CHALMERS

Environmental Policy and Technological Change
A Case Study of the Swedish Charge for NOx Emission Reduction from Combustion Plants

Thesis for the Degree of Master of Science in Industrial Ecology

BRUNO TURNHEIM

Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

The Swedish NOx Refunded Emission Payments (REP) is an innovative environmental policy scheme introduced in 1992 with the aim of driving the stationary combustion system towards lower NOx emissions levels in a cost-effective fashion. A charge is paid by polluters on the basis of their NOx emissions, and refunded on the basis of the production of useful energy[1], introducing an economic incentive for lower-than-average emission rates. This study examines the links between environmental policy and technological change in this particular case, exploring the extent to which the scheme has fostered technology development in terms of creation, diffusion, and adoption of new technology. Particular attention is paid on the elaboration of a framework and on the use of a methodology recognizing the complexity of the dynamics at play, their intertwined nature, and allowing for the exploration of multiple research angles.

Since the introduction of the charge, NOx emissions have been decoupled from energy use, although total emissions have remained the same. NOx-specific abatement technology, along with other structural determinants (such as increased efficiencies, fuel switches and a progressive renewal of old combustion structures) is responsible for the observed changes in emission rates. Abatement investments have been driven jointly by the REP, regulations on maximum allowable emissions, and individual environmental management practices. A wide range of abatement options is available. Options involving very low costs seem to have been largely implemented within the first years, partially explaining a further levelling-off of performance improvements. Other technological options continue to diffuse at sustained rates. Barriers to this diffusion are size, heterogeneous access to competence and information, and the dependency of investments on long-term investment cycles. The supply side seems to have responded to a growing demand for NOx-reducing technology through the creation of new technology and product developments towards a larger integration of high-performance options for different host structures and sizes. This has in turn given suppliers competitive advantages on the international market.

[1] In practice, a single net transfer is performed, avoiding unnecessary mobilisation of monetary resources.

CAVEAT LECTOR

Please beware that the present report draft has been written before reviewing and commenting process. Therefore, results presented here are preliminary and incomplete by nature. Please also note that some of the material used for this study is courtesy of the Swedish Environmental Protection Agency and has been handed out under strict confidentiality clause. Before final reviewing, results presented here may therefore be confidential and cannot be used, communicated or published for any other purpose.

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LIST OF ACRONYMS

Acronym	Meaning
BAT	Best Available Technology
BFB	Bubbling Fluidized Bed
BOOS	Burners-Out-Of-Service
CC	Catalytic Combustion
CFB	Circulating Fluidized Bed
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CP	Cleaner Production
DOE	Department of Energy
EC	European Commission
ECE	Economic Commission for Europé
EE	Environmental Economics
EI	Emission Intensity
EOP	End-Of-Pipe
EPA	Environmental Protection Agency
ESA	Environmental Systems Analysis
EU	European Union
FBC	Fluidized Bed Combustors
FGR	Flue Gas Recirculation
GDP	Gross Domestic Product
GWh	GigaWatt hour
HOB	Heat-only Boiler
IE	Industrial Ecology
IIASA	International Institute for Applied System Analysis
LCP	Large Combustion Plant
LNB	Low Nox Burner
MBI	Market-Based Instrument
Mwe	MegaWatt electrical
MWh	MegaWatt hour
NOx	Nitrogen Oxides
OFA	Overfire Air
R&D	Research and Development
REP	Refunded Emission Payments
RES	Renewable Energy Sources
RIDE	R&D, Innovations and Dynamics of Economies
SCR	Selective Catalytic Reduction
SEPA	Swedish Environmental Protection Agency (Naturvårdsverket)
SI	Steam Injection
SNCR	Selective Non-Catalytic Reduction
SOx	Sulphur Oxides
UE	Useful Energy
ULNB	Ultra Low Nox Burner
UN	United Nations
UNECE	United Nations Economic Commission for Europe
US EPA	United States Environmental Protection Agency
WI	Water Injection

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1 INTRODUCTION

Nitrogen Oxides[2] (NOx) are an important threat to the local environment. Their main environmental impacts include acidification, eutrophication and the formation of tropospheric ozone. Transportation systems and industrial combustion systems are the main anthropogenic sources of NOx emissions. Large stationary combustion systems are substantial concentrated sources of NOx emissions. They constitute ideal targets for emission reduction initiatives. One such initiative was implemented in Sweden in 1992 as a response to national and European targets: the NOx Refunded Emission Payments (REP).

The Swedish REP scheme on Nitrogen Oxides (NOx) was introduced with the aim of driving the stationary combustion system towards lower NOx emissions levels in a cost-effective fashion, through the creation of an economic incentive rewarding those combustion units with the lowest emission intensity. This unique policy scheme has been seen as fairly successful and has received international attention, since emissions intensities have been reduced by 46 percent since 1992. Most of the previous studies focusing on this scheme have been performed from a policy evaluation or an Environmental Economics perspective (Entec, 2005; Höglund Isaksson, 2005; SEPA, 2000; Sterner, 2003; Sterner and Höglund Isaksson, 2006). According to Hemmelskamp (2000), this observation stands for the bulk of studies evaluating the links between environmental policy and technology development. Additionally, there is an expressed need for detailed case studies covering the relationships between environmental policy and technology development (OECD, 2005). This study has been driven by a will to overcome these limitations.

Throughout this study, it is attempted to integrate an evolutionary approach to technological development, drawing from a systems analysis perspective. An in-depth analysis of the links between environmental policy and technological change reveal multiple levels of complexity. They are here explored based on a multi-disciplinary framework and multiple sources of information. The results from this approach are the

[2] See section 3 on NOx formation mechanisms for the identification and discussion of a definition problem.

exploration of components, relationships and dynamics at different levels of detail,[3] the identification of a set of complementary drivers for technology adoption, as well as factors and barriers affecting the process of technology diffusion. The role played by the supply side in the creation of suitable technology is also empirically explored.

1.1 Goal

According to Johnson (2005), the REP is a "technology-forcing incentive". The purpose is here to analyze how and the extent to which this policy scheme has stimulated the creation, diffusion and adoption of new control technology in this particular case. Secondary questions to be treated include:

- What characterizes NOx emissions evolution over the analyzed period in Sweden under the REP?
- What are the main determinants of the changes in emission intensity?
- How has NOx-specific abatement technology diffused? What are the critical determinants of its diffusion?
- To what extent has the REP fostered the development of new technology?

1.2 Scope

This study focuses on a case study in order to identify relationships between environmental policy and technological change. It is not intended to develop new theories but consists of an attempt to demonstrate the intertwined nature of dynamics in this kind of system on a practical basis, drawing from established theories and empirical evidence. Emphasis is put on the necessity for a holistic and interdisciplinary approach, combined with the complementary use of multiple tools. This study does not contain an extensive technology or economic review of the system of analysis and has not been written to serve as a technical reference document. Rather, it is intended to provide the reader with key elements of background information necessary to explore the connections between environmental policy and technological change in this particular case.

Methodology and information sources used here include extensive literature review, the analysis of national reporting data, and the conducting of field interviews to gather

[3] And possible bridges and correspondences between results at different levels of detail.

empirical data among selected stakeholders of the system.

1.3 Structure and organization of paper

In section 2, a discussion of the framework and methodology used throughout this study is discussed, with particular emphasis on complexity and the consequent need for drawing from multiple knowledge fields and using multiple analysis tools. In sections 3, 4 and 5, background information on NOx formation mechanisms and environmental consequences, NOx policy for stationary combustion sources in Sweden, and technology for NOx abatement are presented. Results from the analysis are presented throughout section 6, organized by the secondary research questions defined above. Finally, conclusions and implications from this case study are discussed in section 7, followed by the expression of needs for further research.

2 FRAMEWORK AND METHODOLOGY

The study of the relationships between environmental policy and technological change involves the necessary recognition of inter-dependencies and the inter-woven nature of networks and processes, thus the complexity of the mechanisms at stake. Throughout the analysis, a continuous coming-and-going between different levels of detail (meta, macro, “meso”, micro) is operated, structured by the will to answer pre-defined questions. Each scale change (comparable to close-ups and wider angles) reveals additional levels of complexity, sets of relationships that can then be fed back into the perception of the structure of greater scale (the “bigger picture”). It is additionally recognized that the observations are dependent on time perspectives (static, dynamic and the identification of evolutionary cycles), and on the component central to the analysis and its relationship to other components of the system. Spatial considerations are mostly excluded, for the spatial boundaries are well defined as being Sweden within this case study.[4] The journey throughout these various levels of analysis takes the form of a web, as the unravelling of the systems and mechanisms at stake grows with the exploration of many observer’s points at each level of detail.

2.1 Framework and general model for the analysis

The very subject and aim of this research imply a multidisciplinary approach. It is concerned with looking upon the technological changes and its relation with environmental policy, focusing on a pre-defined and documented policy case. An intuitive approach to this question could lead to considering political institutions as the locus for environmental policy and the industrial system as the locus for technological change (Figure 1). However, the complexity of technological change dynamics and the multiplicity of nested relationships are justified reasons to extend the system perspective beyond this binary relationship, considering many other external and contextual factors and drawing from a wide array of knowledge bases.

[4] Exceptions to this are consideration of comparisons with other national situations, and the consideration of local policies, which remain marginal throughout this work.

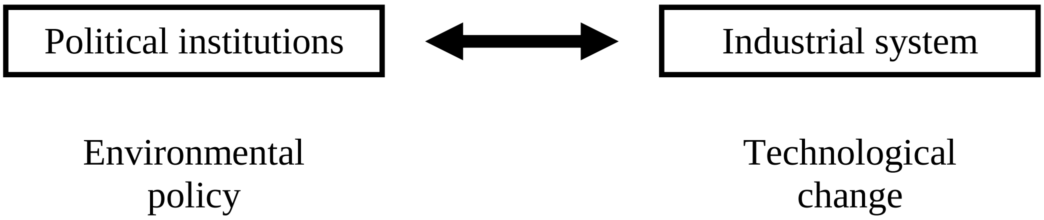

Figure 1: Environmental policy and technological change, a binary relationship

From here on, an attempt of broadening the focus of the analysis is made, with emphasis on a multidisciplinary approach, and useful supporting theories. This leads to the definition of a general model for the analysis that integrates actors and relationships neglected in Figure 1.

2.1.1 Complexity and disciplinary overlaps

Figure 2 exemplifies overlaps of traditional fields, which should be treated if one is to achieve a more holistic understanding of the situation - a deliberate ambition of system thinking. The main theoretical pillars are environmental policy analysis, industrial dynamics, and engineering knowledge and practice. Each of these pillars conventionally deals with specific questions and themes and theoretical studies have led to the elaboration of a range of field-specific key concepts.[5] It is here argued that the boundaries between the identified fields and their respective supporting theories, as provided by old structures of the division of labour, are loose.[6] In this perspective, every practitioner should be empowered with a degree of understanding of the neighbouring fields and theories, and their interaction. This is particularly the case for those who aim at grasping the complex dynamics linking environmental policy and technological change.

[5] Additionally, conventional users of these knowledge bases can usually be identified: economists and policymakers use environmental policy theories, firm managers and industrial economists are concerned with industrial dynamics, whereas engineers and scientists develop technical solutions within industrial processes.

[6] The mere existence of any kind of essential boundary is rejected by constructivist theory of the relationship between science and policy (Sundqvist, 2002).

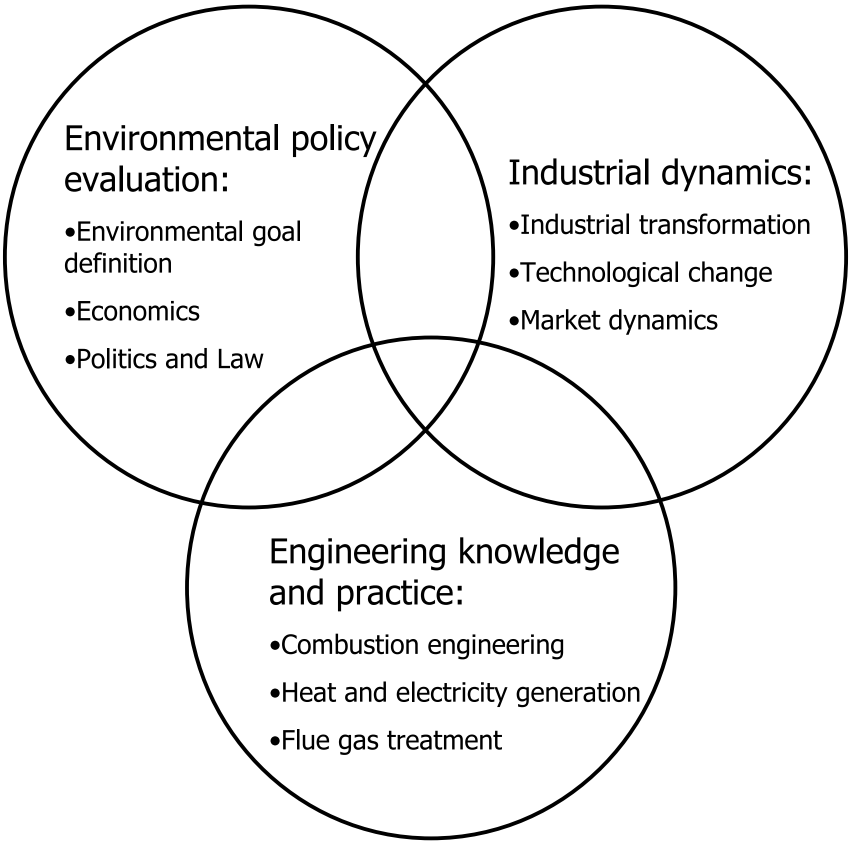

Figure 2: Field overlaps identified as relevant for this study

For practical reasons, however, it can be useful to deal with certain field-specific questions separately, but one should strive to integrate concerns arising from external forces that are traditionally neglected. The remainder of this section presents an exploration of some basic aspects of the various fields involved in this study, their relevance to the analyzed system and the necessary linkages to other fields.

2.1.2 Environmental policy

Environmental policy consists of the formulation of public environmental strategies to be enforced through the creation of laws and regulations to drive societal activities towards more sustainable standards and behaviours. When directed towards industry, the primary objective is to achieve a reasonable integration of environmental externalities by the productive sector. This field of studies has historically been the realm of political scientists and economists. Three categories of environmental policy instruments are traditionally distinguished: market-based instruments (MBIs), “command and control” instruments and informative instruments.[7]

Market-based instruments (MBIs),[8] such as taxes, subsidies or cap-and-trade systems for instance, are common tools for environmental policy. The primary purpose of MBIs is to lead the production system towards cleaner production, by forcing polluters to integrate environmental externalities[9] into their production costs through some form of pricing of it. Unlike regulations, that theoretically hold all firms to the same target,[10] market-based instruments have the advantage of leading a collective pool of polluters towards a social optimum, theoretically achieving reductions by those individuals that experience the lowest abatement cost first. In order to achieve a given socially optimum abatement level, one could either use a price-type instrument, or a quantity-type instrument. Price-type instruments, such as taxes and subsidies, achieve the defined goal through the control of a cost variable, whereas quantity-type instruments, such as permits and cap-and-trade programs control a fixed amount of allowed emissions. Choice of either one is usually related to the uncertainty between expected and realized emission levels that arise from one or the other approach[11] (relative steepness of marginal abatement and social damage curves).

MBIs are acknowledged for their flexibility, which is of particular interest when it comes to addressing situations where abatement costs are believed to vary greatly between polluters[12] and over time (due to rapid development of control technology). Several studies based on "discrete technology choice" models of technology adoption[13] comparing different regulatory frameworks find that market-based instruments provide stronger incentives for the adoption of technology by firms.

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[7] Another common image used by political scientists refers to the normative, suasive or informative aspects of policy instruments (or carrots, sticks and sermons respectively).
[8] As this case study is mainly focusing on a market-based instrument, these kinds of policy instruments are discussed more thoroughly.
[9] According to Sterner (2003), externalities are non-market side effects of production or consumption.
[10] Environmental regulation targets are commonly set on performance levels or a chosen technology (usually Best Available Technology).
[11] For a comprehensive discussion of environmental policy selection, see Sterner (2003).
[12] Potential reasons for abatement costs to vary between polluters include company size and structure, age and design of existing equipment. This will be discussed further.
[13] The term, used by Jaffe et al (2002), refers to models in which firms contemplate the use of individual technologies reducing marginal costs of abatement associated with known fixed costs, accordingly those presented in Zerbe (1970), Downing and White (1986), Milliman and Prince (1989) and Jung et al. (1996).

2.1.3 Industrial dynamics and innovation systems theory

2.1.3.1 General considerations

A system may be defined as a single unit composed of components and their mutual relationships. Systemic approach opposes Descartes' reductionist view by suggesting a more holistic method for problem solving. It recognizes that individual components, but also structure, internal linkage and relationships with the environment matter for understanding the general behaviour of a system. Following this direction, emphasis is put on the central role of networks and bridging organizations, which serve functions of collaboration and information exchanges between key actors. Indeed, it is believed that the historical processes involved in the formation and spread of innovation are intimately tied with the creation of opportunities through these types of networks and "meta-organizations". This approach allows for a new dimension of analysis, acknowledging that the processes involved in technological change and industrial transformation result from collective actions, through an intelligent use of information and competence sharing channels and platforms.

