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Innovation effects of the Swedish NOx charge

Joint Meetings of Tax and Environment Experts

This paper was prepared by Lena Höglund-Isaksson of IIASA and Thomas Sterner of the University of Gothenburg, as an input to the project on Taxation, Innovation and the Environment.

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FOREWORD

This paper was prepared by Lena Höglund-Isaksson[1] of International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, and Thomas Sterner of the Department of Economics, Gothenburg University, Sweden, as an input to the project on *Taxation, Innovation and the Environment* of OECD's Joint Meetings of Tax and Environment Experts.

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INNOVATION EFFECTS OF THE SWEDISH NO_X CHARGE

1. Introduction

1. In 1992, Sweden introduced a charge on emissions of nitrogen oxides (NO_x) from large stationary combustion plants. A strong incentive for emission reduction was attained by setting a high charge level and combining it with mandatory continuous monitoring of emissions. High monitoring costs made it economically feasible only to include large combustion plants. To avoid serious distortions in competitiveness, the charge was made refundable to the collective of regulated plants based on plant output as fraction of total useful energy produced by regulated plants. The NO_x charge has turned out to be a very effective instrument for reducing NO_x emissions per unit of energy produced from stationary combustion plants in Sweden. Emission intensities have been cut by half, which can be considered a substantial reduction for a pollutant like NO_x that is usually technically difficult to reduce.

2. This report links the introduction of the Swedish NO_x charge to technology adoption and development of mitigation technology. The effects of output-based refunding of emission charges on incentives to innovate and spread technology are analyzed theoretically for both regulated plants and external suppliers of mitigation technology. Empirically, evidence of innovations is sought by investigating in detail the development of emission intensities over time, by analyzing changes in cost-savings for abatement technology for given levels of emission intensities, and by studying invention activity measured as number of patented inventions for NO_x abatement technology.

3. The structure of the report is as follows. Chapter 2 describes the construction and performance of the Swedish NO_x charge. Chapter 3 discusses the possible links between the introduction of the NO_x charge and effects on innovations and explores theoretically how incentives to innovate and spread innovations among regulated plants are affected by the refund mechanism of the charge. Chapter 4 describes technologies and presents the adoption of different technologies by plants regulated by the Swedish NO_x charge. Chapter 5 uses different measurements as indicators to find empirical evidence of innovations in NO_x abatement technology following the introduction of the Swedish NO_x charge. Chapter 6 summarizes the findings.

2. The Swedish charge on NO_x emissions from stationary combustion plants

2.1 An effective environmental regulation

4. The Swedish Parliament decided in 1990 to introduce a charge of 40 SEK per kg NO_x (emissions of NO and NO_2 expressed as kg NO_2) emitted from all stationary combustion plants producing at least 50 MWh useful energy per year. The decision was part of a larger strategy to bring down overall NO_x emissions in the country by 30% between 1980 and 1995. Already in 1988, quantitative emission limits were introduced on an individual basis for stationary combustion plants. It soon became apparent that these would not be effective enough to attain the desired reductions and the NO_x charge was introduced as a complementary instrument.

5. The NO_x charge was given a unique design. Plants pay a fixed charge per kg NO_x emitted and the revenues are entirely (except for an administration fee of less than one percent withheld by the regulator)

refunded to the paying plants, but now in relation to their respective fraction of total useful energy produced by regulated plants. The design promotes competition among plants for attaining the lowest NO_x emissions per amount of useful energy produced. A principal reason for the Swedish Environmental Protection Agency (SEPA) to suggest a refundable charge was that continuous monitoring of NO_x emissions was considered important due to the complex formation of NO_x throughout the combustion process. High monitoring costs made it feasible only to target large combustion plants. Refunding served several purposes: it was a way to counteract the effects of distorted competitiveness between the large regulated and the smaller unregulated plants, while simultaneously allowing for a charge level high enough to attain significant effects on emissions and avoiding strong political resistance among polluters.

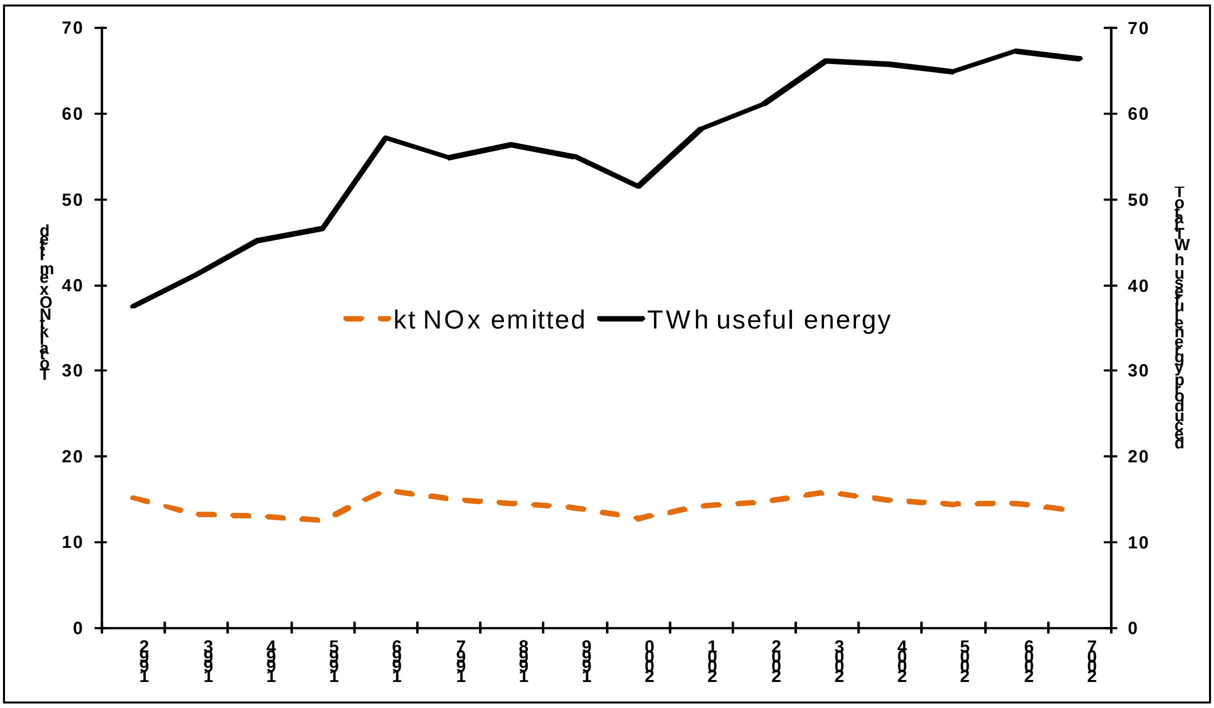
6. The charge came into effect on January 1, 1992 and initially about 200 plants were regulated. In the following three years, average emissions per unit of useful energy produced fell by 40% among regulated plants. Its effectiveness coupled with falling monitoring costs, led to extensions of the charge system, first in 1996 to about 270 plants producing at least 40 MWh useful energy per year, and then from 1997 onwards to about 400 plants producing at least 25 MWh useful energy per year. Currently, all stationary combustion plants producing above the energy output limit and belonging to any of the sectors power and heat production, chemical industry, waste incineration, metal manufacturing, pulp and paper, food and wood industry, are subject to the NO_x charge. Exempt from the charge due to concerns about unfeasibly high costs are *e.g*., cement and lime industry, coke production, mining industry, refineries, blast-furnaces, glass and isolation material industry, wood board production, and processing of biofuel. Despite the extension of the regulation, total emissions from regulated plants have remained fairly constant at about 15 kt NO_x per year or about 40% of NO_x emissions from stationary combustion sources in Sweden. Simultaneously, energy output from regulated plants has increased by 77% between 1992 and 2007. Figure 1 shows how NO_x emissions from regulated plants have been decoupled from increases in energy production.

7. Figure 2 shows the development of NO_x emissions per unit of useful energy produced (*i.e.* emission intensity) for regulated plants. Overall emission intensity among regulated plants fell between 1992 and 2007 from 407 to 205 kg NO_x per GWh useful energy produced, *i.e.*, a reduction by 50%. Large plants, producing at least 50 MWh useful energy per year, have managed to reduce average emission intensities to 194 kg NO_x per GWh in 2007, which is less than the average of 330 kg NO_x per GWh achieved by the smaller plants producing in the interval 25 to 50 MWh useful energy per year. This is probably a result of large producers being able to exploit economies of scale, but also a consequence of the nature of the available NO_x abatement technology, which is characterized by indivisibility and high costs for the most effective types of technology (see Section 4.2).

8. The NO_x charge was kept at a constant level of 40 SEK per kg NO_x between 1992 and 2006, when it was adjusted to 50 SEK per kg NO_x to account for depreciation of the charge level.

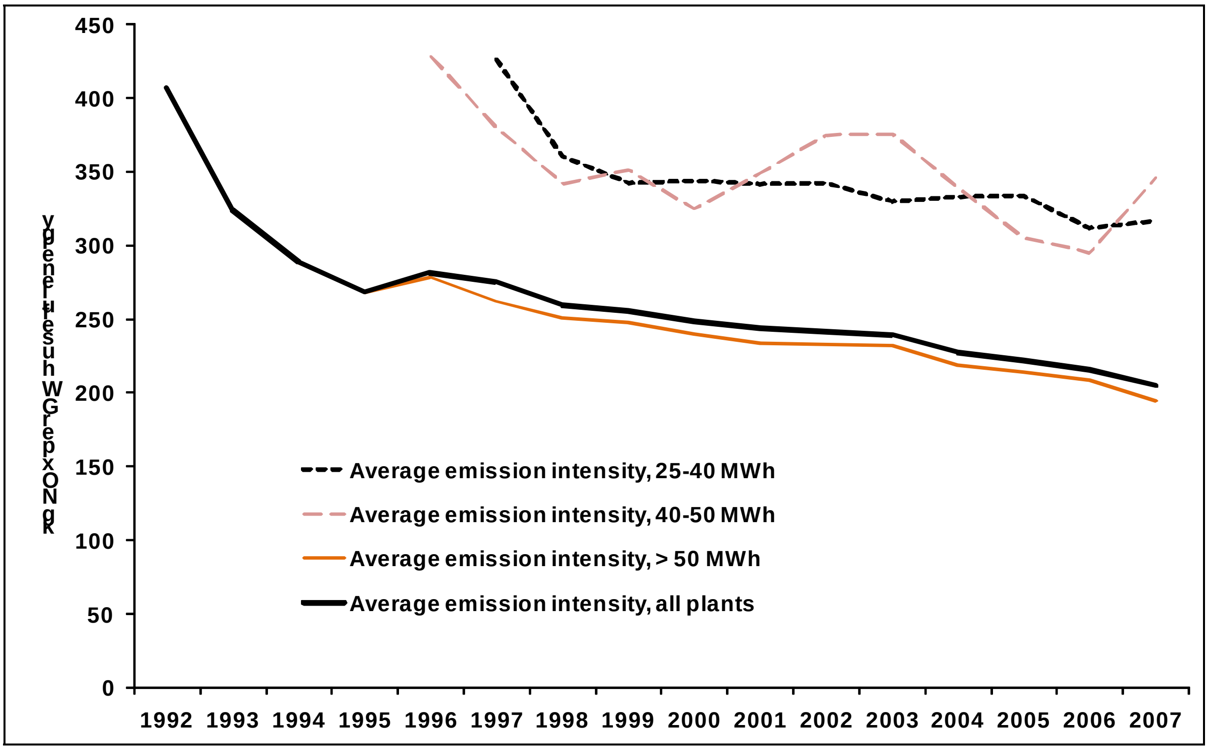
Figure 1. Total NOx emissions and total output of useful energy

From all plants regulated by the NOx charge, 1992-2007



Source: SEPA (2008).

Figure 2. NOx emissions in kg NOx per GWh useful energy
For plants regulated by the Swedish NOx charge, 1992-2007



Source: SEPA (2008).

9. Based on a survey of 114 plants regulated by the NO_x charge in 1992 to 1996, Höglund (2000) estimated the total cost of the charge per unit NO_x reduced. For a full social cost-benefit analysis the total cost should be weighed against the benefits to society of reducing NO_x emissions in terms of *e.g.*, reduced respiratory diseases and reduced effects on acidification or euthrophication. During these first five years of the charge system, the average total cost was estimated at 25 to 40 SEK per kg NO_x reduced. If we assume the benefits of reducing one kg NO_x is at least equal to the charge level of 40 SEK per kg NO_x, then benefits exceed or equal total costs and the net welfare of society has improved.

10. Splitting the total cost of the NO_x charge into detailed cost components, Höglund finds that abatement costs make up about 50% of total costs, or 12 to 25 SEK per kg NO_x reduced depending on the assumed lifetime of fixed investments. Monitoring costs, including annual calibration of monitoring equipment, were estimated at 140 000 to 193 000 SEK per plant per year or about 20% of total costs[2]. Administration costs were found low. About two percent of total costs were spent on additional administration within plants and one percent on administration by the regulatory authority (*i.e.* SEPA). NO_x abatement often gives rise to increased emissions in other pollutants like carbon oxide (CO), nitrous oxide (N_2O), and ammonia (NH_3). Although the damage values of these pollutants to society are difficult to estimate, an attempt was made using estimates by SEPA (1997) and emission charge levels of other pollutants with similar environmental impacts. The cost for emission increases in these pollutants was found at about 23% of total costs. Finally, the refund mechanism of the charge gives rise to a welfare loss due to distortions in resource allocation (see Section 2.2), which was estimated at about one SEK per kg NO_x reduced or three percent of total average costs. The cost components are summarized in Table 1.

Table 1. Relative contribution of different components to the total cost of the Swedish NO_x charge

Cost component	
NO_x abatement	50%
Monitoring and compulsory calibration of monitoring equipment	20%
Plant administration	2%
Regulator administration	1%
Increased emissions of CO, VOC, N_2O and NH_3	23%
Distorted resource allocation due to refunding	3%
Total (25 to 40 SEK per kg NO_x reduced)	100%

Source: Höglund (2000).

11. Based on the same survey of 114 plants regulated by the charge in 1992 to 1996, Höglund-Isaksson (2005) estimates abatement costs. By calculating cumulative abatement costs for each plant in the years 1992 to 1996 and comparing the costs with the attained emission reductions, she finds that about a third of emission reductions have taken place at a zero or very low cost. These measures represent different types of trimming activities, where the combustion process is optimized with respect to a number of parameters. This is something the plants do continuously anyway and the NO_x regulation, with its strict requirement for continuous monitoring of emissions, just brings another parameter into the optimization formula. This procedure is often not perceived as an additional cost to the plants. The zero or very low cost options appear to have been exhausted before plants move on to more expensive abatement investments. The estimated marginal abatement cost functions are used for determining the compliance rate of the regulated plants. A cost-minimizing plant can be expected to reduce emissions until the marginal abatement cost is approximately equal to the charge level (see Section 2.2). Predicted and actual emission intensities in 1996 for the surveyed plants are shown in Table 2.

