Ökopol
Institute for Environmental Strategies

Economic evaluation of NOx abatement techniques in the European Cement Industry

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Author:
Jan Wulf-Schnabel
Dr. Joachim Lohse

Content

1. Background and Scope of this Study

To an increasing extent, cement kilns are burning waste as a secondary fuel. Until today, they are not covered by European legislation that has set standards for pollution to air from plants for municipal waste incineration, in particular Directives 89/429/EEC and 89/369/EEC. The Commission is in the process of considering a revision to the emission limit values set by the 1989 Directives. As part of the revision it is considering extending the scope of these Directives to cover cement kilns that burn waste as fuel, and in particular to set standards for emissions of nitrogen oxides (NOx) from such plants.

It is the objective of this study to consider the costs and benefits of extending the scope of the Incineration Directive to specify emission limit values from cement kilns burning waste as fuel.

Starting from the present situation of actual NOx emission levels from existing cement kilns, the various technical options for a reduction of NOx emissions are to be presented and discussed. These technical alternatives shall be examined for

- the emission reduction that can be achieved by such techniques and
- the investment and operational costs that these techniques will eventually cause for the operator of the cement kiln.

At the macro-economic level, the costs of the NOx abatement measures are to be compared to the damage costs of unreduced NOx emissions from cement kilns burning waste as fuel. [For this cost-benefit-analysis at the macro-economic level, the results from methodology developed by ETSU (1996) for their examination of the costs and benefits of the proposed new emission limits for municipal waste incineration plants, will be transferred without detailed discussion.

On an individual plant level, the NOx reduction costs are compared to the economic advantage that is given for the operator of a cement kiln when he

Nernstweg 32-34
D-22765 Hamburg
Phone: +49 / 40/ 391 002-0
Fax: +49 / 40 / 391 002-33
info@oekopol.de
www.oekopol.de

uses waste as a secondary fuel.

2. NOx emissions from the European Cement Industry

On an average, the European cement kilns emit circa 1.300 milligrams of nitrogen oxides per norm cubic meter of stack gas [mg NOx/Nm³, referring to dry gas, 0 °C, 1 atm and 10% O2]. Emissions of older plants often lie around 2.000 mg NOx/Nm³, while already today some modern kilns emit less than 500 mg NOx/Nm³.

These NOx emissions from the European cement industry add up to a total annual emission of 450.500 Mg NOx. This corresponds to between 10 and 15 per cent of the overall NOx emissions from all industrial point sources, or 3-4 per cent of all NOx emissions (including diffuse sources) in Europe.

3. Techniques for reduction of NOx emissions

A variety of techniques have been developed in order to reduce the NOx emission level from cement kilns (see Annex, Table 1). These include general techniques of process control optimisation and primary measures like fuel selection, low-NOx burners and staged combustion that are able to reduce the formation of NOx at the source, but also secondary measures like selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR). With these latter techniques, NOx emissions are reduced by a chemical reaction with a reducing agent (mostly ammonia or ammonia water) that is injected into the exhaust gas stream at a suitable temperature.[1]

By a combination of primary measures, at many European cement kilns the NOx emission level has successfully been reduced to circa 800-1100 mg NOx/Nm³, depending on individual circumstances. Some modern kilns are even able to control their NOx emissions safely below 500 mg/Nm³ by using only primary measures.

By using the SNCR technique, emission levels of 500-800 mg/Nm³ can be achieved, depending on the original emission level.[2] Today, SNCR is in large scale operation at a number of European kilns. It is applicable to those types of cement kilns (normally preheater kilns) where the required temperature window is accessible.[3]

Still lower NOx emission levels (between 100 and 200 mg/Nm³) can be achieved by the SCR technique. In the past, this technique has been widely used for NOx abatement in other industries like coal-fired power plants and waste incinerators. On cement kilns, exhaust gas treatment before ("high-dust" SCR) or behind the electrostatic precipitator ("low-dust" SCR) is principally possible. High dust systems are preferred for both technical and economic reasons (IPTS, 1998), provided that the catalyst is not destroyed by the high concentrations of dust.