Industrial dynamics studies further recognize the evolutionary aspects of innovation processes along a time line. Borrowing from Darwin's theory, themes such as competition, selection processes and selection environment are explored within an evolutionary economics framework. Integrating a consideration of time through the definition of cycles, it develops the idea of dynamics and rearrangements of structures and relationships between components of the system.

Innovation systems theory deals with the complexity of economic and technological change mechanisms. A number of authors have acknowledged the necessity of conciliating the economist's point of view with the technologist's point of view, but also the sociologist's (Kline and Rosenberg, 1986; Latour, 1993). Innovation and related commercial opportunities result from both market needs and technical achievements. Dynamics of technological change are intimately tied to the political, scientific and informational context in which they occur.

Dynamics studied in this field include the industrial metabolism, industrial transformation and technological change, which are of relevance to the analysis to come. Technological change embodies several aspects, out of which the generation, diffusion and adoption of innovation.

2.1.3.2 Diffusion and adoption theories

Diffusion studies are concerned with explaining the rate of adoption of a new technology by a population of potential adopting firms (total market response, macro-economic perspective). Conversely, adoption studies are concerned with explaining individual firm's adoption decision-making (micro-economic perspective). The difference between diffusion and adoption, as acknowledged in Thirtle and Ruttan (1987), isn't always made by non-economist studies and literature may therefore be misleading. It is attempted to differentiate between the two perspectives throughout this study. Adoption theory is a useful framework for the understanding of the variation of speeds or rates of adoptions within a pool of potential adopters.[14] Adoption theories are concerned with explaining and understanding the factors influencing the individual decision made by a firm to adopt or not to adopt a given technology. In that sense, one tries to determine attributes specific to adopting firms and the decision-making process. This section briefly reviews the two fields, based on an exploration of selected theories.

Early attempts at modelling the diffusion phenomenon have been made by Griliches (1957) and Mansfield (1961), using the so-called logistic model, based on an analogy with the spread of infectious diseases. It may be summarized by the following differential equation:

$$\frac{dn_t}{dt} = r\frac{n_t(n^* - n_t)}{n^*},$$

where the rate of change in the number of adopters $\frac{dn_t}{dt}$ is dependent on the number of adopters at time t, n_t, a fixed population of potential adopters n^*, and an exogenous parameter r, analogous to a parameter reflecting "the likelihood of contracting the disease". The logistic model strongly emphasizes learning and information diffusion. The integration of the logistic differential equation leads to an S-shaped curve

[14] The term "potential adopters" refers here to a wider range of individuals than for the purpose of diffusion studies, since, as will be shown, it can turn out that potential adopters never actually invest in the given technology.

representing the cumulative number of adopters over time. In historical cases, this model shows good correlation with empirical data collected for various innovations. Grübler and Nakićenović (1991) provide neat S-shaped curve examples using growth of US transport infrastructures.

Capital stock adjustment and replacement models constitute an alternative explanation of the S-shaped diffusion patterns observed. These models are based upon the assumption that investments in new capital stock embody the latest technology. Technology is seen as diffusing through the replacement of old capital stock with newer. Existing facilities provide the observer with a history of technology: newer plants demonstrate the latest technology developments and the oldest remainders of past technologies will progressively be scrapped when revenues no longer cover variable costs.

Adoption models deal with the individual behaviour of firms and therefore explore the microeconomic aspects of innovation adoption. Rogers (1995) has examined the mechanism of diffusion, analyzing the innovation decision. He defines this decision process as following five consecutive steps:[15]

- Knowledge: awareness of the innovation and of its functioning;
- Persuasion: formation of an attitude towards the innovation (favourable or unfavourable);
- Decision: adoption or rejection of the innovation;
- Implementation: practical use of the innovation and consequent organization activities;
- Confirmation: evaluation of the innovation decision.

Looking back at diffusion curves, he further developed a division of adopters into five categories, dependent on the timeliness of their adoption:

- Innovators, willing to try new ideas and involve in highly uncertain choices
- Early adopters, who in turn will greatly influence the diffusion rate

[15] Using the terminology discussed above, it is referred to this as the adoption-focused part of Rogers' work. However, his work shows that both adoption and diffusion studies are inherently linked and rather constitute two different but complementary approach levels to technological change.

- Early majority
- Late majority
- Laggards demonstrate strong resistance in new ideas.

An interesting aspect pointed out here is that different actors within a given set behave and respond in totally different ways to the challenge of technology. Firms are inherently heterogeneous: they have different structural features, sizes, activity focuses, approaches towards technology, cultures and values, and are faced with different opportunities. Acknowledging this heterogeneity leads to an additional level of complexity with the distinction of a plurality of behaviours. In turn, this heterogeneity is also embodied by the very technology: accessibility of a certain type of machinery may be tied to the size or activity, and so forth, of the host structure. Additionally, communication channels (an item of great importance to the focus of innovation system studies) and their access also demonstrate large heterogeneities.

Rogers (1995) and most adoption studies focus on the importance of information and awareness for the diffusion of innovation. These thereby emphasize the informational power of external agents and the media, as well as the capacity of users to affect each other, also defined as imitative processes. The latter point has been considered as irrelevant, or at least negligible, to this case because users within the REP scheme are given incentives to retain their technological information if they are to protect their relative position within the scheme. Indeed, Höglund Isaksson (2005) points out to one consequence of the competition being to discourage the spread of information about abatement innovation from plant to plant. This argument will be challenged within the analysis.

When in comes to pollution abatement, technological innovation serves a definite purpose, which is to reduce environmental impact from the productive process. One interesting focus (treated within 6.3.2) is to determine the main characteristics of adopters of innovation for pollution abatement and the factors (internal and external) and barriers affecting that process.

2.1.3.3 The innovation process

Another branch of innovation studies has focused on the innovation process. A noteworthy contribution is the work of Kline and Rosenberg (1986) and the elaboration of the "chain-linked model". Acknowledging the restrictive view emanating from the so-called traditional "linear model" of the linkage of research to production, they identify a set of intertwined relationships between research, invention, innovation and production, formalizing five different paths of innovation. One main advantage of this approach is the identification and formalization of multiple-stage relationships and links between innovative processes and research activities and knowledge bases, as well as a series of independent feedback loops between innovation stages. The central chain of innovation is no longer considered to follow a strictly linear progression, but rather integrates more complexity. Another freedom provided by this approach is the possibility – all steps are described as linked to one another – for the observer to consider different starting points to the innovation process. This framework will be of main interest when discussing changes occurred at the supply-side of the innovation network.

2.1.4 Engineering knowledge and practice

Industry-specific pollution prevention technology and more generally the development and diffusion of cleaner production are fairly advanced technical issues. They primarily require work and research performed by engineers and scientists. Indeed, in practice, it is they, in collaboration with managers, who are brought to express their prospects and needs and make their choices with respect to new technological options. In order to understand developments in this particular area, one must possess technical skills. Indeed, when attempting to grasp issues related to technological development, one should be able to identify the various attributes and specificities of the given technology options, present and future. This concern is applicable when analyzing major technology trends, defining and assessing technology classes, but also when the purpose is to grasp the individual technology choices, usually done in collaboration between engineers and managers.

Knowledge and know-how fields of particular interest to this specific case are:

- Thermodynamics and the "pure" science of combustion
- Engineering knowledge on NOx formation and abatement

- Environmental Science and the consequences of air pollution

Section 5 is concerned with presenting a range of NOx abatement technology options and some of their key attributes. It aims at providing the reader with the basic knowledge needed in order for him/her to understand the various technology options plant operators are faced with, the underlying host structures (combustion systems) they depend on, and to grasp the possible directions of research and future efforts.

2.1.5 General macroscopic model for the system

Following a will to integrate the various above-cited approaches, a general model has been elaborated that allows synthesizing the various mechanisms at play into one single picture. Figure 3 is thus the expression of an effort to integrate many complex phenomena representative of our system, nested at various levels, all of which contribute to technological change. This integrated representation of the system allows an understanding of key players and their main relationships and will be used as a framework structuring the analysis. This general model is only presented as a synthetic guide for the approach taken towards the system, whereas some secondary questions (some of which require increased level of detail) are further treated in the text with reference to other models from the literature. Nevertheless, this model is considered to be useful for the reader to grasp the general vision of this work.

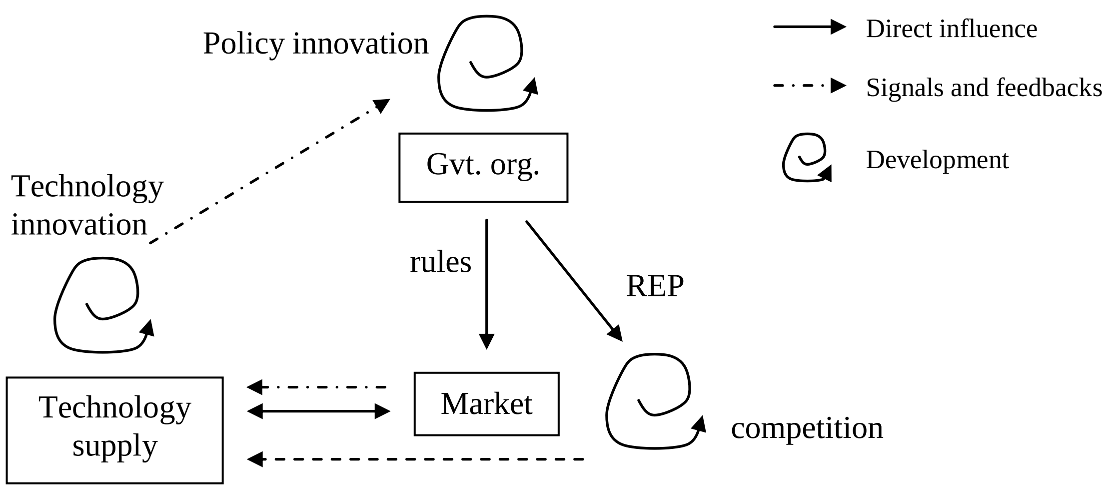

Figure 3: General model for the system under study

Three main entities (or actors) interact with each other and are considered to be of primary significance for the analysis: the potential market (stationary combustion units), the technology supply (machinery suppliers, technology manufacturers, knowledge providers, but also including sources of technology internal to the firm such as operational competence) and the regulatory organisations. Their direct links and communication channels are also described as their primary relationships. Technology providers and the market have a dual relationship based on supply and demand: the market is the locus of demand for NOx reducing technology, and the technology providers have the capacity to supply this market with goods and services. These channels are the ones through which diffusion and adoption of new technology takes place. This schematic represents mainly inter-actor relationships at the macro level,[16] thereby neglecting the multiplicity of individuals within those macro-groups and the various networks and collaboration between them (such as industry groups and organizations…). This limitation will however be overcome throughout the analysis.

The regulatory bodies[17] exert their regulatory power over the market.[18] In a first step,[19] these rules exclude the REP scheme, and include more traditional instruments such as regulatory standards released by the local authorities, which still have an impact on innovation processes.

The dynamic aspect of the actors is then accounted for, giving them their “development” attributes and fields (component specific selection environment and outcomes). The inclusion of the latter will facilitate the identification of secondary relationships and signals as well as feedback channels that all lead to the evolution of the whole system. Additionally, it may be a suitable theoretical location for the identification of intra-actor

[16] The actors presented have been restrained to primary stakeholders for the sake of clarity.
[17] Innovation system studies distinguish between regulatory bodies/governmental organizations, which are actors, and institutions, which refer to a set of explicit and/or implicit rules such as laws and norms.
[18] Of course other organisations also exert their regulatory power over technology providers through the use of different instruments, but this is considered as beyond the scope of this study.
[19] For clarity purposes, the definition of the system and relationships within it are described step by step. It should however be noticed that in some cases throughout this description the order of progression has been chosen arbitrarily and could be discussed, due to the inherent dynamic aspects characteristic to the system under study.

networking at the “meso-level”.[20]

The environmental governmental organizations, aware of the technical feasibility of further NOx abatement, decide to create an incentive that would push the market towards lower emissions: thus the REP is born. This scheme doesn’t have a direct influence over the actors of the market, but rather induces a competition among those actors, making individual performance a location for improvements.

It can be investigated whether or not the creation of this competition has influenced the technological change process (one main challenge of this present study), in terms of diffusion of readily available technology and the generation of new technology. The latter can be referred to as the creation of signals to the technology providers that the market they operate in is likely to change and may exert a stronger pressure on the performance of their products. Again, it should be noted that technology supply can be of different nature (hardware, software, “orgware”) and located within different organizations, including the plants themselves. This process, if it happens, will influence the process of technological innovation (pictured as the evolution of the technology supply). Additionally, the evolution of demand from individual actors of the market can lead to further developments from the technology suppliers, along with larger-scale evolution of the system environment and other contextual factors. A consequence of these developments is the availability of a wider range of products, overcoming pre-established technical and commercial barriers.

Eventually, leaps ahead in technology development may lead policymakers to re-evaluate the system they have created in order to better adapt it to the new situation.

2.2 Methodological issues

As a consequence of the complexity of the analyzed system, a set of complementary methodologies, rather than a single tool, has been used. As argued in Yin (2003), a case-study strategy is justified when there is a deliberate will to investigate contextual

[20] For the three components included here, agents within these networks include international, European, and non-governmental organization; research and development centres, institutes, and associations; activity-specific networks, for governmental organizations, technology supply, and the market respectively. Additionally, some conferences can be useful meeting places for all three identified components (e.g. Förbränningsdagarna, organized by IbcEuroforum yearly).

conditions to the phenomenon under study. The results can be skewed through the use of multiple sources of evidence, quantitative as well as qualitative. The various methodologies that have been used throughout this study are listed below, followed by a discussion of the advantages drawn from this approach.

- Documentation and literature review (field-specific and previous study on the REP)
- Policy and technology review, providing the reader with necessary background information
- Analysis of site-specific reporting data over the pool of firms

The data, generously provided by Naturvårdsverket under agreement of confidentiality, is a compilation of individual plant reporting data covering years 1992 through 2005. Plants subject to the scheme are required to fill in a form each year. This form is presented in Appendix B of SEPA (2000). Information to be returned includes administrative information, energy generation and NOx emissions, technical information and measurement technique. Discussions with SEPA and comparison from interviews however pointed out possible inaccurateness of the information provided. This aspect has been taken into account and results from the database are treated with caution, supplemented by other sources of information.

- Field research and interviews of representative actors

Interviews with specific actors of the system have been performed in order to complement the analysis with empirical results. Interviewees were selected on the basis of their projected relevance and criticality to the subject under study. These interviews were based on a set of predefined questions, but also were kept as open-ended as possible in order to give the interviewees a chance to share their insights drawn from experience. The material collected from personal interviews is mainly qualitative and useful, especially with respect to real-world decision making procedures involved followed by various actors in the system.

The companies visited and interviewed have been selected for a set of different purposes. The main driver for these choices however remained their representative value with respect to the system under analysis, given its particular focus. Therefore the group of interviewees was composed of:

- Combustion plants,

- Technology providers/machinery suppliers,
- Institutional actors and experts.

It is believed that the use of multiple methodologies allows complementary results, providing parallax to the overall system that would not have been achieved through the use of one single source of evidence. For instance, the performance of open-ended field interviews and empirical evidence collected hereby copes with the inaccurate and inherently quantitative results from the database. This is of particular importance when dealing with such a complex issue involving a set of heterogeneous actors with very different perspectives, but also with multiple possible and desirable levels of analysis.

A main argument developed throughout this study, and especially in this section, is the necessity to explore multiple levels of complexity. From an initial step considering a binary relationship linking environmental policy and technological change (Figure 1), the consideration of complementary insights from many neighbouring fields of expertise (Figure 2) has led to the definition of a larger system of analysis, including a set of actors and their main relationships (Figure 3), as a framework for the analysis. This picture is still a partial representation of reality and it has to be acknowledged that additional levels of complexity arise and complement the general picture when analyzing selected items in-depth (sub-systems, actors, relationships, and so on) into more detail.

3 NOx FORMATION AND RELATED ENVIRONMENTAL PROBLEMS

Anthropogenic NOx emissions are formed mainly within system involving combustion, such as energy systems and transportation systems. NOx are considered as atmospheric pollutants and can lead to various environmental and health damages. This section is an attempt to briefly describe NOx formation mechanisms and their impacts. Some complex issues are pointed out that have an influence on both policy strategies and abatement techniques.[21]

3.1 NOx formation mechanisms and other nitrogen oxides[22]

The chemistry and thermodynamics involved in the accurate description and modelling of NOx formation in combustion processes are very complex. During high-temperature combustion, the conversion of nitrogen from the air or fuel-bound nitrogen leads to the formation of various chemical species such as NO, NO_2, N_2O, NH_3, and HCN. The amount of each of these pollutants that is formed mainly depends on combustion temperature and the fuel/air ratio at various stages of the combustion process (Hill and Douglas Smoot, 2000).

Three different NOx formation mechanisms are commonly accepted as thermal NOx, prompt NOx and fuel NOx:

- Neatly explained in Alloway and Ayres (1993), thermal NOx is formed during the Zeldovich mechanism (1), by oxidation of nitrogen present in the air under high-temperature conditions:

N2 + O2 → NO, NO2 (1)

The formation of thermal NOx increases exponentially with temperature, and is of major importance in traditional combustion processes.

