.5 The Choice of the Directional Vector

One important advantage of the directional distance function is the possibility to analyze efficiency by increasing good outputs while simultaneously decreasing bad outputs. However, the wide range of possible directions allows for a great deal of subjectivity regarding the importance of the production of the good output and the abatement of bad output. So far we have assumed that pollution reduction is regarded as an equally important target as the increase of good output. Moreover, we assume that CO₂ abatement is regarded as equally important as NO_x abatement. Nevertheless, as discussed by Agee et al. (2014), increasing output might be regarded as more important than reducing emissions. Furthermore, in line with the discussion in Sect. 2, since the transition to a carbon-free economy is as key environmental goal of the Swedish government, it is reasonable to assume that CO₂ abatement is regarded as more important than NO_x abatement. Hence, in this section, we develop a sensitivity analysis estimating the elasticities of substitution and efficiency for two additional direction sets,

²⁸ These prices ranged from 52.6 to 61.0 €/MWh during the period 2001–2004 and from 61.0 to 62.2 €/MWh in 2005–2009. These prices are converted to units of 2009 constant euros. We use the Sweden Harmonised Index of Consumer Prices (HICP) and an exchange rate of 10.62 SEK/€.

²⁹ Note that the mean relative shadow price differs from the quotient between the means of the absolute shadow prices. The first measure corresponds to $(\bar{q}_1) = \frac{1}{KT} \sum_{t=1}^T \sum_{k=1}^K (\frac{D_{b_1,k}^t}{D_{b_2,k}^t})$, while the second is given

$$\text{by } \bar{q}_2 = \frac{\sum_{t=1}^T \sum_{k=1}^K p_t (D_{b_1,k}^t / D_{y,k}^t)}{\sum_{t=1}^T \sum_{k=1}^K p_t (D_{b_2,k}^t / D_{y,k}^t)}.$$

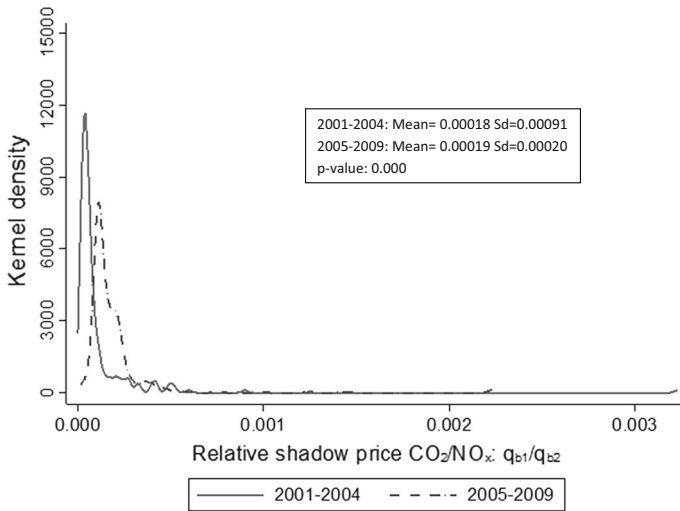


Fig. 5 Kernel distribution of relative shadow prices of CO₂/NO_x. *Note* Relative shadow price estimates greater than 0.0032 are not shown for convenience of presentation

namely (1.2, 1, 1) and (1, 1, 0.8).³⁰ The first vector represents the case where the increase in good output is 20% more important than a decrease in pollution and the second represents the case where reducing CO₂ emissions is as important as increasing output and 25% more important than a decrease in NO_x emissions.

Table 4 shows that our results are generally robust to the choice of the directional vector. For instance, CO₂ and NO_x are substitutes regardless of the directional vector and NO_x–CO₂ substitution increases post-EU ETS implementation. Moreover, when it comes to inefficiency, the differences between periods remain statistically insignificant, though (interestingly) the level of the inefficiencies tend to be lower when there is a greater focus on good output instead of pollution, i.e., the directional vector (1.2, 1, 1) instead of vectors (1, 1, 1) and (1, 1, 0.8).

