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# Innovation and Diffusion of Environmental Technology

*Industrial NO<sub>x</sub> Abatement in Sweden  
under Refunded Emission Payments*

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# **Innovation and Diffusion of Environmental Technology: Industrial NO<sub>x</sub> Abatement in Sweden under Refunded Emission Payments**

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## **Abstract**

In this paper we study the process of technical change in the case of pollution abatement from large stationary sources that have been regulated by a very forceful refunded emission payment policy. Thanks to the high costs of emitting nitrogen oxides (NO<sub>x</sub>), considerable progress has been made in lowering aggregate emissions. This paper seeks to disaggregate average industry improvements to study how much of it is due to innovation (improvement of best practice through investments as well as learning by doing) and how much is due to the spread and adoption of technology. We find both factors very important. Innovation has been rapid: the best firms have cut emissions on the order of 70 percent. Nevertheless, reductions have been even more rapid for the majority of firms, such that the disparity in emission coefficients has also been reduced significantly as the median firms have caught up with best practice.

**Key Words:** nitrogen oxides, NO<sub>x</sub>, R&D, innovation, technology diffusion, environmental policy instrument, technical change

**JEL Classification Numbers:** Q55, Q53, L51

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# **Innovation and Diffusion of Environmental Technology: Industrial NO<sub>x</sub> Abatement in Sweden under Refunded Emission Payments**

Thomas Sternier and Bruno Turnheim\*

## **1. Introduction**

Technical change is at the heart of environmental improvements and economic development in general. It is one of the main forces in economic and social development and at the center of economic theory—at least implicitly. It is, however, elusive. Its very nature is to be partly unknown and incalculable *ex ante*. It is also complex: products not only become cheaper but they are even transformed, acquiring new properties that often transcend the relatively simple numerical and conceptual models we make.

Despite the importance of innovation for the environment, there are relatively few studies in environmental economics that truly delve into the characteristics of technical change and capture empirically the features that make it essential for pollution abatement and the development of more environmentally benign production systems. The study of technology is by tradition quite different in economics and in technical engineering, partly because engineers inevitably are more interested in the workings of the chemistry and the machinery than are economists. To capture the economic importance of technical change, it is necessary to understand such technical aspects, and interdisciplinary work is thus useful in this area.

The refunded emission payment, used in Sweden for abatement of nitrogen oxide (NO<sub>x</sub>) emissions from large stationary combustion sources, was explicitly selected as an instrument to have an effect on technology. It was not the desire of the policymakers to close power plants or paper mills or drive them out of the country, or to reduce the consumption of their final products by making them more expensive. Rather, their goal was simply to affect combustion technology (in the broadest sense of the word, including fuel choice, postcombustion treatment, and other aspects of the operations) and thereby NO<sub>x</sub> emissions.

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Like all acid rain policies in Sweden, this policy was ambitious, imposing marginal costs of pollution several orders of magnitude higher than those in other countries. It therefore provides a good opportunity to study the mechanisms of technical change, including the separate processes of innovation and of technology spread and adoption.

This paper starts with an overview of theories for technological development, in Section 2. We then provide, in Section 3, an overview of the chemistry and technology of  $\text{NO}_x$  formation and abatement. Section 4 introduces the main policy instrument, the refunded emission payment, and Section 5, the empirical findings of the technical change observed. Section 6 offers some technical explanations, and Section 7 concludes.

## 2. Theories of Technology

A large literature addresses the importance of the welfare gains from technological innovation. Such innovation may reduce the cost of environmental protection and could be more important than the static welfare gains from correcting a pollution externality. A critical consideration for the choice of environmental policy instrument would then be its impact on incentives for cleaner production technologies. In the long run, the cumulative effect of technological innovation might in fact resolve what in the short run often appears to be an irresolvable conflict between environmental quality and material standards of living (see Jaffe and Stavins 1995; Kneese and Schultz 1978).

That cumulative effect should make a strong argument for focusing more on technology policy. Parry et al. (2003), however, show that this is generally not the case: the welfare gains from innovation are typically smaller than the standard welfare gains from choosing the optimal level of abatement. The reasons are that the long-run gain from innovation is bounded by the maximum reduction in abatement costs and that research and development are slow, uncertain, and costly. These authors nevertheless also show conditions under which innovation may be very important: when innovation substantially reduces abatement costs quickly and when the optimal (Pigouvian) amount of abatement is modest.

Those two conditions appear to have a good chance of being fulfilled in the case we are studying.  $\text{NO}_x$  abatement in large stationary furnaces can really take place only through either technical change or reduced production and consumption. Reduced production was not an option for the Swedish policymakers. Fuel switching was a third possibility, but it is heavily influenced by other factors (other environmental priorities as well as price differentials). Moreover, fuel switching and fuel flexibility are intimately tied to technical change in the furnace. Many of the

technical options for abatement were still new but appeared fairly promising, and thus one explicit purpose of this program in Sweden was to speed up technical progress.

Starting with Milliman and Prince (1989) and Downing and White (1986), there is a broad literature on the characteristics of innovation and the role played by economic instruments for technical progress (see also Jaffe and Stavins 1995; Jaffe et al. 2000, 2002; Jung et al. 1996; Kemp 1997; Parry 1995, 1998; Fischer et al. 2003). This literature often makes an explicit distinction between the process of research and development (R&D) on the one hand and the diffusion and adoption or use of the new technology on the other.<sup>1</sup> This is a first step toward recognizing the complexity that characterizes what we simply call technical change.

It is sometimes the case that different agents are active in the different stages of technological change. In the invention and innovation phase, the R&D may be conducted by specialized firms (possibly in collaboration with production firms) or by the producers themselves.<sup>2</sup> At this first level all the technological uncertainties are related to R&D. There may be issues of market structure—it is quite common to find thin markets with small numbers of firms in this kind of niche—and “learning by doing” (Arrow 1962) may prevail.

Once the innovation has been made and tried at one unit, we may enter a phase of diffusion. Generally, but not always, the innovations are patented. Adopters have to decide whether and when to acquire the new technology and how to use it. Common technology diffusion modeling approaches include probit models (existence of a moving threshold defining the economic feasibility of the innovation for adopter classes), epidemic models (information-based adoptive capacity of potential adopters), and capital stock adjustment models (old capital stock is replaced by more advanced technology). As shown by many of the articles cited above, various instruments provide quite different incentives for adopters. With permits, for instance, the equilibrium price for emissions will be affected by innovation and by other firms’ adoption, whereas for an environmental tax, there is no such immediate effect.