After several successful pilot plant investigations in Italy, Austria and Sweden in which no loss of catalyst was observed, a full-scale SCR

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[1] For a more detailed technical description, the reader is referred to the "Draft Reference Document on BAT in the Cement and Lime industries" by IPTS, August 1998.

[2] As a general rule, it is said that SNCR can lower the NOx emissions of a kiln by 60 per cent, corresponding e.g. to a reduction from 2.000 to 800 mg/Nm³ or from 1.300 to 500 mg/Nm³. Applying SNCR for further NOx reduction below 500 mg/Nm³ appears to be a merely theoretical option that often leads to problems in practice.

[3] On precalciner kilns, it is more difficult to find a convenient temperature window. These kilns, however, have much better circumstances for successful primary measures.

demonstration plant is now under construction in Germany.

If NOx emissions are controlled by primary measures only, the achievable emission levels mentioned above may occasionally be exceeded for short periods of time. In contrast to this, SNCR and SCR are able to prevent such short-term peak emissions.

4. Costs of the various NOx control techniques

In this section, the annual costs of the various NOx control techniques are calculated as capital expenditure account according to the static method. The depreciation period was set at 10 years, the calculative interest rate at 10 per cent annually (which is fairly high in comparison to an interest rate of 6% p.a. which is common for investments in environmental protection measures).

In addition to the capital costs, the operating costs were calculated on the basis of estimated costs for consumables, electricity, pressure air, maintenance and repair costs, and personnel. Assumptions on costs are based on information received from kiln operators and machine and plant engineering firms.

By this method, annual costs were calculated for the technical options

- combination of primary measures (i.e. process control optimisation, low-NOx burners and fuel selection)
- + staged combustion
- SNCR
- SCR.

Primary measures are effective only when a combination of process control optimisation, improved firing technique, low-NOx burners and fuel selection is applied. Their costs must not be solely allocated to NOx reduction because they bring about significant economic benefits like improved product quality and reduced energy demand of the kiln. Necessary adaptations of low-NOx burners to the specific kiln routine may cause more frequent down times at the beginning that will be overcome after some experience. Operating costs consist of maintenance and repair costs of process automation and low-NOx burners, costs for cooling of the main flame, and increased costs for fuel with a low nitrogen content.

Staged combustion is calculated separately because it is not feasible for all kiln types but mainly for precalciner kilns. Costs of staged combustion therefore must be seen in addition to the costs of primary measures.

The costs of the secondary measures SNCR and SCR are characterised by higher investment costs for SCR but higher operating costs for SNCR. Kiln capacity has little influence on the investment costs but is crucial for the operating costs: these are dominated by the ammonia (NH3) consumption which itself depends on the NH3 dosage, the exhaust gas volume and thus the kiln capacity. NH3 dosage is relatively lower for the catalytic reduction (SCR) technique that achieves optimum performance of 90% NOx reduction at a stochiometric ratio of 0,9 (0,9 Mole of NH3 for reduction of 1 Mole NOx), while SNCR requires an average molar ratio of 1,2 in order to achieve its optimum of 60% NOx reduction. For costs of both SNCR and SCR, key parameters are the initial NOx level in the raw gas and the NOx target concentration, because for economic reasons many kiln operators will inject only the minimum amount of NH3 that will suffice to achieve the target. For calculation of SCR costs, an exchange of catalyst after five years is taken into account. Costs of 25% ammonia water are reported by various experts between 65 and 100 ECU per metric tonne[4] (our calculations are based on

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[4] Some kiln operators can keep these costs low by using e.g. photographic fluid wastes as the reducing agent; however, these are not available throughout Europe.