The magnitude of the absolute shadow prices of CO₂ and NO_x for the period 2005–2009 tends to be lower under vectors (1.2, 1, 1) and (1, 1, 0.8) than under vector (1, 1, 1). Regarding relative prices, under the directional vector (1, 1, 0.8), the relative shadow price of CO₂/NO_x is statistically lower for the period 2005–2009 than for the period 2001–2004. Note that for this vector, NO_x abatement is less important than CO₂ abatement. The reduction in the relative shadow price is consistent with the reduction in the relative price of the regulation. As a robustness check we also estimated the shadow prices and elasticities of substitution for the same set of directional vectors using stochastic frontier analysis (SFA) and corrected ordinary least squares (COLS). In line with the PLP results, SFA and COLS showed that CO₂ and NO_x are substitutes. The results are not qualitatively sensitive to the estimation technique, however for observations satisfying technology properties SFA and COLS yielded higher elasticities and shadow prices (in absolute values) than the PLP method (Du et al. 2015a also found similar results for SFA). A disadvantage of the SFA and COLS methods is that around 74–79% of the observations simultaneously violated monotonicity in good and undesirable outputs. In contrast, our PLP results fully satisfy the properties of the underlying technology through the sample. Finally, for comparison purposes we also estimated inefficiencies using DEA.

³⁰ Some studies have applied optimization methods to endogenously determine optimal directions; see e.g., Peyrache and Daraio (2012) and Färe et al. (2013). However, this is outside the scope of this study.

Table 4 Sensitiveness to the directional vector

Elasticity	Directional vector	Before EU ETS 2001–2004	After EU ETS 2005–2009	<i>p</i> value ^a
CO ₂ -output	(1.2, 1, 1)	−0.558 (0.701)	−0.123 (0.157)	0.000
	(1, 1, 0.8)	−0.549 (0.519)	−0.113 (0.142)	0.000
NO _x -output	(1.2, 1, 1)	−0.994 (2.480)	−0.542 (0.487)	0.012
	(1, 1, 0.8)	−0.896 (2.207)	−0.514 (0.459)	0.054
CO ₂ -NO _x	(1.2, 1, 1)	0.767 (2.800)	0.486 (0.426)	0.178
	(1, 1, 0.8)	0.748 (2.601)	0.499 (0.427)	0.284
NO _x -CO ₂	(1.2, 1, 1)	0.331 (1.209)	0.014 (0.040)	0.010
	(1, 1, 0.8)	0.304 (0.813)	0.016 (0.046)	0.024
Shadow price CO ₂	(1.2, 1, 1)	7.360 (3.478)	11.928 (7.579)	0.000
	(1, 1, 0.8)	10.706 (5.400)	11.722 (8.024)	0.000
Shadow price NO _x	(1.2, 1, 1)	81,919 (42,921)	121,489 (75,439)	0.000
	(1, 1, 0.8)	84,020 (44,385)	121,489 (73,619)	0.000
Shadow price CO ₂ /NO _x	(1.2, 1, 1)	0.0001 (0.0003)	0.0001 (0.0001)	0.766
	(1, 1, 0.8)	0.0002 (0.0004)	0.0001 (0.0001)	0.006
Inefficiency	(1.2, 1, 1)	0.130 (0.195)	0.157 (0.228)	0.704
	(1, 1, 0.8)	0.157 (0.231)	0.190 (0.278)	0.774

Table reports mean values. Standard deviations in parentheses

^a *p* value of the nonparametric Li et al. (2009) test assessing the equality between the density functions for the periods 2001–2004 and 2005–2009

The inefficiencies were much lower in magnitude than those obtained with PLP, indicating that the output set of the quadratic specification contains the piecewise linear DEA output possibility set (see Färe et al. 2005).³¹

³¹ SFA, COLS and DEA results can be obtained from the authors on request. Regarding the firm fixed-effect coefficients, in the SFA and COLS models we tested the null hypothesis whether those coefficients were jointly statistically equal to zero. We found that this hypothesis is rejected at the 1% significance level, indicating that there are differences in technical efficiency across firms.