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<sup>1</sup> Diffusion studies are concerned with explaining the rate of adoption of a new technology by a population of potential adopting firms. Conversely, adoption studies are concerned with explaining the individual firm’s adoption decision; see Thirtle and Ruttan (1987).

<sup>2</sup> Kemp (2000) reminds us that in traditional industries, “new technologies are [often] developed by firms outside the regulated industry,” and thus firms rely upon “suppliers, capital goods suppliers and environmental technology suppliers.”

Figure 1: A simple model of innovation and diffusion

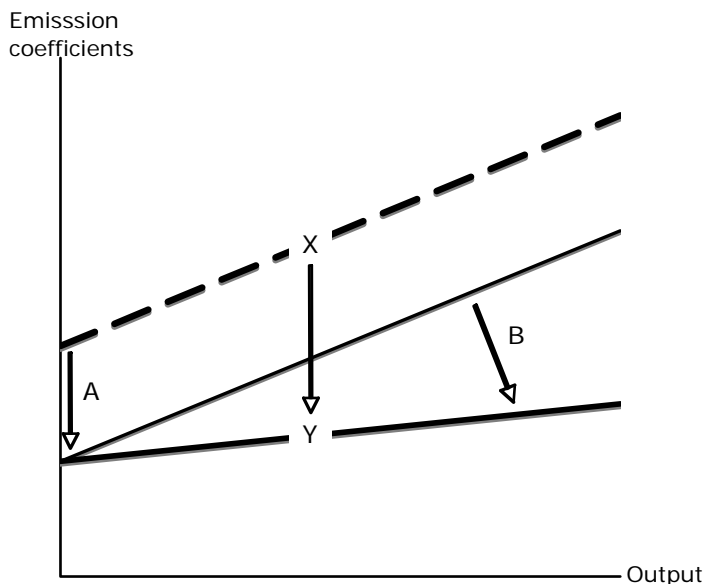


Figure 1 provides a first stylized impression of how one can disaggregate technical progress into innovation and diffusion. In this simplified, one-dimensional, diagram with a histogram of emission coefficients (in this case, emission coefficients for  $\text{NO}_x$ ) for two years, the dashed line marks emission coefficients for all the firms in the base year. The solid heavy line marks emission coefficients for all the firms in some later year. Since the firms are heterogeneous, they typically have different emission coefficients, and in this diagram, they are ordered according to efficiency. Average industry emission coefficients are a weighted average and in this case improve from X to Y. We can now disaggregate the improvement in the industry: arrow A shows the movement of the frontier—which we may ascribe to R&D or to innovation—and arrow B shows the process of technology spread and adoption.

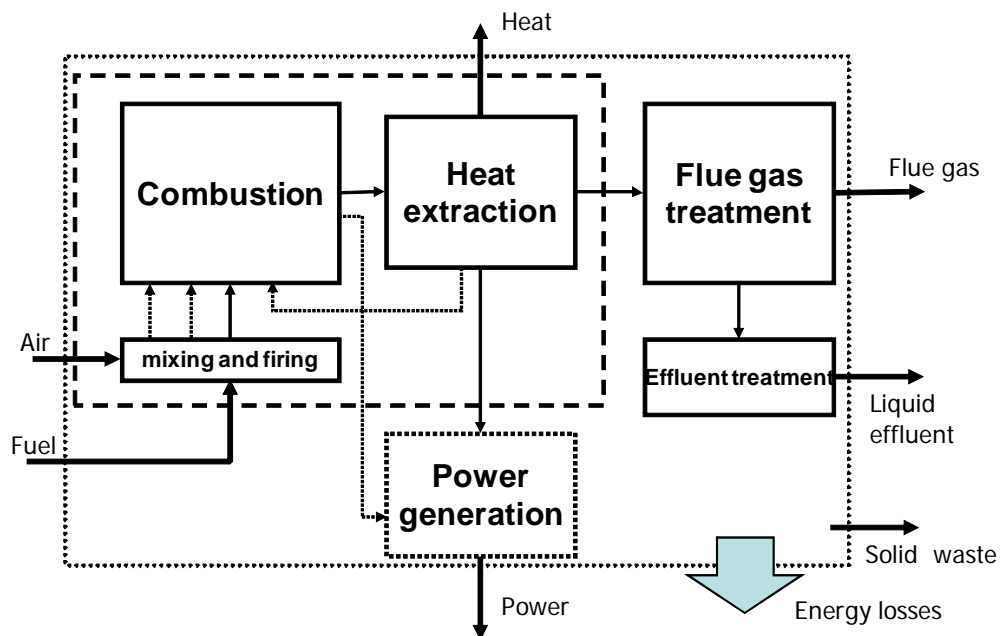
In practice, there may be problems to this approach: the curves need of course not be linear, and we may be interested in several dimensions rather than one. If we want to distinguish between innovations that are capital-embodied on the one hand and learning by doing on the other, then again more methodology would be needed. Still, Figure 1 provides a useful starting point if the appropriate data are available.

### 3. The formation and abatement of NO<sub>x</sub> emissions from stationary sources

#### *A standardized approach to stationary combustion engines*

Several features of NO<sub>x</sub> emissions are fairly special, and we therefore start with a technical explanation of NO<sub>x</sub> formation and abatement in stationary industrial combustion systems. Diagram 1 shows the main steps for the conversion of fuel to heat and/or electricity. Each of these steps has the potential to affect NO<sub>x</sub> formation.

**Diagram 1. Systemic approach to a “standard” combustion unit, functional modules**



The combustion operation uses fuel to produce heat or power. It requires an oxidizing agent, commonly air. All other flows involved (flue gas, liquid effluent, solid waste, energy losses) are nondesirable byproducts or losses that the market alone usually fails to limit. The different steps involved can be described as follows.<sup>3</sup>

- The feeding, mixing, and firing of fuel and oxidizing agent create a flame, which is then propagated throughout the combustion zone. Depending on the nature of the fuel and the

<sup>3</sup> The processes for gas turbines are slightly different in their primary purpose (power) and configuration but can still be described using the previous schematic.



desired degree of flexibility for fuel choice, various kinds of mixing and firing technologies can be used.