2 This is somewhat higher than the annual cost of 100 000 SEK per plant that SEPA estimates for monitoring and calibration costs (SEPA, 2003).

Table 2. Predicted and actual emission intensity levels for regulated plants in 1992-96

Sector	Number of plants	Average charge level 1992-96 in 1990 SEK	Predicted emission intensity kg NO_x per GWh	Actual average emission intensity kg NO_x per GWh
Energy	55	36.3	300	289
Pulp and Paper	28	36.3	250	336
Chemical and Food	24	36.3	100	235

Source: Höglund Isaksson (2005).

12. In 1996, plants belonging to the energy sector have reduced emission intensities by more than their cost-minimizing level, while pulp- and paper, as well as chemical- and food sector plants, fall short of reaching their cost-optimal level of abatement. The over-compliance of the energy sector plants may be explained by the public ownership of these plants, which adds compliance with environmental objectives to the profit-maximizing objective, and that energy is the final product of the sector. In the pulp- and paper and chemical- and food industry sectors, the attention on energy production and its cost effectiveness may be subordinate to more pressing needs in other parts of production.

2.2 Refunding for environmental and political benefits

13. The unique design of the NO_x charge is in the economic literature referred to as output-based refunding of emission payments (Sterner and Höglund 2000, Gersbach and Requate 2004, Fredriksson and Sterner 2005, Sterner and Höglund-Isaksson 2006, and Bernard, Fischer and Fox 2007). Within a refund system, plants compete for the lowest emissions per unit of output produced within the regulated group of plants. Plants emitting exactly the group average emissions per unit of output produced will pay the same amount in emission charges as it receives back as refunds. Plants performing worse than the group average will make a net payment to the system and plants performing better than the average will receive a positive net refund. In this way, it pays off for plants to strive to improve their environmental performance relative other plants in the system. Crucial for the system to operate effectively is that there exists a single output upon which the refunding can be based and that each plant's output is small enough relative the total output by regulated plants to form a competitive situation. These two conditions were met in the case of the Swedish NO_x charge, where the refund basis was useful energy produced and the largest fraction of total output ever produced by a single owner in one year has been 12% (SEPA, 2008).

14. Sterner and Höglund (2000) show that when a group of many small profit-maximizing firms is regulated by an output-based refunded emission charge, the cost-minimizing abatement level of the individual firm is when the marginal abatement cost equals the charge level. Each firm will minimize the sum of abatement costs and emission payments less refunds. With *n* regulated firms (*i=1,...,n*), a representative firm *j* will minimize total cost C_j:

$$C_j = c_j(e_j, q_j) + te_j - t\frac{q_j}{\sum_i q_i} * \sum_i e_i \, , \qquad (1)$$

where e_j are emissions from firm j, q_j are firm j's output, and t is the charge per unit pollutant emitted. Assuming an interior solution, the first order condition for a minimum of equation (1) with respect to e_j and constant output, is:

$$-\frac{\partial c_j}{\partial e_j} = t * \left(1 - \frac{q_j}{\sum_i q_i} \right) \quad . \qquad (2)$$

15. With many small regulated firms, each firm's contribution to total regulated output becomes very small, *i.e.*, $\frac{q_j}{\sum_i q_i} \rightarrow 0$, and the optimal abatement level is found when marginal abatement cost approximately equals the charge level. Thus, in terms of effectiveness in emission reductions, a refunded charge is equivalent to a conventional emission tax without refunding.

16. The main drawback with refunding is that it preserves an already distorted resource allocation. The refund resembles a subsidy from society to the producers where the unit subsidy is equal to the marginal refund. Accordingly, the refund gives rise to a distorted resource allocation with a cost-minimizing output level of the regulated firms exceeding the social optimal output level. Polluters do not pay the full environmental cost of the pollution their production causes. This leads to a welfare loss to society since too much productive resources are allocated to polluting production relative to cleaner production. Hence, the polluter pays principle does not apply when emission charges are refunded to polluters.

17. The main advantages of a refunded charge compared to a conventional tax are environmental and political. The losses in competitiveness of regulated plants relative non-or less regulated plants become considerably lower with a refunded charge. Polluters are likely to protest less against the introduction of environmental charges when the charge revenues are refunded. With less resistance from polluters it becomes politically easier to set environmental charges that are high enough to generate substantial environmental improvements (Fredriksson and Sterner 2005). An indication of this is a comparison between the Swedish and the French NO_x charges (Millock, Nauges, and Sterner 2004). A French charge on NO_x emissions was introduced in 1990 as part of a combined package to reduce emissions of air pollutants SO_2, NO_x and VOC from large combustion plants. Revenues from the charge were earmarked to subsidize investments in abatement technology in regulated plants and for research and development of abatement technology. Due to concerns about distortions in competitiveness, the charge level was set very low, corresponding to about one percent of the level of the Swedish NO_x charge. There was also no requirement for continuous monitoring of emissions. Both factors are mentioned by Millock, Nauges and Sterner as important explanations to why the French NO_x charge did not have any measured effect on NO_x emissions.

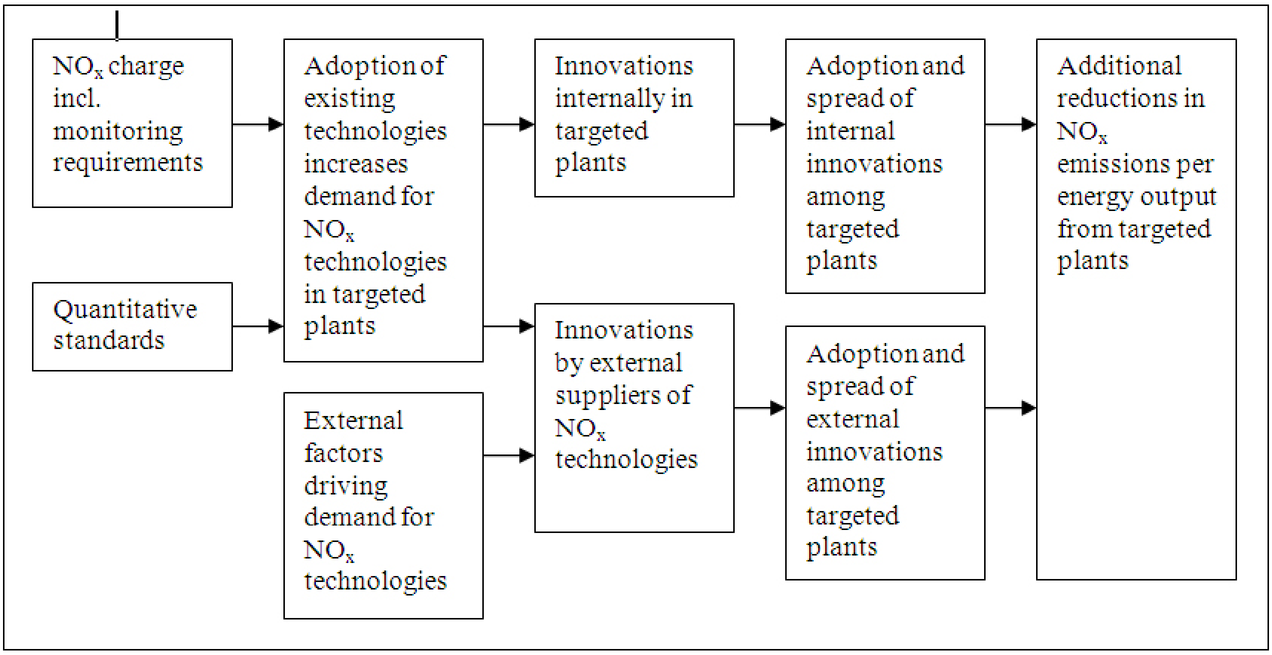
18. The EU Directive on Large Combustion plants (EC, 2001) specifies emission limits for several air pollutants and a requirement to continuously monitor concentrations of SO_2, dust and NO_x in flue gases. All combustion plants with a thermal input of more than 100 MW are subject to continuous emission monitoring from November 2002. For Sweden, the Directive has no real implications on NO_x emissions since most plants affected are already regulated by the NO_x charge. Plants affected by the Directive produce about 40% of total output regulated by the NO_x charge and emit about 30% of regulated emissions. Thus, the monitoring required as part of the NO_x charge regulation is considerably more extensive than the monitoring stipulated by the EU Directive.

3. Innovation effects of the Swedish NO_x charge

3.1 Analyzing innovation effects of environmental policies

19. Kemp (1997) defines an innovation as an invention brought into use. Innovations in abatement technology would hence occur when inventions that have the possibility to improve the environment are applied by polluting firms. By definition, an innovation in abatement technology is made up by a series of events: a new technology is invented, it is produced and supplied on a technology market, and, finally, adopted and spread among users, which leads to environmental improvements. How can the introduction of an environmental regulation spur the development of such a series of events and does the regulatory design affect this development? Figure 3 shows an example of how the NO_x charge can be linked to innovations and additional improvements in NO_x abatement, including how innovations and adoption of innovated NO_x technology are linked to other factors than merely the introduction of the NO_x charge.

Figure 3. Linking the Swedish NO_x charge to innovations, technology adoption and improvement in emission intensities of regulated plants



20. Introduction of effective environmental regulations first leads to adoption of existing abatement technologies. Such a push in demand for certain technologies increases incentives for innovations in new or improved technologies. Innovations take place both within regulated plants and by external suppliers of abatement technology. External suppliers of NO_x abatement technology develop and produce abatement equipment, which is supplied on an international market. Incentives to innovate NO_x technology are therefore only partly driven by the introduction of the NO_x charge in Sweden. For innovations within regulated plants to have significant effect on aggregate emission intensities, adoption needs to spread to other regulated firms. The incentives for a spread of innovations among regulated plants may be weaker in the case of a refunded charge compared to a conventional emission tax of the same magnitude, which is shown in the subsequent Sections 3.2 and 3.3.

21. Models analyzing innovation effects of economic regulations (*e.g.*, Downing and White, 1986 and Milliman and Prince, 1989) usually focus on how different regulatory designs affect firm incentives to innovate and diffusion of innovations among firms. A typical finding is that environmental regulations based on economic incentives, like charges, taxes or tradable permits, promote greater incentives for

innovation than quantitative regulations. With economic instruments, firms minimize the net sum of the direct cost of abatement, the emission charges paid, and the refunds and/or subsidies received. In such a system, it continuously pays off to monitor the possibilities of reducing costs by adopting more efficient abatement technology. Firm incentives to innovate or adopt innovations from external suppliers of technology are always there as long as they bring net cost-savings.

22. With quantitative emission standards there is no cost-saving to be made from reducing emissions further once the standard has been met and, hence, there are no further incentives for innovations. Kemp (1997) points out that quantitative standards may even counteract incentives to innovate abatement technology. If regulators determine the standard levels by matching the effectiveness attained by the best abatement technology currently adopted, adoption of innovations that, on the one hand, bring additional cost-savings will, on the other hand, push down the emission intensity frontier of adopted technology. This reveals to the regulator that the best available technology has improved. The next time the regulator determines an emission standard level, it will push for compliance with even stricter standards, which corresponds to the revealed best available technology. If the number of regulated firms is sufficiently small, they may decide to refrain from adopting innovations. They thereby avoid revealing the improvement in the best available technology to the regulator, which will save firms future compliance costs as emission standard levels remain unchanged. SEPA (2004) shows that the introduction of the Swedish NO_x charge in addition to existing quantitative standards, brought about emission intensities that were considerably below the standard levels for most plants (see Section 4.4).

23. More recent innovation models like Kemp (1997, ch. 3) and Fischer, Parry and Pizer (2003) analyze the effect of different types of economic instruments like emission taxes, subsidies and various forms of tradable permits on endogenous technological change in abatement. Fischer, Parry and Pizer compare the incentives for innovation under an emission tax with free or auctioned tradable permits when innovations can be adopted by paying a royalty *or* by simply imitating the innovation. They conclude that polluters' incentives to innovate are weaker under free permits than under an emission tax or auctioned permits, because there is no emission payment effect for the innovating firm under free permits. Whether innovation incentives are the highest under an emission tax or under auctioned permits is found to be ambiguous and depending on the strength of the imitation effect. Among the models discussed here, it is noteworthy that only Milliman and Prince thoroughly analyze the case when innovation takes place in an outside supplier (*i.e.* a non-polluter) of technology, although Fischer, Parry and Pizer discuss this case briefly in their model.

24. In the following two sections, we analyze[3] the effects of a refunded emission charge on innovation and diffusion of innovations in comparison with a conventional emission tax[4] of the same magnitude[5]. First, the incentives of the regulated firms to innovate and spread innovations to other regulated firms are analyzed under a refunded charge and compared to a conventional emission tax. We then analyze how the incentives of external suppliers of abatement technology to innovate and spread innovations among regulated firms are affected under the two regulatory regimes. The marginal environmental cost of pollution is assumed constant to simplify the comparison. The analysis then avoids

3 This analysis was first published in Höglund (2000).

4 A "conventional tax" refers here to a so called Pigouvian tax, which is a fixed emission tax paid per unit of pollutant emitted without earmarking or refunding the revenues.

5 The assumption of equivalent charge and tax levels is useful for the purpose of comparing the two regulatory regimes. The reader should, however, be reminded that a comparison between a refunded charge and a conventional tax of the same magnitudes is somewhat hypothetical, since a major advantage with a refunded charge is that refunding often makes it politically feasible to set a considerably higher charge level than would have been possible with a tax (see Section 2.2).

the complication of having an optimal tax rate that decreases with downward shifts in the marginal abatement cost curve as innovation in abatement technology proceeds.

3.2 Innovation incentives for firms regulated by an output-based refunded emission charge

25. Suppose there are *n* profit-maximizing firms (*i=1,…,n.*) regulated by an emission charge with output-based refunding, *i.e.*, just like the Swedish NO_x charge. As concluded in Section 2.2, without allowing for the possibility of innovations, regulated firms will choose to invest in abatement until the marginal abatement cost equals the charge level. Assume now that we allow for the possibility of innovations in abatement technology and that an innovation takes place in one of the regulated firms denoted firm *j*. After adoption, firm *j* supplies the innovation to all other regulated firms *i=1,…,n-1*, at the royalty price, *P*. Firm *j* has an exclusive right to the innovation and the right is protected through a patent. Other firms are supposed not to be able to imitate the innovation and are accordingly not able to acquire any of its usefulness without paying the patent royalty. Firm *j* is therefore a monopolist in the market for innovation and is able to set a profit-maximizing royalty price. The demand-side of the innovation market consists of many, small and non-cooperative regulated firms, where a single firm cannot affect the adoption decision of other firms in any way.

