Cost decreases in environmental technology

Evidence from four case studies

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Abstract

The cost of a new technology tends to decrease as its uptake grows, and environmental technology is no exception to this general rule. Factors that can bring about such cost reductions include economies of scale, 'learning-by-doing', incremental technological improvements, and growing competition. In preparing environmental policies, the potential for future cost reductions is often disregarded.

The present study aims to provide some additional empirical evidence on the cost decreases in environmental technology and the factors that lie behind them. To this end, four exemplary case studies have been selected.

The first case (NO_x emission abatement by Selective Catalytic Reduction (SCR)), shows a wide variety in cost estimates, without a clear trend. This is even true for the costs of a fairly homogeneous type of investment (SCR in coal fired power plants). Nevertheless, it is clear that an important cost decrease has been achieved by prolonging the lifetime of the catalyst, which is one of the main cost components in SCR.

In the second case (NH_3 emission abatement by chemical air scrubbers in pig farming) there is not yet sufficient experience with the technology to draw conclusions on the development of costs. However, it is already clear that economizing on the capacity of the system can contribute to important cost savings.

Three-way catalytic converters in cars have shown significant price decreases following their large scale introduction on the European market in the early 1990s. Probably economies of scale have played an important role in this case, as the size of the market made mass production possible. To some extent, cost reductions may also be attributed to improvements such as the need for less materials (e.g. platinum). Furthermore, the performance of catalytic converters has improved, implying that the cost per unit of emission reduction has decreased even more than the cost of the device itself.

Market prices of Compact Fluorescent Lamps (CFLs) also have decreased considerably over the past 20 years. In addition to economies of scale, increased competition (especially from China) seems to have played an important role in this case. Learning-by-doing and incremental technological improvements have mainly contributed to better product quality.

The case study findings suggest that economies of scale and enhanced competition are important sources of cost reduction in standard (consumer) products, whereas 'learning by doing' and incremental technological improvements are relatively important factors contributing to cost reductions in process-related technology.

Samenvatting

De kosten van een nieuwe technologie hebben de neiging om te dalen naarmate de toepassing ervan toeneemt. Milieutechnologie vormt geen uitzondering op deze regel. Tot de factoren die bijdragen aan zulke kostendalingen behoren schaalvoordelen, 'learning-by-doing', incrementele technologische verbeteringen en toenemende concurrentie. Bij de totstandkoming van milieubeleidsmaatregelen wordt het potentieel voor zulke kostendalingen vaak buiten beschouwing gelaten.

Deze studie heeft tot doel om, in aanvulling op eerder onderzoek, empirische gegevens bijeen te brengen betreffende de kostendalingen van milieutechnologie en de achterliggende factoren. Dit is gedaan aan de hand van vier cases.

De eerste case (NO_x-emissiebeperking door middel van Selectieve Katalytische Reductie (SCR)), laat een breed spectrum aan kostenschattingen zien, zonder duidelijke trend. Dat geldt zelfs voor de kosten van één tamelijk homogeen type investeringen (SCR in kolengestookte elektriciteitscentrales). Toch komt uit deze case wel naar voren dat er in de loop van de tijd belangrijke kostenbesparingen zijn gerealiseerd door het verlengen van de levensduur van de katalysator (een van de grootste kostencomponenten bij SCR)..

In de tweede case (NH_3-emissiebeperking door chemische luchtwassers in de varkenshouderij) bleek nog onvoldoende ervaring te bestaan met de technologie om al conclusies te kunnen trekken over de kostenontwikkeling. Niettemin is al wel duidelijk dat het beperken van de capaciteit van het systeem kan bijdragen aan belangrijke kostenbesparingen.

Driewegkatalysatoren in auto's hebben, sinds hun grootschalige introductie op de Europese markt aan het begin van de jaren '90, aanzienlijke prijsdalingen te zien gegeven. Waarschijnlijk hebben schaalvoordelen in dit geval een belangrijke rol gespeeld, aangezien de omvang van de markt massaproductie mogelijk maakte. In zekere mate kunnen de kostendalingen ook worden toegeschreven aan verbeteringen zoals een vermindering van de benodigde hoeveelheid materialen (zoals platina). Bovendien is de prestatie van katalysatoren verbeterd, hetgeen betekent dat de kosten per eenheid emissiereductie sterker zijn gedaald dan de kosten van het apparaat zelf.

Ook de marktprijzen van spaarlampen zijn in de afgelopen 20 jaar sterk gedaald. Niet alleen schaalvoordelen waren hierbij van belang, maar vooral ook de toegenomen concurrentie (met name vanuit China). 'Learning-by-doing' en incrementele technologische verbeteringen hebben in deze case vooral bijgedragen aan een hogere productkwaliteit.

De bevindingen van de cases laten zien dat schaalvoordelen en groeiende concurrentie belangrijke bronnen van kostenreductie zijn bij standaard (consumenten)producten, terwijl 'learning-by-doing' en incrementele technologische verbeteringen belangrijke factoren zijn bij procesgerelateerde technologie.

1. Introduction

The Netherlands Environmental Assessment Agency (Milieu- en Natuurplanbureau, MNP) publishes an annual 'Milieubalans' (Environmental Balance). In 2006, the Milieubalans paid attention to the influence of technological development on the cost of emission reductions. The Milieubalans 2007 will address this issue again, and will in particular deal with cost decreases that occur during the process of development and application of cleaner technology. Such cost decreases are often reflected in so-called 'learning curves', which show the costs of a new technology as a function of its cumulative production or application.

There are several factors that can explain the cost decreases. First of all, 'learning-by-doing' in applying a new technology leads to efficiency gains. Furthermore, incremental technical improvements are quite common, which may lead to lower costs and/or higher quality of the process or product. Economies of scale (for example, made possible by mass production) can reduce the costs per unit significantly, as fixed costs (including R&D) can be spread over a much larger output volume. Competition among suppliers also tends to grow during a technology's life cycle, especially when patents expire. While this competition may not reduce costs for the suppliers, it certainly does so for the users.

Cost reductions over time are common to all kinds of technology, and environmental technology is no exception. Several studies have shown that the cost estimates made in preparing environmental policies ('ex ante costs') often exceed the costs observed when the policy has been in place for some time ('ex post costs') (see, for instance, SEI, 1999; Oosterhuis (ed.), 2006). In other words, ex ante costs are often overestimated, which may sometimes imply that environmental policies that would have been justified from a cost-effectiveness point of view are adopted at a too low level of stringency, or not at all.

One of the explanations for the difference between 'ex ante' and 'ex post' costs of environmental technology is the fact that potential future cost reductions are usually not taken into account during the stage of policy formulation. A relevant question is therefore, whether it is possible to formulate certain 'rules of thumb' regarding the cost decreases that can be expected. An attempt to do so was already made some years ago by Honig *et al.* (2000), who arrived at a possible overestimation of at least 12% for the environmental costs of all target groups in 2020.

The present study does not intend to arrive at a 'better rule of thumb', but rather aims to provide some additional empirical evidence on the cost decreases in environmental technology and the factors that lie behind them. To this end, four case studies have been selected, which cover processes as well as products, and different types of environmental issues. The case studies relate to: NO_x emission abatement by Selective Catalytic Reduction (SCR) (Chapter 2); NH_3 emission abatement by air scrubbers in pig farming (Chapter 3); catalytic converters in cars (Chapter 4); and Compact Fluorescent Lamps (Chapter 5). In Chapter 6, some tentative conclusions are formulated.

Obviously, the approach taken in this study has its limitations. Data on (average or marginal) production costs are usually not directly available, and reported market prices usually had to be used as a proxy. Furthermore, the selected case studies are not necessarily representative for environmental technology in general. Finally, the conclusions relating to the factors behind the cost decreases are based on 'expert judgment' rather than statistical analyses. Nevertheless, the results are believed to contain some useful material illustrating the importance of cost reducing mechanisms in environmental innovation processes.

2. NO_x emission abatement by Selective Catalytic Reduction (SCR)

2.1 Introduction

Selective Catalytic Reduction (SCR) is an ‘end-of-pipe’ technique to reduce nitrogen oxides (NO_x) in the flue gases from combustion and other processes. Essentially, it implies a reaction between NO_x and ammonia (NH_3)[1], resulting in the formation of elemental nitrogen (N_2) and water (H_2O). This reaction is promoted by the presence of a catalyst (such as a combination of TiO_2 and V_2O_5, or zeolite). This technique can achieve high NO_x reduction rates (over 90%), but requires considerable investments.

Japanese power companies started to apply SCR already in the 1970s, in response to stringent NO_x emission standards. Initially, gas and oil fired combustion plants were equipped with SCR. In 1980 the first coal power plant followed suit.

During the mid-1980s, SCR began to conquer Europe as well. By 1987, eight SCR systems (totalling 2,200 MW capacity) were operating in Germany and Austria, with another 20,000 MW under construction or on order in those countries (Offen *et al.*, 1987). Following the EU’s 1988 Large Combustion Plants Directive (which required substantial NO_x emission reductions from power plants) SCR found its way into several other European countries. In the Netherlands, the first power plant was equipped with SCR in 1994. By 1995, 400 SCR units had commenced operations on coal, oil and gas fired boilers in many countries (Takeshita, 1995). Figure 2.1 shows the worldwide growth in SCR in coal fired power plants.