[21] Some arguments presented here serve as a basis for discussion within sections 4 and 5.

[22] The term "nitrogen oxides" refers to oxygen compounds of nitrogen (Nitrogen oxide (NO), nitrogen dioxide (NO_2), dinitrogen oxide or nitrous oxide (N_2O), dinitrogen trioxide (N_2O_3), dinitrogen tetroxide (N_2O_4), dinitrogen pentoxide (N_2O_5)). NOx is a generic term used to define the nitrogen oxides produced during combustion processes. However, in atmospheric chemistry, a significant terminology differentiation is made on a reactivity basis. In the latter case, NOx only refers to NO and NO_2, which are strongly involved in the formation of tropospheric ozone. In turn, NOy (reactive odd nitrogen) refers to the sum of NOx plus the products of the oxidation of NOx. Nitrous oxide and ammonia are not considered as reactive species according to this definition.

- Prompt NOx formation involves more complicated reaction between nitrogen, oxygen, and hydrocarbon radicals. The general net reaction equation is:

CH4 + O2 + N2 → NO, NO2, CO2, H20, trace species (2)

Prompt NOx is relatively important in the case of low-temperature combustion and increases under fuel-rich conditions. In most cases, its formation is negligible.

- Fuel NOx is formed during combustion of nitrogen that is chemically bound in the fuel. It may be important when oil, coal, waste fuels, and even some types of biomass[23] are burned. The typical nitrogen content of coal is 1.3 percent of bound nitrogen (Baukal, 2005), but this parameter still appears to be highly variable with respect to grade, quality, and origin of various fuel types (For an example collection of fuel-bound nitrogen data, see Naturvårdsverket, 2004).

The relative contribution of these mechanisms to NOx emissions is dependent on thermodynamics, combustion parameters such as fuel, temperature, combustion system size and residence time of the combustion gases.

NO is the predominant species of NOx in flue gases. NO_2 formation from NO occurs in conditions where rapid cooling takes place. It is important to note that NO has much lower solubility than the other oxygen compounds of nitrogen.[24] The REP scheme, which is the focal point of this study, is only concerned with NOx emissions. The linkages between NOx emissions and other reactive nitrogen compounds should however be exposed, for their atmospheric chemistry are intimately linked. N_2O appears to be of major importance within the hot, fuel-rich flame zone. It is argued (Hill and Douglas Smoot, 2002) that they are typically destroyed downstream when cooling and oxidization rates increase, and that later formation is negligible. However, the amount of

[23] The type of fuel burned has major influence on NOx emissions, especially when considering that recent policy developments have supported a major structural shift towards increased share of biomass burning capacity in Sweden. This issue is further discussed within sections 4, 5 and 6 – policy review, technology review and results. There is, however, no simple answer to whether biomass burning leads to more NOx emissions. Indeed, the term "biomass" does not integrate a sufficient level of detail for this question to be treated, and fuel-NOx is not the only source of NOx emissions.

[24] The higher relative solubility of nitrogen oxides other than NO creates a potential for abatement through washing and scrubbing of the flue gas and will be discussed in the section concerned with abatement technologies.

N_2O formation within combustion systems operating at lower temperatures and with enhanced mixing such as fluidized bed combustors tends to be of consequence. Additionally, some NOx reducing measures using downstream injection of nitrogen-reducing agents (such as SNCR) result in high levels of N_2O formation (Kramlich and Linak, 1994). Olofsson *et al.* (2002) further demonstrate the conflicting aspect of NOx and N_2O formation processes and the resulting difficulties encountered in an attempt to optimize joint emissions through the control of combustion parameters.[25]

3.2 Environmental aspects and health issues

Due to their high reactivity, NOx have a short lifetime in the atmosphere (from hours to days), and therefore remain a local/regional issue. Their effects are highly dependent on distance and time delay from their emission source and transport media. NOx are considered as primary pollutants, having direct effects on human health and ecosystems. However, the main environmental concern arising from NOx is the secondary pollutants that they spawn (Jackson and Jackson, 2000), namely leading to acid rain and acting as precursors to the formation of tropospheric ozone.

The formation of nitric acid contributes, together with the formation of sulphuric acid from SO_2 emissions, to the formation of acid rain, which is deposited onto ecosystems (of particular importance are forests and lakes). In Sweden, the very nature and geological structures of the soil renders the ecosystem more sensible to acidification.

NOx are involved in catalytic cycles enhancing ozone formation. Tropospheric ozone, a constituent of smog, is formed through the reaction of hydrocarbons, carbon monoxide and/or methane with NOx under sunlight exposure. During this process NOx are "recycled" and thus available again for catalysis. Tropospheric O_3 formation is limited by the surrounding atmospheric concentration of hydrocarbons in region of high NOx concentration, and by the availability of NOx in regions of low NOx concentrations (Sillman et al, 1990). However, parameters such as sunlight exposure and stagnant meteorological conditions enhance these reactions.

[25] Combustion plant operators and designers are constantly confronted with multiple pollutant issues. NOx emission reduction appears to be at cross-purposes for the reduction of other pollutants (CO, N_2O, ammonia slip in the case of SNCR or SCR).

Tropospheric ozone is a greenhouse gas and thereby contributes to global warming. Ground-level ozone[26] can cause serious damage to health. Of major significance are damages to respiratory functions, reduced lung functions, and the triggering of asthma attacks for people with asthmatic predispositions. It can also lead to irreversible lung scarring in conditions of repeated intense exposure.

[26] Ground-level ozone is the fraction of tropospheric ozone that is located at ground level.

4 POLICY REVIEW

This section is intended to present some major aspects of NOx emission reduction policies, with particular focus on the regulation of stationary point sources in Sweden, and the NOx Refunded Emission Payments scheme. The emergence of European policies dealing with NOx emissions is first presented, followed by a description of the NOx REP mechanism. A last subsection discusses other policy schemes of importance to the system under analysis.

4.1 International and European policy dealing with NOx emissions

Acidification and air pollution share a long scientific and political history. Muzio and Quartucy (1997) acknowledge extensive developments in regulation and the subsequent lowering of limits for NOx emissions in industrialized countries over the past 30 years. The debate on acidification and the transboundary aspect of the related environmental impacts has first been brought up with sulphur dioxide in the late 1960s (Odén, 1967, 1968). The first policy initiatives aiming at regulating NOx emissions were international agreements. These, jointly with the first common European policies, paved the way for cooperation between science and policy, and the development of national policies.

The problem of transboundary pollution was first discussed at an international level at the conference of the United Nations (UN) on Human Environment in Stockholm in 1972. In 1979, a first multilateral agreement, CLRTAP, was agreed upon under UNECE by 34 governments and the European Community. The primary objective was to build a common scientific and policy framework in order to enhance science and policy collaboration. Common European policy has allowed the definition of national and regional emission levels not to be exceeded (macro level). Additionally, more industry-targeted policy schemes allowed the implementation of effective reductions through the introduction of standards for point source emissions for specific industrial and agricultural practices (micro-level). These are implemented through national institutions within EU countries. In most cases, regional authorities are in charge of allowing permits for point source. This is a sound response to the localized aspect of environmental damage related to NOx emissions (dependent on local emission density, population density, and sensitivity of ecosystems mainly).

Resulting pieces of policy can be classified with respect to two categories: those providing target values for emissions at national or regional levels, and those regulating specific maximum emission values for targeted NOx emitting sources such as industrial, agricultural, or transportation activities. The policy scheme under study can be considered as a national (Swedish) initiative to tackle emissions from a given activity: energy extraction from stationary combustion systems.

4.2 The Swedish Refunded Emission Payments

As put in the words of Thomas Sterner and Lena Höglund Isaksson, "Sweden has long had a very aggressive policy on the precursors to acid rain. Most of Scandinavia has old geological structures with little calcium and thus little buffering capacity. Sweden is one of the countries that has been most affected by acid rain leading to considerable effects on lake and forest ecosystems. This is one of the reasons why there is a very determined policy on sulphur and nitrogen emissions" (Sterner and Höglund Isaksson, 2006). In 1985, the Swedish Parliament set a goal to reduce national emissions of NOx by 30 percent of 1980 levels by 1995, which was progressively translated into a number of specific policy initiatives.

The Swedish NOx Refunded Emission Payments (REP) scheme was launched in 1992 with the intention to "achieve a more rapid reduction of nitrogen oxides than was otherwise considered possible", and to provide incentives for cost-effective reduction, from large combustion plants for energy production[27] (SEPA, 2000). Utilities concerned by this 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 in relation to diminishing monitoring[28] costs (Höglund Isaksson, 2005). Participants to the REP scheme come from 7 different sectors: heat and power, pulp and paper, metal, waste, food, wood, and chemicals industries. Combustion units can be boilers, stationary engines or gas turbines.

[27] "Energy production" refers to both heat and electricity production.
[28] In air pollution abatement, monitoring equipment refers to measuring equipment.

Companies basically pay a charge indexed to their yearly NOx emissions.[29] After subtraction of administrative costs, remaining revenues are refunded to the participating plants relative to the amount of their production of useful energy.[30] In practice, these operations (payment and refund) are performed simultaneously, thereby avoiding unnecessary mobilisation of monetary resources. Monitoring equipment is to the expense of plant operators and must comply with the standards of the Swedish Environmental Protection Agency (SEPA, Naturvårdsverket). In the absence of monitoring equipment, operators are submitted to predefined levels of emissions.[31]

One benefit of combining a tax with a refund is that, while achieving the same abatement level as a tax of the same value, polluters show themselves less reluctant to the adoption of the scheme. In fact, Sterner and Höglund (2005) show that lower net tax payments reduce resistance from the polluters and make refunded emissions payments politically easier to implement at a sufficiently high charge level to yield significant abatement effects. The French tax on NOx emission from industrial activities[32] is comparatively very low (by an order of magnitude of 100), partially as a result of lobbying activities from the industry. The benefits from a raised tax level, in terms of economic incentives, are however indisputable.

The REP mechanism gives incentives to the combustion units to reduce their emissions intensities to lower-than-average levels.[33] The units with the lowest emission intensities (in terms of emission/useful energy produced) become net economic gainers (they are rewarded), whereas those with the highest emission intensities experience a net economic loss. In that sense, it is believed that the REP encourages an increased rate

[29] The charge is levied at a rate of SEK 40 per kg of NOx, calculated as the sum of NO and NO_2, converted into NO_2. 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 NOx.
[30] See SEPA (2000) Appendix C for an example of individual plant calculation of the net payment.
[31] Predefined levels of emissions are 250 mg/MJ for boilers and 600 mg/MJ for gas turbines.
[32] The "taxe parafiscale sur la pollution atmosphérique" (TPPA) until 1999, later replaced by the "taxe générale sur les activités polluantes (TGAP) sur les substances émises dans l'atmosphère", since January 1st 1999 have been levied at respectively 27 €/ton NOx and 51 €/ton NOx. These rates are to be compared with an approximate 4300 €/ton NOx charge within the REP scheme (at a conversion rate of 9,296 SEK for 1 €).
[33] This argument is dependent on the assumption that individual combustion units behave as "rational economic actors".

of adoption of existing abatement technology by polluters and development in abatement technology beyond target levels taken as a basis for the selection of the optimal charge.

The REP scheme could be criticized for its single-pollutant approach. Indeed, many researchers argue for the need of more integrated air pollution abatement policies. There however still exists division with respect to whether this integration should be based on the environmental effects of pollutants[34] (here acidification, or tropospheric ozone formation), or on biochemical cycles of chemical species[35] (van Egmond et al, 2002, Sliggers, 2004). Again, it should be kept in mind that the REP is merely a part of the whole industrial pollution abatement and acidification strategy of Sweden, within a European policy framework.

4.3 Other policies affecting heat and power production units and their NOx emissions

As mentioned in the section dealing with NOx formation mechanisms, one complex issue that arises with air pollution abatement is that formation mechanisms for various pollutants compete, in such a way that respective abatement measures find themselves at cross-purposes. This often implies compromises and trade-offs between these emissions. From an operator point of view, NOx emission reduction cannot be considered as a single and ultimate goal of emitters, but rather as inscribed in a more complex optimization problem. In this sense, policies regulating other pollutant emissions, but also aiming at reduced energy use and increased energy efficiency[36] should be considered as part of the policy framework affecting the system under study.

Additionally, it should be kept in mind that any industrial activity is under regulatory control, and sector-specific pollution emission levels may interfere with the REP scheme. Within the REP system, the units undergoing the most stringent regulation,

[34] Fighting acidification would lead to joint NOx and SOx emission reduction programs.
[35] Towards an integrated approach towards anthropogenic leaks of reactive nitrogen.
[36] For an interesting discussion of positive spillover effects from Climate Change Policies on air pollution abatement, see RIVM (2001).

driven by EU policy, are waste incineration plants and large combustion plants.[37]

[37] Large Combustion Plants (LCPs) are subject to the 2001/80/EC Directive on the limitation of emissions of certain pollutants into the air from large combustion plants. The criterion for being an LCP is a rated thermal input equal or greater than 50 MW.

5 TECHNOLOGY REVIEW

NOx emission abatement from stationary sources is a complex issue for many reasons. This section attempts to provide the reader with the key issues of NOx abatement, in order for him/her to better grasp the challenges that face plant operators. Technologies may differ by their nature,[38] the physical and chemical processes they involve, but also their abatement efficiencies, costs, scale, flexibility with respect to existing capital infrastructure, and so forth. For the purpose of brevity, only some aspects that are thought as necessary for the understanding of the current research work are here superficially reviewed, including host structures (stationary combustion system), various available techniques and their relative position along the production stream.

5.1 Stationary combustion systems

Combustion systems for heat and/or electricity production can be of various kinds. The technology used for combustion depends on system requirements, which include the purpose of the combustion, the kind and grade of fuel fired, the temperatures to be achieved. Their design and performance are also dependent on technology advances and have constantly improved with growing knowledge and engineering capacity.

Electricity from combustion is generated through the use of turbines. Turbines can be driven by steam (steam power plant) or by hot gases (in a gas turbine). Heat is generally extracted from the furnace via the use of boilers. Higher efficiencies are achieved when both heat and power are extracted (Combined Heat and Power).

A selection of available firing technologies for heat and/or power production and overview certain of their features that are here of interest are presented below.

5.1.1 Burners

Burners are present in most traditional combustion systems. They are used to generate the combustion flame and involve mixing fuel with air (or other source of oxygen). Depending on the combustion system type, their number and positioning in the furnace

[38] Hardware consists of capital-intensive equipment, software consists of optimized operating procedures, and “orgware” consists in organizational structures and resulting competence. Here, mainly hardware and software (trimming and learning activities) are explored.

can vary. They are usually used with liquid or particulate fuel (in the case of pulverized coal or biomass combustion).

5.1.2 Stokers (grate-fired boilers)

The term “stoker” is used for those combustion systems firing solid fuels with a grate. The pieces of coal or biomass are fed by a mechanical chain in the case of travelling stokers, or by an inclined vibrating chute. Their capacity is restricted to 100 MWe and their efficiency is generally lower than Fluidized Bed Combustors or Pulverized Coal Combustors.

5.1.3 Fluidized Bed Combustion (FBC)

Fluidized Bed Combustion takes place in a bed of hot combustible maintained by a flow of fluidizing gas. It is used for burning of solid fuels. A major advantage of this combustion method is a turbulent mixing of combustion gases and solids. Long residence time is achieved for a more efficient combustion of the fuel, also resulting in lower temperatures. FBC is also of great advantage when it comes to fuel flexibility,[39] thereby allowing long-term changes in fuel supply but also quick changes of fuel. This aspect is primary in the waste burning industry, but also for industries with variable fuel grade supply. FBC achieves lower NOx emissions than traditional solid fuel combustion systems (stokers mainly).

5.1.4 Gas turbines

Burning of natural gas in a turbine directly used for the generation of electricity. They can be combined cycle gas turbines where the residual heat is used to create steam, which then goes through a steam turbine for additional electricity generation. Pressurized Fluidized Bed Combustors can be used to generate the combustion gases used by the turbine.

5.2 NOx reduction measures

The Swedish Environmental Protection Agency (2000) distinguishes two types of NOx emissions reduction measures: combustions measures (primary measures) and flue

[39] With respect to both fuel quality and fuel type.

gas treatment (secondary measures).[40] Other types of measures affecting NOx formation, such as increased efficiency of the energy generation and fuel switch, will also be discussed here, However, they are here considered to be of less importance, for their implementation is not primarily driven by NOx reduction goals.

There is by no means one single approach for the reduction of NOx emissions from stationary sources. Rather, the plant operator is faced with complex choices when defining the optimal NOx emission reduction investments.[41] It should also be mentioned that this choice is conditioned by the fact that pollution abatement is most often an optimization from multiple competing pollutants.[42]

5.2.1 Combustion measures

Taking into account the NOx formation mechanisms presented earlier, one can easily understand that thorough control of combustion temperature and optimal burning conditions can lead to emission reductions. Means to control combustion parameters can however be performed both through the optimal use of existing equipment, involving only knowledge, know-how and the modification of organizational structures (software and “orgware”), or through the addition of equipment and infrastructure (hardware), involving capital expenditures. This distinction is important in practice, for the former type of measures involve no or very low costs.