26. The same model and setting is used as when we analyzed the case without possibilities for innovations (Section 2.2), except that we now introduce a variable abatement technology (k_j) for firm *j*, as well as R&D costs (D_j), and revenues from royalty payments (R_j) from *m* non-innovating regulated firms adopting the innovation. The royalty price (P_m) will correspond to the reservation price of the last firm adopting the innovation, *i.e.* the reservation price of firm *m*. Output is assumed constant throughout the analysis.

27. The innovated technology affects firm costs both directly and indirectly. Directly, by affecting abatement costs, R&D costs or royalty revenues and, indirectly, by reducing tax costs as the optimal emission level is reduced to meet a downward shift in the marginal cost curve with respect to emissions. To find an interior solution, the following properties are assumed for the relevant interval of the cost curve. Both emission level and production cost are supposed to be decreasing at a constant or increasing rate in k_j, *i.e.* $\partial e_i / \partial k_j < 0$, $\partial^2 e_i / \partial k_j^2 \geq 0$, $\partial c_i / \partial k_j < 0$, and $\partial^2 c_i / \partial k_j^2 \geq 0$. Thus, the cost-saving from adopting an innovation increases at a decreasing or constant rate with improved innovation level.

28. Suppose that the innovating firm *j* has enough information about the adopting firms to set a profit-maximizing royalty price, which maximizes royalty revenues (R_j):

$$R_j(k_j) = m(k_j)P_m(k_j), \tag{3}$$

where $\partial R_j / \partial k_j > 0$ and $\partial^2 R_j / \partial k_j^2 \leq 0$.

29. Firm *j* will choose an innovation level, which minimizes the following total cost function:

$$C_j = c_j\left(e_j(k_j), q_j, k_j\right) + D_j(k_j) - R_j(k_j) + te_j(k_j) - t\frac{q_j}{Q}\sum_{i=1}^{n} e_i(k_j). \tag{4}$$

30. By setting the first derivative of equation (4) with respect to changes in technology k_j equal to zero, the following condition for a minimum is obtained:

$$\frac{dC_j}{dk_j} = \frac{\partial c_j}{\partial k_j} + \left(\frac{\partial c_j}{\partial e_j} + t\left(1 - \frac{q_j}{Q} \right) \right) \frac{\partial e_j}{\partial k_j} + \frac{\partial D_j}{\partial k_j} - \frac{\partial R_j}{\partial k_j} - t\frac{q_j}{Q} \sum_{\substack{i=1, \\ i \neq j}}^{n} \frac{\partial e_i}{\partial k_j} = 0 \,, \quad (5)$$

where $\frac{\partial R_j}{\partial k_j} = P_m \frac{\partial m}{\partial k_j} + m\frac{\partial P_m}{\partial k_j}$ and $\left(\frac{\partial c_j}{\partial e_j} + t\left(1 - \frac{q_j}{Q} \right) \right) = 0$.

31. Alternatively, the latter condition can be shown by applying the envelope theorem. The change in the total cost function when adjusting emissions (e_j) in an optimal way, is equal to the change in the total cost function when emissions are not adjusted. From this follows that $\left(\frac{\partial c_j}{\partial e_j} + t\left(1 - \frac{q_j}{Q} \right) \right) = 0$. Note that this does not imply that the indirect effect always has to be zero. It only implies that the *sum* of the direct and indirect effects is equal to the direct effect when emissions are unchanged. By rearranging the resulting terms, the condition for an optimal level of innovation for firm *j* is obtained:

$$\frac{\partial D_j}{\partial k_j} = -\frac{\partial c_j}{\partial k_j} + \frac{\partial R_j}{\partial k_j} + t\frac{q_j}{Q} \sum_{\substack{i=1, \\ i \neq j}}^{m} \frac{\partial e_i}{\partial k_j} \,, \quad (6)$$

where $Q = \sum_{i=1}^{n} q_i$ and $\partial D_j / \partial k_j > 0$ and $\partial^2 D_j / \partial k_j^2 \leq 0$.

32. Equation (6) equates the marginal cost of innovation with the marginal benefit of innovation for firm *j*, where the latter can be decomposed into three different terms. The first term is the cost effect, which expresses the magnitude of the marginal effect on production cost, *e.g.* in terms of reduced abatement costs or in terms of reduced tax costs as emissions are reduced, or in terms of effects on both. The second term is the royalty revenue effect, which reflects the marginal revenue from royalty sales to other regulated firms adopting the innovated technology. The third and last term is the marginal effect on the refund from reduced overall emissions when other regulated firms adopt the innovation. Note that the marginal refund effect is not infinitely small even if $q_j / Q \to 0$, since also a very small output share is approximately constant for changes in the technology k_j. Instead, the marginal effect on the refund depends on the marginal change in the overall emission level, which cannot be assumed to be infinitely small.

33. If a conventional emission tax, set to the same level, had been used instead, firm *j* would be minimizing the total cost in equation (4) less the last refund term. The corresponding condition for an optimal R&D level is accordingly:

$$\left[\frac{\partial D_j}{\partial k_j} \right]^{Tax} = -\frac{\partial c_j}{\partial k_j} + \frac{\partial R_j}{\partial k_j} . \quad (7)$$

34. Comparing the condition for an optimal R&D level under a refunded charge (equation 6) with the condition under a conventional emission tax (equation 7), we find that the difference in marginal R&D cost

(*i.e.* marginal spending on R&D) is caused by the refund term in equation (6). It is, however, less straightforward to compare equilibrium levels of marginal spending on R&D between the two regimes, since the marginal effects on costs and royalty revenues are likely to differ between innovation levels. A comparison requires further restrictions[6]. With approximately constant marginal effects on production costs and revenues from royalty sales, firm j is willing to invest in R&D to a *lower* marginal cost when using a refunded emission charge than when using a corresponding conventional emission tax. The discrepancy is approximately equal to the marginal effect on the emission refund.

35. The intuitive explanation is that with an emission charge with output-based refunding, a regulated firm's willingness to share innovations with other regulated plants is hampered by the refund, since a spread of the innovation to other regulated firms will reduce firm j's own refund. By keeping the innovation to itself, the innovating firm is able to improve its relative position within the charge system, thereby increasing its net refund. With a conventional emission tax, there are no gains[7] to be made from reducing a firm's emission intensity relative other regulated firms.

36. A special case, which is of interest to mention because it has relevance for NO_x abatement, is when the royalty price for an innovation is zero. This may for example occur when a regulated firm through experience accumulates knowledge, which improves the environmental effectiveness of the firm but is too indistinct to protect through a patent. Compared with a tax, refunding restricts any spread of knowledge among regulated firms and particularly knowledge about emission reducing innovations that cannot be protected through a patent, *i.e.* often the small and simple, but sometimes effective, measures. This may have been important in the case of the Swedish NO_x charge, where extensive emission reductions were attained at a low or even zero cost through trimming activities (see Section 5.2).

3.3 Innovation incentives for an external firm supplying technology to firms regulated by an output-based refunded emission charge

37. Firms outside the regulated group of firms may develop and supply new and improved abatement technologies to the regulated firms. Innovation incentives then depend on the general demand for innovated technology. Is the demand for a given innovation the same under a refunded charge as under an equivalent conventional emission tax? We show here that this is approximately the case when the demand-side of the innovation market consists of many, small and non-cooperating regulated firms.

38. When calculating the profit-maximizing price, the monopolist innovator will take into consideration the cost of innovation and the expected number of royalties sold. The price will correspond to the reservation price of the last firm adopting the innovation. The reservation price will, in turn,

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6 An assumption that appears plausible is that $\partial^2 c_j / \partial k_j^2 < 0$ and $\partial^2 R_j / \partial k_j^2 > 0$ for low levels of k_j and $\partial^2 c_j / \partial k_j^2 > 0$ and $\partial^2 R_j / \partial k_j^2 < 0$ for high levels of k_j. Cost-savings from adopting innovations are then assumed to increase at an increasing rate for low levels of innovation and at a decreasing rate when higher levels of innovation are reached. Under these assumptions it is difficult to speculate on the direction of the difference in the level of $\left(-\partial c_j / \partial k_j + \partial R_j / \partial k_j\right)$ between a refunded charge and a tax. Still, if the difference in optimal k_j-level between the regimes is not too extreme, a plausible assumption seems to be that the main effect on differences in marginal spending on R&D comes from the refund term and not from differences in the sum of the marginal cost-saving and the marginal revenue.

7 If regulated firms compete on the same market for final output, sharing knowledge for free about how to reduce emission tax payments, could potentially change relative production costs and the competitiveness of the firm in the output market. Since this indirect effect would be the same under a refunded charge as an emission tax, it does not affect our findings and we do not enter it in our analysis.

correspond to the additional profit the last adopting firm makes from adopting the innovated technology (*k=1*) compared with not adopting it (*k=0*). The total cost function of the last adopting firm *m* is:

$$C_m^{k=1} = c_m^{k=1}\left(e_m^{k=1}, q_m\right) + P_m^{k=1} + te_m^{k=1} - t\frac{q_m}{Q}\left(\sum_{i=1}^{m} e_i^{k=1} + \sum_{i=m+1}^{n} e_i^{k=0}\right). \qquad (8)$$

39. With a refunded charge, a new innovation adopted by some of the regulated firms affects the cost of firms *not* adopting it by reducing the refund as the innovation deteriorates the firm's environmental effectiveness relative to the adopting firms. In its decision between adoption and non-adoption, the last adopting firm therefore compares the cost of adoption with the cost of non-adoption:

$$C_m^{k=0} = c_m^{k=0}\left(e_m^{k=0}, q_m\right) + te_m^{k=0} - t\frac{q_m}{Q}\left(\sum_{i=1}^{m-1} e_i^{k=1} + \sum_{i=m}^{n} e_i^{k=0}\right). \qquad (9)$$

40. The reservation price of the last adopting firm is accordingly:

$$P_m = C_m^{k=0} - C_m^{k=1} = \Delta c_m + t\Delta e_m\left(1 - \frac{q_m}{Q}\right). \qquad (10)$$

41. With all firms being small, the effect of the last firm's adoption decision on the same firm's refund can be taken to be very small. Hence, the reservation price of the last adopting firm for a given innovation will be approximately the same as under an equivalent conventional emission tax, namely:

$$P_m^{Tax} = C_m^{k=0} - C_m^{k=1} = \Delta c_m + t\Delta e_m \,. \qquad (11)$$

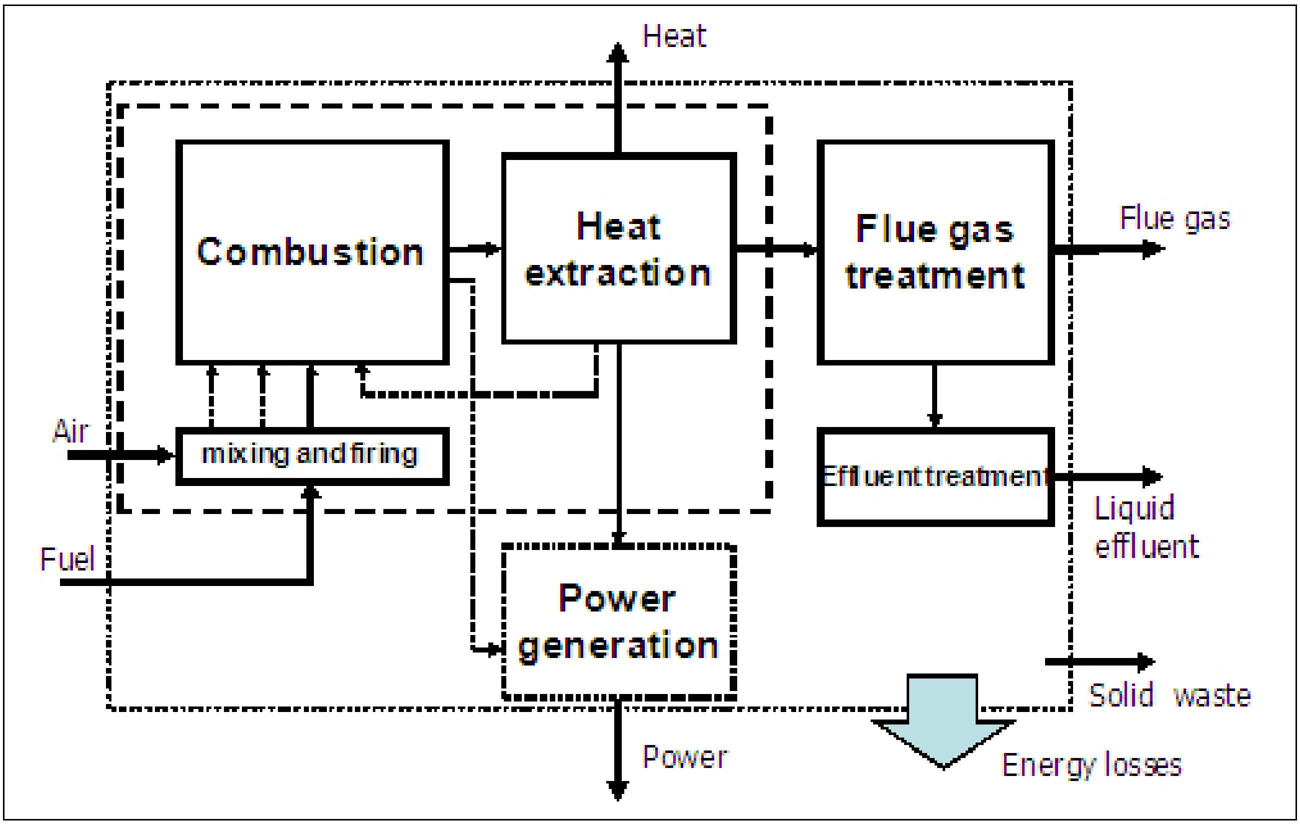
42. Note that the resulting reservation price holds only when the regulated group of firms consists of many firms that are small in relative size and not cooperating. In the special case when regulated firms cooperate and act as one entity and bargain over the price in a situation where either all regulated firms adopt the innovation or none, incentives to adopt are likely to be considerably weakened. If all firms adopt and the innovation is equally effective (in terms of effects on emissions) for all firms, the change in net refund is zero. Incentives to invest in improved technology are therefore the same as in the completely unregulated case. The assumption of many non-cooperating firms in the market for innovations is accordingly crucial for the result that the reservation price (and demand) for a given innovation is approximately the same under a refunded emission charge as under an equivalent emission tax.

4. Technology adoption by plants regulated by the Swedish NO_x charge

4.1 NO_x formation in the combustion process

43. There are many potential sources for NO_x formation during the combustion process. Figure 4 shows the main steps for the conversion of fuel to heat and/or electricity. Each step has the potential to affect NO_x formation.