- The combustion then spreads throughout the combustion chamber, whose shape, size, and materials can all affect emissions and overall efficiency. A first conflict appears here between energy efficiency and  $\text{NO}_x$  emissions, for one way of increasing efficiency is to intensify combustion and raise temperature and pressure. This, however, considerably increases the formation of  $\text{NO}_x$ , which is very sensitive to temperature. Second-generation solid fuel combustors (fluidized bed combustors) overcome this limitation and allow simultaneous efficiency gains and cleaner flue gas relative to their predecessors (stokers or “grate-fired” boilers).
- Heat extraction and conversion are the primary function of combustion units. It is during this step that the energy is converted into a useful form: piped steam, hot water, hot oil, and/or electricity.<sup>4</sup>
- Once the exhaust gases have left the combustion chamber, they go through a series of flue gas treatment processes intended to reduce the reduce air pollutants ( $\text{NO}_x$ ,  $\text{SO}_2$ ,  $\text{CO}$ ,  $\text{PM}\dots$ ). These pollutants can be transformed, precipitated, and washed in liquids or deposited as sludge, depending on their nature and concentrations.

All those choices need be integrated into a single design, which can be modified to a certain extent depending on factors such as scale. Many of the modules are interdependent, however, and thus industries often face a limited choice of discrete designs. Improvements in  $\text{NO}_x$  intensity can be carried out in two basic ways:

- reduction of  $\text{NO}_x$  formation (abatement) along the fuel—mixing and firing—combustion—heat extraction—flue gas treatment chain; or
- reduction of energy losses and efficiency improvements along the fuel—mixing and firing—combustion—heat extraction—power generation chain. This kind of operation is mainly driven by policies aiming at energy and resource conservation as well as greenhouse gas mitigation and climate-related and biofuels initiatives.

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<sup>4</sup> Heat is always extracted from a combustion unit, whereas power extraction is optional and can substantially increase total efficiency.

### ***NO<sub>x</sub>-reducing technologies and strategies***

NO<sub>x</sub> emissions are formed through three main mechanisms: fuel, thermal, and prompt NO<sub>x</sub> formation. *Fuel* NO<sub>x</sub> arises from the oxidation of nitrogen bound in fuels, particularly biomass or coal. *Thermal* and *prompt* NO<sub>x</sub> are formed through reaction of nitrogen and oxygen present in the combustion air (around 78 percent of air volume consists of nitrogen, N<sub>2</sub>, and 21 percent is oxygen, O<sub>2</sub>). Because the relationship between combustion parameters and NO<sub>x</sub> formation is highly nonlinear and complex, there is less potential for straightforward mitigation strategies compared with, for example, sulfur dioxide, since all the sulfur comes from the fuel. Moreover, direct real-time measurement of NO<sub>x</sub> emissions at the plant are very important because simple rules of thumb are not useful, and not even the plant engineers themselves know the emissions unless they are continuously monitored. We can distinguish three types of abatement: precombustion, combustion, and secondary, or flue gas, treatment.

Precombustion strategies seek to inhibit NO<sub>x</sub> formation mechanisms by controlling the type of combustion inputs: the fuel and the oxidizing agent. Avoiding the use of high-nitrogen-content fuel can substantially reduce NO<sub>x</sub> formation (fuel NO<sub>x</sub>), whereas using oxygen instead of air inhibits thermal and prompt NO<sub>x</sub> formation.<sup>5</sup> Coal is typically the dirtiest fuel from an atmospheric pollution perspective. Substituting cleaner oil or gas can effectively reduce emissions. Fuel switches are common in modern energy systems but not mainly driven by NO<sub>x</sub> reduction purposes. Other considerations, such as reduced operating costs or greenhouse gas mitigation, are often more important and tend to take precedence over NO<sub>x</sub> reduction.

Combustion measures seek to inhibit the formation of thermal and prompt NO<sub>x</sub>. Strategies typically involve the optimal control of combustion parameters (temperature, pressure, stoichiometry, flame stability and homogeneity, and flue gas residence time) for minimal NO<sub>x</sub> formation. These kinds of “trimming” measures usually involve the most creative approaches because the complexities of the mechanisms call for tailored solutions. The strategies can employ a wide range of technologies, relying on hardware (installation of new equipment or modification of existing equipment) as well as soft-“orgware” (optimal use of existing equipment, involving only knowledge, know-how, and the modification of organizational structures). Fine tuning of operational conditions has turned out to be a significant means of abatement, and thus potentially it could be important to consider the introduction of incentives for operator improvements.

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<sup>5</sup> When pure oxygen is used as oxidizing agent, N is removed from the air. Therefore, neither thermal nor prompt NO<sub>x</sub> can be formed. It remains, however, fairly costly and is rarely done.

Flue gas treatment measures aim at cleaning up the  $\text{NO}_x$  once they have been formed, usually through conversion to benign chemical species. Two main flue gas treatment technologies are in use today: selective catalytic reduction (SCR) and selective noncatalytic reduction (SNCR):

- SCR uses ammonia ( $\text{NH}_3$ ), urea or isocyanuric acid to reduce  $\text{NO}_x$  into water and molecular nitrogen ( $\text{N}_2$ ) on catalytic beds at temperatures ranging from  $150^\circ$  to  $600^\circ\text{C}$ .<sup>6</sup> This type of installation is rather large and costly but achieves highly efficient reduction. The technology was used as early as the late 1970s in Japan and was introduced to Europe in 1985 (Forzatti 2001). More advanced SCR technologies have been applied to combined removal of  $\text{NO}_x$  and  $\text{SO}_x$ , and of  $\text{NO}_x$  and  $\text{CO}$ .
- SNCR uses ammonia or urea to reduce  $\text{NO}_x$  at a high temperature. This implies lower costs than SCR, since there is no need to cool the gases or use a catalyst. SNCR is, however, restricted to a temperature window (commonly  $900^\circ$ – $1,150^\circ\text{C}$ ) for optimal efficiency, and ammonia slip is a problem.<sup>7</sup> It is less costly than SCR in both capital and operating costs but achieves lower performance.

One striking feature associated with  $\text{NO}_x$  reduction technology is the extent of the possibilities and the consequent complex choice arising from the multiple options. Indeed, a wide array of  $\text{NO}_x$ -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 been decided to invest in  $\text{NO}_x$ -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). In addition to standard goals, such as profit maximization,

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<sup>6</sup> The temperature depends on the type of catalyst in use.

<sup>7</sup> Ammonia slip refers to the emission of ammonia, either gaseous or aqueous. There is a constant trade-off between the quantity of ammonia to be injected, driving the efficiency of  $\text{NO}_x$  abatement, and acceptable ammonia emission levels.

firms must also consider obligations to satisfy annual and peak demand, and many firms have additional concerns about their public image.