6 Synergies and Trade-Offs Between Reductions of CO₂ and NO_x Emissions

Has the overlapping of climate policies brought about increased NO_x emissions? Since pollutants are substitutes, we do find a tendency in this direction. However, NO_x emissions have not actually increased in practice as technological development has led to reduced emissions of both pollutants. Furthermore, contrary to what one may have expected, the regulatory relative price of CO₂/NO_x emissions has decreased since harmonization with the EU actually implied a sizeable fall in the price of carbon emissions for most CHP plants in addition to the simultaneous increase in the local NO_x charge in 2008. This is to say that in relative terms, CO₂ policies in Sweden have become less stringent after the introduction of the EU ETS due to the variations in the levels of the local policies. A natural question that arises is what would have happened if the carbon tax had not been phased out. In such a case, the regulatory relative price (CO₂/NO_x) per ton during the period 2005–2009 would have been 2.625 times higher (i.e., 0.029 instead of 0.008). Based on our estimates for the CO₂–NO_x elasticity for the period 2001–2004, we calculate that the (NO_x/CO₂) emissions intensity would have increased from 0.186% in 2001–2004 to 0.520% in 2005–2009. In reality, however, it increased to a much lower extent than predicted (i.e., 0.207%) due to the combined effect of technological progress and the fact that the regulatory relative price of CO₂/NO_x decreased sharply.

As mentioned in the introduction, some previous studies have found ancillary benefits from reductions in greenhouse gases in the U.S. For instance, [Burtraw et al. \(2003\)](#) simulate the effects of moderate carbon taxes for electricity production on reductions of NO_x emissions beyond the requirements of the 1990 Clean Air Act Amendments. Their results indicate that health-related ancillary benefits appear significant relative to the costs of those reductions and that they should play an important role in facilitating the debate regarding near-term policies to address the threat of climate change. Similar evidence is provided by [Agee et al. \(2014\)](#), who report that the marginal effect of reducing NO_x on CO₂ emissions is positive, roughly of equal absolute magnitude, and explained by adoption of more efficient production and pollution control technologies.

How do we reconcile their findings with the findings of our study? We believe that the differences are explained by several factors, including significant differences in emission intensity as well as in the type and stringency of the regulations in place. For instance, information provided by [Mekaroonreung and Johnson \(2012\)](#) for a sample of 336 U.S. bituminous coal-burning electricity plants over the period 2000–2008 indicates that the average CO₂ and NO_x emissions were 922.56 and 1.790 tons/GWh, respectively. By contrast, the average CO₂ and NO_x emission intensities in our sample were 74.87 and 0.238 tons/GWh. As discussed in Sect. 2, the low emission intensity of Swedish CHP plants is the result of very ambitious national policies with extremely high stringency levels compared with those in the U.S. Stringent policies have yielded significant reductions in emissions, putting Swedish plants in a situation where there is no slack or low-hanging fruit that will increase general efficiency and thus cut emissions of both pollutants. Instead, as indicated by our results, if further CO₂ emission reductions are to be achieved we would expect hard tradeoffs in the form of increases in NO_x emission intensities. Finally, there is a difference when it comes to the type of NO_x regulations in place. In the U.S., NO_x regulations generally take the form of tradable permits while Sweden has chosen to control NO_x emissions through a refundable fee. As shown by [Ambec and Coria \(2013\)](#), under price regulation firms modify their abatement levels of both pollutants in response to an increased stringency of climate policy, while

if NO_x were regulated through quantity regulations we would only observe an increase in the marginal cost of reducing NO_x without any effects on the level of emissions.