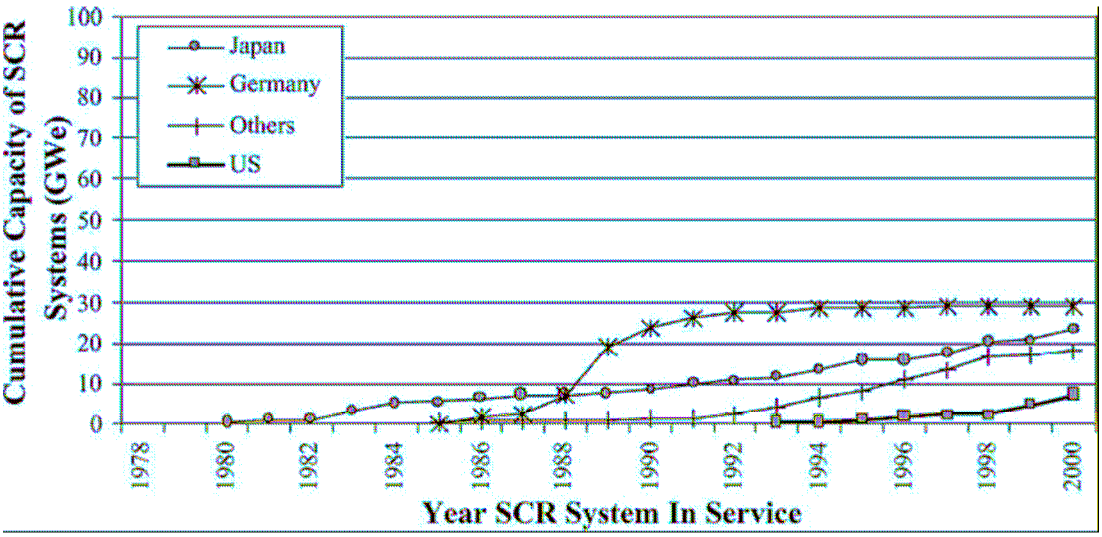

Figure 2.1. Cumulative installed capacity of SCR systems on coal-fired power plants in the US, Japan, Germany, and rest of the world. (Source: Rubin et al., 2004).

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[1] Instead of ammonia, urea is sometimes used as a reduction agent.

In Section 2.2, the development of cost estimates per tonne of NO_x abated for a broad range of SCR applications is addressed. For comparison purposes, however, the investment costs associated with SCR in a standardised plant are the preferable variable to look at. This eliminates as much as possible the variation caused by parameters such as production process (with resulting variation in NO_x concentration, flue gas temperature etc.), plant size, differences in interest and depreciation rates etc.. In the present case study, SCR in coal fired power plants was selected, providing the most uniform type of application, with a reasonable number of cost estimates over time (Section 2.3).

2.2 Cost estimates per tonne of NO_x abated in various applications

Table 2.1 presents a sample of SCR cost estimates found in the literature. They are grouped by area of application, and within the same area in chronological order. The figures presented include both *ex ante* and *ex post* data.[2]Table 2.1 clearly shows a wide range of estimates, precluding any clear trend to be distinguished in the cost development over the past 25 years.

The wide variety of cost estimates is caused by a number of factors. First of all, even within one area of application there are substantial variations in types of flue gas streams (in terms of NO_x concentration, presence of other pollutants, temperature etc.). Size, scale and time of operation also play an important role. Then there are of course different types (e.g. ‘high-dust’ versus ‘low-dust’) and different suppliers of SCR systems. Construction costs may also vary, especially if SCR is applied to an existing plant. Furthermore, (assumptions regarding) abatement efficiency, the costs of materials (catalyst, ammonia etc.), operation and maintenance costs, lifetime of the catalyst[3], depreciation and interest rate are not uniform. Finally, the figures include both ‘ex-ante’ cost estimates and ‘ex-post’ data. Against this background, it is hardly surprising that the cost estimates as presented in Table 2.1 do not reveal a clear trend in the cost of NO_x reduction by SCR over time.

Even for one specific SCR investment project different cost estimates may come up with widely diverging amounts. An example is the retrofitting of SCR on a cogeneration unit at Cerestar (a food processing plant in Sas van Gent, The Netherlands). For this project, Van Esch (2001) mentions a cost of € 2,300 per tonne of NO_x removed, whereas the cost of the same project is estimated at € 1,100 per tonne in Paul and Maaskant (2001), at € 1,040 per tonne in Novem (undated a) and at € 1,750 in Novem (undated b). The latter two sources show differences in project costs as well as in emission reductions achieved. Obviously, in addition to the factors mentioned above, data availability and reliability is also a cause of uncertainty and variation in cost estimates of SCR.

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2 Generally, the *ex ante* estimates do not yet take future cost decreases due to learning curve effects into account.

3 To complicate things further, the catalyst costs are sometimes treated as capital cost, but in other cases as operational cost (the lifetime of the catalyst is limited to a few years).

Table 2.1. Cost estimates for SCR (per tonne of NO_x abated) in various applications.

Specifics (type, country etc.)	***Year (*)***	***Costs per tonne of NO_x abated***		***Source***
		In original currency	***In euros of 2007 (**)***	
Power plants / combustion plants				
NL, coal fired	1983	NLG 1,701	1,256	VROM (1983), Table 10
NL, gas fired	1983	NLG 608	449	VROM (1983), Table 10
NL, coal fired	1984	NLG 4,779	3,457	Van Oostvoorn and Van Arkel (1984), Table II.2
NL, coal fired	1987	NLG 4,000	2,723	Bruggink *et al.* (1987), p. 69
NL, coal fired	1988	NLG 3,770 – 6,230	2,515 – 4,157	Bakema and Kroon (1988), p. 40
Pulverized-coal boilers	1989	USD 4,000 – 6,000 (***)	5,754 – 8,631	Eskinazi *et al.* (1989)
Cyclone equipped boilers	1989	USD 600 – 700 (***)	863 – 1,007	Eskinazi *et al.* (1989)
Japan	1989	USD 1,000 – 1,500	1,439 – 2,158	Ando (1989)
	1995	USD 1,213 – 4,681	1,546 – 5,965	Takeshita (1995), Table 7
	± 2000	EUR 1,442 – 3,016	1,661 – 3,474	European Commission (2006), Table 3.13
800 MW plant size	2001-2006	EUR 1,500 – 2,500	1,531 – 2,822	Rigby *et al.* (2001); European Commission (2006), p. 112
Refineries				
Japan	1984-1986	FRF 25,000 – 37,000	5,790 – 8,922	Raymond (2001)
NL (gas turbines)	1987	NLG 1,957	1,332	VROM (1987), p. 57
NL	1994	NLG 6,300 (****)	3,724	RIVM (1994), p. 50
NL (furnaces)	1997-2000	EUR 1,193 – 3,290	1,374 – 4,027	Novem (undated a and b)
Austria	2000	EUR 467 – 1,309	538 – 1,508	UBA (2000), quoted in Schindler (2001), Table 7
Waste incineration plants				
NL	1988	NLG 7,800	5,204	Bakema and Kroon (1988), p. 40
NL (based on offers from suppliers)	1992	NLG 8,000 – 13,000	5,024 – 8,164	Schipper-Zablotskaja (1992)
NL, 8 plants	1992 - 1997	NLG 8,800 – 8,900	5,416 – 5,477	Timmer (2001)
NL, 4 plants	1996	NLG 7,500 – 10,000	4,257 – 5,677	Wetzels (1996)
NL, 1 plant	1996	NLG 3,850	2,186	Crocker *et al.* (1996)
France	1999	FRF 59,000	10,508	Rossati (2001)
Belgium	2000	EUR 1,800 – 2,200	2,073 – 2,534	Matthys *et al.* (2001)

General / other applications				
General	1986	NLG 3,000 – 5,000	2,084 – 3,474	Olsthoorn and Thomas (1986), Tables 4.1 and 4.3
Industrial installations	1987	NLG 5,000 – 15,000	3,404 – 10,213	Bruggink *et al.* (1987), p. 69
Industrial boilers	1987	NLG 4,100 – 6,000	2,792 – 4,085	VROM (1987), p. 57
Cement	1996	ECU 1,200 – 2,300 (****)	1,499 – 2,872	Kossina (2001)
Gas turbine	1997	< NLG 2,750	< 1,530	Crocker *et al.* (1996)
Gas turbines (cogeneration) in paper industry	1996-1997	NLG 1,900 – 2,200	1,057 – 1,249	Van Kessel and Roukens (2001), Table 5
Gas turbine in chemical industry	1997-2000	EUR 1,870 - 1,930	2,154 – 2,362	Novem (undated a and b)
Ovens in metal industry	1997-2000	EUR 1,561 - 1,930	1,798 – 2,362	Novem (undated a and b)
Nitric acid plants	1997-2000	EUR 110 – 1,280	127 – 1,567	Novem (undated a and b)
Gas turbines (cogeneration) in food industry	1997-2000	EUR 1,040 - 4,538	1,198 – 5,554	Van Esch (2001); Paul and Maaskant (2001); Novem (undated)
Abrasive grit production	1999	FRF 5,182	923	Wagner *et al.* (2001)
Various	2000	NLG 2,600 – 14,000 (****)	1,361 – 7,330	Vringer and Hanemaaijer (2000)
Glass industry	2001	EUR 588 - 904	664 – 1,020	Schindler (2001), Table 2
Gas turbines	2001	NLG 1,100; USD 1,800; USD 2,480	564 – 2,800	Maaskant and Miggelbrink (2001), p. 17-18
Nitric acid plants	2001	USD 400	452	Maaskant and Miggelbrink (2001), p. 17
General	2003	EUR 500 – 5,000 (*****)	542 – 5,420	European Commission (2003a), p. 270

(*) Year of SCR installation. If this is unknown, year of publication has been used.
(**) The following simplified calculation rules were used: a constant inflation rate of 2% per year, and a fixed exchange rate of EUR 1 = ECU 1 = USD 1 = DEM 2 = NLG 2.2 = FRF 6.6.
(***) Costs per tonne of NO_2.
(****) Calculated by the present authors on the basis of the mentioned source. Actually, there is even a single SCR application (on a caprolactam plant) costing over NLG 66,000 per tonne NO_x, but this is a small scale measure that is clearly not cost-effective.
(*****) Unclear whether this includes annualized capital costs.

2.3 Investment costs for coal fired power plants

Identifying a trend in the development of SCR costs might be facilitated by narrowing down the application area. In this regard, we have focused on the investment cost of SCR in a coal fired power plant. In cases where estimates were available for different plant capacities, the figures in the 500-600 MW_e range have been selected.

In METRA (1979, p. 46.4) the capital cost of a Hitachi Zosen SCR unit on a 500 MW coal fired power plant was specified as NLG 11 million. Given the calculation rules used in the METRA report (10% annuity over 10 years), this implies an investment of NLG 135 per kW. This type of SCR units had been commissioned in 6 plants in the years 1975-1977.

Van der Brugghen *et al.* (1983), reporting on experiences in Japan, found a wide range of investment costs for SCR in coal power plants: between NLG 43 and NLG 100 per kW. They stated that the NLG 43 value was probably too low, as the costs of the catalyst itself was already between NLG 41 and NLG 53 per kW. According to the authors, a 'reasonable' estimate for the total investment was NLG 80 per kW.