Figure 4. Scheme of the main steps in a combustion process



Source: Sterner and Turnheim (2008).

44. Combustion uses fuel to produce heat. Heat extraction and conversion are the primary functions of combustion units. It is during these steps that the energy is converted into a useful form: piped steam, hot water, hot oil, and/or electricity. Heat requires fuel and an oxidizing agent, generally air. Fuel and air are fed, mixed and fired to create a flame, which is propagated throughout the combustion chamber, whose shape, size, and materials can all affect NO_x formation and overall efficiency. A conflict may appear between energy efficiency and NO_x formation, as one way of increasing combustion efficiency is to raise temperature and pressure, which considerably increases the formation of NO_x. Fluidized bed combustors partly overcome this limitation and allow simultaneous efficiency gains and cleaner flue gases. The relationship between combustion parameters and NO_x formation is highly nonlinear and complex. There is less potential for straightforward mitigation strategies compared with, for example, sulfur dioxide where almost all sulfur comes from the fuel. The exhaust gases leave the combustion chamber and may go to post combustion processes intended to reduce air pollutants (*e.g.*, NO_x, SO_2, CO, PM). These pollutants can be transformed, precipitated, and washed in liquids or deposited as sludge, depending on their nature and concentrations. Given the complexities of NO_x formation, it is crucial with direct, continuous monitoring at the plant.

4.2 Technologies affected by the NO_x charge

45. With a refund system based on competition for the lowest NO_x emissions per energy output produced and with its requirement to install equipment to monitor NO_x emissions on a continuous basis, the Swedish NO_x charge affects demand for several different technologies. We divide these technologies into five main groups: pre-combustion, combustion, post-combustion, energy efficiency, and monitoring technology.

- *Pre-combustion technology*: limits NO_x formation mechanisms by controlling the type of combustion inputs: the fuel and the oxidizing agent. Avoiding the use of high-nitrogen-content fuels can substantially reduce NO_x formation, whereas using oxygen instead of air inhibits the formation of NO_x from nitrogen in the air. *E.g.*, substituting coal for oil or gas can effectively reduce NO_x emissions. Fuel switches are common in modern energy systems but rather driven by cost-saving purposes than NO_x control.

- *Combustion technology*: seeks to inhibit the formation of NO_x in the combustion stage. Strategies typically involve the optimal control of combustion parameters like temperature, air supply, pressure, flame stability and homogeneity, and flue gas residence time. Measures include both installations of physical equipment as well as trimming of the combustion process without physical installations and changes in organization and routines. Physical combustion technology includes a wide variety of installations, which rely on *e.g.*, lowering temperature, controlling air supply, or enhancing the mixing of the flue gases. Table 3 contains short descriptions of different types of combustion technology adopted by plants regulated by the Swedish NO_x charge.

- *Post-combustion technology*: reduces NO_x in the flue gases once they have been formed, usually through conversion to less harmful or benign compounds. The two flue gas treatment technologies in use today are selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR). SCR uses ammonia (NH_3) or urea to reduce NO_x into water and nitrogen (N_2) on catalytic beds at temperatures ranging from 150° to 600°C. This type of installation is rather large and costly but achieves highly efficient emission reductions. Because of the indivisibility of the SCR technology it is better suited for large plants. The technology was first developed and used in the 1970s in Japan and introduced to Europe in the 1980s. SNCR uses ammonia or urea to reduce NO_x at a high temperature without cooling the gases or using a catalyst. SNCR is less costly but also less efficient than SCR.

- *Energy efficiency improvements*: Plants in the NO_x charge system compete for the lowest NO_x emissions per unit of energy produced. The charge is therefore likely to increase demand for measures that improve energy efficiency without increasing NO_x emissions. Flue gas condensation is a technology that has been adopted by many plants regulated by the NO_x charge. It recovers the heat from the flue gases and improves energy efficiency without affecting emissions (SEPA, 2003). For implementation of energy efficiency measures, it is of course difficult to determine the importance of the NO_x charge relative other reasons like cost effectiveness.

- *Monitoring technology*: Plants regulated by the NO_x charge are required to comply with detailed instructions on how NO_x emissions should be monitored continuously. This includes annual compulsory calibration of the monitoring instruments by an external party. Failure to meet the high monitoring standards or temporary interruptions in the continuous monitoring are usually expensive to plants, as they then pay a fixed fee of at least one and half times the normal emission amount under comparable conditions.

Table 3. Combustion technologies adopted by plants regulated by the Swedish NO_x charge
1992-2007

Technology	Description
Flue gas recirculation	A portion of relatively cool exhaust gases is recirculated back into the combustion process in order to lower the flame temperature and reduce NO_x formation.
ECOTUBE technology	The furnace is equipped with retractable lances - ecotubes - with nozzles through which NO_x reducing agents are injected at high pressure and velocity directly into the combustion chamber.
Injection technology	Water or steam is injected into the flame, which reduces flame temperature.
Low-NO_x burner	Combustion, reduction and burnout are achieved in three stages. First, combustion occurs in a fuel rich, oxygen deficient zone. A reducing atmosphere follows where hydrocarbons are formed, which react with the already formed NO_x. Finally, the combustion is completed in an air staging process with controlled air supply.
Reburner	After-treatment of combustion gases, where additional fuel is injected in a second combustion chamber to enhance the burnout of the fuel.
Over-fire-air (OFA)	Over-fire air (OFA) technology separates the combustion air into primary and secondary flows to achieve higher completeness in the burnout (has many similarities to a Low-NO_x burner).
Rotating over-fire-air (ROFA)	Enhanced circulation of the air in the combustion chamber improves the mixing of the flue gases, which lowers temperature and improves the completeness in chemical reactions.
ROTAMIX technology	Rotating over-fire air is mixed with reducing chemicals for even better performance. Apart from reducing NO_x further, this technology also result in lower emissions of NH_3 and N_2O.

46. A striking feature associated with NO_x reduction technology is the extent of the possibilities and the consequent complex choice arising from the multiple options. Indeed, a wide array of NO_x-reducing technologies for stationary sources is available, and as concluded by the U.S. Environmental Protection Agency (1999), “there seems to be no control technology which is superior for all combustion systems, boilers, engines, or fuels.” That statement points to the difficulty facing plant operators once it has decided to invest in NO_x-reducing technology and may explain the simultaneous existence of so many competing designs. In real life, a plant operator has multiple optimization challenges. The main requirements plant operators set for their systems focus on total system efficiency, fuel flexibility, and complying with existing environmental regulations (Åmand 2006; Ådahl and Lilienberg 2006; Lundberg 2006; Kitto *et al.* 1999). The strive to control NO_x appears to be at cross-purposes with many other objectives facing the plant, *e.g.*, obligations to satisfy annual and peak demand, reductions in other pollutants, enhancements in thermal efficiency, and concerns about their public image.

47. The fact that larger combustion plants in general are able to reach lower emission intensity levels than smaller plants can be explained by the existence of capital indivisibilities in technological options and the higher technological capacity of larger firms. Discussions with machinery suppliers (Lundberg 2006; Slotte and Hiltunen 2006) indicate that the prices of abatement technology and combustion systems do not increase linearly with unit size, leading to a disadvantage for smaller units. Additionally, adoption of both physical mitigation equipment and mitigation strategies involving no physical installations, *e.g.*, trimming, depend on access to information and financial ability to involve in innovation activities, which may well be size dependent, particularly since some technologies are not even commercially available below certain size thresholds.

4.3 Technology adoption by regulated plants

48. Data on technology adoption by plants regulated by the Swedish NO_x charge was kindly provided to us from SEPA (2008). In total, 626 different plants participated at least one year in the system during the period 1992 to 2007. Table 4 summarizes the technology types adopted by the plants. 63% of plants report application of some kind of NO_x abatement technology, *i.e.*, leaving 37% of plants without reported measures to control NO_x emissions. Flue gas treatment (SCR or SNCR) had been installed on 171 plants (*i.e.*, 27%). SNCR is the dominating flue gas treatment technology with installations on almost one third of plants. SCR was adopted primarily by large plants producing in the interval 80 to 1700 MWh useful energy

per year. Still, only 15% of the very large plants (producing on average at least 200 MWh per year) have installed SCR.

49. Almost half of the plants report some kind of combustion measure. Trimming of the combustion process has been reported for 98 plants, which may be an understated number since most regulated plants that monitor NO_x emissions continuously are likely to engage in trimming activities. It may be that trimming is not always reported as a NO_x abatement technology because it does not involve installation of physical equipment. The combustion process has been altered through some kind of technical installation on 264 plants (*i.e.*, 42%). The most common combustion technologies installed are flue gas recirculation (26%) and low-NO_x burners (13%). Other types of combustion technologies have each been adopted by a few percentages of plants. 28% of regulated plants have installed flue gas condensation.

Table 4. Application of NO_x technologies on plants regulated by the Swedish NO_x charge
Plants that were covered by this charge at least one year between 1992 and 2007

			Number of plants	**Fraction of all plants**
Any type of NO_x abatement applied			393[a]	63%
Flue gas treatment	SCR		31	5%
	SNCR		157	25%
Combustion measures	Trimming		98	16%
	Other combustion measures than trimming		264	42%
		Fluegas recirculation	163	26%
		ECOTUBE technology	7	1%
		Injection technology	13	2%
		Low NO_x burner	83	13%
		Over-fire-air	12	2%
		Rotating over-fire air	16	3%
		Reburner	1	0%
		ROTAMIX technology	6	1%
		Other combustion measure	17	3%
Flue gas condensation			177	28%
Total number of plants having participated in the NO_x charge system at least one year in 1992-2007			626	100%

Source: SEPA (2008).

[a] Note that the total number of plants with technology applied does not match the sum of plants split by different technologies, since a plant can apply more than one technology.

4.4 Linking technology adoption to the NO_x charge

50. Can we relate the technology adoption among regulated plants to the introduction of the NO_x charge in 1992? SEPA started annual collections of information about adoption of NO_x abatement technology on regulated plants in 1992. We do not have systematic information about technologies adopted before this date. This makes it hard to determine the exact effect of the introduction of the NO_x charge on technology adoption. Table 5 presents some results from the annual surveys of regulated plants, which SEPA collected in 1992-2007. Only twelve plants (*i.e.*, 7%) report having NO_x abatement installed in 1992. Two plants have installed SCR, six SNCR, three flue gas recirculation, and two low-NO_x burners. Six plants have flue gas condensation installed in 1992, but only in one case is it combined with a NO_x abatement technology (flue gas recirculation).

51. Already one year after the introduction of the NO_x charge, the picture looks very different. In the 1993 survey, 62% of plants report having some kind of NO_x abatement technology installed. Overall adoption of NO_x abatement measures increase from 62% of regulated plants in 1993 to 72% in 1995. When the output limit for inclusion in the NO_x charge system is lowered in 1997 to 25 MWh useful energy per year, 150 plants enter the system. This immediately lowers the fraction of plants with NO_x abatement

adopted to 60%. Already in 2000 the fraction of abating plants is back again at about 70% of plants. The fast response in technology adoption, both after the introduction of the charge and its two extensions, indicates a strong incentive effect of the charge.

Table 5. Adoption of NO_x mitigation technology and flue gas condensation
Plants regulated by the Swedish NOx charge, 1992-2007

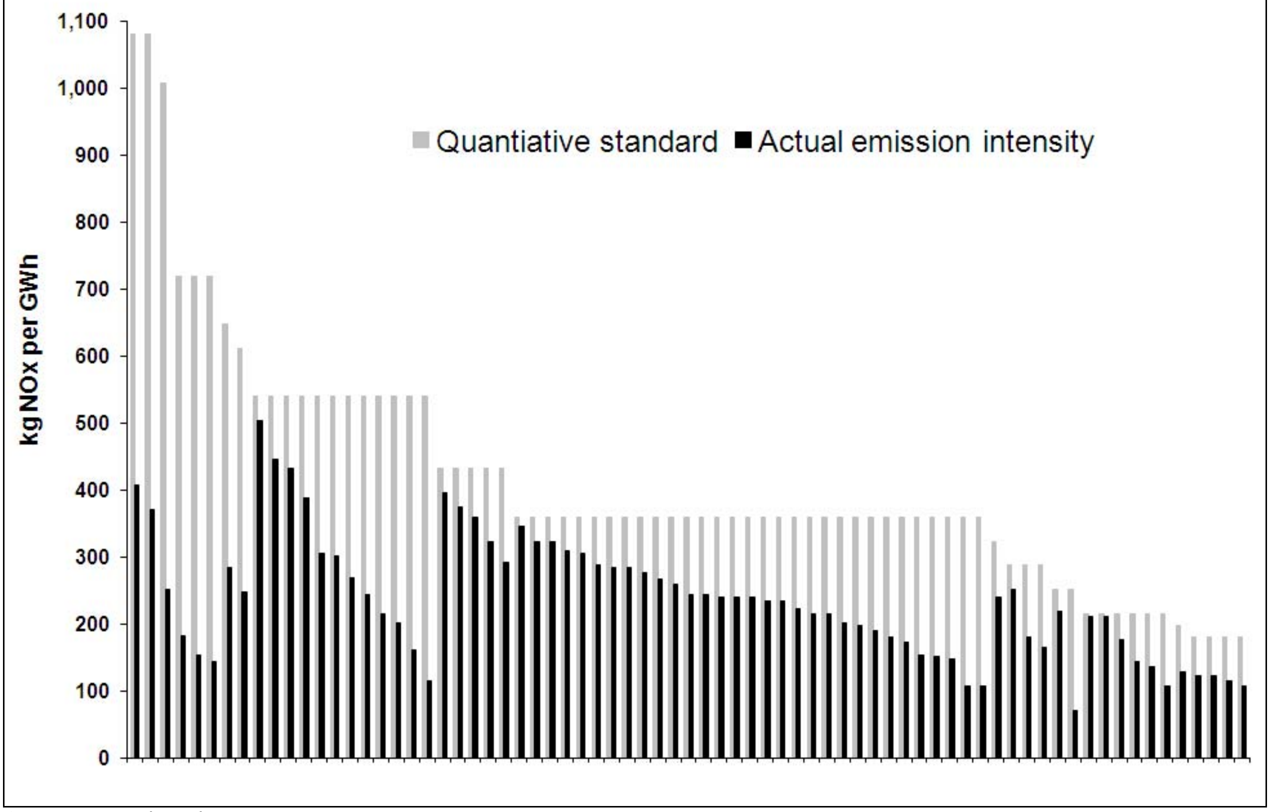
Year	Output limit for inclusion (MWh per year)	Number of regulated plants	Fraction of plants with NO_x technology installed: Total fraction of plants with NO_x mitigation	Post-combustion technology: SCR	Post-combustion technology: SNCR	Combustion technology: Trimming	Combustion technology: Other combus-tion measures	Flue gas conden-sation
1992	50	182	7%	1%	3%	0%	3%	3%
1993	50	190	62%	3%	21%	18%	30%	4%
1994	50	203	68%	5%	26%	21%	36%	4%
1995	50	210	72%	5%	30%	22%	40%	4%
1996	40	274	69%	5%	25%	22%	40%	19%
1997	25	371	60%	3%	22%	17%	39%	19%
1998	25	374	62%	3%	23%	19%	39%	21%
1999	25	375	65%	3%	24%	20%	43%	23%
2000	25	364	69%	4%	26%	21%	47%	26%
2001	25	393	67%	3%	25%	20%	47%	30%
2002	25	393	71%	4%	26%	20%	50%	33%
2003	25	414	70%	5%	26%	20%	48%	32%
2004	25	405	70%	4%	28%	19%	49%	34%
2005	25	411	69%	5%	30%	18%	47%	34%
2006	25	427	72%	6%	32%	19%	47%	34%
2007	25	415	71%	6%	33%	18%	46%	34%

52. In the survey of 114 plants regulated in the first five years of the Swedish NO_x charge, Höglund-Isaksson (2005) finds that the adoption of NO_x technologies was a combined effect of the charge and the quantitative emission standards that plants had been subject to since 1988. She finds that of 162 NO_x-reducing measures undertaken, 47% were said *not* to have been implemented without the introduction of the NO_x charge, 22% were undertaken primarily to meet quantitative standards, and 31% primarily for other reasons, *e.g.*, improved cost-effectiveness (unrelated to NO_x reductions) or compliance with emission standards for other pollutants than NO_x (predominantly SO_2). Thus, the NO_x charge appears to have been the most important, but not the only, factor for NO_x abatement adoption during this first phase of the NO_x charge system.