7 Conclusions

The implementation of environmental policies to reduce greenhouse gas (GHG) emissions does not only have a global impact, but can also bring local co-benefits (or costs) by reducing (increasing) other air pollutants due to complementarity or substitution. These interactions have clear implications for policy design as many European countries are committed to reach the Kyoto obligations and there are currently multiple policies in place aiming to reduce CO_2 emissions. The question is what ancillary benefits (costs) we can expect from pursuing GHG reduction policies and local air pollution policies simultaneously. We explore this question formally by analyzing the patterns of substitution between CO_2 and NO_x in the heat and power sector in Sweden induced by the interaction of national and international environmental policies.

We model the pollution technology of generating units in the Swedish heat and power sector as a non-separable production process where CO_2 , NO_x , and production are treated as joint outputs. We use a directional output distance function that accounts for the simultaneous expansion of good outputs and contraction of bad outputs, which is a fair representation of the problem that many regulated firms deal with. We choose a quadratic representation of the technology and subsequently derive the estimates of elasticities between CO_2 and NO_x and heat and power generation. Through this method, we characterize changes in the relative performance of Swedish combined heat and power (CHP) plants with respect to CO_2 and NO_x emissions in response to variations in the level of stringency of CO_2 and NO_x policies and multiple layers of regulation. To evaluate the change in elasticities or relative shadow prices, we compare the probability distributions between the periods 2001–2004 (pre-introduction of the EU ETS) and 2005–2009 (post-introduction) by means of a kernel consistent density test.

Our results indicate that there are important interactions between the abatement efforts for CO_2 and NO_x . Indeed, we find that in the combined heat and power generation sector, CO_2 and NO_x are substitutes, implying that regulatory efforts that limit emissions of one pollutant might have the unintended consequence of increasing the other pollutant. Overall, the degree of substitution for CHP plants between these two pollutants increases after the introduction of the EU ETS in response to technological development and regulatory changes that led to a reduced relative price of CO_2/NO_x .

Our results also indicate that CO_2 is more sensitive than NO_x to prices, which means that if the regulator is to encourage a large reduction in NO_x emissions, the charge must be increased to a much higher level than the present. This is also confirmed by our estimates of the shadow price of NO_x , which is much higher than the current value of the NO_x fee. It is also consistent with the fact that technological development has been biased towards CO_2 emission reductions, implying that it has become easier to reduce CO_2 emissions than NO_x emissions per unit of output.

Finally, our results are robust to choice of directional vectors. The fact that generating units respond to variation in the relative prices of emissions by changing the intensity of their abatement efforts suggests that there is a need for policy coordination to avoid unintended effects of one policy instrument on the emissions of other pollutants. This is particularly important if abatement of climate and local air pollutants are substitutes since the unintended

costs of climate policy in the form of local pollution can make it less acceptable to the public and policymakers. This is an area where much research is needed since we are experiencing a polycentric approach to climate change with mitigation and adaptation activities undertaken by multiple policy actors at a range of different levels. Furthermore, a caveat of our analysis is that our dataset only includes generating units of the heat and power sector. Nevertheless, different industrial sectors might differ significantly in terms of the relative burden of local and global air pollution regulations. Thus, even though the analysis of the variations in technical complementarity/substitutability across industries is beyond the scope of the study it is suggested as a relevant area for further research.

Acknowledgements Jorge Bonilla gratefully acknowledges financial support from the Swedish International Development Cooperation Agency (SIDA) through the Environmental Economics Unit of the University of Gothenburg, and from the Universidad de los Andes, Colombia. Jessica Coria and Thomas Sterner gratefully acknowledge financial support from Göteborg Energi and the Swedish Energy Agency (Energimyndigheten). This paper is dedicated to the memory of our dear colleague Lennart Hjalmarsson, who gave advice on an early version, and unfortunately passed away over the course of this project. We thank Finn Førsund and Rolf Färe for useful comments and suggestions.