Graas and Wijdeveld (1984) stated that the investment costs of SCR are strongly influenced by local conditions. As an indication they mentioned an amount of about NLG 100 per kW (of which 60 to 70% costs of the catalyst) for a 600 MW coal fired power plant.

In Tangena (1985, Table 5.6) the additional investment costs of SCR in a 600 MW_e coal power plant were estimated at NLG 33 per kW_e for a new plant, and NLG 37 per kW_e for an existing plant. From VROM (1983, Table 10), Thomas *et al.* (1983, Table 3.3) and Olsthoorn and Thomas (1983, Table 2.2) an investment estimate of NLG 33 per kW_e can be calculated as well (for a similar coal power plant). These unusual low values can only be explained by assuming that the authors did not include the cost of the catalyst in the investment cost (but in the operational cost instead).

In 1986, Schaerer and Haug (cited in SEI, 1999) made an estimation for the costs of SCR in German power plants. For a 1500 MW_{th} power plant (which is equivalent to a 600 MW_e plant, assuming an efficiency of 40%) they presented a figure of DEM 24 per kW. However, given that they express the capacity of the plant in MW_{th}, this amount presumably also relates to the costs per kW_{th}, and it would therefore be DEM 60 per kW_e.

Offen *et al.* (1987, p. 868) mentioned capital costs reported by European utilities ranging between USD 65 and USD 125 per kW. Competition had reportedly driven the costs of the catalyst down significantly since the first units were ordered in Germany. In the same article, a Japanese utility (EPDC) is quoted, reporting that new catalyst formulations and a halving of the catalyst pitch had reduced the capital cost of SCR systems to USD 30 per kW. On the other hand, an EPRI[4]-commissioned study arrived at an estimate of USD 175 per kW.

From Bakema and Kroon (1988, Table D6, p. 149) an investment cost for SCR in existing coal power plants of NLG 143 to 151 per kW_e can be calculated, and of NLG 94 to 102 for new plants. The capacity of the plant was not specified.

Ando (1989) stated that an SCR plant for 80% removal costs USD 50 to 70 for coal fired boilers, including the initial charge of the catalyst (which would account for about half of the cost).

In Eskinazi *et al.* (1989, p. 1135) the capital costs for retrofit hot-side (i.e. high-dust) SCR installations operating in Europe were reported between USD 60 and USD 180 per kW, averaging approximately USD 125 per kW. In the same article, an EPRI-sponsored

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4 EPRI = Electric Power Research Institute (United States).

study is quoted which estimated the costs for SCR retrofits to a 500 MW boiler at USD 100 per kW (of which USD 42 for the catalyst and reactor). Another source that Eskinazi *et al.* refer to is the Japanese power company EPDC, which reported investment costs for SCR on a new 400 MW boiler at USD 71 per kW. The authors also stated that because of competition in Europe, catalyst costs had recently come down by a factor 3.

Schipper-Zablotskaja (1991) mentions an investment cost of DEM 66.30 for SCR retrofitting on German power plants. This amount probably did not include the cost of the catalyst, as the catalyst depreciation costs were specified separately as DEM 14 per kW (without specifying the depreciation period, however). Assuming an economic lifetime of 3 years for the catalyst, this would imply investment costs of about DEM 100 per kW. For a Dutch demonstration plant (EPON power plant, Nijmegen), Schipper-Zablotskaja (1991) gives an investment cost figure of NLG 300 per kW. This relatively high amount can be explained by the small size of the plant involved (65 MW).

Takeshita (1995, based on different other studies)) makes a distinction between SCR investement costs for new plants (ranging from USD 70 to 90 per kW_e) and existing plants (retrofit, ranging from USD 80 to 150 per kW_e).

In the NEA/IEA/OECD (1998, p. 141) calculations on the cost of electricity production, an investment for SCR of USD 50 to 90 per kW_e was used for (new) coal fired power plants.

From UNECE (1999, p. 18, Table 2) an investment cost for SCR of EUR 48 million can be calculated for a coal fired power plant of 1,500 MW_{th}. Assuming an electric efficiency of 40%, this would be equivalent to EUR 80 per kW_e.

Rigby *et al.* (2001), quoting a 1999 study by Staudt, mention a range of € 50 to € 100 per kW (depending on plant size) for retrofit applications removing between 60 and 90% NO_x (presumably for a coal plant, though this is not mentioned explicitly). These figures are quoted again in the BREF on Large Combustion Plants (European Commission, 2006). That same BREF shows a range of SCR investment costs for a 500 MW_e power plant between € 25 and € 75 million, or € 50 to € 150 per kW_e. The source of this latter estimate is Eurelectric.

In Figure 2.2 the information from the above mentioned sources is summarized, expressed in Euros of 2007.[5] The picture does not show any clear trend in real investment cost, except that the highest estimates (above EUR 200 per kW) are not encountered anymore after 1990.

[5] Like in Table 2.1, simplified calculation rules were used: a constant inflation rate of 2% per year, and a fixed exchange rate of EUR 1 = USD 1 = DEM 2 = NLG 2.2.

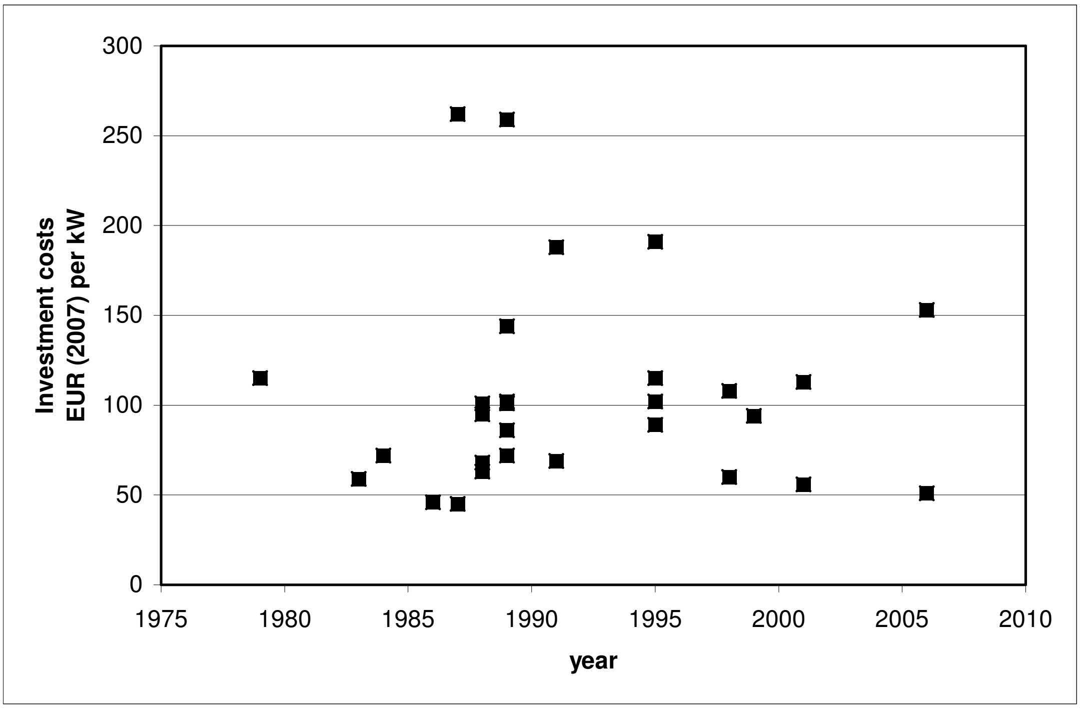

Figure 2.2. SCR investment costs for coal power plants, according to various sources, expressed in Euros of 2007 per $kW_{(e)}$.

Rubin *et al.* (2004), however, managed to construct a learning curve for SCR (see Figure 2.3), arriving at a learning rate of 0.12 (i.e., the capital cost of SCR decreases by 12% for each doubling of cumulative installed capacity).[6] According to the authors, the observed cost decreases reflect the effects of investments in R&D as well as learning by doing and other factors. SCR process improvements have substantially lengthened the average catalyst lifetime, while improvements in catalyst manufacturing methods, as well as competition among catalyst manufacturers, simultaneously lowered catalyst prices by 50% over a 10-year period. During this time there was no systematic change in the real price of the principal metals, mainly vanadium and titanium, used for SCR catalysts. Unfortunately, Rubin *et al.* do not specify the sources of their cost data.

[6] The learning rate follows from the learning curve's exponent by the relationship: $1 - 2^{-0.18} = 0.12$

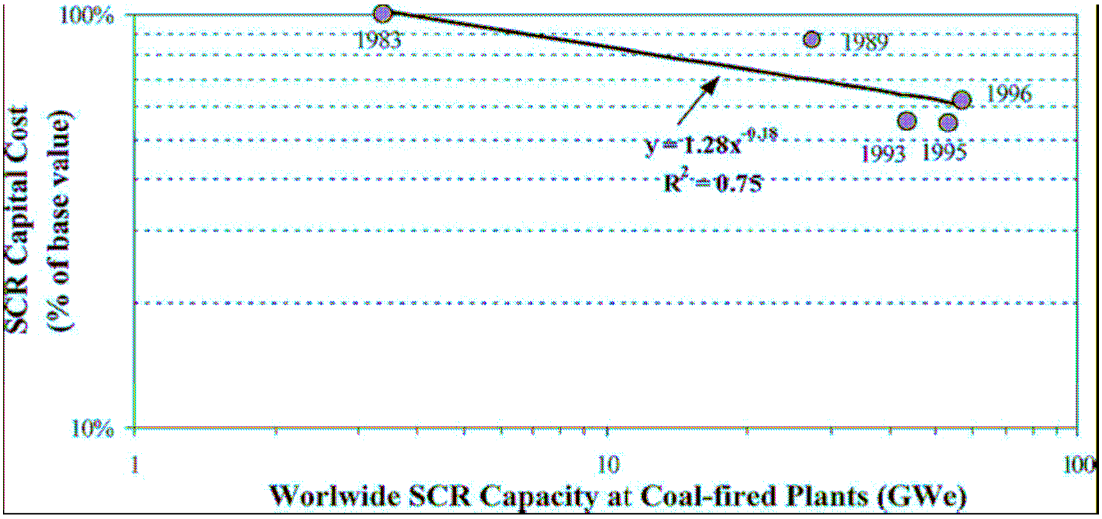

Figure 2.3. SCR capital costs for a standardized coal-fired power plant (500 MW, 80% NO_x removal) vs. cumulative installed capacity worldwide. All data points normalized on an initial (1983) value of US$ 105/kW in constant 1997$. (Source: Rubin et al., 2004).