In many applications, NO<sub>x</sub> emissions reduction appears to be at cross-purposes with reductions in other pollutants (particularly CO, NH<sub>3</sub>, and N<sub>2</sub>O) and with increases in thermal efficiency.

#### 4. The refunded emission payment, or REP

In 1985, the Swedish Parliament set a goal to reduce national emissions of NO<sub>x</sub> by 30 percent of 1980 levels by 1995. Specific policy initiatives followed. The Swedish NO<sub>x</sub> Refunded Emission Payments (REP) scheme was launched in 1992 to “achieve a more rapid reduction of nitrogen oxides than was otherwise considered possible” and to provide incentives for cost-effective reduction from large plants using combustion to generate energy<sup>8</sup> (SEPA 2000).

Utilities affected by the new legislation were combustion plants producing at least 50 GWh of useful energy per boiler and per year, which was later lowered to 40 GWh in 1996 and 25 GWh in 1997. This sequential inclusion of participants has been justified by diminishing monitoring<sup>9</sup> costs (Höglund Isaksson 2005). Participants in the REP scheme come from seven sectors: heat and power, pulp and paper, metal, waste, food, wood, and chemicals. Combustion units can be boilers, stationary engines, or gas turbines.

Companies basically pay a charge based on their yearly NO<sub>x</sub> emissions.<sup>10</sup> After subtraction of administrative costs, revenues are refunded to the participating plants according to the amount of their production of useful energy.<sup>11</sup> In practice, payment and refund operations are performed simultaneously, thereby avoiding unnecessary overhead. Monitoring equipment is at the expense of plant operators and must be in compliance with the standards of the Swedish Environmental Protection Agency (SEPA). In the absence of monitoring equipment, emissions

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<sup>8</sup> Energy production refers to both heat and electricity production.

<sup>9</sup> Monitoring equipment refers to equipment to measure NO<sub>x</sub> emissions. This equipment is quite expensive and in 1992 was considered an unreasonable expense for smaller plants. After some years, however, innovation in this industry brought down the cost of monitoring, making it feasible to include medium-sized and smaller units.

<sup>10</sup> The charge is SEK 40 (roughly 4€) per kg of NO<sub>x</sub>, calculated as the sum of NO and NO<sub>2</sub>, converted into NO<sub>2</sub> equivalent. However, it has been suggested by an expert group commissioned by the Swedish government that this rate be increased to SEK 50 per kg of NO<sub>x</sub> (Naturvårdsverket 2005).

<sup>11</sup> See SEPA (2000, Appendix C) for an example of individual plant calculation of the net payment.

are calculated on emission factors that are deliberately set high to encourage operators to undertake real measurements.<sup>12</sup>

The REP mechanism rewards the combustion units that reduce their emission intensities to lower-than-average levels. For units with average emission intensity, the charge and refund will be equal, and hence there is no net payment. The units with the lowest emission intensities (emissions per useful energy produced) become net beneficiaries of the system, whereas those with higher-than-average emission intensities make a net payment (and even for them, the net payment is smaller than it would have been if the charge had been a tax of equal magnitude).

The innovative design of the REP presents many advantages over traditional instruments; see Sternier and Höglund Isaksson (2005). One benefit of combining a tax with a refund is its political economy. Although the abatement incentives are the same as for a tax of the same value, polluters are less averse to the REP scheme, and thus potential resistance is defused and lobbying from the polluters is reduced. Refunded emission payments are politically easier to implement at a sufficiently high charge level to yield significant abatement effects; see also Fredriksson and Sternier (2005). Other policies, such as the U.S. NO<sub>x</sub> trading schemes and the French tax on NO<sub>x</sub> emissions from industrial activities,<sup>13</sup> all imply much lower marginal abatement costs.

Since the monetary flows from the pool of polluters are redistributed within the same system, the REP causes very little competitive loss for the targeted group as a whole. This is an important feature for a policymaker wanting to implement a policy in one small, open economy. It also makes it possible to target subsets of firms—such as, in this case, all the plants big enough to bear the cost of continuous monitoring.

It is worth noting that the REP has no output effect: the scarcity rent represented by a tax is not incorporated into final product prices, and there is no effect through reduced consumption of final products that embody emissions. There is also no revenue recycling effect. However, as Gersbach and Requate (2004) show, refunding emission taxes may imply a harmful output effect under perfect competition. REPs can nevertheless be first-best instruments under imperfect

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<sup>12</sup> Predefined levels of emissions are 250 mg/MJ for boilers and 600 mg/MJ for gas turbines.

<sup>13</sup> This was the *taxe parafiscale sur la pollution atmosphérique (TPPA)* until 1999, when it was replaced by the *taxe générale sur les activités polluantes (TGAP) sur les substances émises dans l'atmosphère*. The tax rates were, respectively, 27 and 51 €/ton NO<sub>x</sub>, compared with an approximate 4300 €/ton NO<sub>x</sub> charge within the REP scheme (exchange rate 9.3 SEK/€).

competition when the output effect is undesirable, since restricted competition leads to unoptimally low output anyway.

The REP is difficult to evaluate because it is not the only instrument applied to these sectors and their NO<sub>x</sub> (or other) emissions. There are sectoral policies for heating, energy, waste treatment, and other industrial sectors. There are combustion standards, and there are local permitting processes. And there are management practices required by various labeling or certification schemes. Many of these instruments interact, complicating things further. Local or regional authorities will not set standards or permits below what firms would be doing anyway in response to the REP. It is thus quite likely that the permits would not have been so tough if there had not been an REP scheme that provided strong economic incentives for abatement. Since it is virtually impossible to disentangle the effects of the various instruments, our approach here is to study the innovation and spread of technology caused by the joint effect of all the policy instruments.