An inexpensive way of reducing NOx formation during combustion is to *trim* the combustion process (SEPA, 2000). According to a 1996 study by Höglund (1999), more than half of the *trimming*[43] measures implemented in Swedish boilers had been done at zero costs, thereby proving the existence of “low-hanging fruits”. These trimming measures can be associated with learning methods (knowledge and know-how

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[40] Other synonymous terminologies include “front-end” for combustion measures, and “add-ons”, “back-end” for flue gas treatment.

[41] Taking into consideration those pointed out in a technical publication by Kitto et al. (1999), main variables for optimal cost-effective control technology choice include the existing unit combustion system (conventional or low NOx), the fuel, overall furnace configuration and boiler layout, planned operating strategy (of major importance seems to be base load), remaining life, and actual and target NOx levels.

[42] This point relates to the stated need for more integrated pollution abatement solutions. Indeed, at a defined time, a plant operator optimizes his process with respect to many variables. These include cost variables, planned investments, output of energy (in its different forms), input flows, and various emissions, out of which NOx emissions.

[43] *Trimming* is also referred to as *fine-tuning* in the literature.

intensive) and emerge within the operating plant.

Combustion control systems are *stoichiometry-based*, monitoring the mixing of fuel and air to control the concentration of oxygen in the flame zone, or *dilution-based*, aiming at reducing flame temperature (Agrawal and Wood, 2002). An overview of primary NOx reduction measures is here provided:

- *Wet combustion controls*, such as *steam injection* or *water injection* (SI and WI), are *dilution-based* measures that limit thermal NOx formation through flame temperature reduction. The steam/water injected cools off combustion products, thereby lowering average combustion temperature.
- *Lean combustion* is a *stoichiometry-based* measure. Lean fuel (or excess air) conditions are characterized by a fuel to air equivalence ratio[44] below 1. The excess air reduces flame temperature, thereby limiting thermal NOx formation.
- *Low NOx burners*[45] (for gas, oil & gas or pulverized coal) allow for the formation of an optimal flame:
    - Tangentially fired Low NOx burners consist in an alternation of air nozzles and fuel nozzles in the main windbox.
    - Wall fired Low NOx burners aim at the creation of a split flame. The burners simultaneously inject fuel and air to create an optimal flame. Substoichiometric conditions are maintained in the center of the flame. Additional *swirling* is provided for increased flame stability and flame mixing.
    - *Lean premixed combustors (*More and more premixing of fuel and air.)
- *Reduced Combustion Residence Time* is a measure that can be applied to gas turbines. In most gas turbines, combustion gases have to be cooled through dilution with air before entering the turbine for power generation. Cooling the hot gases sooner leads to NOx emission reductions. This can be done through *Heat extraction/Flue Gas Condensation.*
- *Flue gas recirculation* consists in the forced return of cooler combustion gases below the flame zone. This process reduces mean flame temperature, but also

[44] Equivalence ratio of 1 refers to the fuel to air (mass ratio) necessary to fulfil stoichiometric oxidative fuel combustion conditions.
[45] Low NOx burners are also referred to as Dry Low NOx burners (DLN). A difference is also made between Low NOx burners and Ultra Low NOx burners.

oxygen concentration, and therefore reducing mean oxidation rate and the formation of thermal NOx. In that sense, it may be considered to be both *dilution-* and *stoichiometry-based*. In some systems, retrofitting of a boiler with this kind of equipment requires a lot of ductwork and available space around the combustion chamber. For optimal reductions, the installation of fans to force the recirculation is necessary.

- *Air staged combustion (*or *Overfire Air, OFA)* is a *stoichiometry-based* strategy involving the creation of different combustion zones (usually two stages, for different stoichiometry) through the introduction of different air flows:
    - Primary air (70%-90%) is mixed with the fuel and creates a fuel-rich zone, thereby limiting combustion temperature and subsequent fuel NOx formation;
    - Secondary air (the remaining 15-30%, referred to as *Overfire Air*) is injected above the combustion zone through separate nozzles. The remaining fuel is thus burned at a larger flame volume in a fuel-lean zone, limiting flame temperature and the formation of thermal NOx.
- *Fuel staging* is another way of creating fuel-rich and fuel-lean zones (*stoichiometry-based*) to limit the combustion temperature and limit thermal NOx formation. Here, the controlling flow is the fuel rather then the air. Fuel staging can be done in different ways, involving optimized use of existing infrastructure ("orgware"/software measures), or installation of additional modules (hardware):
    - *Burners-out-of-service (BOOS)* consists in selectively switching off some of the burners with multi-burner equipment (another option is to have them provide air instead of fuel or fuel mixed with air).
    - *Fuel biasing* can be done with vertically arranged multi-burner equipment. In this case, one can create a primary fuel-rich zone and a secondary fuel-lean zone through the modulation of the fuel injection flows throughout the combustion chamber.
    - *Reburning* usually involves 3 combustion stages. In the primary zone, low excess air achieves limited NOx formation. In the secondary zone, fuel is injected (usually natural gas, or flue gas recirculation), creating fuel-rich conditions and forcing the reduction of any NOx to N2. In the third zone, OFA is introduced, achieving the combustion of remaining fuel and CO.

- *Oxygen instead of air* is a measure in which the potential oxidizing N is removed from the air. Therefore, neither thermal, nor prompt NOx can be formed. Using oxygen instead of air for combustion, however, is fairly costly.
- *Catalytic Combustion (CC) for Gas Turbines* consists in the introduction of a catalyst to achieve same combustion performance under lower combustion temperature, thereby lowering the potential for thermal NOx formation.

5.2.2 Flue gas treatment

5.2.2.1 Single-pollutant approaches

- Selective Catalytic Reduction (SCR)

SCR is a flue gas treatment system using ammonia (NH_3), urea or isocyuranic acid to reduce NOx into water and molecular nitrogen (N_2) on catalytic beds.[46] This type of installation is rather large and costly but achieves highly efficient reduction. The technology has been used as early as the late 1970s in Japan, and was introduced in Europe in 1985 (Forzatti, 2001). There are many different applications of SCR technologies; it has been applied for combined removal of NOx and SOx, and of NOx and CO. Depending on catalyst in use, these system can operates in ranges between 150-600°C,[47] which constrain their position along the flue gas exhaust and can eventually require the installation of heat extractors/injectors.

- Selective Non-Catalytic Reduction (SNCR)[48]

SNCR is a flue gas treatment system using ammonia or urea ($CO(NH_2)_2$) to reduce NOx at a high temperature. This implies lower costs than SCR for there is neither need of cooling of the gases nor of using a catalyst and consequent large infrastructure. The use of SNCR is, however, restricted to strict operating temperature window (commonly 900-1150°C) for optimal efficiency, and the ammonia slip.[49] One of the related technical issues is the pressure loss that can occur because of an early intervention with the

[46] Commonly used catalysts are Vanadium, Titanium, Tungsten, and Molybdenum oxides (Radojevic, 1998)

[47] Approximate ranges are 250-450°C, 150-300°C and 350-600°C for Vanadium/Titanium Oxides, Platinum/Palladium Oxides and Zeolite-supported catalysts respectively.

[48] SNCR is also called Thermal DeNOx.

[49] Ammonia slip refers to the emission of ammonia (in gaseous or aqueous phase). There is a constant trade-off between the quantity of ammonia to be injected, driving the efficiency of NOx abatement, and acceptable ammonia emission levels.

combustion gases.

5.2.2.2 Multi-pollutant and other integrated approaches

- SCONOx™ (commercially available from ABB Alstom since 1999)

SCONOx™ is a system allowing simultaneous removal of CO and NO in natural gas-fired turbine engines using water injection. CO is oxidized to CO_2, NO to NO_2, with the help of a K_2CO_3 catalyst. Then NO_2 absorbs to the catalyst, forming KNO_2 and KNO_3. Diluted H_2 is regularly passed through the catalyst to regenerate it, forming H_2O and N_2.

- Electron beam flue gas treatment for the dual removal of NOx and SO_2

Electron beam flue gas treatment belongs to the new generation of air pollution control equipment, developed in Japan, the U.S., Germany and Poland, with two full-scale applications in 2004 and more projects to come (Chmielewski *et al.*, 2004). It allows for simultaneous removal of SO_2 and NOx emissions. The different steps involved are the cooling and moisturizing of flue gas with water vapour, ammonia gas injection, irradiation with electron beams producing reactive free radicals, the reaction of SOx and NOx with radicals producing sulphuric acid and nitric acid and further ammonium sulphate and ammonium nitrate aerosols. An electrostatic precipitator allows for removal and storage of the aerosols for eventual recovery in by-products such as fertilisers.

5.2.3 Other measures affecting NOx emissions

5.2.3.1 Fuel switch

What is here discussed as fuel switch is the substitution of main fuel fired for combustion. There are two main reasons for fuel switch within the combustion industry today: cost minimization and CO_2 emission reduction. Historical reasons also include reduced emissions from fuel-bound Sulphur.

Fuel switch can lead to lower NOx emissions if the change is done towards fuels of lower bound nitrogen content. Practical experience however shows that the issue isn't as simple as it seems. Indeed, while fuel-NOx emissions may be lowered through this kind of measure, the combustion and firing conditions will be changed, which in turn can lead to variations in thermal and prompt NOx formation,[50] thereby affecting the total amount of NOx emissions. There is a tendency in combustion systems, and particularly in the Swedish combustion system to shift from low-grade fuels to higher-grade fuels (coal→oil→gas), and to develop the capacity of biomass and waste burning. These can have varying impacts on NOx emissions. As a general rule, it is reasonable to assume that coal and oil lead to greater NOx emission intensities that natural gas or biofuels. Höglund Isaksson (2005) concludes from statistical analysis that plants using biofuels and/or gas as a main fuel are able to achieve better performance for a given cost than plants using other fuels.

It should be kept in mind that these tendencies are primarily driven by climate change policy and energy security and reasons related to the rational use of resources, rather than NOx emission concerns, although they can have substantial positive effects on the latter. Therefore, effects from this tendency on NOx emissions (positive and negative) will not be taken into consideration as a NOx abatement technology. In Höglund Isaksson (2005), the cost-savings resulting from fuel switch are seen as being driven by other reasons than the NOx charge and are therefore not considered as NOx-reducing measures although they contribute to lowered NOx emissions in some individual cases (mostly when coal or peat are replaced by other fuels). In this work however, fuel switches will be considered as non-negligible spillover effects (positive or negative) of policies exogenous to the system.

5.2.3.2 Energy efficiency increase

Energy efficiency increase consists of a more effective extraction of energy from the energy carrier (in the case of combustion, the fuel), thus reducing intermediate conversion losses.[51] This can be done via the use of more adapted materials at the combustion level (reducing heat losses), or via improved conversion and extraction technology or integrated combustion system thinking (optimal heat to power ratio, etc.). Significant consequences of an increased focus on increased energy efficiency are the intensification of the combustion process (increased temperature and volumes) and the combined extraction of both heat and power.

[50] See section 3 for a description of NOx formation mechanisms.
[51] This concern is inscribed within a larger tendency of pollution reduction "coincident with improving the productivity with which resources are used" as put by Porter and van de Linde (1995).

The use of flue gas condensation and heat recovery allow better efficiency to be achieved while burning the same amount of fuel, leading to similar amounts of emissions. One way to benefit from the REP scheme and to reduce emission intensity is therefore to increase energy efficiency of the utility.

This is though not considered as a measure primarily motivated by NOx regulation, but rather by climate change policies, and cost savings. In fact, energy efficiency policies usually consist of self-standing initiatives, such as the Swedish Program for Improving Energy Efficiency Act (2004:1196). Energy efficiency is a non-negligible factor explaining decreases of NOx emissions intensity that should be considered. Benefits from energy efficiency increases can be substantial, provided that output remains constant.

5.2.3.3 Computational Fluid Dynamics modelling (CFD)

Computational Fluid Dynamics (CFD) is a virtual development method for projects involving fluid dynamics. Considering the complexity of the chemical reactions, and fluid and thermal flows involved in large combustion systems, CFD has become a necessary component of research and development in the thermal sector. CFD can be used as a complement to hardware (optimal gas distribution for prolonged lifetime of SCR catalyst, design of boilers…), or for optimal trimming (integrated monitoring and control, cf. ABB product). Many boiler operators, especially small ones, are reluctant to invest in this kind of simulation technology. Given the rather high capital costs of NOx emission control technologies, investments in CFDs are however relatively small, and usually worth the expense (King et al., 1996), and should be given more attention.

5.2.3.4 Monitoring equipment

The costs related to monitoring equipment have declined a lot over the analyzed period. Indeed, Höglund Isaksson (2005) cites this tendency as the main reason for an extension of the scheme to smaller plants in 1996 and 1997, which has been confirmed through conversations with employees at Naturvårdsverket (Sjögren, 2006). The control and reliability requirements of monitoring equipment constitute a great deal of both the operations and legal basis necessary for the REP to sustain itself. Indeed, unless complying with requirements for monitoring equipment, firms are assigned a standard emission rate. The hourly measurement required can also lead to an increased awareness of operators to NOx emission levels and has appeared to further motivate fine tuning initiatives.

5.3 System perspective on stationary combustion units

One striking feature associated with NOx reduction technology is the extent of possibilities and the consequent complex choice arising from the multiple options. Indeed, a wide array of NOx-reducing technologies for stationary sources is available, and as concluded by the US EPA (1999), "there seems to be no control technology which is superior for all combustion systems, boilers, engines, or fuels". This points to the difficulty facing plant operators once it has been decided to invest in NOx-reducing technology and may explain the simultaneous existence of so many competing designs.

Stationary combustion plants can be descriptively broken down to essential elements that are translated into elementary functions: fuel and air mixing and firing, combustion, heat extraction, power generation and effluent treatment. These functions can be satisfied in a large range of ways, depending on operating requirements (capacity, fuel, demand for power, demand for heat…). This contributes to heterogeneity in design of combustion units, thus opening a new level of complexity.

Figure 4 responds to an effort to identify those key elements of stationary combustion units, allowing a more integrated approach to pollution abatement and improvements. Some optional flows (mainly redirection of flows in, for instance fuel pre-heating or reburning, or recycling of waste flows) have however not been described for the purpose of clarity, but should be treated when considering system options in a more extensive and integrated fashion.

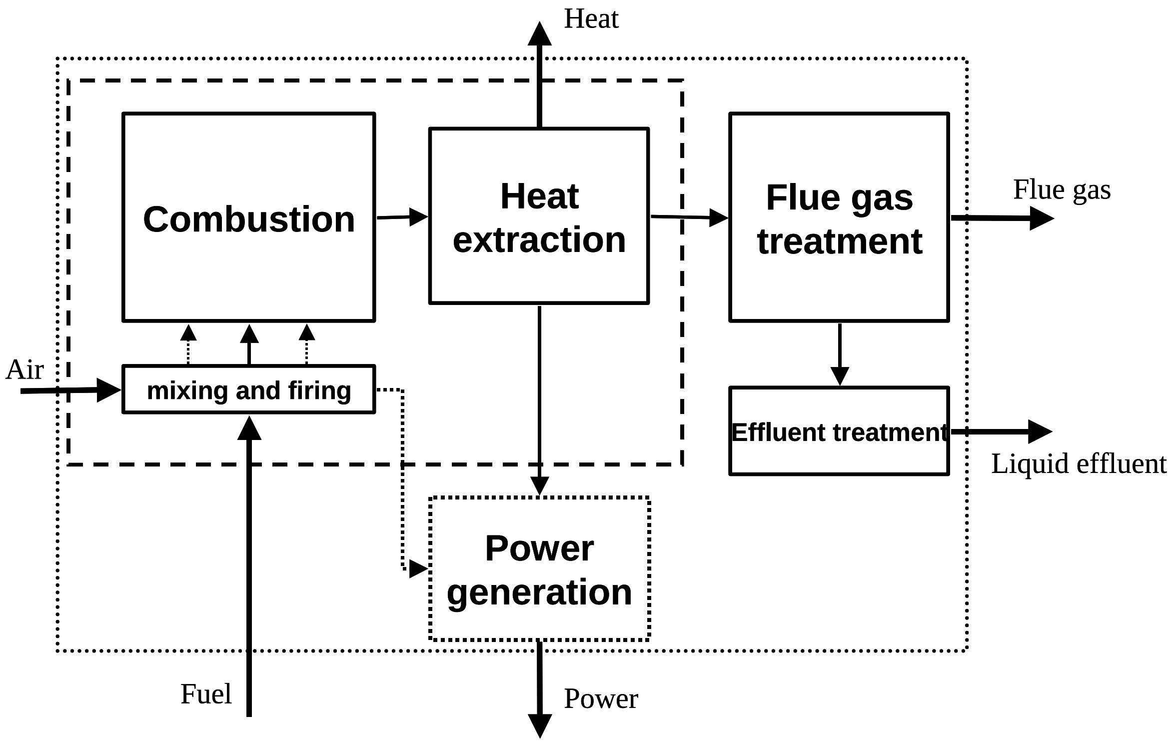

Figure 4: Schematic representation of combustion unit functions

It should be noted that some routes (such as the combination of heat and power generation) are still optional in most of systems considered here but have considerable improvement potentials. Let us follow the flows described above in order to summarize locations for increased performance. The process of fuel and oxidizing agent (usually air) mixing and firing, determined mainly by fuel type, can be greatly improved towards NOx emission reduction (optimized air-to-fuel ratio, low-NOx burners, low nitrogen content fuels, pure oxygen instead of air…). Further, the positioning and organization of burning zones (staged combustion, BOOS, re-burning…) within the combustion process are potential locations for primary NOx reductions measures, along with optimized combustion chamber design mainly based on the control of parameter such as residence time of flue gases and mixing. The energy extraction processes, which are the primary functions of combustion units, can be done through different media: heat (generally hot water or steam) and/or power (generated through steam and/or gas turbines). The choices of conversion methods greatly affect the overall energy efficiency of the system (from 30 percent to nearly 90 percent), but also, from a NOx intensity perspective, the combustion-to-output-ratio, directly affecting the NOx intensity along with other pollutant and emission intensities. Flue gas treatment is the last opportunity for a reduction of emissions within the system. Two main designs are operative for NOx flue gas treatment, SNCR and SCR, and have variable operating conditions, costs, and abatement efficiencies.