2.4 Other aspects

The costs of SCR are to a large extent determined by the costs of the catalyst. The frequency of catalyst replacement is therefore an important factor. In the early sources (e.g. Van der Brugghen *et al.*, 1983) the life of the catalyst was estimated at about 2 years. In CONCAWE (1984, p.23) it is stated that a catalyst life of more than four years had been proven in several commercial units. According to Ando (1989) the average catalyst life was 4 to 5 years. Schipper-Zablotskaja (1991) mentions a lifetime of 5 to 8 years for modern catalysts. UNECE (1999, p. 17) remarks that catalyst lifetimes are much longer than initially projected and have reached as much as 6 – 10 years for coal-fired units and 8 to 12 years for gas and oil fired units. The same figures are mentioned in the BREF on Large Combustion Plants (European Commission, 2006). In some cases catalyst lifetime can be extended by means of regeneration (see e.g. Budin *et al.*, 2001).

For the cost-effectiveness of SCR the efficiency of NO_x removal is relevant as well. Initially, this was estimated at 80 to 90% (e.g. METRA, 1979; Olsthoorn *et al.*, 1982; Van der Brugghen *et al.,* 1983). Actual reduction percentages achieved in the Dutch Industrial Emissions Reduction Programme between 1997 and 2000 (Novem, undated a and b) range from 81 to 97%.[7] The BREF on Common Waste Water and Waste Gas Treatment / Management Systems in the Chemical Sector (European Commission, 2003a) mentions a 90 to 94% performance rate for NO_x from gas and liquid fuel boilers/heaters, and 80 to 97% for NO_x from nitric acid production.

[7] With the exception of an application in the steel industry, where an average efficiency of only 60% could be achieved. See Novem (undated b), p. 19.

2.5 Conclusions

The wide variety in cost estimates of applying SCR to abate NO_x emissions precludes any firm statements on their evolution. Even if confined to the investment costs in coal power plants, it is hard to identify a clear trend. Though Rubin *et al.* (2004) have constructed a learning curve for this type of SCR application (Figure 2.3), it is based on a small number of observations and without access to their original sources its validity can not be tested.

For power plants, the highest SCR investment cost estimates that were presented in the past (above EUR 150 per kW_e, in Euros of 2007) are clearly not applicable anymore (if they have ever been). On the other hand, the lowest (inflation-corrected) estimates from the past (around EUR 50 per kW_e) appear to be still valid.

An important cost decrease has been achieved by prolonging the lifetime of the catalyst, which is one of the main cost components in SCR.

3. NH_3 emission abatement by air scrubbers in pig farming

3.1 Introduction

Chemical air scrubbers[8] are an effective means of reducing ammonia (NH_3) emissions: a reduction of 95% can be achieved. In addition, they reduce dust and odour emissions (although to a much more limited extent). Generally, air scrubbers are more effective in reducing emissions than measures in the area of sty design. Chemical scrubbers are also more effective than biological scrubbers in terms of NH_3 reduction. Recently, combined chemical and biological air scrubbers have been introduced which should reduce NH_3 as well as odour and dust effectively.

By 2004, about 160 chemical air scrubber systems had been installed in Dutch intenisve livestock farming (Melse and Ogink, 2004). The high investment and operational costs are still impeding a more widespread application.

The costs of air scrubbers are dependent on many factors, including the size of the farm (number of animals), and the question whether it concerns an existing situation (retrofitting) or a new situation (in practice mostly extension of an existing farm).

In this case study, we focus on air scrubbers in pig farming, in particular production pigs. Furthermore, the figures presented relate to application in newly built sties. It is impossible to make a generally valid investment cost estimate for application in existing situations, because this would depend largely on the specific design of the sty, especially the air ventilation system and the spatial lay-out of the building. If air scrubbing would require a completely new ventilation system, the investment costs could be several times higher than if an existing central exhaust system could be used (Melse and Willers, 2004).

3.2 Abatement costs

3.2.1 Investment costs

Estimates of investment costs in chemical air scrubbers for new production pig housing vary. In Melse and Willers (2004, Table 4) an amount of EUR 42 per animal place is mentioned, whereas agricultural real estate organisation LTO Vastgoed mentions an amount of EUR 58 per animal place (Agrarisch Dagblad, 25 March 2006). In the trade journal 'Boerderij' (21 November 2006) a case is described where a pig farmer invested in a new sty for more than 2,000 production pigs. The additional construction costs for the chemical air scrubber were EUR 50,000, implying an investment of less than EUR 25 per animal place.

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8 Also called 'acid' scrubbers, as their operation is based on the use of an acid (usually sulphuric acid).

3.2.2 Costs per unit of emission reduction

In the BREF on the intensive rearing of poultry and pigs (European Commission, 2003b, Table 4.26) the additional annual emission abatement costs of chemical wet scrubbers for production pigs ('finishers') are estimated at EUR 5.19 per kg NH_3.[9] This estimate was based on the 'Dutch notes on BAT for pig- and poultry intensive livestock farms', which were made in 1999. It is unclear to what sty size this estimate relates.

Melse and Willers (2004, Table 3) estimated the cost of emission reduction by means of chemical air scrubbers at EUR 6.62 per kg NH_3 removed. This estimate relates to a 'standard' sty for 2,160 production pigs. The main cost components are fixed costs (depreciation, interest and maintenance; together 42%) and electricity (35%). The authors argue that the investment costs will probably decrease when the air scrubbers will be produced at a large scale. Assuming a potential halving of investment costs, they arrive at a possible decrease in overall costs by 21%, to EUR 5.21 per kg NH_3 abated.

Van Horne *et al.* (2006) estimate the costs of chemical air scrubbers in production pig farming for new situations at EUR 4.90 per kg NH_3 reduction. This estimate relates to a farm size of 1,920 production pigs.

3.2.3 Perspectives for cost decreases

Melse and Ogink (2004) have addressed the opportunities to lower the costs of air scrubbers. Their calculations showed that a bypass system, in which the air treatment capacity is reduced by 70-80%, could lead to a cost decrease of 40-70% while still meeting Dutch emission standards.

Other attempts at reducing the costs of air scrubbers are going on as well. Many of these are directed towards a reduction of the necessary capacity of the system. For example, by combining air scrubbers with a cooling system for the ventilation air, less ventilation is needed on hot days and therefore the capacity of the air scrubber can be reduced (Agrarisch Dagblad, 5 July 2005).

3.2.4 Comparison with earlier estimates

The application of chemical air scrubbers in intensive livestock farming is a relatively recent phenomenon, and experience with this system is largely confined to the Netherlands. In the late 1990s the technology was still in an experimental stage (see e.g. Verdoes and Zonderland, 1999), even though awareness of its applicability existed much earlier (see e.g. Baltussen *et al.*, 1990, p. 25). Empirical time series data on its cost development are therefore not yet available over a sufficiently long period.

In a wider technology perspective, however, air scrubbers show a clear cost reduction. For example, in Tangena (1985, Table 5.14) the costs of reducing NH_3 emissions from production pig sties by means of (presumably biological) air scrubbers were estimated at NLG 15.50 per kg NH_3 for 1990, and at NLG 8.90 for the year 2000. In euros of 2007

[9] Pellini and Morris (2002, Appendix), who also used the BREF drafts as their source of information, refer to the same costs as amounting to **GBP** 5.19 per kg NH_3 abated, which would equal EUR 7.65 at current exchange rates.

this equals EUR 11.00 and EUR 6.30, respectively. In Baltussen *et al.* (1990, Bijlage 2) the investment cost of a biological scrubber was estimated at NLG 163 per animal place (EUR 104 in euros of 2007).

3.3 Conclusions

Chemical air scrubbers provide an opportunity to achieve substantial ammonia emission reductions from livestock farming, at lower costs than were anticipated in the past for their main alternatives (biological scrubbers).

The main cost components of chemical air scrubbers are investment costs and electricity. To what extent the investment costs can be reduced (through economies of scale and learning by doing in production) is as yet unknown. However, it has already become clear that economizing on the capacity of the system can contribute to important cost savings (including on electricity).

Presently, air scrubbers are not yet considered as 'Best Available Technique' (BAT) under the Integrated Pollution Prevention and Control (IPPC) Directive. However, they may already be necessary at present in order to meet emission limits in areas that are particularly sensitive to ammonia. Moreover, if the Netherlands will have to reduce its NH_3 emissions further under the new National Emission Ceilings (NEC) Directive, chemical air scrubbers may become a necessity for a large part of intensive livestock farming. This diffusion of the technology may in turn lead to further cost reductions, which could eventually result in its 'BAT' status at a European level.

4. Catalytic converters in cars

4.1 Introduction

The development of the catalytic converter for cars was triggered by emissions legislation in the United States in the early 1980s. European car manufacturers such as Volvo, however, were the first ones to introduce cars equipped with this device on the American market. In Europe, the catalytic converter was introduced at the end of the 1980s, following EU Directives that required significant emission reductions from passenger cars.

The cost estimates in this chapter relate to the additional cost of a standard regulated three way catalytic converter (3WCC) on a standard (petrol) passenger car. In the comparison, taxes and the costs of additional fuel consumption due to the 3WCC are excluded.

4.2 Chronological development of cost estimates

Rijkeboer (1983) estimated the costs of 3WCC's at NLG 1,000 to 1,500. This estimate was based on a study for the German Environmental Protection Agency (UBA Bericht 2/80). In the same year, the Dutch Ministry of Environment (Ministerie van VROM, 1983, Bijlage 2) arrived at a higher estimate: NLG 2,100. The latter figure is also used in Olsthoorn and Thomas (1983) and Thomas *et al.* (1983). This substantial difference can be explained by the fact that the latter sources relate to the price for the consumer, which includes a tax on the purchase of passenger cars (BVB; now BPM) as well as VAT. In 1983, the BVB rate was 16% on the first NLG 10,000, and 24% on the part of the price exceeding NLG 10,000. VAT at the time was 18%. Roughly estimating, the 3WCC price for the consumer would therefore be some 40% higher than the price net of tax, which means that the latter would have been about NLG 1,300.