## 5. The development of NO<sub>x</sub> abatement technology in Sweden

### *The evolution of NO<sub>x</sub> emissions*

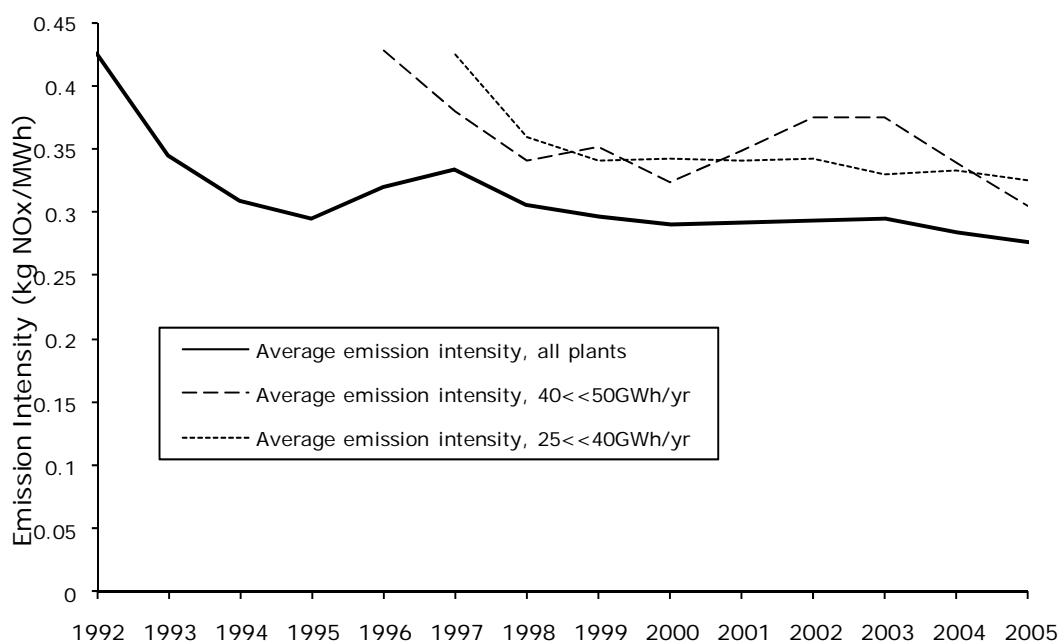
Total NO<sub>x</sub> emissions from the units targeted by the REP have barely fallen over the period 1992–2005. Considering, however, that total output of useful energy from participating plants has increased by more than 70 percent over the same period,<sup>14</sup> the reduction in NO<sub>x</sub> emission intensity is significant.<sup>15</sup>

Improvements in emission rates can be seen as result of technology development, spread, and adoption. Emission rates depend on the combustion host structure (type of stationary combustion equipment), fuel fired, abatement technology (ranging from combustion measures to flue gas treatment), and operational conditions (where learning by doing can be substantial).

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<sup>14</sup> In 1992, total energy reported was about 37 TWh, whereas it has been above 60 TWh since 2002 (around 65 TWh in 2005).

<sup>15</sup> This decoupling effect was, in reality, even stronger: the discussions with industry started in the late 1980s, and some companies had already improved their processes considerably by 1992.

**Figure 2. The development of emission coefficients over time**

Over the period of analysis, the average emission rate has been nearly cut in half, from more than 0.4 to about 0.25 kg NO<sub>x</sub>/MWh (Figure 2), indicating that on average, combustion units included in the REP scheme have improved their performance. This reduction has been achieved despite the enlargement of the scheme in 1996 and 1997. The new units were smaller and initially had emission coefficients that were higher than the larger plants for the same year, but comparable to those of the larger plants before they were forced into the REP. The smaller units have also decreased their emission intensities (although not as far as the bigger units).

The rate at which emission intensities have declined is not constant over the analyzed period. For each set of plants, reductions in emission intensity were rapid (up to 30 percent) during the first three to four years but then slowed. There could be various explanations for these patterns. Maybe the easiest “low-hanging” abatement is picked first. Maybe it simply takes a long time before the capital stock in certain plants is ripe for refurbishing. In any case, this trend could be seen as an indication that further reductions would require raising the charge, as indicated by industry officials (Johansson 2006) and also a SEPA study (Natuvårdsverket 2005). The charge level may be raised after 2008, depending on various legislative and administrative processes. Issues of interpretation are critical for the decision: what are the ultimate causes of the technological development observed, and what can be expected in the future?

### ***Variability and distribution of emission coefficients***

A first step in better understanding the average emission figures above is to look at the distribution of emission coefficients at the micro level (Figure 3). Emission coefficients appear to have become more homogeneous over time. The standard deviation of individual emission intensities has decreased from 0.23 to 0.16.

**Figure 3. Distribution of plant emission coefficients, 1992, 1997, and 2005.**  
Horizontal axis: Emission intensities in kg NO<sub>x</sub>/MWh.

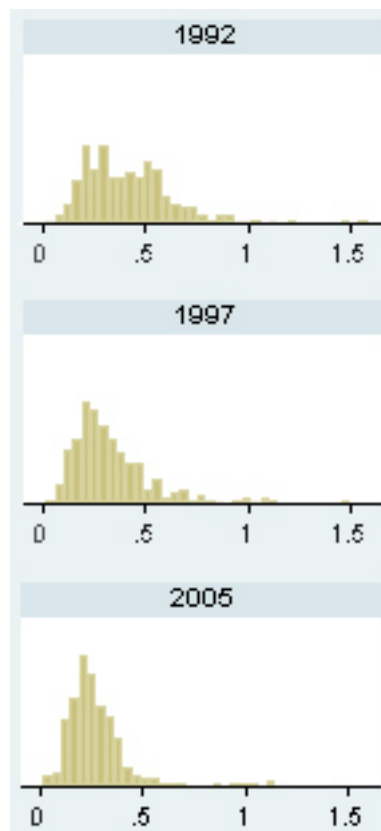


Figure 3 shows a clear tendency toward lower emission intensities but also a historical process of homogenization at the firm level. Between 1992 and 1993, there was a noteworthy shift from a bimodal distribution (centered on 0.3 and 0.5 kg NO<sub>x</sub>/MWh) to a unimodal with enhanced performance (centered on 0.3 kg NO<sub>x</sub>/MWh), indicating a direct effect of the policy instrument in driving the system toward increased performance. A large majority of the units within the system are progressively shifting toward a narrowing emission intensity window



(narrowing to the left), representative of a general homogenization trend. This is the result of technology spread or adoption.

Both the best and the worst performance levels have improved, but the worst has improved faster, thus reducing the range. The behavior at the limits provides interesting information. Improvements at the lower limit can be interpreted as innovation: the development of “best practice.” At the other end, the evolution of the upper limit provides an indication of the worst performance. This illustrates the temporary limits to technological diffusion.