53. Quantitative standards for NO_x emissions from stationary sources were introduced in 1988. The standard levels are determined by regional authorities on an individual plant basis, however, with nationwide recommendations from the Swedish EPA in mind. Although the regional authority is the final decision maker, plants also participate in the decision process and the resulting standard level should not only take environmental aspects into account, but also consider potential effects on regional economic development and job opportunities. A complete comparison of the effectiveness of quantitative standards and the NO_x charge in reducing emission intensities of regulated plants is not possible because the central authority (SEPA) does not collect this information. The information is only collected by the 21 regional authorities. For an evaluation of the NO_x charge, SEPA (2004) collected information on standards and actual emission intensities for 73 plants that were regulated by the NO_x charge both in 1997 and 2001 and that had quantitative standards expressed in mg NO_x per MJ. The results are shown in Figure 5. Worth noticing are the similarities of the standard levels over different plants, indicating that levels have been determined following the standardized national recommendations by SEPA rather than taking individual plant circumstances into account. The actual emission intensity levels were on average 40% below the

limits specified by the quantitative standards for these plants. Also, actual emission intensities for plants with very generous standards were in level with plants with considerably stricter limits. Thus, the NO_x charge appears to have given rise to strong incentives to lower emission intensities well below the limits of the quantitative standards for most of the surveyed plants.

Figure 5. Qualitative standards and actual emission intensity for individual plants
73 plants regulated in 1997 and 2001, with standards specified in NOx per MJ.



Source: SEPA (2004).

5. Empirical evidence of innovation effects of the Swedish NO_x charge

5.1 Empirical measurements of innovation

54. Innovations in abatement technology describe a series of events, where an abatement technology is developed or improved, then adopted by firms and, finally, reduce emissions. Such a series of events cannot be measured empirically using a single measurement unit. Instead, we need to find measurements that can be used as indicators for the occurrence of innovations. We identify three such measurements: distances to a technological frontier, cost-savings in abatement for given emission intensity levels, and invention activity levels measured as number of patented technologies.

55. Chung, Färe and Grosskopf (1997) and Pasurka (2001) provide frameworks for identifying best-practice frontiers that allow for assessment of the innovation impacts of an environmental regulation. These methods require detailed information not only on the environmental impact, but also on production factors like capital, labor, and energy. This type of data is not available for plants regulated by the Swedish NO_x charge and we are therefore not able to apply this methodology fully. Instead, we make a detailed descriptive analysis of how emission intensities of regulated plants develop over time. Shifts in the

adoption of abatement technology and in emission intensities associated with adoption, may indicate technological development. By analyzing plant characteristics, we may be able to explain some of the shifts in technology adoption and emission intensities.

56. Cost-savings in firm abatement costs are often used as indicative of the probability that innovations in mitigation technology have occurred. For profit-maximizing firms, any net cost saving should be exploited, at least in the long run. If we can show empirically for plants regulated by the NO_x charge that abatement costs for given emission intensity levels have fallen over time, this could be taken as an indication of innovations in mitigation technology.

57. Finally, we will assess changes in invention activity before and after the introduction of the NO_x charge by investigating the number of patented inventions related to NO_x abatement. Linking such activity levels to adoption of innovations by plants regulated by the Swedish NO_x charge is not straightforward. First, far from all patented inventions are adopted as innovations and only some fraction of them will be adopted by plants regulated by the Swedish NO_x charge. Second, if we assume demand for NO_x abatement technology is the driving force for new inventions, the demand increase caused by the NO_x charge may constitute a small fraction of overall market demand. As NO_x abatement technology is traded on an international market, the Swedish NO_x charge may be one reason among many for engaging in development of NO_x abatement technology.

5.2 Evidence from analyses of emission intensities

5.2.1 Development of emission intensity levels over time

58. The analyzed sample consists of 626 combustion plants that were regulated by the Swedish NO_x charge during at least one year in 1992 to 2007. The plants are located on 346 plant sites with one to six individual plants (boilers) on each site. There are 231 plant owners including both private and public companies. If we define an observation as the occurrence of a plant in the regulated sample in a particular year, then the sample comprises 5401 observations. 61 plants are identified as peak load plants during at least one year in the analyzed period. This means that they are situated on a plant site with two or more other plants, but produce less than ten percent of overall site output in a given year. Peak load plants are only used sporadically to meet temporary peaks in energy demand and are therefore often not considered for NO_x mitigation installations. We exclude observations of plants in years when they meet our criteria for peak load plants. Thus, the analyzed sample comprises 604 plants and 5209 observations.

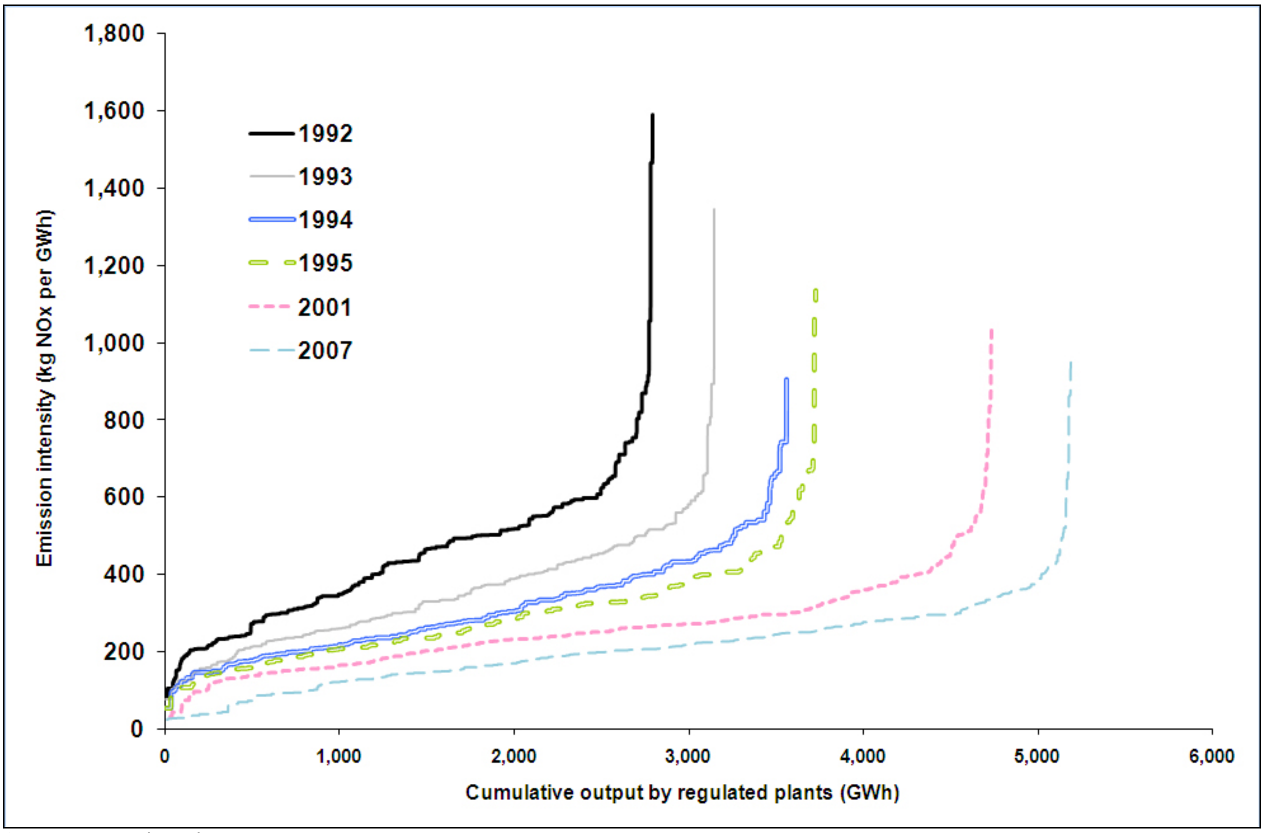
59. In Figure 6, plants regulated by the Swedish NO_x charge have been ordered by increasing emission intensities and plotted against the cumulative output of the plants. This gives us an illustration of the emission intensity attainable for a given level of cumulative output in a particular year. As shown, for a given level of cumulative output, emission intensities in later years are considerably lower than in 1992 when the charge was introduced. *E.g.*, in 1992 regulated plants were able to produce 30 000 GWh emitting less than 550 kg NO_x per GWh. Sixteen years later in 2007, regulated plants are able to produce the same amount of energy emitting less than 181 kg NO_x per GWh –an improvement by 67%. There are three main explanations for this:

- Cumulative output produced by regulated plants has increased by 74% over the period. The expansion in output has to a large extent taken place in plants that are relatively emission efficient or, when increases have taken place in new plants, these are in general more emission efficient than old plants.
- Regulated plants invest in NO_x mitigation and are therefore able to produce more output with less emission.

- Innovations in mitigation technology make it possible to reach even lower emission intensity levels for the same output level.

60. All three explanations will have the effect that the slope of the curves in Figure 6 flattens over time.

Figure 6. Emission intensity levels for given levels of cumulative output
1992-95, 2001 and 2007



Source: SEPA (2008).

61. In an attempt to separate out the effects on emission intensities from investments in NO_x mitigation, we divided the plants into two groups. The first group includes plants that have reported not (yet) to have undertaken any type of mitigation measure, while the second group includes plants that report mitigation measures. We refer to the first group as “pre-mitigation plants” and the latter group as “post-mitigation plants”. Note that the same plant can switch from being a pre-mitigation plant to a post-mitigation plant over the analyzed period if it decides to undertake NO_x mitigation measures.

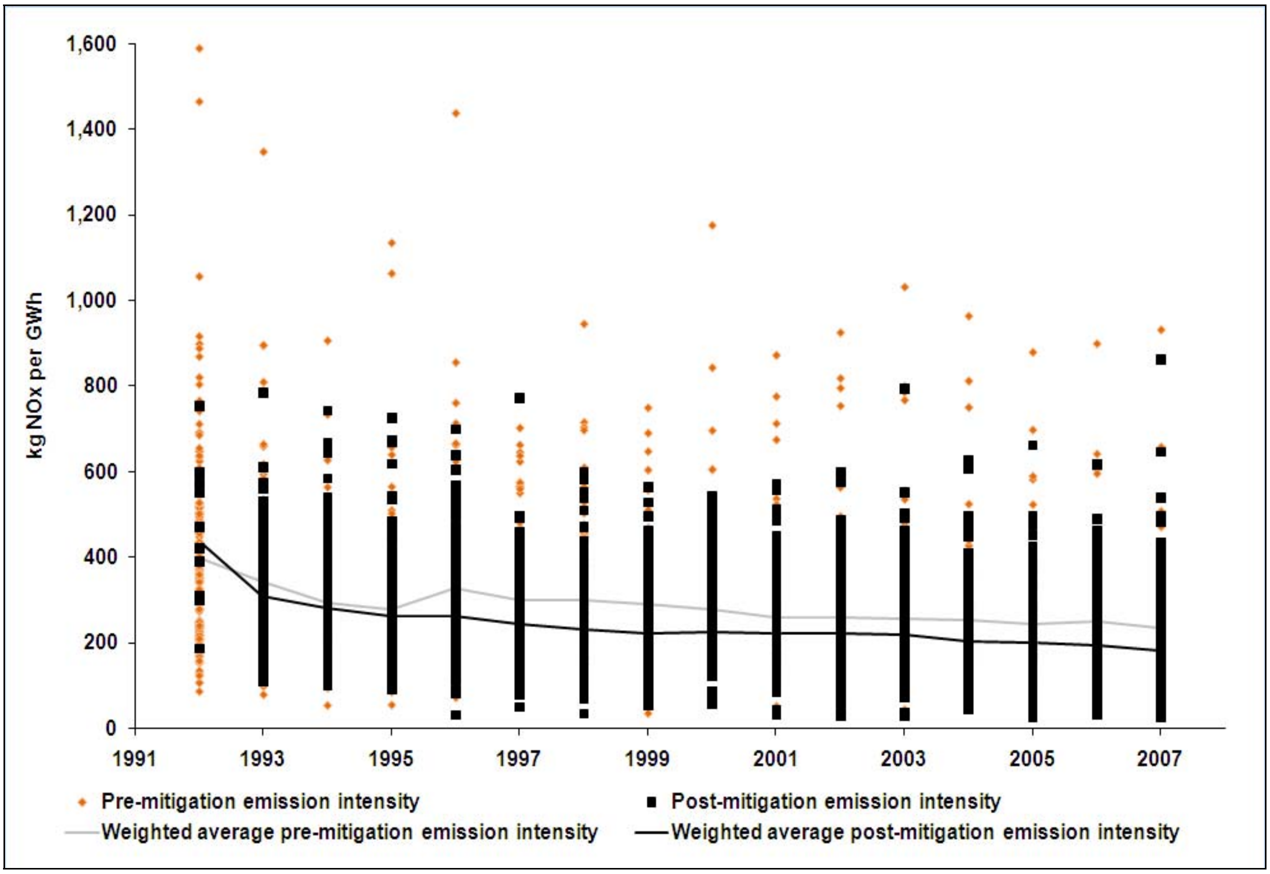
62. Figures 7 and 8 present plots of plant emission intensities for large (> 50 MWh per year) and small (25-50 MWh per year) plants, respectively. The large plants have been regulated by the NO_x charge since 1992 and produce over 90% of overall regulated output. As such, they make up a relatively consistent group of plants, whose abatement behaviour can be studied over a considerable length of time. Observations for pre-mitigation plants have been plotted in grey and post-mitigation plants in black. The development of the weighted average emission intensity of the pre-mitigation and post-mitigation groups is marked as grey and black lines, respectively.