Van Beckhoven (1984) stated that according to the German car industry the additional cost of a 3WCC would be on average DEM 1,250. In Tangena (1985, Table 5.7) the additional cost of a 3WCC was estimated at NLG 740 per vehicle, but this estimate probably related to a non-regulated 3WCC. Zwalve (1985) mentioned an amount of around NLG 1,700, based on prices observed on the German market.

In March 1985, during the negotiations on the EU proposals for the introduction of (*de facto)* mandatory catalytic converters, costs were an important argument, and a wide range of amounts were presented. *The Economist* (2 March 1985) stated that a 3WCC would add about USD 500 to the cost of a car. In two articles in that same month, the *Financial Times* (7 and 8 March 1985) came up with estimates of GBP 500 and DEM 2,300 respectively. An arcticle by the *Associated Press* (4 April 1985) mentioned USD 470 to 900 per car.

Jantzen and Van der Woerd (2006) refer to an OECD symposium held in 1986, at which a Japanese cost estimate for a regulated 3WCC was presented of about NLG 3,000 (price level 1994).

In VROM (1987, Bijlage 8, p. 10) the (gross) additional cost of a regulated 3WCC was estimated at around NLG 1,500. Jantzen (1989, Bijlage 1, page B1.66) mentioned an estimate of NLG 1,700.

The latter figure may have been an overestimation. In 1989, the Dutch government introduced a subsidy of NLG 1,700 on cars fitted with a regulated 3WCC, and this reportedly more than compensated for the additional cost. In any case, the sales of 3WCC cars in the Netherlands increased dramatically in response to this fiscal incentive (see Van den Bergh *et al.*, 2004).

Also in 1989, Vauxhall became the first UK car maker to announce that catalytic converters would be fitted as standard to all its models. According to the car manufacturer, the modification would add between GBP 300 and GBP 400 to the cost of a car. Other UK manufacturers at the time still came up with estimates of up to GBP 1,000 (*The Independent*, 20 April 1989). In the same year, the UK gave up its opposition against EU proposals for emission limits requiring 3WCCs to be fitted on all cars (including small ones) as from 1993.

SEI (1999) states that the motor industry, in its response to the new EU emission limits ('Euro I', introduced in 1991 by Directive 91/441), claimed that catalytic converter technology would cost between GBP 400 and GBP 600 per vehicle. The authors added that the effect of the stricter standards on costs had not actually been studied, and few references were available on this point. Some manufacturers were reported to have added GBP 200 to 400 to the price of a car, and others more than this. Overall, however, prices did not change suddenly or markedly, according to SEI (1999).

Honig *et al.* (2000) refer to a study by Dings (1996), in which the development of 3WCC costs was illustrated by a decrease from NLG 1,350 in 1986 to NLG 700 in 1992. They also refer to a study by TME (Jantzen *et al.*, 1995), in which a time series of cost data for 3WCCs was presented: NLG 3043 (1985, Japan); NLG 1764 (1986, Europe); NLG 1843 (1987, Europe); NLG 1092 (1992, The Netherlands); and NLG 1300 (1994, The Netherlands).[10]

In CPB (2000, p. 129) it is estimated (based on data from Statistics Netherlands (CBS)) that the investment costs for a regulated 3WCC gradually decreased from NLG 1,700 in 1990 to NLG 750 in 1997.

Jantzen and Van der Woerd (2006) have calculated the development of the costs of a 3WCC in the Netherlands over a period of 15 years, also based upon CBS data (see Table 4.1).

[10] These figures were also used in Jantzen and Van der Woerd (2006, Figure 4.1). The original sources of these data is Jantzen *et al.* (1995), based on OECD (1986), CBS (1991), and Touring Club der Schweiz (1994) Jantzen and Van der Woerd (2006) conclude that their findings confirm that the rate of cost decrease of environmental technologies tends to be well above the average 'technological progress factor' (of 2%) which is used in macro-economic models (as reported in Honig *et al.*, 2000).

Table 4.1. Development of the (investment) costs of catalysts (average for the Netherlands).

Year	Cost of catalyst per vehicle (current prices)
1985	€ 771
1990	€ 771
1995	€ 340
2000	€ 227

Source: Jantzen and Van der Woerd (2006), based on CBS data.

Figure 4.1 presents the various cost data as mentioned above graphically, using the same exchange rates and price indices as in chapter 2. Although the range of cost estimates is quite broad, the decreasing trend is obvious.

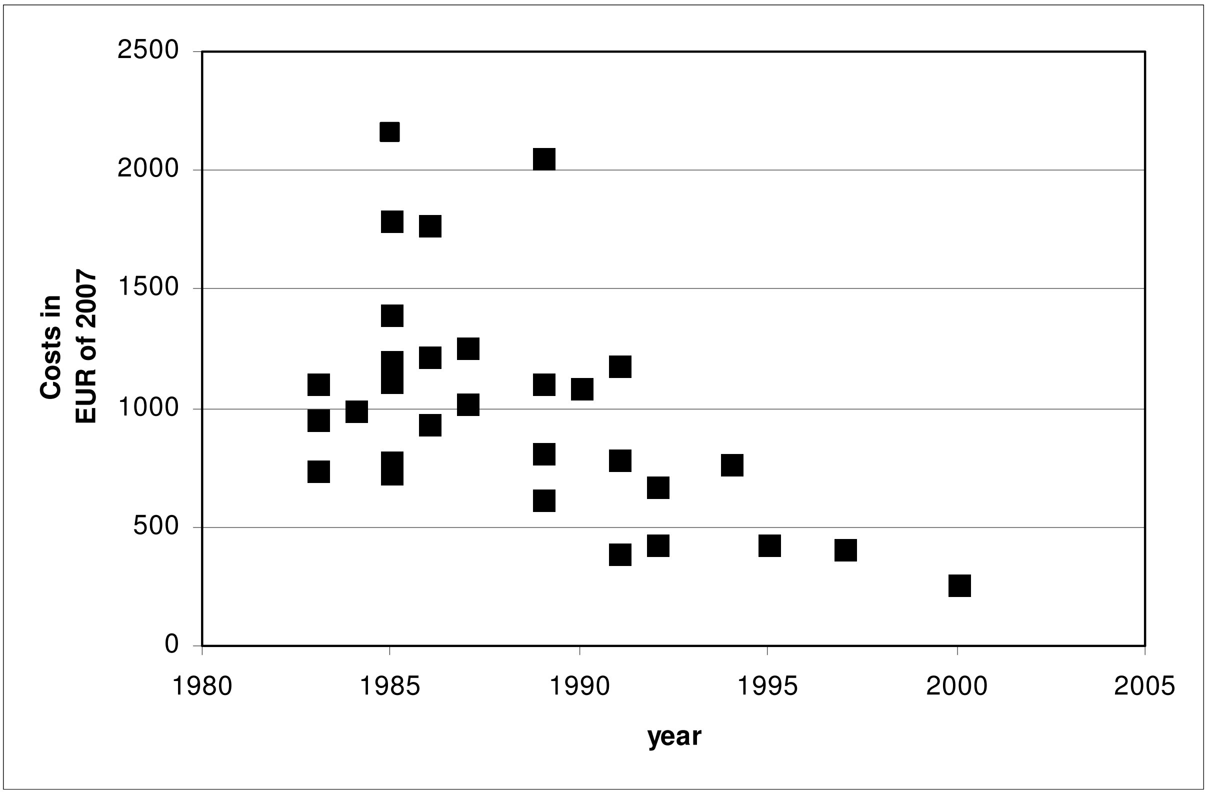

Figure 4.1. Cost development of a regulated 3-way catalytic converter (in euros of 2007).

4.3 Conclusions

The available evidence suggests that significant price decreases have occurred following the large scale introduction of 3WCCs on the European market in the early 1990s. It seems reasonable to assume that economies of scale have played an important role in this case, as the size of the market (millions per year) made mass production possible. To some extent, cost reductions may also be attributed to improvements such as the need for less materials (e.g. platinum).[11]

Some caution, however, is justified in drawing conclusions on the basis of the data presented above. First of all, the validity of the cost data is unknown. Neither statements by car manufacturers nor observed market prices are necessarily reliable indicators for actual production costs.

Furthermore, the 3WCC cannot be considered as a homogenous product over the whole period of observation. Car emission standards have been tightened several times, and even though the basic technology remained the same, the catalysts were adapted in order to be able to meet the stricter standards. However, this only implies that the cost *effectiveness* of the catalysts have improved even faster than their cost *level*.

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[11] On the other hand, the price of platinum may have increased as a result of the growing demand for 3WCCs. As 40% of the world platinum production is used for 3WCCs (Buijsman, 2006), this demand is likely to have a significant impact on the platinum market. Given current platinum prices of around EUR 30 per gramme (*Financial Times*, 15 May 2007) and a platinum content of 1 to 3 grammes per catalytic converter (Buijsman, 2006), the share of platinum costs in total production costs of a 3WCC is considerable. However, instead of platinum the less expensive palladium is increasingly being used nowadays.

5. Compact fluorescent lamps

5.1 Market development

The compact fluorescent lamp (CFL) was patented in 1972 and first commercialized (by Philips) in 1980. Ten years later, CFLs began to find their way to the consumer market.

In 1989 and the early 1990s , the global CFL market increased by more than 30% annually. Afterwards, growth of the global CFL market slowed down (IAEEL Newsletter 4/94) .