There are various ways of tackling NOx emission abatement. Systems' thinking provides a useful framework for the exploration of many options, in a more extensive and possibly integrated manner. Historically, pollution prevention has been mainly concerned with an end-of-pipe approach (EOP) in its beginnings. Resource use constraints systems approach and cost-effective pressure have progressively led towards more Clean Production approaches (CP) and integrated pollution prevention systems. In the case of NOx control technologies, and more generally air pollution prevention technologies, EOP solutions consist of flue gas treatment and CP consist of all the measures taken upstream of the exhaust gas conduct.

Table 1 synthesizes the above description and discussion in a classification of NOx reduction technologies with respect to their positioning along the functional components of a combustion unit.

Nature of technology	Position along the production stream: Input flows	Firing and mixing	Combustion chamber	Flue gas treatment
Hardware	Premixing of fuel and air	Low-NOx Burners	SI/ WI	SCR
		Catalytic Combustion	Burner positioning	SNCR
			Reduced residence time	Electron beam
			Cooling of Flue Gas	
			Heat extraction	
			Flue Gas Recirculation	
			Staging (air or fuel)	
Software and "Orgware"		Primary air/fuel trimming	Secondary air/fuel trimming	
			Tertiary air/fuel trimming	
			Burners-Out-Of-Service	
			Fuel biasing	
			Reburning	
Other	Fuel change			
	Oxygen instead of air			

Table 1: Classification of NOx reduction measures

6 MAIN RESULTS AND DISCUSSION

This section presents results from the analysis of country-wide plant data and field interviews in accordance to the framework elaborated in section 2. A first sub-section presents general evolution patterns of the energy production units subject to the REP scheme. A set of structural and NOx abatement specific drivers for these shifts are then identified in sub-section 6.2. A third sub-section explores abatement technology choices within the system, and factors affecting these choices. A last sub-section is concerned with analyzing to which extent the supply side has responded to signals related to the policy incentive. Throughout the whole analysis, an effort has been made to reveal system complexities at many levels, from macroscopic to individual plant-specific considerations.

6.1 Evolution of NOx emissions and identification of group dynamics

This sub-section is mainly intended to explore the macroscopic evolution of the system of analysis, focusing on its average and aggregate performance in terms of emission intensity and total emissions. Additionally, some differences observable through the use of analytical filters (such as size and sector) are explored at a “meso”-level.

Figure 5 shows that, in 2005, total NOx emissions from plants subject to the REP have amounted to around 14 kilotons, nearly as much as in 1992, when the scheme was started. Total emissions have fluctuated, but have not really been reduced as a result of the scheme. Even when taking into account that the number of participants has grown - that is, considering only emissions from firms targeted from 1992 (producing over 50 GWh of useful energy per year) - there has been no visible reduction in emissions. Contribution in total emissions of smaller plants remains below 15 percent.

The output of useful energy from participating plants has, however, increased by more than 70 percent from 1992 to 2005,[52] which indicates a strong decoupling of NOx emissions from energy output. Indeed, had the emission intensity remained the same over the years, an increase in total emissions of about 70 percent from 1992 levels

[52] In 1992, total energy reported was about 37 TWh, whereas it was above 60 TWh since 2002 (around 65 TWh in 2005).

would have been observed.[53] Therefore, the focus is here set on emission intensity as a measure of performance instead of total emissions.

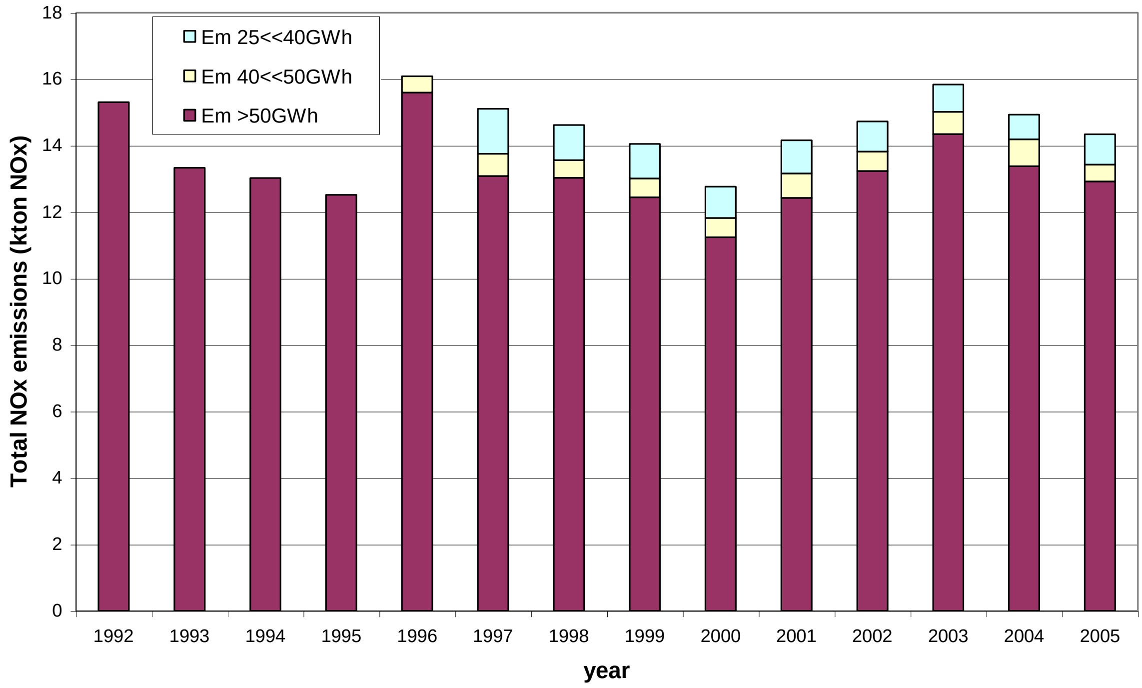

Figure 5: Total yearly emissions, contribution from different size groups (elaboration on data supplied by Naturvårdsverket)

Figure 6 presents the evolution of emission intensities over the years (i.e. the average of plant-specific emission intensities, regardless of size). Over the period analyzed, and for which data is available, NOx emission intensities have declined. Indeed, average emission intensity has evolved from above 0,4 kg NOx per MWh of useful energy in 1992 to roughly 0,25 kg NOx/MWh in 2005. This has been achieved despite the enlargement of the scheme to smaller units in 1996 and 1997. This indicates that on average, combustion units included in the REP scheme have increased their performance over the analyzed period.

Another interesting trend – maybe more representative at the national level – is what is referred to as "aggregate" emission intensity, i.e. the yearly ratio of total emissions by

[53] This figure may have been slightly lower in reality, when assuming that new capital stock necessary for the projected enhanced output and the renewal of outdated capital infrastructure would embody cleaner technology than the installed market average.

total useful energy production.[54] This indicator considers the whole polluter collective as one single system, and informs about its aggregate performance level. It has decreased more than the average intensity, indicating underlying scale issues.[55]

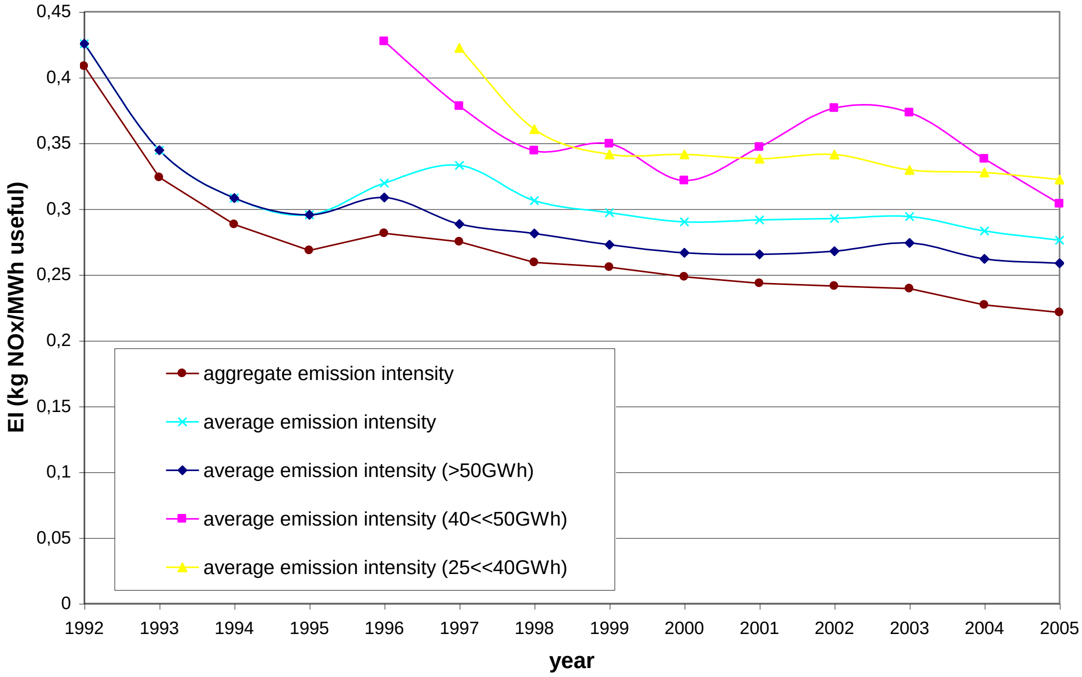

Figure 6: Emissions intensities

(elaboration on data supplied by Naturvårdsverket)

The rate at which emission intensities have declined doesn't appear to be constant over the analyzed period. Indeed, rapid reductions (of about 30 percent) occurred during the first 3 to 4 years, and seem to be levelling-off after that, as if the potential for reductions had been weakened[56]. This phenomenon reproduces itself for units within the different thresholds, although the amplitude of the reductions is lower and smaller units don't seem to reach the same performance level as bigger units once levelling-off has occurred.[57] Progressive capital stock renewal[58] and the homogenization of performance (discussed below) are potential explanatory factors for this loss of velocity in the

[54] Aggregate emission level also corresponds to the "virtual" performance limit between net payers and net receivers.

[55] Scale issues are discussed below.

[56] Some observers may, however, notice that, on the aggregate level, emissions intensities are continuing to decrease.

[57] An interesting aspect to investigate would be whether this levelling-off has been associated with a rather static repartition of revenues (units keeping their "position", static stratification).

[58] The role of capital stock renewal (replacement) is presented in section 2.1.3.2 and further discussed through sections 6.2.1 and 6.3.2.

average increase of performance. This trend can also be seen as an indication that further reductions would require a raised charge level, which has been claimed by industrials interviewed (Johansson, 2006), but also in a SEPA inquiry (Natuvårdsverket, 2005). The raise of the charge level can be expected to occur after 2008, depending on the lengthiness of administrative processes.[59] There is definitely an argument according to which a cost-effectiveness limit has been reached for most of the plants operating within the scheme and that further improvements, on average, are slowed down by the limited number of remaining potential adopters of technology at current market prices and given their access to it. Still, emission intensities are ameliorating, although not at the same rate as in the first years.

If the focus is driven towards an increased level of detail, beyond national averages, increases in performance appear not to be uniform, which sounds to be a reasonable consequence of a scheme designed to first achieve abatement where it is feasible at least cost. Standard deviation of individual unit NOx emission intensity has decreased from 0,22 to 0,15, which indicates that performances tend to homogenize on average. Figure 7 allows an explicit demonstration of the historical process of homogenization of firm level performances. Firms have been classified in arbitrarily defined performance ranges.[60] The yearly curves represent the cumulative useful energy production of firms within each range, thereby providing a measure of total contribution of both useful energy (output), and NOx emissions. There is a clear tendency towards lower emission intensity (as the curves shift to the left year after year), and of increased output. Between 1992 and 1993, there was a noteworthy shift from a two-tiered performance group to a single group with enhanced performance, indicating a direct effect of the policy instrument in driving the system towards increased performance. Another striking fact that can be observed from the cumulative figures is that the increase in output (rise of curves) is progressively operated within a lower emission intensity window (narrowing to the left), ranging from 0,1 kg NOx/MWh to 0,4 kg NOx/MWh, representative of a general homogenization trend.

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[59] Fredriksson and Sterner (2005) point out that REP schemes can even foster situations where “relatively clean firms may lobby for a higher pollution tax rate”. This argument is relevant with respect to the initial high charge level, but also to the recent discussions of a raised charge level.

[60] The range size has been defined as 0,1 kg/MWh.

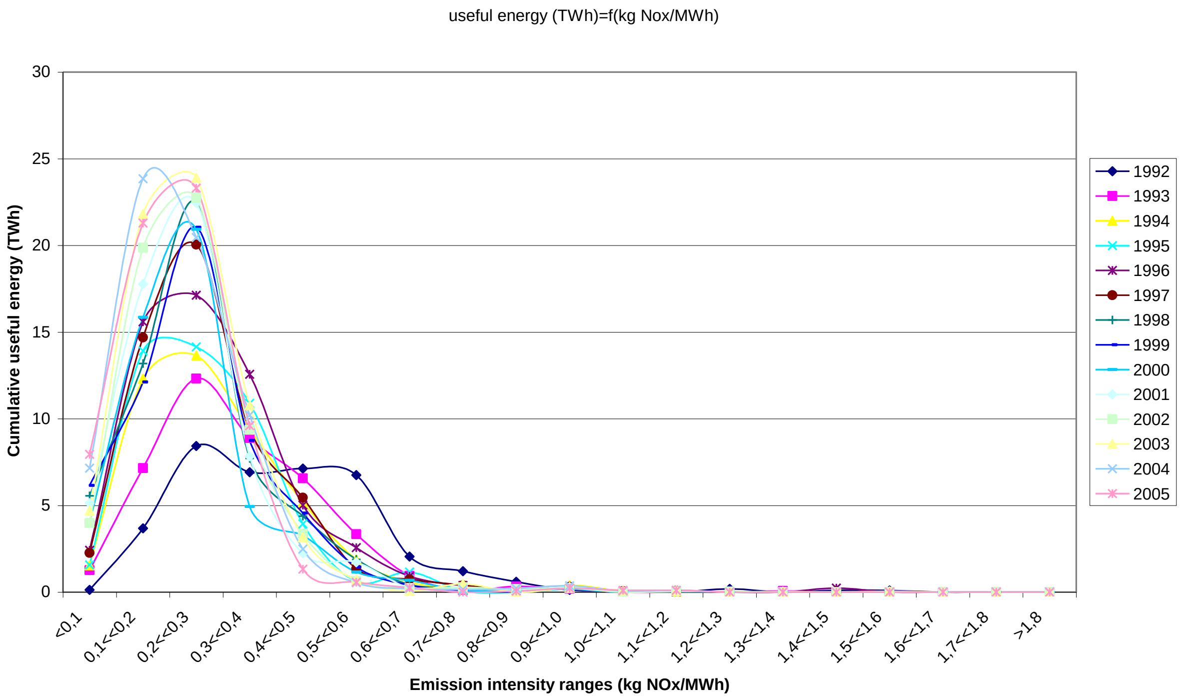

Figure 7: Cumulative useful energy output from different emission intensity ranges, yearly curves (elaboration on data supplied by Naturvårdsverket)

Individuals operating within the system of analysis, however, still demonstrate a high degree of heterogeneity. Given the availability and intelligibility of the data, the variability of performance can be related to many different factors[61] allowing the definition of "meso"-level groups. Here, however, only size and operating sector are briefly explored.

From this "meso"-scopic perspective,[62] size appears to be an interesting factor influencing NOx emission intensity. The history of the REP scheme itself indicates that scale has been an issue, since firms with lower useful energy production have been introduced later on. This has been claimed to be due to decreasing monitoring equipment[63] costs, which are estimated at around 30 000 SEK for the minimal full equipment following Naturvårdsverket's requirements (Sjögren, 2006). The most trivial abatement operations such as fine-tuning of combustion conditions require monitoring

[61] See the discussion of parameters affecting the adoption of air pollution abatement technology in section 6.3.2, and the technology review (Section 5) for arguments.
[62] That is, here, without getting down to individuals, but rather considering large groups or classes of individuals.
[63] It should be reminded that monitoring equipment refers to direct measurement of emissions.

equipment for effective control. The diffusion of NOx monitoring equipment appears in that sense to have led to decreased costs allowing its further diffusion to smaller units with reduced financing capacity. Still, however, it appears that average NOx emission intensities have remained higher for smaller units than for bigger ones, which indicates the existence of an underlying scale effect when it comes to abatement potential.[64] This distinctive phenomenon can be observed beyond the few years following entrance within the scheme. Scale will further be investigated as a barrier for the diffusion of abatement technology in section 6.3.2.