63. The plot of emission intensities for the smaller plants does not show any particular development pattern. The spread of observations stay rather unchanged over time and average emission intensities for

pre- and post mitigation plants coincide for most years. The smaller plants have invested primarily in combustion technology and there is a bias towards worst performers in the abatement decision. Emission intensities in the year preceding the first mitigation investment are for these plants on average 17% higher than the average for the entire group of pre-mitigation plants. This may explain why the average emission intensity for pre- and post mitigation plants tend to coincide for the smaller plants.

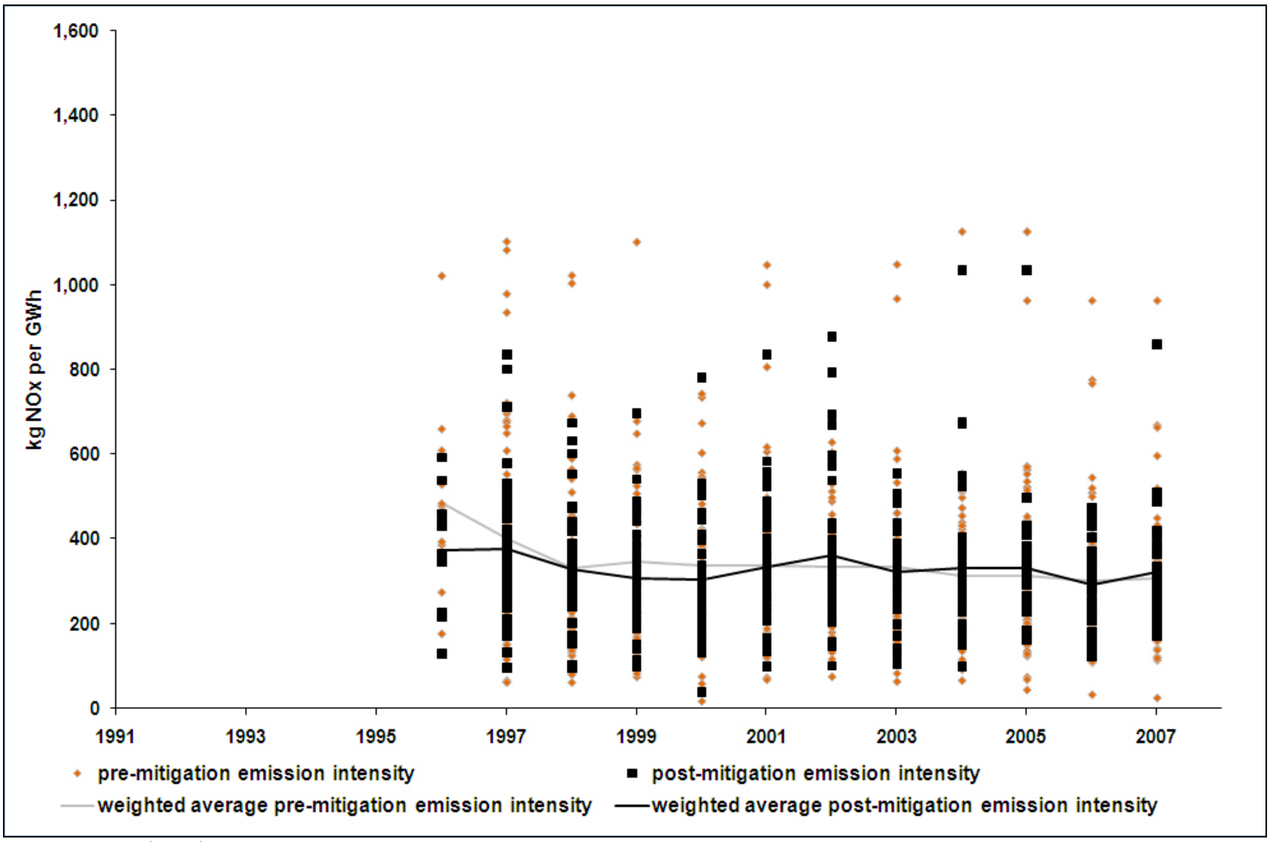
Figure 7. Plot of emission intensities of large plants regulated by the Swedish NO_x charge

Larger than 50 MWh



Source: SEPA (2008).

Figure 8. Plot of emission intensities of small plants regulated by the Swedish NO_x charge
25 - 50 MWh



Source: SEPA (2008).

64. The plot of emission intensities for the large plants in Figure 7 shows an increasing concentration in emission intensities towards the end of the period. This is primarily an effect of plants investing in mitigation technology (and switching from a grey to a black dot). The extreme emission intensities observed are all pre-mitigation plants and over time the extreme values disappear, presumably as the worst performing plants have high incentives to invest in mitigation. Among post-mitigation plants (black dots) the performance of the whole group improves over time, but the spread of emission intensity within the group remains rather constant. Table 6 presents descriptive statistics for the two samples of large plants. The weighted average emission intensity of post-mitigation plants (illustrated as a black line in Figure 7) falls rapidly, by 29 and 10%, in the first two years following the introduction of the NO_x charge. Thereafter, the annual change in emission intensity evolves around an average level of -3.2% per year. Interesting enough, the pre-mitigation plants follow a similar development, with rapid decline of about 15% per year in 1993 and 1994 and then, with the exception of 1996, an average annual change in emission intensity evolving around -2.9% per year. As these plants do not report adoption of physical mitigation technology, the entire decline must come from performance improvements within the boundaries of the existing physical technology. Over the last ten years, the average post-mitigation emission intensity has remained at about 80% of the average pre-mitigation emission intensity.

Table 6. Descriptive statistics of sample of large plants
Pre-mitigation and post-mitigation plants, larger than 50 MWh

Year	Pre-mitigation plants > 50 MWh				Post-mitigation plants > 50 MWh			
	No. of plants	Weighted average emission intensity	Annual change in weight. average emission intensity	TWh useful energy produced	No. of plants	Weighted average emission intensity	Annual change in weight. average emission intensity	TWh useful energy produced
1992	168	402	…	34.5	12	438	…	2.7
1993	72	345	-14%	13.2	117	309	-29%	27.7
1994	68	294	-15%	12.9	131	279	-10%	31.9
1995	75	279	-5%	12.2	133	260	-7%	34.1
1996	92	327	17%	13.6	154	260	0%	41.6
1997	86	298	-9%	14.0	146	242	-7%	35.6
1998	93	301	1%	13.1	153	229	-5%	38.4
1999	97	289	-4%	16.1	145	221	-3%	33.8
2000	70	277	-4%	10.7	165	225	2%	35.8
2001	74	260	-6%	11.9	177	221	-2%	40.5
2002	82	258	-1%	13.1	189	221	0%	43.1
2003	89	255	-1%	13.7	198	219	-1%	47.3
2004	85	252	-1%	13.6	189	204	-7%	46.8
2005	85	242	-4%	14.1	192	200	-2%	45.3
2006	81	249	3%	12.0	200	193	-3%	49.1
2007	79	234	-6%	12.2	191	181	-6%	48.3
Average 1997-2007			-2.9%				-3.2%	

Source: SEPA (2008).

65. The rapid improvement in emission intensity that we observe at the beginning of the analyzed period for both pre- and post mitigation plants can partly be referred to that the worst performing plants respond faster to the charge than plants that are already relatively emission efficient. An indication of this is that the 12 plants that report adoption of NO_x technology in 1992 emit nine percent more NO_x per output unit after installation than the pre-mitigation group of plants in the same year. When isolating the 63 plants that move from pre-mitigation to post-mitigation in 1993, we observe that the pre-mitigation emission intensity of these plants is 20% higher in 1992 than for the plants that still remain in the pre-mitigation group in 1993. Thus, the black dots that we observe in 1992 and 1993 represent many former "worst performers" that have managed to improve emission intensities considerably, but that are still not among the most emission efficient of plants.

66. The number of regulated plants producing at least 50 MWh per year increases by almost 40 plants (or 20%) between 1995 and 1996 following the lowering of the output-limit for inclusion in the NO_x charge system from 50 to 40 MWh per year. This causes the average emission intensity of pre-mitigation plants to temporarily increase by 17% between the two years (see Table 6). A closer look at these plants reveals that 16 are plants that report no NO_x technology adoptions, produce less than 70 MWh per year, and have never been in the charge system before. We can suspect that before the lowering of the output-limit, several of these plants were strategically producing just below the output-limit of 50 MWh in order to escape inclusion in the charge system and avoid the associated costs, *e.g.*, the costs for compulsory monitoring of emissions. These plants produce 1.7% of overall output and emit 2.5% of NO_x emissions from regulated large plants. This can be considered a relatively modest exit-effect of the NO_x charge.

67. From an innovation and technology development perspective, the most interesting results are the moderate continuous declines in average emission intensities that can be observed from 1997 onwards in both pre-mitigation and post-mitigation plants. In 1997, the large plants had been regulated by the NO_x charge for five years and plant engineers should have had enough time to adopt and try out existing

technology to find the most efficient NO_x emission intensity level for their individual plant. If we assume this is the case[8], we need to find other explanations than investments in existing mitigation technology to why emission intensities for this group of plants continue to fall and, in particular, that they continue to fall both for plants that report to have undertaken mitigation measures (black line) and for plants that report no NO_x mitigation measures (grey line). We distinguish three main explanations:

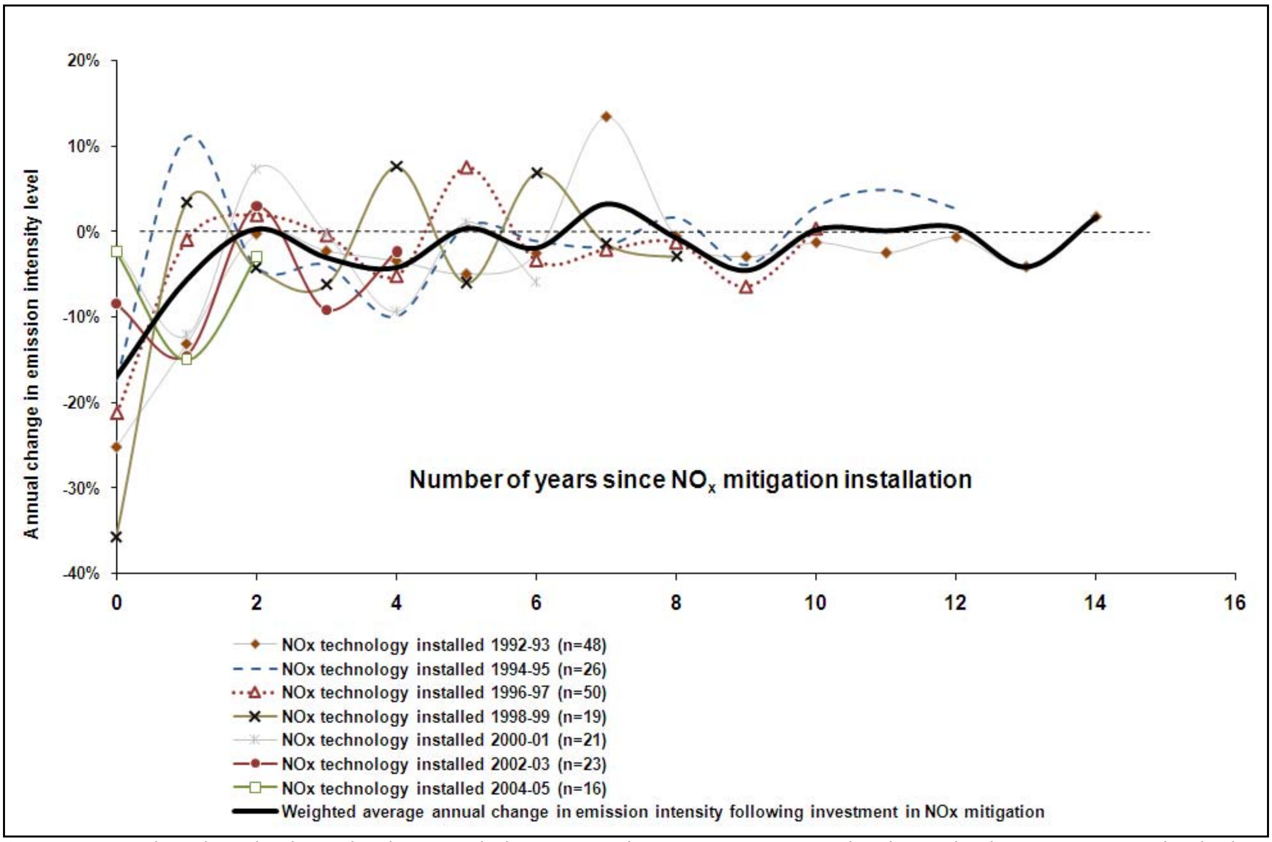
- An effect of plants improving their performance without investing in new equipment, *e.g.*, by learning better to control NO_x formation, by optimizing the various parameters in the combustion process given the boundaries of the existing physical technology, or by changing routines and firm organization. Such changes in the non-physical mitigation technology shows up as a fall in emission intensity both in plants that have installed mitigation equipment and in those that have not.
- A result of improved efficiency of physical mitigation installations. Plants adopting mitigation technologies at a later point in time are able to attain lower emission intensities than those investing at the beginning of the period.
- The realization of the full mitigation potential of an investment in physical mitigation equipment may not be immediate, but may require testing and learning that take several years before working optimally.

68. The first two explanations are effects of innovations both in physical mitigation technology and non-physical mitigation technology. The last explanation is a mere effect of that it may take more than a year of phasing in and testing before an investment in existing technology becomes fully efficient. If we can separate out this effect, we would be left with an effect on emission intensity that with some plausibility can be referred to as effects of innovations in mitigation technology.

69. In Figure 9 we analyze the annual adjustment in emission intensity levels following an installation in NO_x abatement. The analyzed sample includes those plants that have only reported *one* installation during the period 1992-2007 and the installation should be SCR, SNCR or installations in physical combustion technology (described in Table 3). As shown in Figure 9, the adjustment is relatively rapid. On average, emission intensities drop by 17% in the first year and six percent in the second year after installation of a NO_x mitigation technology. After the first two years, the average annual change evolves around zero percent change with an average annual drop of 0.9%. Thus, the phase-in of a new technology, including testing and learning how to use it optimally, appears to take one to two years on average. After the phase-in period, additional gains from optimizing the existing technology are limited and slow and may well be effects of innovations in non-physical mitigation technology like trimming.