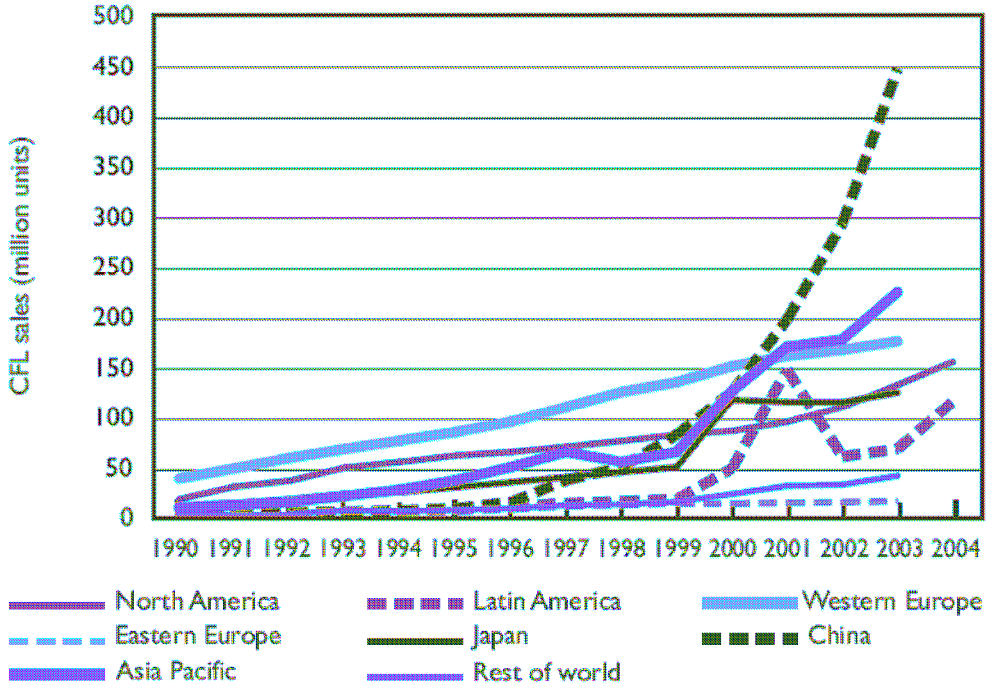
In a number of individual countries, dedicated market transformation programs during the 1990s led to an increased uptake of CFLs by households (see e.g. IEA, 2006; Ürge-Vorsatz and Hauff, 2001; Sathaye *et al.*, 1994). In the Netherlands, energy distribution companies have run several promotional campaigns during the 1990s to stimulate the use of CFLs by households. In the first 'Environmental Action Plan' (MAP) of utilities' association EnergieNed, a target of 3.5 CFLs per household was specified for 1995. This target was not achieved (Jeeninga, 1997).

By the mid-1990s there was some slowdown in CFL market growth in OECD countries. This coincided with cuts in DSM (Demand Side Management) programs spending, following the uitility deregulation trend (Iwafune, 2000).

A review of CFL ownership across the OECD in 1999 estimated that there was an average of 0.8 CFLs per household, with ownership levels ranging from just 0.1 CFL in Australia/New Zealand and North America to 3.2 CFLs in OECD Europe (IEA, 2006).

Since the end of the 1990s, worldwide CFL sales growth has accelerated, especially due to the spectacular growth in China and other Asian countries (see Figure 5.1). By 2003, global sales of CFLs had attained an estimated 1.1 billion units (IEA, 2006).

Traditionally, the world market for light bulbs was dominated by the 'big three' (Philips, Osram end GE), but recently competition from Chinese manufacturers has grown dramatically. Nowadays there are estimated to be more than 1,000 CFL manufacturers in China and they are thought to account for about 70% of the global CFL market in volume terms (IEA, 2006).



Source: IEA (2006)

Figure 5.1 Estimated global CFL sales by region, 1990-2004.

5.2 Development of prices and production costs

Table 5.1 presents a time series of observed and reported prices for CFLs, both in The Netherlands and abroad. Prices usually refer to CFLs with integrated ballasts[12], although this is not always specified in the sources that were used. The wattage of the CFLs is not specified, as prices among different wattages tend to be rather similar. ‘Artifically’ reduced prices (e.g. through utilities’ subsidies) are not included.

[12] In the early stages, ‘modular’ CFLs (with separate ballasts and tubes) were more common.

Table 5.1. Observed and reported market prices of CFLs.

Year	Country	Price (range)	Source	Notes
mid-1980s	USA	USD 25 - 35	Sandahl *et al.* (2006), referring to Calwell *et al.* (1999)	
1987	DK	USD 50	Menanteau and Lefebvre (2000)	(1)
1990	France	FRF 150	Menanteau and Lefebvre (2000)	(2)
1991	DK	USD 20	Menanteau and Lefebvre (2000)	
1991	UK	GBP 10 - 17	The Guardian, 8.11.1991	
1992	NL	NLG 50	Algemeen Dagblad, 14.5.1992	(3)
1992	USA	USD 15 - 20	Public Utilities Fortnightly, 15.7.1992	
1992	UK	GBP 8 - 15	The Guardian, 6.6.1992	
1993	NL	NLG 35 - 37	De Dordtenaar, 29.5.1993	
1993	NL	NLG 34-35	Algemeen Dagblad, 25.8.1993	(4)
1994	USA	USD 15	Scientific American, October 1994, p. 109	
1994	USA	USD 13	Salt Lake Tribune (Utah), 11.7.1994	
1995	USA	USD 15 - 18	Energy Conservation News, February 1995	
1995	NL	NLG 15	De Volkskrant, 6.10.1999	
1997	Hungary	HUF 1350	Ürge-Vorsatz and Hauff (2001)	
1997	Sweden	SEK 39	IAEEL Newsletter 3-4/97	(5)
1997	UK	GBP 6 - 12	The Guardian, 18.10.1997	
1997	USA	USD 7 - 20	Sandahl *et al.* (2006), referring to Decision Sciences Research Associates, Inc. (1998)	
1998	USA	USD 10	Energy Conservation News, April 1998	
1999	Hungary	HUF 1125	Ürge-Vorsatz and Hauff (2001)	
1999	NL	NLG 6 - 7	De Volkskrant, 6.10.1999	
1999	UK	GBP 6	The Guardian, 25.3.1999	
2000	France	FRF 50 - 100	Menanteau and Lefebvre (2000)	
2001	NL	NLG 13	De Volkskrant, 21.8.2001	
2001	USA	USD 10	PR Newswire, 20.3.2001	
2001	USA	Up to USD 20	Newsweek, 13.8.2001	(6)
2004	USA	± USD 10	The Augusta Chronicle (Georgia), 27.6.2004	
2006	USA	± USD 5	The Associated Press State & Local Wire, 21.2.2006	
2006	UK	GBP 3	The Mirror, 13.7.2006	
2007	USA	USD 2 - 4	New York Times, 2.1.2007	
2007	NL	EUR 7	NRC Handelsblad, 15.3.2007	
2007	NL	EUR 5 - 12	Algemeen Dagblad, 4.5.2007	

Notes to Table5.1:

(1) Price in constant USD of 1991.
(2) Price refers to “the beginning of the 1990s”.
(3) By 1992, the price of CFLs in the Netherlands was reported to have decreased rather quickly from NLG 100 to NLG 50, following promotional actions by Philips and Osram, together with the Dutch energy companies. At the time, supply capacity could hardly follow the increase in demand for CFLs, temporarily preventing further price reductions. Nevertheless, a further decrease to NLG 30 was expected.
(4) Prices found in a test by consumer organisation Consumentenbond (for 8 out of the 9 best performing CFLs).
(5) Refers to Ikea’s own brand CFLs (manufactured in China).
(6) Refers to the newest generation CFLs.

Figure 5.2 presents the data from Table 5.1 graphically, using the same exchange rates and price indices as in chapter 2.[13] Despite the wide range in observed prices, the rapid decline is obvious, especially during the 1990s.

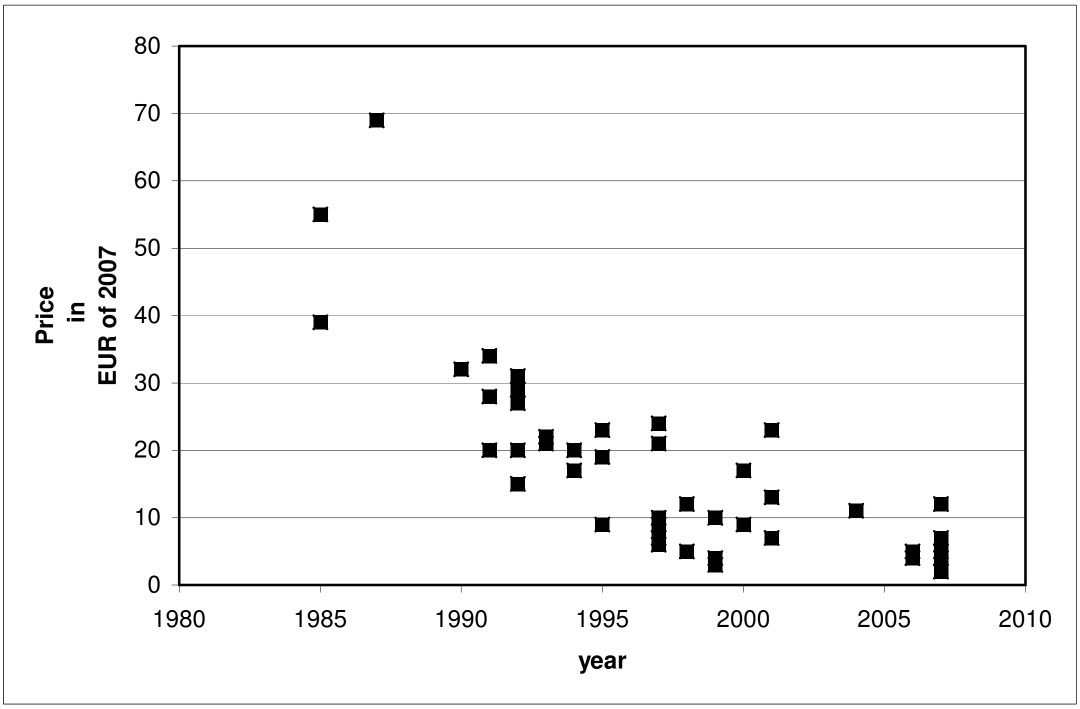


Figure 5.2 Observed and reported market prices of CFLs, in euros of 2007.

A main factor behind these price decreases has been the growing competition by Asian producers. In 1997, Ikea introduced a low-price CFL, produced in China, on the European market. In addition to low labour costs and economies of scale, the low price could also be afforded because Ikea found a way to produce the lamps without using technology patented by any of the major lamp manufacturers (IAEEL Newsletter 3-4/97). In the following years, price competition from Chinese producers became so strong that the European Commission even imposed anti-dumping duties on CFL imports from China in 2001.[14]

Technical improvements (such as reductions in the size of the ballast) have also contributed to reductions in the production cost of CFLs. Furthermore, several kinds of other technical improvements have taken place[15], implying that the 'price-quality ratio' has shown an even faster progress rate than the mere price data would suggest. On the other hand, the fierce price competition in China has led CFL producers there to compromise on product quality to reduce production costs (Lin, 1999).