The plants subject to the REP operate within various industrial sectors. Variability of performance levels with respect to sector can be investigated. Figure 5 in Naturvårdsverket (2006) shows how all seven sectors of activity have on average reduced their emission intensity. It appears, however, that the pulp and paper industry and the timber industry lag behind of the other groups. The chemicals industry also shows higher NOx emissions intensities on average. A result of this is that they are the only groups that are net payers on average in 2005. This indicates that there are structural differences between sectors with respect to their ability to increase their performance levels.

In sum, the analysis of changes in performance of the combustion industry at the macroscopic level shows a strong decoupling of NOx emissions from useful energy production (stable total emissions while increased useful energy production). There are, however, signs of a levelling-off of this tendency, which raises doubts with respect to limits to development within the current setting. A high degree of heterogeneity motivates the investigation at an increased level of detail, at the “meso”-level, and the observation of extractable group dynamics.[65] It comes out from this analysis that different behaviours can be extracted from groups based on output size or operating

[64] An important warning concerning this statement is that unit “size” is here used with respect to yearly output of useful energy. Therefore, the so-called “small” units can in reality be rather high capacity units with low load factors (i.e. small number of operating hours per year), operating on the margin to supply peak demand. Taking this into consideration, the scale effect can be of different natures. On the one side, indivisibilities of capital or labour investments necessary to achieve more than a given amount of abatement may favour larger combustion units (“traditional” scale effect). In other cases, low intensity of use of a combustion unit (for instance to provide energy “on the margin”) can justify both its low output of energy (defined as “small” size) and the negligence of the operators with respect of NOx emission reduction.

[65] These groups bare physical and/or theoretical meaning.

industrial sector.[66]

6.2 Determinants of NOx intensity changes

This section is concerned with defining determinants that can explain the observed NOx emission intensity trend. The focus is first put on the identification of long-term structural changes that the industry is undergoing, that have an impact on emission intensity. Secondly, motives for intentional reductions - that is investments in identifiable NOx reduction technologies and/or practices - are investigated at firm level.

Individual variations of NOx emissions can arise from different processes. They can be the result of clearly identifiable investments in abatement technology, but also spillovers (side-effects) from other operational management decisions (structural equipment renewal, input shifts, operating conditions, enhanced control and training of personnel…). Following this argument, a further distinction can be made with respect to the intentionality of the reduction. Let us operate a distinction between indirect NOx reductions (mainly spillovers from other structural changes), and direct NOx abatement strategies (clearly identifiable as such).

6.2.1 Structural changes as determinants of performance

It has been discussed in section 5 that a number of external parameters can affect the chosen performance indicator, NOx emission intensity. It is therefore necessary to consider a set of structural changes that may have influenced NOx emission intensity, but cannot be considered as intentional abatement measures. In the particular case of the Swedish combustion energy sector, three major long-term structural trends are here of importance to consider: a) the growth of biomass burning and other fuel switches, b) improvements in overall energy efficiency of energy extraction (raising conversion efficiencies, reduction of losses, increased share of joint heat and power extraction), and c) a progressive modernization of the combustion system through the replacement of stokers by CFBs, for instance.

a) The growth of biomass and other fuel switches

Fuel choice can affect NOx emissions, as presented within the section dealing with

[66] This extraction of behaviours could be performed with other criteria, such as fuel, combustion structure, age, among others.

technology options. The reasons underlying fuel switches are not considered as being directly related to NOx abatement. Issues related to fuel choices, be they in response to local conditions or cost-effective process requirements, can greatly influence the performance in terms of NOx intensity (positively and negatively). For instance, a steel manufacturer operating three of the better power plants in the scheme disclosed in an interview that their performance was not related to specific NOx abatement measures but was a consequence of the combustion of rest gas from the blast furnaces (Gustavsson, 2006). Other fuel switches mainly arise from carbon policies, process-specific pressures or reasons related to cost-effectiveness.

Figure 10 in Naturvårdsverket (2006) presents the contribution of various fuels to the total useful energy production of the system over the years 1992 through 2005, providing a striking evidence of the growing use of biomass,[67] while the combustion of other fuel types remains rather stable. The increase of biomass burning is mainly a consequence of stringent CO_2-reduction targets,[68] which have driven the focus towards "carbon-neutral" substitutes for "carbon-intensive" energy carriers (such as coal). Considering emission intensities of various combustion fuels, biomass burning is beneficial if it replaces "dirtier" fuels, such as some coals, oils, and peat[69].

b) Improvements in overall energy efficiency of energy extraction

The initial combustion host structure has been described as a determinant per se of NOx emission intensity.[70] The optimization of the energy pathways can greatly affect the chosen performance indicator. In that sense, recent improvements in energy efficiency and the reduction of heat losses have contributed to an overall increase in performance of the system. It should however be kept in mind that conversion efficiencies can also be increased through the use of more intense combustion conditions (raised temperature and pressure), thus increasing the NOx emission challenge. It would be interesting to quantitatively estimate the contributions of these trends to the evolution of

[67] Discussions brought up in section 5.2.3.1 should be kept in mind.
[68] Other drivers include the relative low cost of these kinds of fuels, and a search for independency from oil.
[69] From a different perspective, one could affirm that the increased focus on biomass burning has increased overall burning for energy extraction, in turn increasing potential total NOx emissions. In that sense, if biomass replaces, say, nuclear energy, or is the means to supply an increased energy demand, then it can have an overall negative impact on total NOx emissions.
[70] See section 5.

NOx emission intensity, but remains beyond the scope of this study.

c) Progressive modernization of the combustion system

Another trend of major importance and impact is the renewal of old capital infrastructure[71] and the diffusion of second-generation solid fuel combustion equipment such as FBCs. Indeed, FBCs are considered to lead to much lower NOx emissions than grate-fired boilers for the same type of fuel (Lundberg, 2006). Nevertheless, they cannot be considered to be direct NOx reduction measures, but merely second-generation combustion system for solid fuels. As revealed by Lundberg (2006), the diffusion of FB technology is driven by a will to achieve greater fuel flexibility, and optimized combustion of solid fuels. They are very practical combustion structure for the burning of coal, waste or biomass based fuels, which explains their growing demand throughout Sweden. Additionally, they achieve fairly low emissions of pollutants. Within the system of analysis, reported FB-based output of useful energy has grown from 4,6 TWh in 1992 to 20,3 TWh in 2005, contributing to respectively 12 percent and 31 percent of total system output. According to Åmand (2006), there are not many old burners or combustion equipment remaining in Sweden, and progressive replacement of outdated combustion structures has mainly been done.[72]

The complementarities of these determinants appear clearly in the specific case of biomass combustion. Here, an interesting phenomenon is the combination of recent major investments in a new innovation system (the growth of Swedish bio power) and the timing of second-generation solid fuel combustion structures. Indeed, according to tables 37 and 38 in Energimyndighet (2006), the total use of biofuels, peat etc. in industry and district heating rose by around 60 percent from 1992 to 2005, whereas the amount of useful energy extracted from biomass within the system under study has increased by more than 100 percent over the same period, which reveals that the growth in biomass burning capacity has been done through the joint introduction of new, higher performance technology and improvements in efficiency.

This sub-section has reviewed important structural changes of the Swedish combustion

[71] See discussion of capital replacement models of innovation (Section 2.1.3.2).
[72] The confirmation of this argument through the provision of quantitative data would be of interest.

system that are affecting NOx emission intensities. The next sub-section deals with the motives for NOx-specific abatement investments.

6.2.2 Motives for NOx-specific abatement measures at firm level

NOx emission is an economic externality of combustion systems. Therefore, it is not accounted for in today's production functions, except in the presence of pollution abatement and responsible production incentives. Assuming that NOx emissions reductions are primarily determined by the control technology in use,[73] let us investigate the drivers that can push individual firms to implement NOx-specific abatement technologies. Drivers for such investments can be external to the firm in the form of institutional or market pressures, but can also originate from firms themselves, under environmental management and strategy conditions. In this particular case, interviews have pointed to three main drivers for NOx emission reductions via the investment in new technology:

- Standards, defined by local and national authorities, are case-specific maximal emission levels for various pollutants and environmental externalities,[74]
- The REP scheme and the resulting economic incentive,
- Environmental management and public image of the company.

These drivers have been identified within most of the interviewed plants (although with diverging views with respect to their relative importance), but also by technology suppliers. Indeed, Lundberg (2006) revealed that Kvaerner Power, within its internal strategic decision-making relative to the further development of SNCR technologies, has pointed out these three drivers as determinant of their market. It remains, however, not an obvious task to quantitatively determine the relative weight of these drivers. The remainder of this section explores these drivers and possible ways of distinguishing

[73] Once the structural trends discussed above, this seems to be a sound assumption.

[74] Standards for NOx emission from combustion sources have been introduced in 1988. They mainly provide guidelines for technology requirements to be enforced by local authorities administering plant operation permits (at the regional level of the different Läns), in relation to technology costs and local conditions (density of existing polluting activities, density of local population and related social damage, local ecosystem…). According to discussions at Västra Götalands Länstyrelse (Barrefors, 2007), in practice, the delivery of such permits and respective emission levels are based on negotiations between the plant owner and the authorities, involving mainly abatement cost estimation and the definition of reasonable levels, in accordance to BAT. The two parties involved however do not use the same payoff times and discounting rates: authorities base their calculations on 10 year's payoff time whereas plant owner would often require less than one year's payoff time.

their relative influences.

A study of individual performance of units within the REP scheme during 2001 (results presented in Figure 8 below) has compared real emissions levels to the maximum levels required by local standards. Striking evidence is that for every unit analyzed, achieved performance exceeded the level enforced by the regulation. On average, emission intensities were about half the level of the individual standards. This indicates the existence of drivers other than the local standards for further emission reductions.[75]

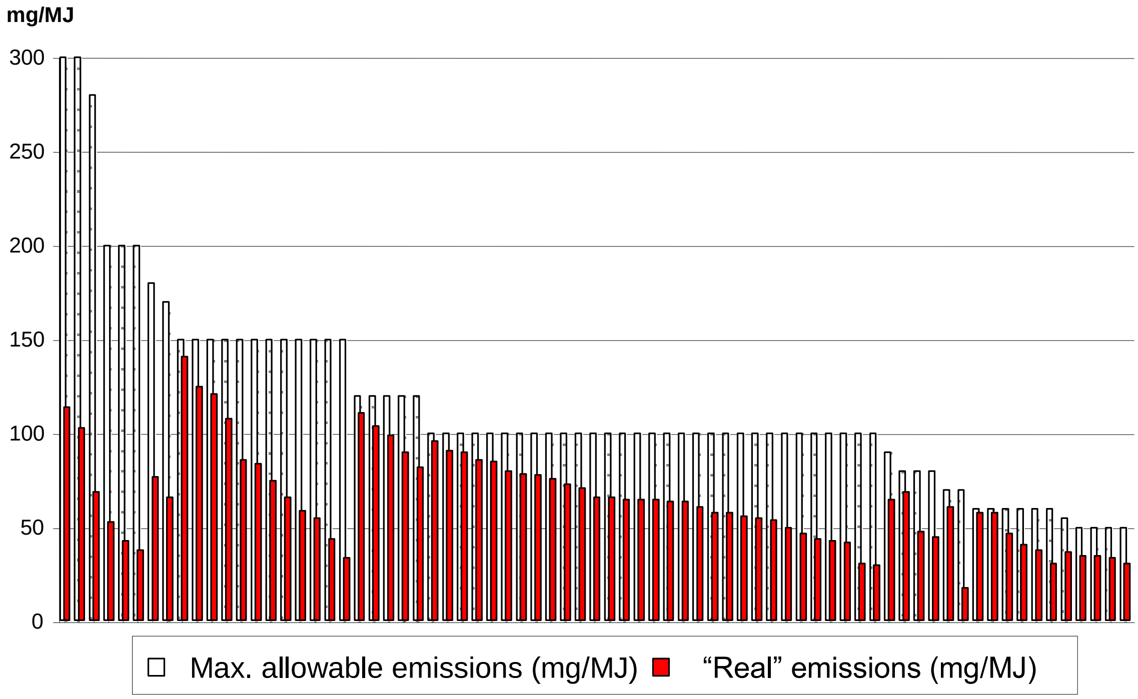

Figure 8: Comparison of plant requirements with actual performance in NOx emissions (2001)

Source: Naturvårdsverket (2003)

In Höglund Isaksson (2005), an analysis of 162 NOx-reducing measures performed over the period 1990-1996 by 114 plants is presented. It is concluded "that the NOx charge was the decisive reason to almost half of the implemented measures". Further, "quantitative standards are reported as the principal reason for 22 percent of the measures, while 31 percent are reported out of other reasons such as cost-effectiveness (that is not related to NOx-reduction) or compliance with emission

[75] A more thorough investigation of the delivery of permits, including consideration of geography, time and plant characteristics would yield very useful data for further determination of the relative contribution of various policy instruments to the increase of performance levels.

standards for other pollutants than NOx".

Discussions with Ådahl and Lilienberg (2006) have provided an interesting case, where local emission standards combined with the REP seem to have played an important role in driving NOx reduction in the very beginning (early 1990s), but sustained improvements in performance are justified by internal management and the will to provide the customer with energy with reduced environmental impact. In recent years, the competition induced by the REP is not seen as playing such an important role in shaping their strategy towards NOx emissions anymore.

Sysav, a waste incineration company from southern Sweden, achieved the lowest measured NOx emission intensities of plant subjected to the REP in 2005 with its most recent unit. Environmental and process engineers claim that these levels are tied to the environmental strategy of the firm. Indeed, the plant director seems to be greatly involved in environmental action, both in his business and internationally, in such a way that his will is to constantly achieve the best possible environmental performance (Johansson and Sirviö, 2006).

Engineers at the Renova incineration plant of Sävenäs justify their efforts towards low NOx emissions as driven by the potential income at stake, their environmental management system, but also as a sign of their assiduity to the authorities with the aim of receiving permission to operate a 4th plant (Gustafson and Alm, 2007).

The empirical examples from interviews presented above confirm the joint influence of many determinants for NOx-specific abatement investments. Additionally, they consist in evidence of the difficulty to determine the relative weight of these factors, since inter-firm perspectives are highly variable.[76]

[76] It would be useful to consider time lags between the introduction of a given technology within a firm and its first appearance within the scheme (Time lag = date (1st technology reporting) – date (entrance in the scheme)). Indeed, it can be assumed in most cases (Excluding those firms that underwent permit renewal processes during the period of interest. Renewal of emission requirements by local authorities can occur as a standard procedure (at frequencies of about 15 years), or when a major change has been done within the process.) that there has been only one permit negotiation during the presence of the firm in the REP scheme. Thus, whenever NOx reduction technology has been purchased after entrance in the scheme, it could be concluded in many cases that it has been driven by reasons other than emission

The discussion of determinants for changes in NOx emission intensities has allowed the identification of structural changes on one side, and NOx-specific abatement measures on the other. Structural trends of major importance to the Swedish combustion system are the growth of biomass burning and other fuel issues, the increased focus on energy efficiency and the reduction of losses, and the progressive achievement of capital infrastructure renewal with the generalization of second-generation machinery. There however remain large uncertainties relative to the importance of these structural drivers. Indeed, their contribution can be positive or negative on NOx emissions, and their relative weight in the industry has not been quantitatively assessed.

When it comes to NOx-specific abatement investments, the REP scheme cannot and should not be considered as a strong incentive on its own, neither from a descriptive point of view (isolation), nor in practical decision-making at the individual unit level. Rather, a complex set of drivers should be considered as pushing the pool of stationary combustion units towards higher performance standards. A reasonable interpretation is that the existence of the REP within this set of policy instruments for pollution abatement and other non-policy incentive allows further reductions than the existing structure would have achieved alone.[77] This outcome is in agreement with the initial intention of the scheme which was to "achieve a more rapid reduction of emission of nitrogen oxides than was otherwise considered possible, by relying on the administrative guidelines in place at that time, and also to provide an incentive for cost-effective emission reductions in excess of these guidelines." (SEPA, 2000).

6.3 NOx reduction choices

This section is concerned with dealing with the questions: How has NOx abatement technology diffused? What are the critical determinants of its diffusion? A first sub-section is dedicated to the analysis of reduction strategies at aggregated and firm levels, exploring the diffusion of technologies and a set of behaviours towards the

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standards (e.g. the REP and environmental management and strategy according to those identified here). The data used for this study has however not been considered suitable for this purpose as for now.

[77] Especially when considering the potential structural pressures on combustion units that may affect NOx emissions negatively.

adoption of technology. A second sub-section consists in an attempt to extract critical factors and barriers to the adoption and diffusion of abatement technology.

6.3.1 Overview of NOx-specific abatement technology diffusion

Any investment in NOx abatement technology (be it at zero or very low cost as for trimming operations) directly improves NOx emissions intensity,[78] and appears to be a strong explanatory factor affecting NOx emission patterns. NOx reductions vary greatly among the type of explicit measures taken towards abatement, be they knowledge-based, artefact-based or both. Reductions from 5 percent to more than 95 percent have in fact been achieved, depending on the type of technology used and the existing infrastructure. Radical but costly measures often yield the best results, whereas incremental measures (firing technology change, additional combustion stages…) and fine-tuning can be more cost-effective in some cases as they involve lower capital costs. Some experiences involving the simultaneous use of a selection of technologies have also led to improved performance at relatively low costs.