### ***Patterns of change in NOx emission rates***

We are particularly interested in studying the speed and characteristics of the best available technology, since this is a reflection of innovation. Furthermore, we are interested in understanding the spread or adoption of technology, which is reflected by how fast the average or laggard plants catch up with those at the frontier. To gain explanatory insight into the rate and direction of technological change and diffusion, the emissions data have been constrained to a simple descriptive model to correspond as closely as possible to the model in Figure 1. For each year, polluting units have been sorted by increasing emission intensity. Cumulative output is then depicted as a function of the ordered sequences of observed (emission rate) values. The outcome consists of yearly monotonous (increasing) step functions in the figure below.

**Figure 4. Cumulative histograms showing emission intensities for various years**

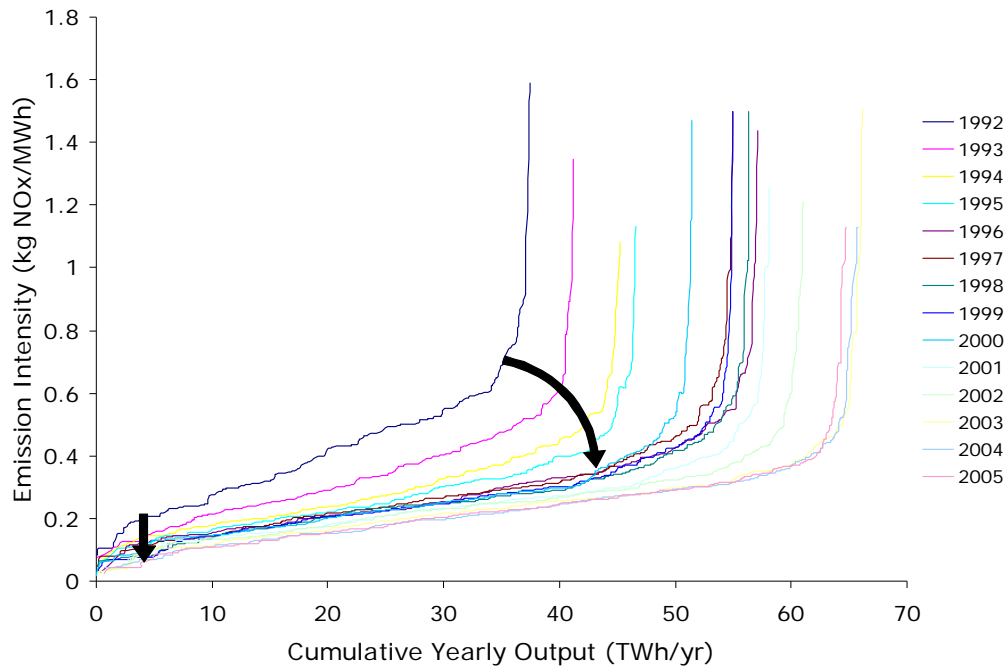


Figure 4 illustrates that our data fit rather well into three categories that correspond to our theoretical assumptions. There are some units at the frontier, and the frontier is moving in a more or less smooth and continuous manner to lower levels (vertical arrow). The vast majority of plants evidence a gradual process of technological diffusion or adoption, which leads to a “catching up” in terms of emission coefficients. This is shown by the decreasing slope (curved arrow). Finally, a small number of firms have very high emission values (but accounting for only 2 to 3 percent of output) for various reasons (including technical mishaps).

The laggards correspond to the vertical segments in Figure 4. They are vertical because they are a small number of units accounting for an insignificant amount of output but with very high emission factors. Leaving these out, the data for each year can be described by a linear model with an intercept and a slope. The advantage of this approach is that in principle the intercept corresponds to best practice for that year. The change in the intercepts thus gives us a perspective on the rate of innovation, while the change in slope between the years gives us an impression of the spread in technology from best practice to the rest of the firms.

To get some simple numerical estimates of the size of technological innovation and adoption, we have estimated the yearly curves in Figure 4 by linear regression.<sup>16</sup> Thus, for each year  $t$ , we estimate  $a_t$  and  $b_t$  in the regression  $e_{it} = a_t + b_t \sum q_t$  where  $\sum q_t$  is cumulative output for the firms ordered by increasing emission rates.

**Figure 5. Linearized emission coefficients**

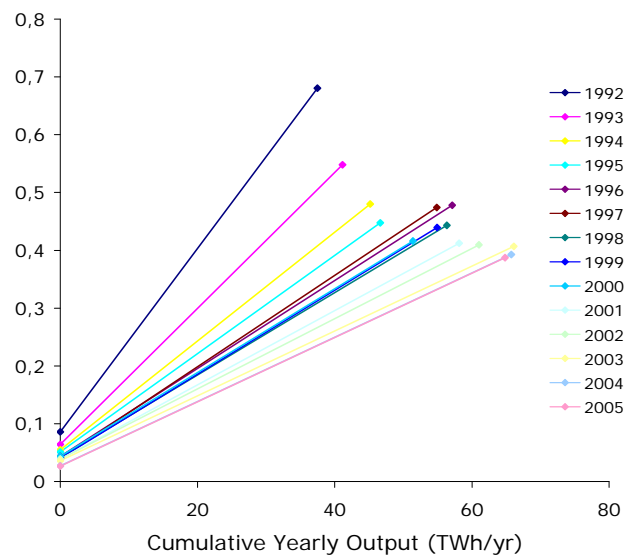
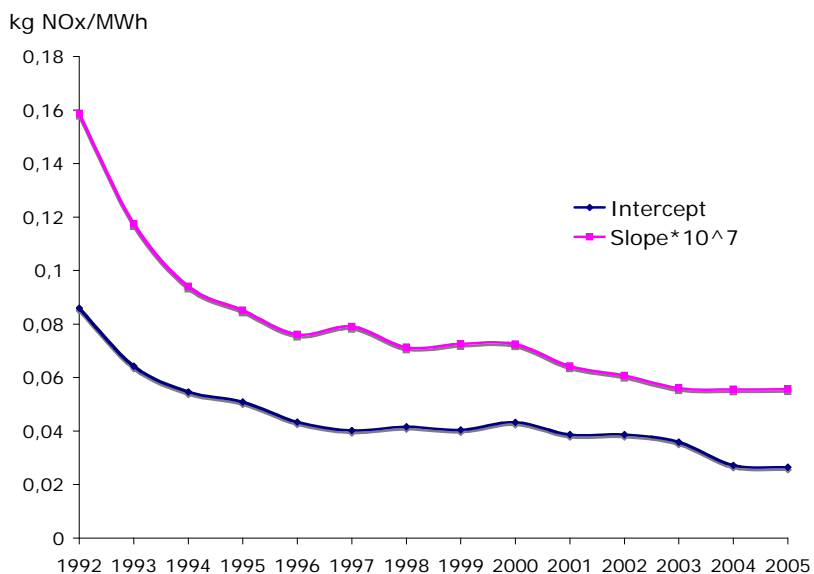


Figure 5 is thus a linearized and simplified version of Figure 4, an empirical counterpart to Figure 1. We observe a significant decrease in both intercept  $a_t$  and slope  $b_t$  over time. Figure 6 shows the development over time of the intercepts and slopes in Figure 5.