If the price of CFLs is depicted as a function of cumulative production (rather than time), learning curves can be constructed. Iwafune (2000) has attempted to do so (see Figure 5.3). For the average observed prices, he arrived at a learning rate of 21.4%, i.e. a price

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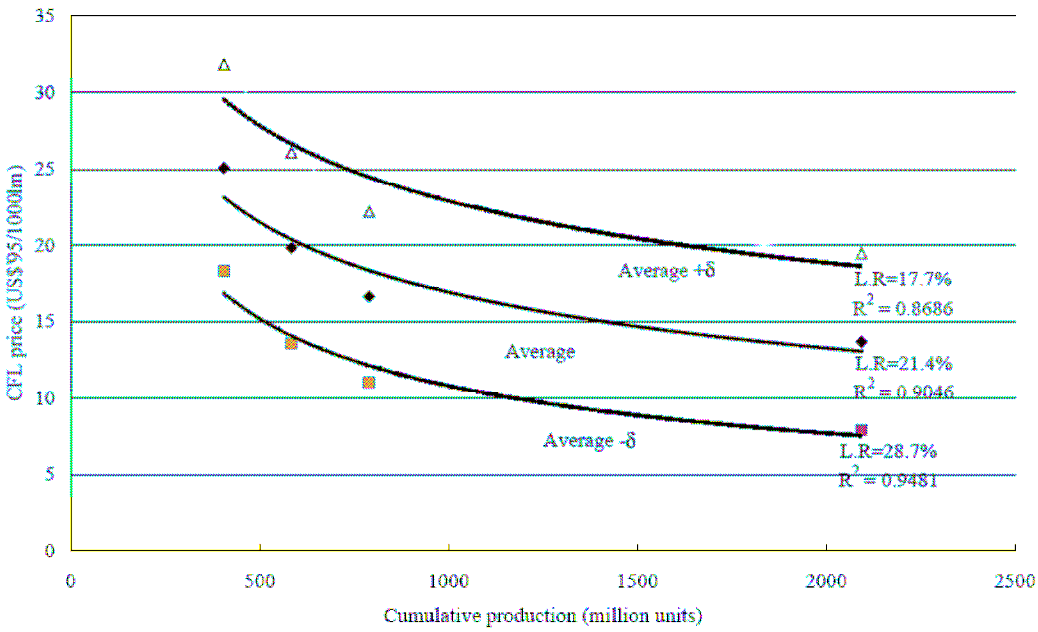
13 In addition, an exchange rate of SEK 8.5 per euro was used, and of HUF 200 and 250 per euro for 1997 and 1999, respectively.

14 Regulations 255/2001 (OJ L38, 8.2.2001) and 1470/2001 (OJ L195, 19.7.2001).

15 Including a market shift from magnetic towards electronic ballasts

decrease of 21.4% for each doubling of cumulative production. Given the wide spread of price observations, he also constructed learning curves for 'high' and 'low' prices (one standard deviation above and below the average, respectively), obtaining learning rates of 17.7% and 28.7%, respectively.



Source: Iwafune (2000)

Figure 5.3 CFL learning curve.

5.3 Conclusions

CFLs have shown considerable decreases in market prices over the past 20 years. In addition to economies of scale, increased competition (especially from China) seems to have played an important role in this case. Furthermore, incremental technological improvements have contributed to a better 'price-quality ratio'.

6. Conclusions

Just like other innovations, newly developed technologies for emission reduction tend to be expensive in their initial stages and to become cheaper once they are widely used. If this is not accounted for, the *ex ante* pollution control costs may be overestimated.

Learning curves are often used to estimate the possible future cost reductions in pollution control. Such curves assume a constant 'learning rate' (the percentage by which the cost or price of a technology drops for each doubling of cumulative sales or installed capacity). However, an uncritical use of learning rates may lead to misleading results. In a proper analysis, the specific factors that may (or may not) contribute to the cost decrease should be considered. These factors may include economies of scale, 'learning by doing', (incremental) technological improvements, and increased competition.

In the present study, four cases have been addressed, in which the roles of the various factors clearly differ. For example, in the cases of catalytic converters and CFLs it is likely that economies of scale in production have played a major role. For CFLs, increased competition has also been an important factor. In the SCR case, cost reductions have been achieved by prolonging the lifetime of the catalyst. The 'chemical scrubbers' case shows substantial cost reductions can be achieved by looking for options to reduce the necessary capacity of the system, especially when construction costs are the main component of the total costs. Tentatively, one might state that economies of scale and enhanced competition tend to be important sources of cost reduction in standard (consumer) products, whereas 'learning by doing' and incremental technological improvements are relatively important factors contributing to cost reductions in process-related technology.

One should also be aware of cost components that are unlikely to decrease, such as labour, energy or raw materials (unless the needed amount of these inputs can be reduced).

The present study furthermore illustrates clearly the complexities involved in comparing the costs of a technology over time. Time series data for market prices should be treated with caution, because market prices are not always accurate indicators of production costs. Moreover, as the technology or product usually develops over time (incremental innovation), the data do not refer to a 'homogeneous' technology. To the extent that these incremental innovations lead to improved quality or performance, the observed price decreases will underestimate the actual gains in 'value for money'. On the other hand, growing price competition may sometimes lead to the appearance of lower quality products on the market (as in the case of CFLs).

Finally, cost estimates are always based on certain assumptions, not only regarding the technology itself and the context in which it is applied, but also regarding depreciation, interest rates, expected future price levels etcetera. In comparing cost data, one should always be aware of possible differences in these assumptions.

References

Ando, J. (1989). Recent developments in SO_2 and NO_x abatement technology for stationary sources. *Lucht en Omgeving,* 115-120.

Bakema, G.F. & Kroon, P. (1988). *Vermijden of bestrijden? Emissies en kosten van emissie-beperking van SO_2, NO_x en stof tot 2010, behordend bij de Nationale Energie Verkenningen 1987.* Report ESC-44, Energie Studie Centrum, Petten.

Baltussen, W.H.M., Os, J. van & Altena, H. (1990). *Gevolgen van beperking van ammoniak-emissie voor varkensbedrijven.* Onderzoeksverslag 62, Landbouw-Economisch Instituut, The Hague.

Brugghen, F.W. van der, Graas, J.G.A., Pijnenburg, J.B.A.M., Tossaint, H.J. & Weier, W.L.C. (1983). *Rookgas-denitrificatie in Japan.* Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, Publikatiereeks Lucht 6.

Bruggink, J.J.C., Boonekamp, P.G.M., Bakema, G.F., Verhagen, L., Kroon, P. & Oostvoorn, F. van (1987). *Nationale Energie Verkenningen 1987.* Report ESC-42, Energie Studie Centrum, Petten.

Budin, R., Krotla, K. & Hartl, H. (2001). *Latest developments and the state of the art of catalytic DeNOx plants after 15 years of experience.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Buijsman, E. (2006). *Platinametalen in lucht. Een verkennend literatuuronderzoek.* MNP report 500093001/2006. Milieu- en Natuurplanbureau, Bilthoven.

CBS (1991). *Milieukosten van het verkeer, 1989 – 1990.* Centraal Bureau voor de Statistiek, Voorburg.

CPB (2000). *Naar een efficiënter milieubeleid. Een maatschappelijk-economische analyse van vier hardnekkige milieuproblemen.*Centraal Planbureau, The Hague.

Crocker, M., Ylstra, W. & Maaskant, O. (1996). Toepassing van een nieuwe generatie $DeNO_x$ systeem bij de reiniging van rookgassen. *Lucht, 4*, 116-118.

Dings, J.M.W. (1996). *Kosten en milieueffecten van technische maatregelen in het verkeer.* CE, Delft.

Eskinazi, D., Cichanowicz, J.E., Linak, W.P. & Hall, R.E. (1989). Stationary Combustion NO_x Control. A Summary of the 1989 Symposium. *Journal of the Air Pollution Control Association* 39(8), 1131-1139.

European Commission (1998). *Economic evaluation of air quality targets for sulphur dioxide, nitrogen dioxide, fine and suspended particulate matter and lead.* Final Report. Office for Official Publications of the European Communities, Luxembourg.

European Commission (2003a). *Reference Document on Best Available Techniques in Common Waste Water and Waste Gas Treatment / Management Systems in the Chemical Sector.* European IPPC Bureau, Sevilla.

European Commission (2003b). *Reference Document on Best Available Techniques for Intensive Rearing of Poultry and Pigs.* European IPPC Bureau, Sevilla.

European Commission (2006). *Reference Document on Best Available Techniques for Large Combustion Plants.* European IPPC Bureau, Sevilla.

Graas, A.J.G.A. & Wijdeveld, H.W.J. (1984). Verwijdering van stikstofoxyden uit (rook)gassen. *Lucht en Omgeving,* 28-31.

Honig, E., Hanemaaijer, A., Engelen, R., Dekkers, A. & Thomas, R. (2000). *Techno 2000; Modellering van de daling van eenheidskosten van technologieën in de tijd.* Report number 773008003, RIVM, Bilthoven.

Horne, P.L.M. van, Hoste, R., Haan, B.J. de, Ellen, H., Hoofs, A. & Bosma, B. (2006). *Gevolgen van aanpassingen in het ammoniakbeleid voor de intensieve veehouderij. Onderzoek naar de economische aspecten van en de gevolgen voor de ammoniakdoelstellingen bij intern salderen van ammoniakemissie, versoepeling van de WAV en het niet emissiearm maken van bestaande stallen.* Rapport 3.06.03, juli 2006. LEI, Den Haag, i.s.m. Milieu- en Natuurplanbureau, Bilthoven.

IEA (2006). *Light's Labour's Lost. Policies for Energy-efficient Lighting.* International Energy Agency, Paris.

Iwafune, Y. (2000), *Technology Progress Dynamics of Compact Fluorescent Lamps.* Interim Report IR-00-009, International Institute for Applied Systems Analysis (IIASA), Laxenburg.

Jantzen, J. (1989). *Kosten van het milieubeheer, 1985-2010. Een drietal milieubeleidsvarianten in het kader van 'Zorgen voor morgen' en het 'Nationaal Milieubeleidsplan'.* Publikatiereeks Milieubeheer no. 5, Ministerie van VROM, Den Haag.

Jantzen, J., Heijnes, H. & Duyse, P. van (1995). *Technische vooruitgang en milieukosten, aanzet tot methodiekontwikkeling (Technological progress and environmental costs, initiative for methodological development).* Institute for Applied Environmental Economics (TME), The Hague.