[8] This may not be completely the case. As Höglund-Isaksson (2005) shows (see Section 2.1), in a sample of 114 plants regulated by the NO_x charge in 1992-96, about half of the plants comply (or over-comply) with the charge in 1996, while the residual half of plants do not reach up to an efficient investment level in abatement, *i.e.* where the marginal abatement cost equals the unit charge.

Figure 9. Annual change in emission intensity level following a NO_x mitigation installation



Source: SEPA (2008). Only plants that have made investments in SCR, SNCR or combustion technology at one occasion in time included (n=216, *i.e.* 50% of plants > 50 MWh).

70. To conclude, the adjustment in emission intensity following an investment in physical NO_x abatement technology is rather immediate and completed within one to two years for most plants. Thus, the continuous fall in average emission intensity that can be observed for large plants from 1997 onwards in both the pre-mitigation and post-mitigation group of plants, cannot be explained by long adjustment periods that drag on for many years before the phasing in and testing of installations in physical mitigation technology are completed. Instead, much of the annual decline in emission intensity of -2.9% in pre-mitigation plants and -3.2% in post-mitigation plants is likely to come from improved knowledge about how existing technology should be run more efficiently *and* adoption of innovated mitigation equipment. For pre-mitigation plants, the entire improvement in emission efficiency can be referred to innovations in non-physical mitigation technology. For post-mitigation plants, the continuous decline of -3.2% per year after 1997 is partly (*i.e.* by -0.9% per year) explained by improved knowledge about how to operate existing SCR, SNCR and combustion technology installations more efficiently, and partly, by adoption of innovated physical mitigation technology.

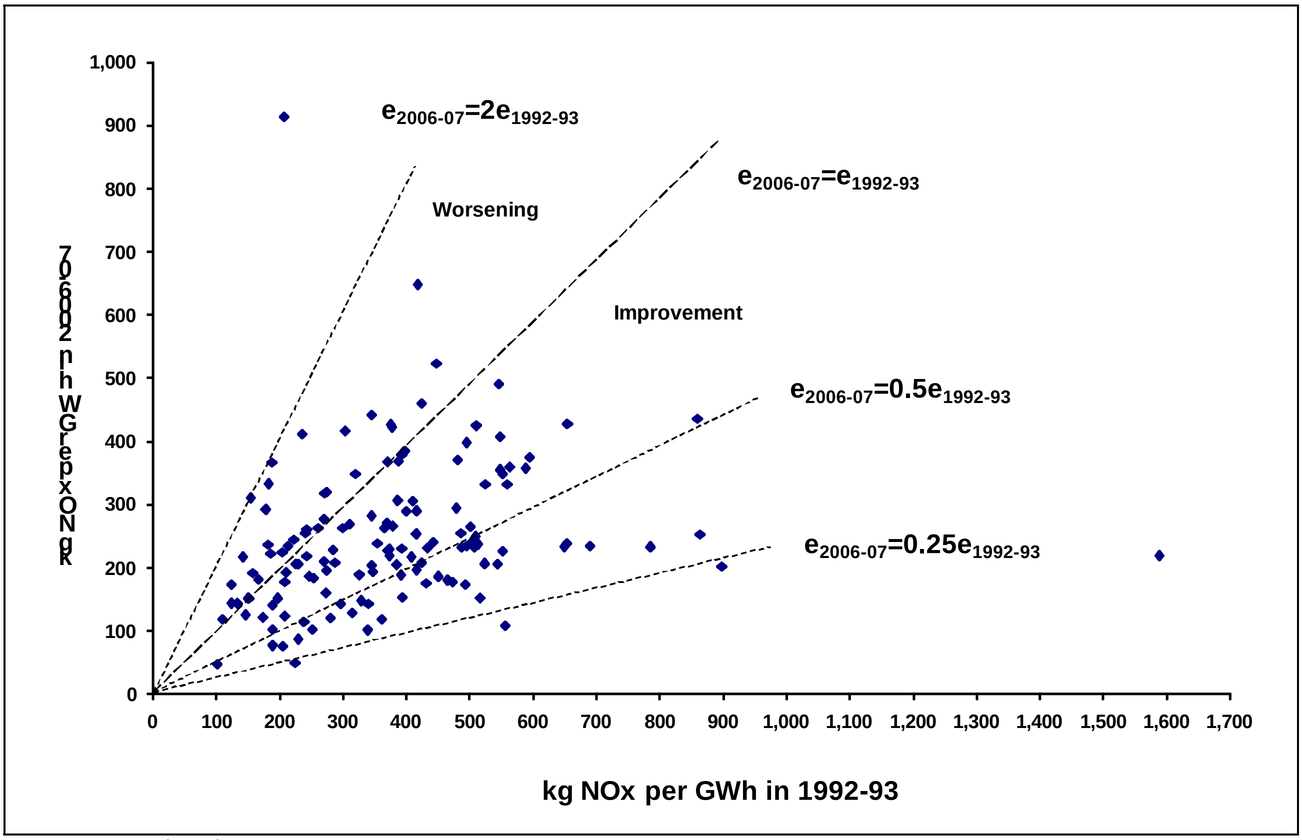
5.2.2 Improvements in emission intensities for individual plants

71. In the analysis above it is not possible to visualize the evolution of emission intensity in individual plants over time. However, we are naturally curious about whether it is typically the same plants that improve their performance or whether emission intensity varies strongly from one year to the next for the same plant. Figure 10 plots the average emission intensity of the plants in 2006-07 against the average emission intensity in 1992-93 for a set of 137 large plants that were regulated by the NO_x charge in both periods. The dots situated to the right of the 45-degree line ($e_{2006\text{-}07}=e_{1992\text{-}93}$) have lowered emission

intensity levels between the two periods. As expected, a majority of plants (76%) is in this category. Only a few units have significantly worsened their emissions in relation to output between the two periods.

Figure 10. Individual plant emission intensity

2006-07 relative to 1992-93.



Source: SEPA (2008).

72. Roughly half of the plants reduced emission intensity by up to 50%. Another third cut emission intensity by more than 50%, while four plants cut them by more than 75%. Two of these are oil fuelled plants that have installed SCR technology, while the other two have made major shifts from fossil to bio fuel. Every single plant with really high emission intensity in 1992-93 (> 600 kg NO_x per GWh) improved its performance, although their emission intensity levels in 2006-07 are still high relative plants starting from lower initial levels. This indicates a large spread between individual plants in the best performance levels that are technically attainable.

73. Increases in emission intensity were experienced by 24% of plants, but the increases were small - only for eight plants (*i.e.*, 6%) did it exceed 50%. We looked carefully at the 33 plants that had worsened the performance and found that nine of them had started from already low levels (< 250 kg NO_x per GWh) in 1992-93 and made slight increases (< 10%) in emission intensity. After having excluded these plants, we are left with 24 plants that have started from levels above 250 kg NO_x per GWh in 1992-93 and still worsened emissions per output in 2006-07. Did these plants not adopt the improvements in mitigation strategies adopted by most other plants, or did they adopt them but worsened emission intensities for other reasons? Seven of these plants did not report any installations of NO_x mitigation technology during the period 1992-2007, which may partly explain why these plants did not improve. For the other plants, the main reason for worsening performance appears to have been fuel switches from fossil fuels or pure bio fuels to less pure bio fuels such as unsorted municipal waste, recycled wood, fat waste, unsorted rest

products from forestry, and black liquor from pulp- and paper production. Such fuels have higher nitrogen content and switches are generally driven by economic factors unrelated to the NO_x charge. For instance, some may have reacted to the rising costs of fossil fuels and emitting carbon. In some cases, they were using “alternative” biofuels that meet climate goals but are still significant sources of local pollutants like NO_x. In some cases, access to waste such as bark and other by-products was plentiful and their use as fuel was promoted by other policy initiatives.

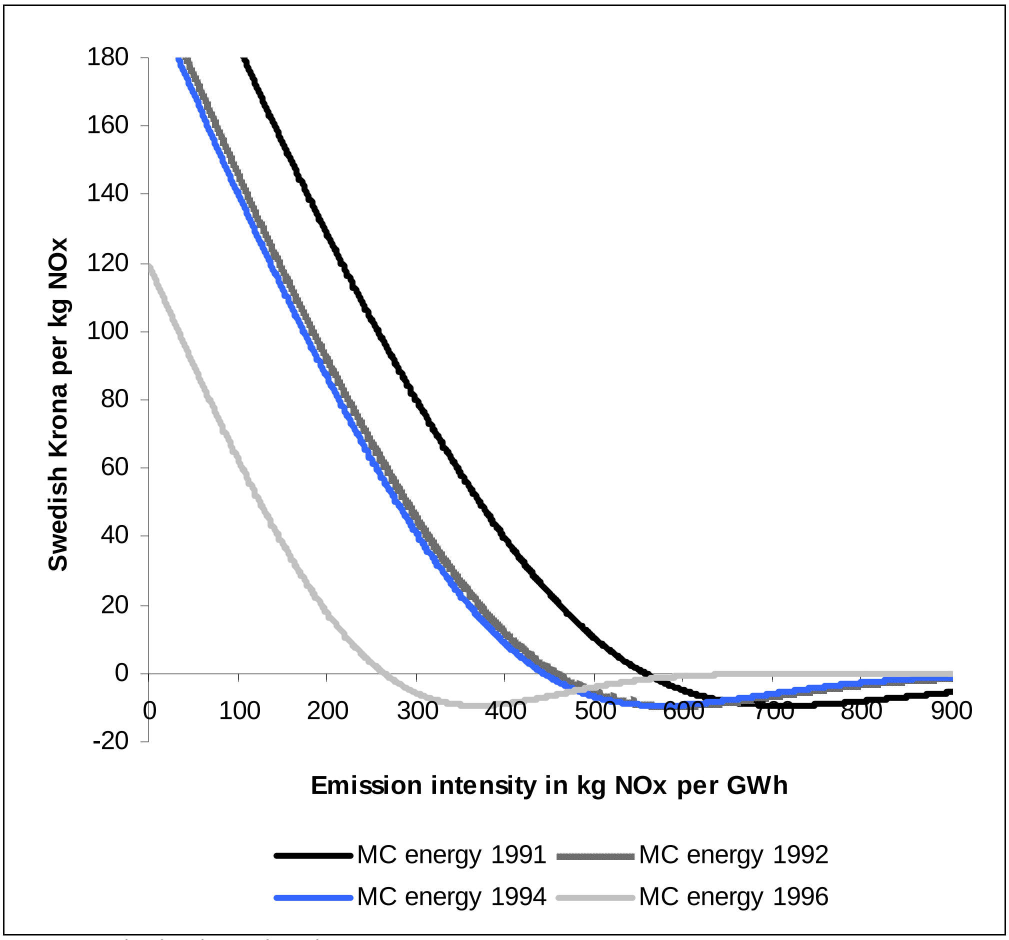
5.3 Evidence from abatement cost estimates

74. If we use cost-savings in abatement for given emission intensity levels as indicator for the occurrence of innovations in abatement technology, we would be able to measure the incidence of innovations by measuring changes in abatement costs for given emission intensity levels over time. This, however, requires detailed information about actual investment and operation costs of abatement technologies from firms having actually installed the technologies. Systematic collection of this kind of abatement cost data is very rare. To measure effects on innovations, the data needs to encompass a very large number of abatement measures undertaken by the same firms over a longer period of time. Since abatement potentials vary considerably with plant specific factors (in particular for NO_x), it is important that the same plants are followed over time. The introduction of the Swedish NO_x charge with its high incentive effect on abatement, offer a rare opportunity to follow abatement costs among a limited group of plants during a period when they were very active in abatement.

75. Unfortunately, SEPA does not collect information on costs for the mitigation technology adopted by regulated plants. Instead, we rely on the results of the survey of 114 plants regulated in 1992-96 conducted by Höglund-Isaksson (2005). In the estimations of marginal abatement cost curves, she added time as an explanatory variable in order to capture effects of technological development. Estimations were performed for the three industrial sectors energy, pulp-and paper, and chemical-and food. Innovation effects were measured as downward shifts of the marginal abatement cost curve from one year to the next. The energy sector had been most active in abatement during 1990-96 and only for this sector was it possible to find statistically significant evidence for falling marginal abatement costs over time. Compared to year 1996, marginal abatement costs were significantly higher for the same level of emission intensity in years 1991, 1992, and 1994. The predicted marginal abatement cost functions for these years are presented in Figure 11. These show *e.g.*, how the emission intensity attainable at zero abatement cost (*i.e.* the efficient abatement level without regulation) moves from 557 kg/GWh in 1991 to about 300 kg/GWh in 1996. This shift is likely to come from adoption of innovations in abatement technology, which has made it possible to produce energy with less NO_x emissions without increasing costs. To a large extent the effects are referred to trimming activities. The introduction of the charge has revealed opportunities to pick “low-hanging fruit” in abatement. Some of these opportunities existed also before the introduction of the NO_x charge, but the charge, with its requirement to monitor NO_x emissions continuously, made it possible for firms to discover and develop them to attain even lower emission intensity levels.

76. For the other two sectors, pulp-and paper and chemical-and food, parameters measuring shifts in marginal abatement costs over time were not found significantly different from zero and could accordingly not show any evidence of innovation effects.

Figure 11. Shifts in marginal abatement cost curves over time
For 55 plants in the energy sector regulated by the Swedish NOx charge in 1992-96



Source: Höglund-Isaksson (2005).

5.4 *Evidence from analysis of patent data*

5.4.1 The Swedish NO_x charge and market demand for NO_x mitigation technology

77. Incentives for external suppliers of abatement technology to engage in research and development of NO_x abatement technology are likely to be driven by market demand for these technologies. The larger the fraction of a market affected by a certain environmental regulation, the larger the effects on incentives to develop improved technologies that can be linked to the environmental regulation. NO_x abatement technology is traded on an international market, however, there may still be reasons to believe that the specific needs of the domestic market shape the type of technologies developed in a country, simply because information about the needs of the domestic market is more readily available.

78. In Sweden, total NO_x emissions from stationary combustion in power plants and industrial boilers amounted to 44 kt NO_x in 1990 falling to 39 kt in 2005 (GAINS, 2008). Thus, the 15 kt NO_x emitted from regulated plants account for about 35% of total emissions from stationary sources. With their strong incentives for abatement, plants regulated by the NO_x charge are likely to contribute considerably to demand in the domestic market for NO_x abatement technology.