<sup>16</sup> We wanted to avoid the outliers with very high values in Figure 4. These include units that had technical mishaps, reserve units, and units that are being phased in or out of production. The number of such observations varies from year to year. For convenience, we simply work with the first 90 percent of cumulative output.

**Figure 6. The development of innovation and diffusion parameters**

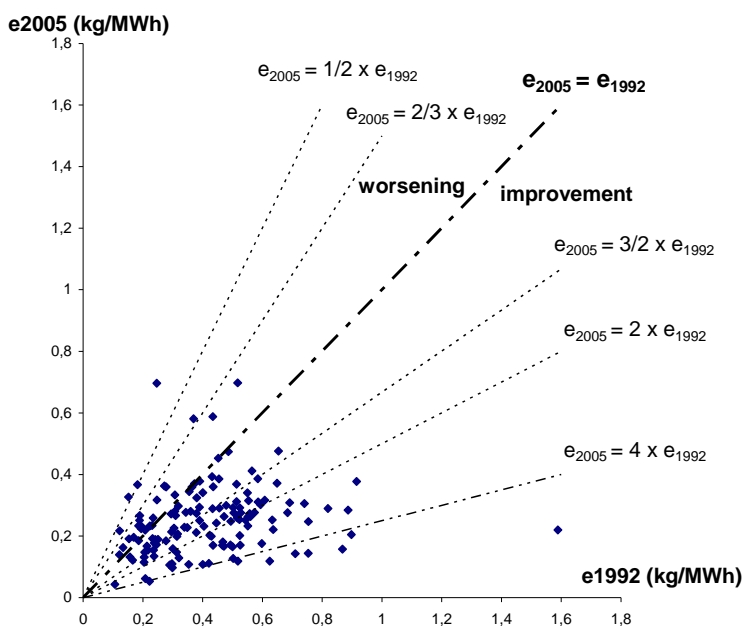
The figures show progress that happens to be numerically of roughly the same order. The intercept has been cut by about 70 percent, reflecting a rapid progress in innovation at the frontier. Similarly, the slope—reflecting adoption or spread of technology—has also been cut although by a somewhat larger amount, about 60 percent. Performances have thus tended to homogenize toward a lower level of emissions over time, at a relatively high rate (from nearly 0.09 kg NO<sub>x</sub>/MWh<sup>2</sup> to 0.03 kg NO<sub>x</sub>/MWh<sup>2</sup>). The units are thus converging quite fast toward a best practice that is also improving over time. Notice that in both cases, most of the progress takes place in the first five years. The fact that not only innovation but more importantly diffusion appear to slow down in this way could perhaps be carefully interpreted as implying that the current level of the fee will not produce very significant reductions in the future.

### ***The performance of individual production units***

Since we have ordered the individual units before plotting the system performances, it is not possible to visualize the evolution of individual units over time: the order is not conserved. However, we are naturally curious about whether it is typically the same firms that improve their performance or whether emission coefficients vary strongly year by year. Figure 7 plots the emission rate of 2005 against the emission rate of 1992 for a set of 139 units that were in operation in both 1992 and 2005. The units situated below (to the right of) the 45-degree line

( $e_{2005}=e_{1992}$ ) have lowered their emission coefficients. As expected, a majority (more than 80 percent) are in this category; only a few units have significantly worsened their emission coefficients.

**Figure 7. Individual emission rates of 2005 relative to emission rates of 1992**



**Table 1. Emission coefficients, 1992 and 2005**

Improvement factors						
<0.5	0.5 to 2/3	2/3 to 1	1 to 3/2	3/2 to 2	2 to 4	>4
2.2%	1.4%	14.4%	25.9%	22.3%	28.1%	5.8%

Almost half the units are in the category that improved but reduced their emission factors by less than 50 percent. Another third of the firms cut their emission factors by more than 50 percent. A small number, 6 percent, cut them by more than 75 percent. Units with such considerable improvements all made major investments in abatement technology and/or shifted from dirty to cleaner fuels. It is also noteworthy that every single unit with really high emission rates in 1992 ( $>0.6$  kg  $NO_x$ /MWh) improved its performance.

For most of the 18 percent of firms that experienced an increase in their emission factors, the increase was small; only for 2.2 percent of the firms did the increase exceed 50 percent. We looked carefully at these units and found that they belonged to firms that had made major fuel switches, generally driven by economic factors other than the NO<sub>x</sub> fee. 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, such as nitrogen oxides. In some cases, waste such as bark and other byproducts may be plentiful and their use as fuel is promoted by other policy initiatives.

Larger combustion units have, on average, reduced their emission rates more than smaller units. This 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.<sup>17</sup> Additionally, technology absorption and the acquisition of competence largely depend on access to information, financing, and the degree of involvement in R&D and innovation activities, which all seem to depend on the size of firms.

## 6. Explanatory factors

According to Höglund Isaksson (2005), extensive reductions have been performed at very low, even zero or negative costs, at least as in terms of capital costs. Generally, those improvements are the results of “trimming” activities that seek to optimize combustion parameters. Many involve little or no cost for new equipment and thus the expense is often said to be low even though they may require considerable time and effort by the firms’ engineers and management. We examined the technical solutions at different plants and interviewed both the production firms and the technology suppliers, using a case study approach.<sup>18</sup>

### ***General determinants of emission factors***

Changes in emission intensities can be attributed to structural determinants on the one hand (increased efficiencies, fuel switches, and the progressive shift toward second-generation

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<sup>17</sup> Some technologies are not even commercially available below certain size thresholds.