Jantzen, J. & Woerd, H. van der (2006). *Ex-post estimates of costs to business of EU environmental policies. Case study road transport.* Institute for Applied Environmental Economics (TME), Nootdorp. http://ec.europa.eu/environment/enveco/ex_post/pdf/transport.pdf

Jeeninga, H. (1997). *Analyse energieverbruik sector huishoudens 1982-1996. Achtergronddocument bij het rapport 'Monitoring energieverbuik en beleid Nederland'.*Report no. ECN-1-97-051, Energieonderzoek Centrum Nederland, Petten.

Kessel, R. van & Roukens, J. (2001). *The feasibility of retrofitting a gas turbine cogeneration plant with (hybrid) DeNOx technology.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Kossina, I. (2001). *Reduction of NOx emissions from exhaust gases of cement kilns by selective catalytic reduction.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Lin, J. (1999). *China Green Lights Program: A Review and Recommendations*. Energy Analysis Department, Lawrence Berkeley National Laboratory.

LNV & VROM (1990). *Plan van aanpak beperking ammoniak-emissie van de landbouw. Regeringsbeslissing.* Tweede Kamer, vergaderjaar 1990-1991, 18 225, nrs 42-43.

Maaskant, O.L. & Miggelbrink, M. (2001). *A catalytic system for Nox and dioxins removal : applications, performance and costs.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Matthys, K., Boels, K., Goemans, M., Clarysse, P., Joannes, J. & Clercq, P. de (2001). *SEGHERSdeDInOX : catalytic NOx reduction with simultaneous dioxin destruction in a municipal waste incinerator in Belgium.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Melse, R.W. & Willers, H.C. (2004). *Toepassing van luchtbehandelingstechnieken binnen de intensieve veehouderij. Fase 1: Techniek en kosten.* Report 029, Agrotechnology & Food Innovations BV, Wageningen.

Melse, R.W. & Ogink, N.W.M. (2004). *Toepassing van luchtbehandelingstechnieken binnen de intensieve veehouderij. Fase 2: Mogelijkheden tot kostenverlaging van wassers.* Report 271, Agrotechnology & Food Innovations BV, Wageningen.

Menanteau, P. & Lefebvre, H. (2000). Competing technologies and the diffusion of innovations: the emergence of energy-efficient lamps in the residential sector. *Research Policy, 29*(3), 375-389.

METRA (1979). *Manual of Air Pollution Control Techniques.* In appointment of the Ministry of Health and Environmental Protection compiled by METRA consulting Ltd., London, February 1979. Published by the Government Publishing Office, The Hague.

Novem (undated a). *NO_x reduction from stationary sources using End-of-Pipe Technologies.* Leaflet, Novem, Utrecht.

Novem (undated b). *Nageschakelde NO_x-reductie in de industrie. Resultaten van het programma Reductie Luchtemissies Bedrijven.* Publication 3RLB-02.01, Novem, Utrecht.

NEA/IEA/OECD (1998). *Projected Costs of Generating Electricity. Update 1998.* Nuclear Energy Agency, International Energy Agency and Organisation for Economic Co-operation and Development, Paris.

OECD (1986). *Enclair '86, Energy and cleaner air: costs of reducing emissions*. Proceedings of a symposium held in October 1986, Italy.

Offen, G.R., Eskinazi, D., McElroy, M.W. & Maulbetsch, J.S. (1987). 1987 Joint EPRI/EPA Symposium on Stationary Combustion NO_x Control. *Journal of the Air Pollution Control Association, 37*(7), 864-871.

Olsthoorn, A.A., Thomas, R., Vos, J.B., Hettelingh, J.-P., Hordijk, L. & Jansen, H.M.A. (1982). *Drie scenario's voor de ontwikkeling van de NO_x-emissies in Nederland 1978-2000.* Instituut voor Milieuvraagstukken, Vrije Universiteit, Amsterdam, report no. 82/16, December 1982.

Olsthoorn, A.A. & Thomas, R. (1983). *Kosten van bestrijding NO_x-emissies.* Instituut voor Milieuvraagstukken, Vrije Universiteit, Amsterdam.

Olsthoorn, A.A. & Thomas, R. (1986). *Scenario's voor vier milieugevaarlijke stoffen in 2000: emissies en kosten van emissiebestrijding van SO2, NOx, lood en cadmium.* Publikatiereeks Milieubeheer no. 6, Ministerie van VROM, Den Haag.

Oosterhuis, F. (ed., 2006). *Ex-post estimates of costs to business of EU environmental legislation. Final report.* IVM Report E-06/08, Instituut voor Milieuvraagstukken, Vrije Universiteit, Amsterdam.

Paul, P.G. & Maaskant, O.L. (2001). *Catalytic NOx emission reduction at a cogeneration plant in the food industry.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Pellini, T. & Morris, J. (2002). IPPC and Intensive Pig Production in England and Wales: Compliance Costs, Emission Abatement and Affordability. *European Environment, 12*, 332-347.

Raymond, B. (2001). *NOx reduction measures at the Nippon Mitsubishi refinery of Negishi in Yokohama, Japan.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Rigby, K., Libuda, T., Klatt, A. & Zürbig, J. (2001). *SCR: the most effective technology for NOx reduction in large combustion plants.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Rijkeboer, R.C. (1983). *The European policy on automotive emissions and the development of car- and engine technology.* Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, Publikatiereeks Lucht, 5.

RIVM (1994). *Milieurendement van het NMP-2. Bijlagen E t/m H.* Rijksinstituut voor Volksgezondheid en Milieuhygiëne, Bilthoven.

Rossati, F. (2001). *The catalytic NOx and dioxin removal unit of the sewage treatment plant of Colombes, France.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Rubin, E.S., Taylor, M.R., Yeh, S. & Hounshell, D.A. (2004). Learning curves for environmental technology and their importance for climate policy analysis. *Energy, 29*, 1551-1559.

Sandahl, L.J., Gilbride, T.L., Ledbetter, M.R., Steward, H.E. & Calwell, C. (2006). *Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market*. PNNL 15730, Pacific Northwest National Laboratory, Richland, Washington.

J. Sathaye, Friedmann, R., Meyers, S., Buen, O. de, Gadgil, A., Vargas, E. & Saucedo, R. (1994). Economic analysis of Ilumex. A project to promote energy-efficient residential lighting in Mexico. *Energy Policy, 22*(2), 163-171.

Schindler, I. (2001). *SCR : state-of-the-art for NOx reduction across the sectors.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Schipper-Zablotskaja, M. (1992). *Selectieve katalytische reductie.* In: RIVM/TNO (1992). Monografieën informatiesysteem technieken. Compartiment Lucht. RIVM/TNO, rapportnr. 736101007. Bilthoven.

SEI (1999). *Costs and Strategies presented by Industry during the Negotiation of Environmental Regulations.* Stockholm Environment Institute, Stockholm.

Takeshita, M. (1995). *Air pollution control costs for coal-fired power stations.* Publication no. IEAPER/17, IEA Coal Research, London.

Tangena, B.H. (1985). *Optimalisatie bestrijding verzurende emissies*. Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, Publikatiereeks Lucht, 40.

Thomas, R., Vos, J.B., Hettelingh, J.P., Hordijk, L., Jansen, H.M.A. & Olsthoorn, A.A. (1983). *Uitworp van stikstofoxiden in Nederland in het jaar 2000*. Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, Publikatiereeks Lucht, 7.

Timmer, G. (2001). *NOx emission reduction over the past decade and environmental opportunities for the future for Waste to Energy plants in the Netherlands.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Touring Club der Schweiz (1994). *10 Jahre Katalysatorautos.* Emmen.

UNECE (1999). *Draft Guidance Documents on Control Techniques and Economic Instruments to the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone.* United Nations Economic Commission for Europe, Geneva, EB.AIR/1999/2.

Ürge-Vorsatz, D. & J. Hauff (2001). Drivers of market transformation: analysis of the Hungarian lighting success story. *Energy Policy, 29*(10), 801-810.

Van Beckhoven, L.C. (1984). Luchtverontreiniging door de auto. *Lucht en omgeving*. 74-78.

Van den Bergh, J., Leeuwen, E. van, Oosterhuis, F., Rietveld, P.& Verhoef, E. (2004). *Innovaties voor duurzaam vervoer. Succes- en faalfactoren in acht casestudies.* IVM Report R-04/06, Institute for Environmental Studies, Vrije Universiteit, Amsterdam.

Van Esch, F.A.J. (2001). *Decreased NOx emissions by use of selective catalytic reduction on a gas turbine in the food-processing sector.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Van Oostvoorn, F. & Arkel, W.G. van (1984). *Optimale strategieën voor de bestrijding van zure regen veroorzakende SO2- en NOx-emissies gebaseerd op berekeningen met SELPE.* Energie Studie Centrum, Petten.

Verdoes, N. & Zonderland, J.J. (1999). *Het effect van een chemische luchtwasser op de ammoniakemissie uit een vleesvarkensstal (The effect of a chemical air scrubber on ammonia emission from a growing-finishing pig house).* Proefverslag nummer P 4.39, Praktijkonderzoek Varkenshouderij, Rosmalen.

Vringer, K. & Hanemaaijer, A.H. (2000). *Kosteneffectiviteit van milieumaatregelen.* RIVM-rapport 773008002, RIVM, Bilthoven.

VROM (1983). *Technologische gegevens voor het NO_x-beleid.* Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, Publikatiereeeks Lucht, 8.

VROM (1987), *Tussentijdse evaluatie verzuringsbeleid.* Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, Den Haag.

Wagner, F., Depauw, J.P. & Hamon, C. (2001). *Highly effective SCR to control the very high initial NOx content.* Paper presented at the International conference on atmospheric pollution - NOx and N2O emission control: panel of available techniques, Paris-La Défense (France), 21st and 22nd March 2001.

Wetenschappelijke Raad voor het Regeringsbeleid (WRR) (1987). *Ruimte voor groei. Kansen en bedreigingen voor de Nederlandse economie in de komende tien jaar.* Staatsuitgeverij. Den Haag.

Wetzels, F. (1996). Vermindering NO_x-emisie bij afvalverbranding. *Lucht, 4*, 113-115.

Zwalve, W.J. (1985). Schone auto's, waarom en wanneer? *Lucht en omgeving,* 156-160.