In order to seize the diffusion of abatement technology over the years, and to pave the way for the identification of current and future potentials, let us investigate the type of “direct” measures that have been implemented over the analyzed period. Based on yearly reporting of units within the REP scheme, and assuming that this has been generally done cautiously and honestly, it has been possible to analyze the adoption and diffusion of technologies in the form of cumulative installation curves.[79] The technologies reported include combustion measures and flue gas treatment of various kinds. Figure 9 presents selected cumulative installed technologies within plants subjected to the scheme, which allow a general view on the diffusion of readily available control technologies.

[78] Although in some cases it has been reported that the adoption of a new control technology had led to temporary increases in emissions. Only after an adaptation time that could exceed a year did emission levels drop, for staff had been formed and optimal running conditions of the new equipment had been achieved. In other cases, performance increases resulting from the adoption of a new technology appeared to be lower than expected. Sysav’s experience with FGR has proven not to be so cost-efficient as expected, which has led to the decision of not including it in the new plant under construction (Johansson and Sirviö, 2006).

[79] For this purpose, first reporting occurrences of a new control measure by participating combustion units have been assimilated to years of investment. These numbers have then been summed over years in order to provide cumulative curves.

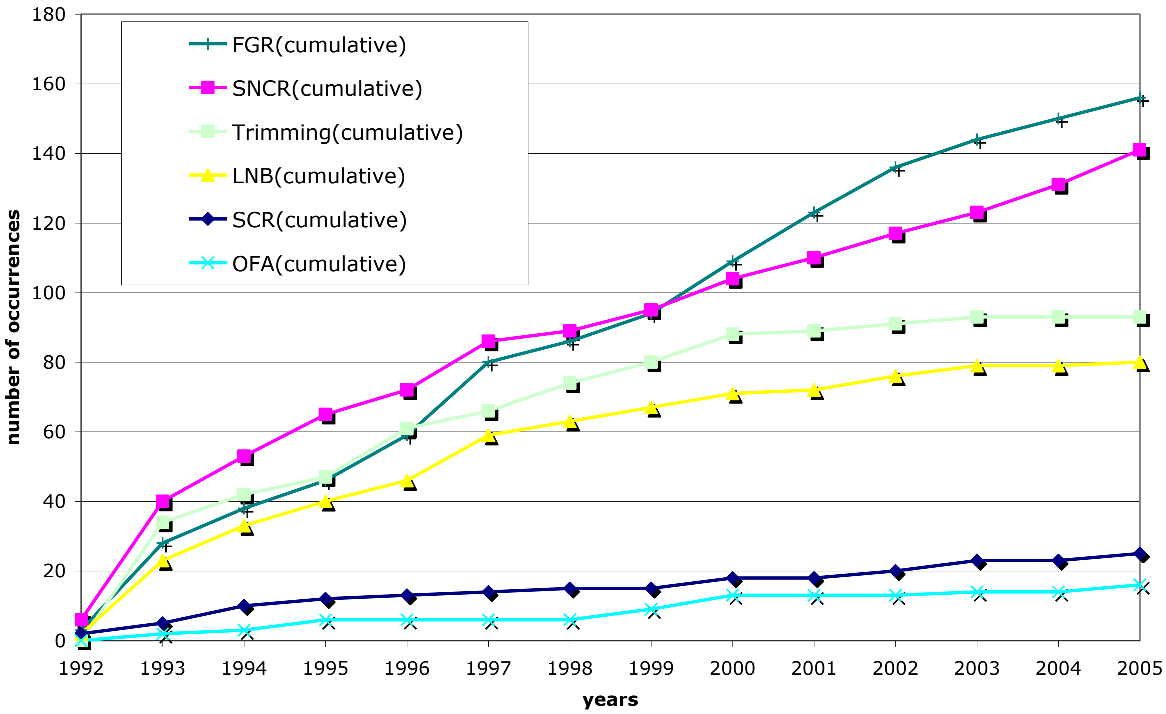

Figure 9: Cumulative NOx abatement measures (selection)[80]
(elaboration on data supplied by Naturvårdsverket)

As of 2005, 557 abatement measures have been reported by 367 units out of the 584 units having participated from 1992 to 2005.[81] Most of the reported measures have been flue gas recirculation (156), SNCR (141), trimming operations[82] (93) and the installation of Low NOx burners (80). 16 installations of SCR have been reported, which in turn makes the total number of flue gas treatment measure reported 157. Possible explanations to the low diffusion rate of SCR include the relative small overall size of Swedish combustion units when compared to, for instance, German or American standards (Åmand, 2006), and historical cases of non-optimal uses of this technology in Sweden.[83] Overall, there is no clear majority of technology choices between primary combustion measures and flue gas treatment, as their respective shares are roughly 50

[80] See list of acronyms and section 5 for the description of the technologies.
[81] It should be noted that some combustion units host more than one NOx abatement technology.
[82] The small number of trimming measure reporting is thought to be mainly due to the fact that some engineers don't consider it as a technology, but rather normal operating practice. The data used in Höglund Isaksson (2005) however concludes that about a third of the implemented measures were trimming measures, conducted at very low, zero or even negative costs, and can be used as a comparative source of evidence.
[83] Options for SCR positioning along the flue gas stream seem to be of major importance to its efficacy. "Front-end" use (before particulate filtering) is thought of as "dirty", whereas "tail-end" seems to be more optimal, but more costly for there is a need to re-heat the flue gas in order to be in the optimal operating temperature window (Kvaerner, 2006).

percent of the total targeted technology choices (if trimming measures are excluded). This figure further consolidates the assertion according to which there is no clear winner, as many competing designs for NOx abatement technology share the market.

When extrapolating current trends, it appears that the cumulative technology instalment curves seem to be continuing to grow at sustained rates and only trimming and LNB seem to have reached a potential, for their growth rates have been dramatically slowed down.[84] SNCR seems to be expanding faster than other technologies, which is a signal for a possible further diffusion of this technology. One explanation would be the transgression of a technological frontier (the adaptability to BFBs, see box 1, section 6.4), opening new applications, and expanding SNCR's diffusion potential.

It should, however, be kept in mind that the data presented here is dependent on reporting procedures, and on a pre-conceived representation of what is seen as a NOx abatement technology by the reporting agent. Typically, software-type technologies, such as training, learning, experience, and the solicitation of CFD have here not been considered. Yet, industrial experiences testify of the importance of such activities for the optimal use of existing equipment (trimming) and newly purchased hardware (learning time).

The above presented diffusion curves consist an evidence that investments in NOx-specific abatement technology have been performed continually over the analyzed period. There remains, however, a large diversity in abatement choice, as a consequence of the simultaneous existence of competing designs and heterogeneous host structures. In such a situation, it is not an easy task to assess the diffusion potential of abatement technologies, and that is also beyond the scope of this study. It would, however, be interesting to estimate the number of potential adopters and to relate the current state of diffusion to this number. It would allow a discussion of saturation, limits to a further diffusion of the current technological options. The next subsection can be seen as a first step towards the identification of the technology diffusion potential, since it qualitatively discusses determinants and barriers to the

[84] Again, these tendencies could be explained by the standardization of these technologies over time, leading to reduced reporting rates.

adoption of abatement technologies.

6.3.2 Determinants and barriers to the adoption of abatement technology

The process of abatement technology adoption is an activity performed by individuals that is tied to many factors. These factors can be internal or external the firm (arising from the interaction from the selection environment). In turn, the configuration of the system under analysis (and its declinations arising from the different possible levels of detail) presents varying attributes stimulating, but also preventing the diffusion of abatement technology. The structural heterogeneity of the pool of firms analyzed (in terms of size, sector of activity, fuel, host combustion structure, etc.) has given opportunities to explore a range of aptitudes and attitudes towards technology, allowing the identification of critical factors and barriers to technology acquisition.

It has been discussed above (Section 6.1) that firm size is a determinant of NOx emission intensity. Firm size also appears to have a great influence when it comes to implementing NOx-reducing measures.[85] Indeed, for the above-cited measures, more than 90 percent have occurred at plants targeted from 1992 (producing more than 50 GWh useful energy per year), with the exception of flue gas recirculation for which about a quarter of the installed systems in 2005 are within plants producing less than 50 GWh useful energy per year.

[85] David (1969) developed a threshold model of innovation adoption, relating likelihood of adoption to firm size. He showed that the mechanical reaper remained unprofitable below a certain acreage - which he referred to as the threshold farm size - and therefore wasn't adopted and traditional reaping technology prevailed. Eventually, decrease in capital investment cost and/or exogenous factors affecting individual revenues move the threshold downward and further adoption by “smaller” adopters becomes possible.

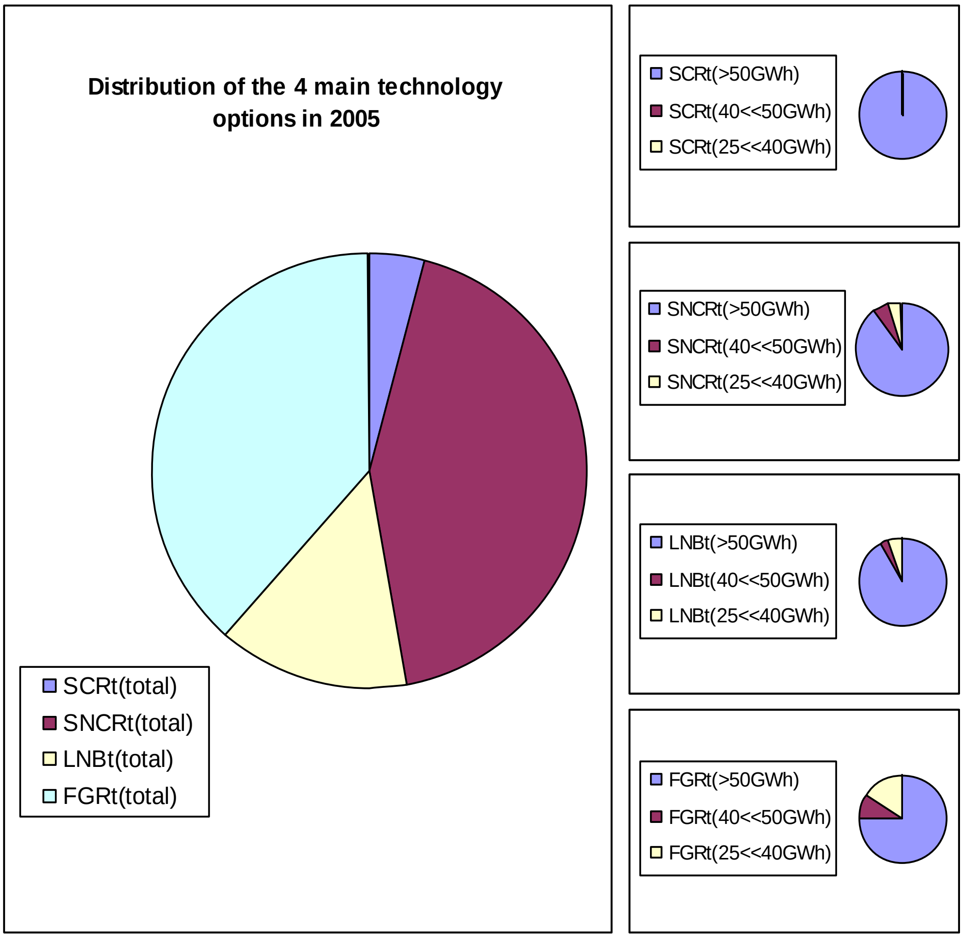

Figure 10: Distribution of selected technology throughout size classes (2005) (elaboration on data supplied by Naturvårdsverket)

Figure 10 presents the distribution of 4 selected technologies in 2005. The relative weights of the 4 selected options are presented on the left-hand side, while the four boxes on the right-hand side show distribution through size thresholds of the various selected options. These provide striking evidence that most of NOx-specific abatement technology adopters have been firms of larger size. SCR has still not been diffused throughout units producing less than 50 GWh of useful energy per year (a closer glance at the data shows that the apparent threshold for SCR is even higher, close to 100 GWh/year). SNCRs and LNBs have only weakly diffused in the lower size ranges, whereas a quarter of the FGRs have been installed in units producing less than 50 GWh/year.[86] The scale sensitivity of adoption is tied to many reasons. One reason is

[86] The figures presented here should however be complemented by the proportion of the population within the different size classes. Indeed, in 2005, out of the 411 units, 70%, 9% and 21% of the population

related to the availability of fitted cost-effective technology for the different size ranges. Capital goods suppliers providing systems such as SNCR confirm the non-linear relationship between capital investment and boiler size, giving bigger units a competitive advantage over smaller combustion units. Smaller utilities, because of their reduced turnover, suffer from lower financing capacity and longer payback times, which can further explain the few purchases of this kind of equipment. According to Foster Wheeler (2007), Swedish market history (especially when considering the 1990s) shows that public-owned or partially public-owned boilers tend to be of larger size, which would tie ownership to size, and thus performance opportunities.

Another argument, first developed by Mansfield (1963), states that smaller firms are more risk-averse than larger ones. Indeed, experience shows that later adoption of technology can involve reduced risks for its potential and performance has already been demonstrated.[87] Section 6.4 discusses the supply-side point of view, pointing out necessities for large scale demonstration projects if the new technology is to be widely and rapidly diffused. A delay between the availability of a given cost-effective technology (that is both in economic and technical terms) and its massive diffusion is to be expected.

Access to knowledge and competencies is of major importance when it comes to implementing abatement strategies. NOx reduction technology choices have been discussed as involving complex optimization procedures, which suppose a degree of interest and involvement from firms. Access to information from external sources, and, thus, the increase in abatement opportunities, can be biased by various factors internal to the firm, such as its size. A company owning many combustion units yields, for example, increased returns from information collection procedures for the accumulation of knowledge and reduction of risks is allocated throughout its many units. An illustration of this has been provided during an interview at Renova (Gustafson and Alm, 2007). The Sävenäs site hosts three incineration units of similar capacities, acquired at

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had a yearly output of more than 50 GWh, between 40 GWh and 50 GWh and between 25 GWh and 40 GWh, respectively. According to these numbers, there was, in 2005, no real sign of size-heterogeneity of adoption of FGR. The adoption of the other technologies seems to be scale-sensitive.

[87] This relates to Rogers' identification of groups within adopters with respect to timeliness (see section 2.1.3.2).

different years, but using the same NOx reduction technologies (built-in FGR and SNCR). The success resulting from the first installations (1994) has clearly influenced their choice for investment in new equipment performed in 2001. Additionally, investing in the same technology for all units has allowed focusing and intensifying the internal learning procedures and optimization projects when it came to the use of these technologies (Gustafson and Alm, 2007). The structure and organization of labour (number of dedicated personnel and degree of involvement), or simply strategy towards pollution abatement and environmental questions (integrated pollution prevention, system thinking, environmental management systems…) are other internal factors influencing information collection, and thereby the absorptive capacity of a firm.

Beyond a strict microscopic focus on the individual firm, it has to be acknowledged that technology development is a collective process, relying on many components, agents and their relationships that can be considered as being within the selection environment of firms. In order to overcome external barriers to technology development (such as limited access to information and competence, risks and uncertainties relative to a new technology), companies within a given industrial activity make use of established bridging organizations to enhance inter-firm collaboration. In Sweden, the association of waste treatment activities[88] provides an interesting example of this type of organization and the active role they play in technology development process for combustion plants. Indeed, in opposition to the common belief that the competition arising from the REP scheme would push firms to retain their information with respect to technology, Avfall Sverige provides large opportunities for information sharing. In practice, plant operators are given opportunities to share their knowledge and experiences, which in turn leads to the allocation of efforts throughout the collective of firms.[89] This activity-focused cluster is enabled with cost-effective approaches to technology development processes. This is in accordance with literature in innovation studies, with its recognition of interaction, interdependence and blurred boundaries between actors in the formation and diffusion of technical knowledge (Bergek *et al*., 2007). Technology development therefore also happens and evolves through channels that can be described as being situated at a

[88] Avfall Sverige, former RVF (Svenska Renhållningsverksföreningen).
[89] Professionals refer to Avfall Sverige as a “big family”, where everyone knows each other and confront their individual problems, solutions and experience. They also share a common vision of their activities and the platform gives opportunities for the development of projects.

“meso”-level, external to the individual firm, between individual actors and the whole market.

As stated earlier, capital-intensive goods tend to be replaced once their lifetime has expired rather than being upgraded. This cyclical process is of major interest for the analysis of technology adoption, especially in such capital-intensive industries with such lasting assets.[90] There are, however, positive and negative consequences of capital replacement procedures in terms of pollution abatement strategies. As identified through discussion at Industri Teknik Bengt Fridh AB (Johansson, 2006), the expectations of new machinery equipment purchasers in terms of technical performances (here of interest NOx emissions) are rising with time. Nevertheless, lasting physical assets may also constitute an additional barrier to a faster adoption of new technology, and only relatively older units may be keen to invest in radically improved technologies since their previous investments have been paid back. It is, however, not a simple task to investigate capital expenditure cycles at a macro-level. At the micro-level, there is evidence of both incremental technological change (independent from capital stock renewal) and radical technological change (potentially tied to capital stock renewal). An analysis of time lags between installation of a new plant and first technology declaration could allow an assessment of whether capital renewal assumptions are of any interest as adoption explanatory factors. The accuracy of the available data has, however, been a restriction to this operation until today.