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Appendix

See Tables 5 and 6.

Table 5 Assessment of monotonicity conditions and null-jointness property of the directional output distance function using the parametric linear programming approach

Period	Directional vector (g)	Monotonicity conditions in outputs ^a				Monotonicity conditions in inputs ^b				Null-jointness property ^{a,c}		
		D_{b_1}		D_{b_2}		D_{x_1}		D_{x_2}		$\bar{D}_o(x, y, 0; g)$		
		Mean (SD)	Obs. with values ≥ 0 (%)	Mean (SD)	Obs. with values ≥ 0 (%)	Mean (SD)	Obs. with values ≤ 0 (%)	Mean	SD	Mean (SD)	Obs. with values < 0 (%)	
2001–2004	(1, 1, 1)	0.008 (0.007)	100	0.216 (0.116)	100	-0.775 (0.114)	100	0	0.785	0.087	-0.185 (0.215)	100
	(1.2, 1, 1)	0.010 (0.006)	100	0.188 (0.109)	100	-0.669 (0.089)	100	0	0.672	0.072	-0.165 (0.201)	99
	(1, 1, 0.8)	0.017 (0.010)	100	0.229 (0.135)	100	-0.800 (0.105)	100	0	0.790	0.082	-0.199 (0.251)	99
2005–2009	(1, 1, 1)	0.019 (0.011)	100	0.277 (0.143)	100	-0.704 (0.141)	100	0	0.686	0	-0.243 (0.339)	99
	(1.2, 1, 1)	0.011 (0.008)	100	0.233 (0.123)	100	-0.630 (0.103)	100	0	0.635	0	-0.202 (0.280)	100
	(1, 1, 0.8)	0.013 (0.011)	100	0.282 (0.148)	100	-0.761 (0.120)	100	0	0.767	0	-0.244 (0.337)	100

Variables are: x_1 = installed capacity, x_2 = fuel consumption, x_3 = labor, y = useful energy, b_1 = CO₂, and b_2 = NO_x

^a Standard deviations (SD) are reported in parentheses

^b Monotonicity conditions in inputs are shown for the average values of input usage. That is, the derivatives are evaluated at the mean level of inputs. For simplicity when evaluating these derivatives the values of the undesirable and good outputs are also assumed at the mean level. Given that these derivatives are nonnegative, the monotonicity conditions are satisfied

^c The null-jointness property indicates that if no bad output is produced (i.e., CO₂ and NO_x emissions are simultaneously zero), then the production of good output is infeasible, which implies that the directional output distance function is negative. In some cases the percentage of observations satisfying this property was slightly lower than 100% because a strict inequality constraint in the computer algorithm is interpreted as the associated non-strict inequality

Table 6 Assessment of concavity property of the directional output distance function using the parametric linear programming approach

Period	Directional vector	First order principal minors		Second order principal minors		Third order principal minor		
		β_2	θ_{11}	θ_{22}	$\beta_2\theta_{11} - \mu_1^2$		$\beta_2\theta_{22} - \mu_2^2$	$\theta_{11}\theta_{22} - \theta_{12}^2$
2001–2004	(1, 1, 1)	-0.159	-0.003	-0.158	0.0005	0.0005	0.0005	0
	(1.2, 1, 1)	-0.099	-0.003	-0.137	0.0003	0.0003	0.0003	0
	(1, 1, 0.8)	-0.107	-0.006	-0.153	0.0005	0.0005	0.0005	0
2005–2009	(1, 1, 1)	-0.129	-0.0001	-0.129	0.0000	0.0000	0.0000	0
	(1.2, 1, 1)	-0.084	-0.0003	-0.122	0.0000	0.0000	0.0000	0
	(1, 1, 0.8)	-0.094	-0.0004	-0.147	0.0000	0.0000	0.0000	0

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