79. In an international perspective, emissions from plants regulated by the Swedish NO_x charge are very small. In fact, they only make up less than one percent of total emissions from stationary sources (power plants and industrial boilers) in the 19 EU member states that have ratified the Gothenburg Protocol from 1999 and thereby committed to NO_x emission reductions (GAINS, 2008). Thus, if mitigation technology developed in Sweden is primarily indented for an international market, the introduction of the NO_x charge is unlikely to affect invention activity levels. If, however, inventions are primarily driven by the specific needs of the domestic market, then we can expect the charge to affect invention activity levels. It is possible that inventions first intended for the regulated Swedish market with its high abatement incentives, spills over and becomes adopted on a broader international market.

5.4.2 Patent data analysis

80. Counting the number of patent applications filed for NO_x mitigation technologies can give an indication of changes in the incentives for developing this type of technology. It should, however, be stressed that the number of patent applications is not a direct measure of innovation levels, since the relative importance of different patents is highly variable and a single patent may be more important in terms of NO_x abatement than dozens of others. Furthermore, not all granted patents are brought into use and only innovations to which exclusive rights can be clearly defined, are possible to protect through patents. As many innovations in NO_x mitigation technology take place through small alterations in the combustion process, without additional installations of physical equipment, the analysis of patent data is limited in its scope to indicate incentives to develop NO_x mitigation technology. With this in mind, we still find it illustrative to analyze the timing of Swedish patent applications for NO_x mitigation technology with respect to the introduction of the NO_x charge and to compare Swedish invention activity levels with those of other countries.

81. The search[9] for patent applications was made in the Worldwide patent database (2009) including 81 patent offices worldwide. Only counts for claimed priorities were generated, *i.e.*, patents for which an application is filed at an additional office (*e.g.* a national patent office) to that of the priority (*i.e.* worldwide) office. Two main technology types were searched for:

1. combustion apparatus modifications characterized by arrangements for returning combustion products or flue gases to the combustion chamber (IPC code F23C9/00), and

2. post-combustion treatment of flue gases addressing nitrogen oxides or nitrogen and sulfur oxides (IPC codes B01D53/56 and B01D53/60).

82. Patent applications were searched for by country of residence of inventor and country of residence of applicant. The inventor is a physical person, while an applicant can also be a company. The two categories give similar results for most countries and we therefore show only the results of the search by country of residence of inventor. Table 7 shows the number of applications filed by country of residence of inventor.

83. There were 24.3 patent applications filed by Swedish inventors in the period 1970-2006. 47% of applications were filed for inventions in combustion technology and 53% for inventions in post-combustion technology. The average number of patent applications filed per year over the entire period was 0.08 patents per million inhabitants. Figure 12 shows the development in the number of patents filed per million inhabitants in Sweden and all other countries (Austria, Denmark, Finland, Germany, Japan, and Switzerland), where the average annual application rate of patents for these technology categories

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9 The authors are grateful to Ivan Hascic and Nick Johnstone, both at OECD, for assistance with performing the patent searches.

exceeded 0.05 patent applications per million inhabitants in the period 1970-2006. In Sweden, there appears to have been continuous activity in this field since 1988. Particularly the period 1988-93 shows high activity, with 0.22 patents filed per million inhabitants per year. The intense activity during this particular period coincides with the introduction of quantitative standards for NO_x in 1988 and the NO_x charge in 1992. After 1994, there has been a relatively steady flow of on average 0.07 patent applications filed per year per million inhabitants.

84. With 0.08 patent applications filed on average per million inhabitants in 1970-2006, Sweden ranks among the top four countries for patent applications in these technology categories. Switzerland is by far the leading country, with an annual application rate of 0.23 patents per million inhabitants. Also Germany and Finland have higher average patent application rates than Sweden. The comparison of the timing of patent applications presented in Table 7 shows that Japan is the only country with the highest average application rate in the period before 1988. Also Switzerland and Germany were highly active in this early period, but just like most other countries, the activity rate measured in terms of patent application rates, peaked in the period 1988-93. Countries identified as late starters, *i.e.*, having the highest application rates after 1994, are Finland, France, South Korea, Norway, and the United Kingdom.

85. We may formulate two different hypotheses about the drivers for the intensive invention activity in the years 1988-93, *i.e.* at the time of the introduction of the Swedish NO_x charge. The obvious hypothesis would be that the introduction of a NO_x charge of a high magnitude spurs incentives to engage in research and development in NO_x abatement technology. An alternative hypothesis would be that the decision to set a high charge level was made possible by an existence of effective Swedish NO_x abatement technology. The latter is a political economy argument that suggests lobbying, or at least interaction, between the innovating firms and the decision makers. Conclusive evidence of either hypothesis is not available and would require a much more detailed analysis of each individual patent than what is possible within this study. Still, it may seem more than a coincidence that Sweden ranks fourth in the World in patents per inhabitant during the short period when regulations and high charge levels were being discussed and introduced.

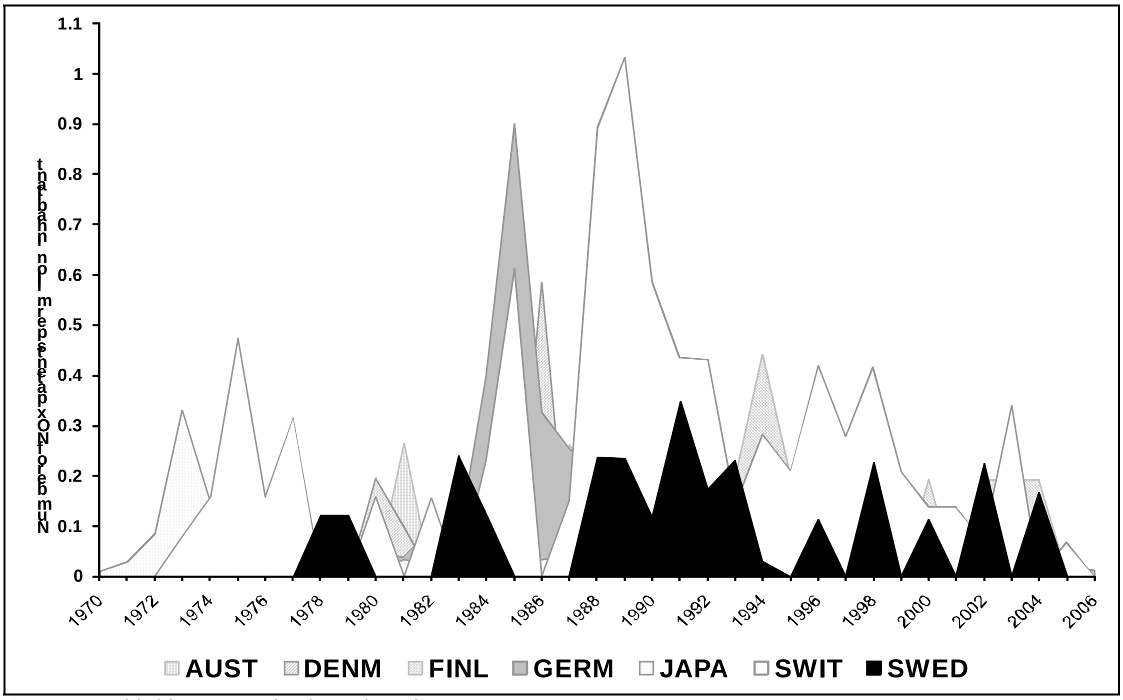
86. An interesting observation from Table 7 is that the fraction of patent applications filed for inventions in combustion vis-à-vis post-combustion technology, vary considerably between countries. In most countries, patents on post-combustion technology dominate, with more than 70% of all applications filed. The opposite pattern can be found in Norway and Switzerland, where inventions in combustion technology dominate. In countries like Sweden, France, Italy, the Netherlands and the US, the distribution of patents over the two technology types is relatively even, with at least a third of inventions concerning combustion technology improvements. Such distinct differences between countries in the type of technology developed, indicates that domestic circumstances are important for the development of NO_x mitigation technology. For example, what we may observe here is that countries with many small combustion plants develop more combustion technology, while countries with larger units focus on development of post-combustion technology. A plausible explanation is that information about technologies needed is more readily available from the domestic market than from the international market and inventors therefore more often respond to the needs of the domestic market.

Table 7. Number of patent applications filed by country of residence of inventor

Country	Number of patents 1970-2006 by country of residence of inventor			Average number of patents per year measured per million inhabitants			
	Total	whereof combustion technology patents	whereof post-combustion technology patents	1970-2006	1970-1987	1988-1993	1994-2006
Austria	20.3	27%	73%	0.071	0.062	0.147	0.047
Australia	1	0%	100%	0.001	0	0	0.004
Belgium	4	0%	100%	0.011	0.008	0.017	0.011
Canada	14.7	20%	80%	0.014	0.007	0.022	0.020
Czech Rep.	2	0%	100%	0.005	0	0	0.015
Denmark	10.5	19%	81%	0.055	0.049	0.194	0
Finland	15.6	19%	81%	0.083	0	0.144	0.146
France	54.8	35%	65%	0.026	0.015	0.032	0.039
Germany	353	28%	72%	0.120	0.131	0.164	0.085
Italy	20.5	41%	59%	0.010	0	0.023	0.012
Japan	289	11%	89%	0.066	0.072	0.063	0.060
South Korea	9.3	14%	86%	0.005	0	0.004	0.014
Netherlands	12.5	40%	60%	0.023	0.014	0.033	0.030
Norway	6	75%	25%	0.037	0	0.040	0.086
Russia (incl. USSR)	5	20%	80%	0.001	0.000	0.001	0.002
Spain	2.2	0%	100%	0.001	0	0.004	0.002
Sweden	24.3	47%	53%	0.076	0.033	0.223	0.067
Switzerland	58.5	69%	31%	0.232	0.138	0.587	0.197
United Kingdom	47	24%	76%	0.022	0.017	0.021	0.029
United States	269.6	33%	67%	0.028	0.020	0.049	0.029
Other countries	10.1	30%	70%	n.a.	n.a.	n.a.	n.a.
World	1230	27%	73%	n.a.	n.a.	n.a.	n.a.

Source: Worldwide patent database (2009).

Figure 12. Number of patent applications filed per million inhabitants
By country of residence of the inventor



Source: Worldwide patents database (2009).

6. Conclusions

87. Since the Swedish charge on NO_x emissions from stationary combustion plants was introduced in 1992, NO_x emissions per unit of useful energy produced by regulated plants have declined by 50%. This can be considered a significant reduction for a pollutant like NO_x, which is usually considered technically difficult to control due to its complex formation process. Two important factors contribute to this success; the mandatory continuous monitoring of emissions from regulated plants and the high charge level, which was made feasible by the refund mechanism of the charge. In this study, we analyze the effects of the Swedish NO_x charge on adoption and innovation of NO_x mitigation technology.

88. Under competitive conditions, the refunded charge gives rise to approximately the same incentives to invest in emission control as a non-refunded emission tax of the same magnitude, *i.e.* regulated plants invest in mitigation until the marginal cost per unit of emission reduced is equal to the unit charge (or tax). Effects on demand for mitigation technology are therefore the same under the two regimes, which also imply that incentives to invest in research and development of mitigation technology remain equivalent for firms developing and supplying mitigation technology to regulated plants. Innovations in mitigation technology can also take place within regulated plants. These are often learning-by-doing innovations that are too indistinct to protect through patents. Such innovations are of particular interest for NO_x control in combustion plants, since considerable emission reductions can be attained through trimming of the combustion process without installing physical equipment. Compared with an emission tax of the same magnitude, a refunded charge may inhibit the spread of innovations among the regulated plants. By keeping the knowledge about the innovation to itself, a plant is able to reduce its emission intensity and improve its position relative the other regulated plants, which will render it a higher net refund through the refund mechanism.

89. We analyze empirically the adoption of mitigation technology among 626 plants that participated at least one year in the Swedish NO_x charge system during 1992 to 2007. Most plants report adoption of some kind of NO_x mitigation technology. The adoption rate is particularly high just after the introduction of the charge in 1992 and after the extensions of the charge system in 1996 and 1997. This indicates that the introduction of the NO_x charge, as a complementary instrument to the quantitative standards introduced in 1988, was very important for attaining the extensive reductions in emission intensity. The findings of two previous studies further strengthen this conclusion. The introduction of the NO_x charge was found the single most important reason for adoption of NO_x mitigation measures in 1990 to 1996 by 114 regulated plants. In a survey of 73 plants regulated by both quantitative standards and the NO_x charge in 1997 and 2001, actual emission intensity levels in 2001 were found on average 40% lower than the emission intensity limits specified by the quantitative standards.

90. By analyzing the development of plant emission intensity levels over time and the timing of the adoption of NO_x mitigation technology, we are able to conclude that for larger combustion plants, producing at least 50 MWh per year, a continuous drop in emission intensity levels of about three percent per year can be observed in the long term. This is observed both for plants that report adoption of NO_x mitigation technology and for plants that report no technology adoption. After having concluded that the adjustment of emission intensity levels after installation of physical mitigation technology is rather immediate (one to two years), we refer the entire long-term effect on emission intensity levels to innovations in mitigation technology. For plants that report no installations in physical mitigation equipment, the entire long-term drop in average emission intensity level comes from innovations in non-physical mitigation technology, *i.e.* acquisition of knowledge about how to better control NO_x formation given the limitations of the existing physical technology. For plants that report adoption of mitigation technology, innovations occur in both physical and non-physical mitigation technology.

91. In a comparison of individual plant performance between 1992-93 and 2006-07, three-quarters of plants have improved the performance and emit at lower emission intensity levels in the later period. In particular, plants starting from very high emission intensity levels have improved performance the most, but many of them are still not able to reach down to the very low emission intensity levels attained by plants that have started reductions from lower initial emission intensity levels. This indicates a large spread between individual plants in the best performance levels that are technically attainable. Adoption of NO_x mitigation technology often calls for tailored solutions, which has opened up for the development of a large variety of mitigation options.

92. For a measurement of innovation effects on marginal costs for NO_x mitigation, we refer to the results of a previous study, where estimations of marginal abatement cost curves for 55 power plants regulated by the NO_x charge in 1992-96 show that the marginal abatement cost curve shifts downward over time. The average emission intensity level attainable at no mitigation cost moves from 557 to 300 kg NO_x per GWh between 1991 and 1996. These findings are the strongest empirical evidence we have of innovation effects of the Swedish NO_x charge.

93. The patent data analysis shows a high level of activity in development of NO_x mitigation technology in Sweden, especially after 1988 when the regulation of NO_x emissions from stationary sources began with the introduction of quantitative standards, then followed by the NO_x charge in 1992. Although the activity level has been high in Sweden, it is not exceptional in an international comparison. The development we observe in Sweden appears to be much in line with an overall international trend. The different focuses of the types of mitigation technology developed indicate that domestic demand for NO_x mitigation technology are important for incentives to develop technologies and that many inventions may result from attempts to improve existing technologies to better meet the specific demands of the domestic market.

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