From the analysis presented here, a set of determinants to the adoption of NOx abatement technology have been identified. Firm size appears as having a large impact on abatement investments. Indeed, for a given technology, larger units are relatively more likely to adopt than others (except for FGR). This can be explained by the existence, among other factors, of capital indivisibilities of equipment (non-linear progression of costs with respect to scale). Further, smaller firms have limited access to information and competence, which are key determinants of their absorptive capacity. Cooperation and information sharing, through bridging organizations for instance, however are effective means to reduce those barriers. Finally, investments in abatement technology are not strictly independent from other investments, and are

[90] The standard lifetime of a combustion unit is between 30 and 40 years.

often tied to predefined capital renewal cycles (in accordance with the lifetime of the host structure).

6.4 Supply-side response

This section is concerned with exploring to what extent the REP has fostered the development of new technology by the supply side. Discussions with technology providers have allowed grasping dynamics of technological innovation over the years. Knowledge-based measures such as trimming that are *per se* performed within the operating plant and don't require the introduction of hardware apart from monitoring equipment are here excluded.

One important aspect of the technologies discussed here is that they usually require high amounts of capital investment. Indeed, most of them consist of changes in the combustion chamber, or in the flue gas conducts. Technologies such as flue gas recirculation and flue gas treatment can be retrofitted, but interviews with professionals have revealed that this usually results in higher costs that when these are integrated into initial plant design. Some machinery suppliers have explained that retrofitting is rarely performed (Johansson, 2006). Lundberg (2006), however, provides many examples of retrofitting of old boilers with SNCR technology provided by Kvaerner Power. For operations such as burner replacements,[91] plant operators tend to ask for better performing ones at the same prices. Most of the interviewed machinery suppliers have noticed an increasing demand for products integrating better NOx performance over time. This a clear sign of higher pressures set by the domestic market on the technology providers, forcing them to push both technical and commercial limits further downwards in scale.

Box 1 traces the story of SNCR developments within Aker Kvaerner Power's (a boiler manufacturer) basic plant design, providing an ideal example of technology development process and related informational and organizational networks/flows involved, relying largely on the support of a much larger innovation system where research, universities, and demonstration capacity are central. Another specificity of this case is that SNCR technology is a highly "visible" technology provided for NOx

[91] Burner replacements are done for reasons such as major changes in fuel type, or outdated equipment.

reduction, in the sense that it is meant strictly for this purpose (and therefore clearly fits the criterion of being a NOx-specific abatement technology using the terminology introduced in sub-section 6.3.1). The timing of innovation or invention procedures and the context in which they emerge appears to be a crucial factor influencing the success of such activities. Indeed, the example above is a clear demonstration of the opportunities created from a well-planned strategic management combined with providential contextual factors such as the creation of a market through the introduction of strengthened policy instruments. Additionally, successful full-scale demonstration has allowed for reduction of scepticism with respect to performance uncertainties tied to a new design.

At Foster Wheeler, another boiler manufacturer operating on the Swedish market, research and development activities (investment in the research process) have been pointed out as costly activities (Foster Wheeler, 2007). Therefore, the creation of entirely new technology is rare and most of the developments consist in improvements of existing structures. Usually, the improvement process or the development of a new product are done through the following steps, in an iterative fashion:

- Problem identification (driven by market needs or from a visionary idea)
- Potential solution,
- Development of potential idea(s) to solve the problem at stake,
- Theoretical study (digging in the knowledge base), mainly patent screening, literature reviews. This process involves different competence and information sources. Depending on problem at stake: modelling in order to improve mechanical structure.
- Earlier there was a lot of testing (now this tends to be replaced by the increasing use of CFD)
- Testing on models, slipstream size.
- Demonstration plants pave the way to diffusion of a new improvement once it has been approved and demonstrated.

Box 1: The development of SNCR at Kvaerner Power:

Kvaerner Power is the section of the machinery supplier Aker Kvaerner concerned with power generation. EnCoRe deal with all boiler supply at Kvaerner. They sell boilers, evaporators and services to the combustion industry. Customers are mainly originating from the Pulp and Paper, and Heating and Electricity sectors (e.g. community/municipal heating). Boilers sold by Kvaerner Power are rather big (15-20 MW). Smaller units (5-15 MW, mainly for oil firing) are provided by a sub-company, Veå. Kvaerner Power provides 3 major boiler technologies: BFB, CFB and Recovery boilers (specific for Pulp and Paper).

In 1989, SNCR technology, which had been provided by Fueltech at the time, was being tested within Aker Kvaerner labs as a potential future part of their range of product options. A large research cooperation program had been started in 1990 with the help of three different neighbouring universities. Main outputs from this program were modelling and full-scale tests of SNCR technology potentials. The research focus was mainly improvements and influences of different additives on the performance of the system, and large-scale demonstration projects.

From this base, Aker Kvaerner mobilized in-house engineering capacity in order to develop an effective, optimized use of SNCR within their machinery, in an integrated manner. Problems of major importance were by then optimal ammonia injection positioning and corresponding flows. Multi-variant modelling was done using CFD technology during this solving process.

Kvaerner Power was able to deliver its first boiler equipped with SNCR treatment in 1991. At that time it was only commercially available for CFB boilers, but in 1997 the first BFB boiler was retrofitted with SNCR.

Three factors are considered as having jointly contributed to this success story: the timing of research developments and plant-scale demonstration projects, the absence of royalties on SNCR technology since the patent (owned by Exxon) was freely usable by then, and the emergence of a potentially strong market in Sweden.

Another strong business advantage is considered to be the extensive service provided by Kvaerner thanks to the in-house competence, providing the fitting service and adapting SNCR hardware to very specific conditions.

Future and research needs are considered to be set on how to adapt SNCR technology to more harsh conditions (smaller boilers, larger variations in temperature…).

Source: Lundberg (2006).

Partnerships with universities and research institutes (e.g. VTT Technical Research Center of Finland, Tampere University of Technology, Chalmers University of Technology, Stuttgart Technical University…) are very central to most of the research and development steps, theoretical as well as practical and testing steps. Indeed, they provide knowledge, testing facilities and activities, which seem to be in phase with the model developed in Kline and Rosenberg (1986), where many feedbacks loops and knowledge mobilisation are operated. An effort is, however, made in order to keep most of the knowledge in-house, through the strategic use of contracting and patents.

The creation of a new product takes several years in the machinery supply industry. It is an uncertain activity. Dealing with risk and the necessity to legitimize products remains a strong barrier to the development of new products with enhanced performance within an industry with very discrete deals. Some ideas prove to be very successful (compact CFB, patent for SNCR with "slipkiller" catalyst), but some others, such as their Fluxflow (CFB waste heat boiler 80s-90s), appear not to have received the same enthusiasm.[92] As a consequence, there has not been a profusion of great inventions or leaps ahead of technology within NOx control in the recent years (at least for distribution within the Swedish market). Rather, improvements of existing products, integration to standard designs of existing technologies have been a general rule. This is a consequence of the particularities of the NOx control problem, which are that it is hard to tackle given the requirements of combustion systems and the emission of other pollutants. The supply industry has adapted in providing more and more integrated pollution control solutions for combustion units, simultaneously not neglecting the main requirements of their customers, fuel flexibility and increase energy efficiency. Another interesting and central trend of the provision of technology has been making abatement technology available on a larger scale, with the progressive integration of advanced technology for a larger range of host combustion structure types and sizes, through product development focused on diversification and down-scaling of demonstration plants (see box 1 and the extension of SNCR from CFBs to BFBs for an example). These efforts can allow overcoming the apparent limitations of the technology and increasing the population of potential adopters, opening gateways to further abatement improvements in the long

[92] About ten items have been sold, and the product didn't seem top be so successful, and certainly not profitable when looking back to the research investment made.

run.

The machinery supply industry appears to have adapted to raised customer standards emanating from, among others, higher institutional pressure affecting the Swedish market for combustion machinery (out of which the REP). Discussions with engineers from Kvaerner (Lundberg, 2006) and Foster Wheeler (Slotte and Hiltunen, 2006) pointed to the importance of localized ambitious environmental policy schemes, namely in Sweden and California, in the creation of advanced local markets in the beginning of the 1990s. Their understanding of these rising markets and responsive efforts to innovate in order to supply adequate products have given those companies early-mover advantages in international markets according to the Porter hypothesis (Porter and von de Linde, 1995).

The creation of an innovative policy scheme has fostered competitive advantages for responsive suppliers, who have achieved to develop new technologies and to further develop their existing products towards more availability, thereby reaching a wider range of customers. These developments are risky, knowledge-intensive and rely on existing structures and networks, involving research institutes, universities, as well as customers.

7 CONCLUSIONS AND FURTHER IMPLICATIONS

Focusing on a case study of the Swedish Refunded Emission Payments on NOx emissions from stationary sources, the present study was intended to investigate the links between environmental policy and technological change. This section provides a highlight of the main results as answers to the research questions in a first sub-section. A second sub-section is built from these results, exploring policy implications.

7.1 Summary of result

Investigating relationships between environmental policy and technology development is a complex issue. This complexity presents many facets and is embedded at many levels. A framework based on the legacies of different academic fields and the exploration of their inter-linkages and possible overlaps has here been developed in order to explore these complex dynamics. It is also acknowledged that in order for this study to be useful, and not to lead to a merely disorganized and disorienting wandering between different viewpoints, there is a necessity for the reader to be guided throughout this multidimensional world. Therefore an effort has been made to clarify the perspective taken for every argument throughout the analysis, in an effort to put the light on their links.

The purpose of this study has been to analyze how and the extent to which the REP policy scheme has stimulated the creation, diffusion and adoption of new control technology in this particular case. The four secondary questions and their answers are reviewed hereafter.

1. *What characterizes NOx emissions evolution over the analyzed period in Sweden under the REP?*

The REP is an innovating policy scheme inciting Swedish combustion units to improve their NOx emission performances further than what is prescribed by regulations. Since its introduction in 1992, it has fostered a strong decoupling of NOx emissions from the production of useful energy. Indeed, a 70 percent increase of useful energy output of the system has not led to a rise in total NOx emissions. Improvements of performance have, however, levelled-off relatively early, indicating a limitation of the current setting.

A more detailed analysis reveals inter-firm heterogeneities in abatement. Firms can be classified into “meso”-level groups based on size or industrial activity, for instance. Smaller units tend to achieve lower performance on average, indicating that scale matters when considering access to raised performance, while performance through different activity sectors also appear to be heterogeneous.

To summarize, there has been a strong decoupling of emissions from useful energy production over the analyzed period. The decoupling rate is however levelling-off and presents inter-firm heterogeneities.

2. *What are the main determinants of the changes in emission intensity?*

Changes in emission intensities can be attributed to structural determinants on the one hand (increased efficiencies, fuel switches and the progressive shift towards second-generation machinery), and NOx-specific abatement strategies on the other. The general trend towards increased energy efficiency and heat loss reductions can lead to reduced emission rates through a raise in output per input ratio, but intensification of combustion for the same purposes can lead to increased emissions. Fuel switch towards cleaner fuels (coal → oil → gas) as well as the growing use of biomass also have an impact on emissions. While substitution of dirtier fuels has a positive impact on emissions, the substantial increase of biomass use within energy system in Sweden can also be seen as a relative increase of the role of combustion, thus of atmospheric pollution potential. The progressive renewal of the capital infrastructure and the consequent modernization is not always driven by NOx-reduction performance but still can have a positive impact.

Finally, investments in NOx-specific abatement technology can, of course, substantially reduce emissions. Combustion plant operators as well as machinery suppliers have identified three main drivers to NOx-specific abatement investments: maximum allowable emission levels, the REP scheme and the resulting economic incentive, and the implementation of environmental management and strategy. These drivers are considered to have variable importance with respect to different individual operators and over time. The REP scheme has definitely had an influence on emission intensity. There is, however, a need for acknowledging the joint influence of a set of contextual factors and drivers in contributing to the performance improvements through the adoption of abatement technology. One could investigate the dynamic aspects of these different drivers, documenting historical trends in emission regulation tightening at the local level and the diffusion of firm involvement in environmental management systems.

To sum it up, the main identified determinants for emission intensity changes are structural tendencies (energy intensity, fuel switch, capital stock renewal), and investments in NOx-specific abatement technology. Abatement procedures have been motivated mainly by emission standards, the REP, and environmental management strategies.

3. *How has NOx-specific abatement technology diffused? What are the critical determinants of its diffusion?*

Investments in NOx abatement technologies have grown steadily since the beginning of the REP scheme. Main reported technologies have been SNCR, FGR, trimming measures and LNB within the pool of REP-subjected combustion units. There is, however, no clear preference between primary combustion measures and flue gas treatment. Requirements set on monitoring equipment have greatly contributed to the identification of trimming opportunities that can increase individual performance at very low costs. Mandatory measuring equipment has increased firms' interest in abatement and provided a necessary tool for the optimization of processes in search for cost-efficiencies.

The technologies involved present capital indivisibilities that can give advantages to larger firms. Internal factors such as access to information and involvement in strategic competence building, positioning towards risks and uncertainties, lifetime of capital infrastructure greatly influence firm behaviour and technology absorption capacity, explaining inter-firm heterogeneities. Additionally structural trends and barriers affect individual innovation processes. Lasting physical assets (especially considering lifetime of combustion machinery) limit investments in new technology. Capital 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 scheme. Critical determinants of this diffusion include size, access to information and competence, risk-aversion and the timing of investments.

4. *To what extent has the REP fostered 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 an responsive market for cost-effective NOx reduction technology has had an impact on their activity, namely structuring their effort 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. The relative high expectations of the Swedish market in the 1990s and the capacity of suppliers to develop products meeting those needs has contributed to give firms operating within the Swedish market an early-mover advantage in international market that has developed since then, in accordance with the Porter hypothesis.

In sum, the REP, the institutional and cultural setting in place alongside a number of structural tendencies of the combustion sector, have triggered large changes in emission intensities. The overall reduction can be partly attributed to investments in abatement technology. Opportunities are varied and localized, depending on many determinants at firm level, and there is evidence of barriers to the diffusion of technology. These barriers however tend to be reduced with an active development of networks, and a responsive supply side.

7.2 Policy implications

When it comes to the consideration of industrial systems and technological change, it appears clear that the creation of national environmental policies with the potential of spurring innovation, as complements of existing regulation, are beneficial at many levels. This kind of setting allows:

- Effective pollution intensity reductions at the macroscopic level through diffusion of readily available technologies;
- An effective allocation of efforts where it is cheapest;
- The strengthening of national industrial systems and networks, creating a potentially exportable competence block and competitive advantages;

- Ongoing efforts directed towards pushing the techno-economic frontiers of the technology, generating more competing designs for more diverse applications.

An important innovative aspect of the REP[93] is its political economy, allowing the implementation of a high charge level, which has not been possible with traditional fiscal instruments used in other contexts (the current French tax is, for instance, 100 times lower than the REP charge). Recent tendencies however indicate that this level is still not high enough, requiring a dynamic adaptation of the policy-technology setting.

The successful outcome of this scheme in Sweden is tied to many contextual parameters, which are of importance when considering the applicability of such a mechanism in other national situations. The existence of a strong supporting regulatory and cultural setting appears to be essential. Strong regulation and technology requirements for the attribution of operating permits, and a relatively high consideration of environmental management and public image at firm level seem necessary. This setting is however a consequence of harmonized European legislation[94]. Administration-wise, the existence of a governmental body empowered to administer and enforce the control of industrial activities is necessary, yet financing of such monitoring can be done through setting aside a share of the collected charge, such as it has been done in the present case.

Additionally, some market attributes have appeared to contribute to the success. These include a heterogeneous pool of actors in terms of market share (as opposed to a monopolistic situation)[95], access to supply, information provision, networking, and the existence of affordable monitoring equipment. The state of technology provision at the start of the scheme, in terms of technology options and variety, is another important factor. It should be kept in mind that REP schemes are not specifically innovation-

[93] Probably the most appealing from a policy perspective.

[94] It would be useful to further investigate the temporal and spatial dependencies of permit attribution procedures (but also of other contextual determinants such as the consideration of environmental management, capital renewal cycles…), at national levels within different European countries for a continuation of this discussion.

[95] Recent trends in the purchase price of electricity, mainly as results of CO_2 allocation, have led to an increase of self-generation of energy by industrials on an international level in order to meet their needs at competitive costs (Reinaud, 2007). This indicates a diversification of industrial energy producing agents in the future.

oriented schemes[96] but merely allow the creation of market signals that can work as a "spark" for the enhanced creation and diffusion of innovation.

Throughout this study, it has been strived to deliver an accurate picture of the mechanisms at stake. The identification of a certain number of system complexities, and the limitations of single (traditional) approaches to tackle these complexities have led to the definition of a flexible framework, which allowed for the recognition of context, interrelatedness and history as being crucial to the study of the links between environmental policy and technological change, thus complementing results from former approaches.

[96] There exists, however, a wide range of potential policy instruments directly focused on strengthening market attributes at a systemic level that have not been discussed here.

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