<sup>18</sup> For more technical details, see Turnheim (2007).

machinery), and NO<sub>x</sub>-specific abatement strategies on the other. The general trend toward increased energy efficiency and heat loss reductions leads by pure arithmetic to reduced emission rates by raising output per input ratio, but the intensification of combustion to achieve more energy output (and reduce carbon emissions) necessarily implies an increase in temperature that leads to strongly increased NO<sub>x</sub> formation potential. Fuel switching toward cleaner fuels (from coal to oil to gas) as well as the growing use of biomass also affect NO<sub>x</sub> emissions. Although substitution of clean fuels has a positive impact on emissions, the increase of biomass use in Sweden could increase NO<sub>x</sub> formation, for two reasons: biomass fuel may contain more nitrogen, leading to fuel NO<sub>x</sub>, and in some cases, the biomass fuel may be poor-quality residues that are contaminated, wet, or not homogeneous, complicating the combustion conditions for optimal NO<sub>x</sub> control. The progressive renewal of the capital infrastructure and consequent modernization are not always driven by concern for NO<sub>x</sub> reduction but usually has other goals; still, they can have a positive impact on NO<sub>x</sub> emission rates.

Finally, investments in NO<sub>x</sub>-specific abatement technology can, of course, substantially reduce emissions. Combustion plant operators as well as machinery suppliers have identified three main drivers to NO<sub>x</sub>-specific abatement investments: maximum allowable emission levels, the REP scheme and the resulting economic incentives, and the implementation of environmental management and strategy.<sup>19</sup> It is not clear which is most important, but in this paper we are interested in the joint effect of all drivers on the evolution of technology.

### ***R&D: The development of new technology***

The machinery supply industry has been actively involved in research and development activities, and the REP and consequent creation of a responsive market for cost-effective NO<sub>x</sub> reduction technology has affected their activity, namely structuring their efforts in research. Invention and innovation processes have greatly relied on the mobilization of knowledge and competence, involving other agents such as universities and research institutes. Improvements in existing technology have increased the number of potential adopters. Progressive integration of advanced technology has been possible for a larger range of host combustion structure types and sizes, through product development focused on diversification and down-scaling of demonstration plants. The story of the development of selective noncatalytic reduction

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<sup>19</sup> Åmand (2006), Ådahl and Lilienberg (2006), Gustafson and Alm (2007), Gustavsson (2006), Johansson and Sirviö (2006), Lundberg (2006).

technology at Kvaerner Power is a good example of how responsive technology suppliers can be to the needs of the production firms.<sup>20</sup>

During the 1992–2005 period, Sweden has thus become a testing ground and hothouse for new NO<sub>x</sub>-lean technologies. At the same time, this technological progress is no surprise, given that most of the abatement technologies that have been adopted were in principle available for a range of combustion systems from the start, waiting to be adopted. No major invention has appeared; rather, incremental innovations have spread throughout a growing number of combustion units. A very important factor appears to have been the learning by doing made possible by the very advanced monitoring required for the payments in the REP. This monitoring gives the plant engineers direct real-time data concerning emissions that they typically did not have earlier—data that appear to be crucial. Since NO<sub>x</sub> emissions cannot be reliably calculated (unlike, for instance, SO<sub>x</sub> emissions, which are a simple function of sulfur content in the fuel minus sulfur captured in filters), plant engineers did not previously have the necessary information to minimize emissions, and—NO<sub>x</sub> formation being such a complex process—this fine tuning turns out to be very important.

We also have to explain the rapid improvements that tended to level off after the first few years. The most reasonable explanation probably lies in the initial existence of optimization potential (fine tuning of processes with the additional constraint of reducing NO<sub>x</sub> emissions) exploited at the early stages of the program, such as trimming and other “low-hanging” fruits.

### ***Diffusion of NO<sub>x</sub>-specific abatement technology***

Investments in NO<sub>x</sub> abatement technologies have grown steadily since the beginning of the REP scheme. Emission coefficients have been falling faster for the average plants than for those already following “best practice.” Thus the catching up effect is very prominent except for a very small minority of firms at the tail end (whose high emissions probably indicate special conditions). The main reported technologies have been selective noncatalytic reduction, flue gas recirculation, trimming measures and low-NO<sub>x</sub> burners. There is, however, no clear preference between primary combustion measures and flue gas treatment. Requirements for monitoring equipment have greatly contributed to the identification of trimming opportunities that can increase individual performance at very low cost. Mandatory measuring equipment has increased

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<sup>20</sup> For a full account of the development of SNCR technology at Kvaerner Power, see Turnheim (2007, Box 1, 64).



firms' interest in abatement and provided a necessary tool for the optimization of processes in search for cost efficiencies.

The technologies involved present indivisibilities that can give advantages to larger firms. Internal factors such as access to information and involvement in strategic competence building, positioning toward risks and uncertainties, and the lifetime of capital infrastructure greatly influence firm behavior and technology absorption capacity, explaining interfirm heterogeneities. Additionally, structural trends and barriers affect individual innovation processes. Lasting physical assets (especially the lifetime of combustion machinery) limit investments in new technology. Indivisibilities translate into weaker technico-commercial opportunities for smaller plants.

In brief, many different abatement technology options have diffused at a steady pace since the introduction of the REP scheme. Critical determinants of this diffusion include size, access to information and competence, risk aversion, and the timing of investments to the general business needs of the enterprise.

## 7. Conclusion

NO<sub>x</sub> emissions from large stationary sources in Sweden have been regulated by a set of strict policies, including refunded emission payments that impose a very high marginal cost on emissions. Thanks to these policies, considerable progress has been made in lowering emission coefficients. This paper has looked into the black box commonly called technical progress to trace the origins and modalities of this improvement, and we have studied how much of it was due to innovation (improvement for best practice) and how much to the spread and adoption of technology. We find that both processes have had a very substantial role: not only have the best plants made rapid progress in emission reductions, but there has also been considerable catching up, such that today the majority of plants have lowered their emission intensities much more than the best plants. In addition to major investments in new technology and specific abatement technologies, learning by doing and interactions with other environmental and social goals have played important parts. Although the policy to promote NO<sub>x</sub> reductions is very strong, other forces at play may be even stronger—primarily the search for new, cheaper fuels that address global climate concerns and the related desire for fuel flexibility and thermal efficiency. The fact that NO<sub>x</sub> reduction has been so successful despite these other concerns is a tribute to the strength of this policy. Since the policy was explicitly designed to affect technology, it must be considered an achievement that it has had such an effect on various aspects of technology,

including innovation, R&D, diffusion of technology, adoption, and learning by doing in the form of fine tuning new equipment.

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