80 ECU/Mg).

Repair and maintenance costs are assumed at 2% of the capital investments. For all calculations, energy costs are assumed at 0,04 ECU/kWh (according to CEMBUREAU, 1997). They make up only a minor contribution to the overall costs.
The cost accounting results were related to three different kiln sizes, "kiln A" with a capacity of 1.000 Mg clinker per day [Mg/d], "kiln B" producing 2.500 Mg/d and "kiln C" with a daily production of 5.000 Mg clinker. For these typical kiln sizes, the specific costs of NOx reduction measurements in terms of ECU per metric tonne of clinker produced [ECU / Mg clinker] are calculated (see Annex to this study).

The respective costs of the various NOx reduction techniques at the different kilns are calculated for two different initial emission levels (2.000 and 1.300 mg/Nm³) and for both optimum reduction and reduction to a pre-set emission level (Tables 2, 3 and 4). The results are presented in graphical form in Figures 1-4.

In effect, the costs of the combined primary measures are between 0,68 and 1,6 ECU per Mg of clinker; an additional staged combustion will cost an extra 0,05 - 0,23 ECU/Mg clinker. (It should be kept in mind here that costs of process control bring about other economic benefits with respect to product quality and energy demand).

As can be seen from Table 4, NOx reduction to 800 mg/Nm³ or lower by the SNCR technique will cost between 0,47 and 1,4 ECU/Mg clinker, depending largely on the quantitative ammonia consumption and hence on the initial NOx emission level and the target level to be achieved.

Concerning the costs of the SCR technique, less practical experience has been made so far. Starting from an initial level of 1.300 mg NOx /Nm³, these costs will make up between 0,49 and 1,44 ECU / Mg clinker as long as the same target levels as for SNCR are to be achieved (e.g. 800 or 500 mg/Nm³).

SCR is the only technique that can safely achieve NOx levels below 200 mg/Nm³. It will then cost circa 0,75-1,87 ECU/Mg clinker. Ultimately, the operating time of the catalyst will be crucial for the annual costs of SCR. This life-time of catalyst, however, has not yet been determined at a full-scale installation.

In Table 5 (Annex), an alternative mathematical model is used to calculate the annual equivalent costs of the NOx minimisation measures. For this calculation, the discount rate was set at 8 per cent annually.

When this model is applied to "kiln B" and an initial NOx emission level of 2.000 mg/Nm³, the annual equivalent costs are between 4,1 and 6,9 per cent higher than the respective costs calculated by the static method.

5. External Costs of unreduced NOx emissions

The external costs of industrial emissions of nitrogen oxides have been assessed for waste incinerators by ETSU (1996). For three municipal locations in Europe, ETSU calculated the damage to human health, materials and buildings, and secondary effects of ozone that is formed by atmospheric reactions of NOx as follows:

External costs of NOx (in ECU / Mg of NOx) for a stack height of 100m [ETSU 1996]				
Location	Human health	Materials & Buildings	Ozone	Sum
Paris	16.874	236	2.530	19.640
Stuttgart	15.576	307	2.530	18.413
Birmingham	6.726	165	2.530	9.421

For all three sites, damage to human health is the biggest external effect even although only the acute injuries to human health were taken into account by the authors. Damage to materials is relatively low in relation to the other external costs. The external damage from ozone formation is considered to be irrespective of the location because of long-range atmospheric transport.

Along the lines of the ETSU study, the externalities of NOx emissions from the European cement industry must be assumed to lie between the theoretical extremes of circa 2.500 per Mg of NOx for a fictitious cement kiln in an absolutely remote area where no health and material damages are caused and damage from ozone is the only external factor, and an upper value of circa 20.000 ECU / Mg NOx for a cement kiln in a densely populated area like Paris.

In practice, waste incinerators are often located in more densely populated areas where most of the municipal waste arises. Cement kilns are normally located on the site of the geogenic ressources of raw materials, which can be in rural areas as well as in close vicinity to a city.

For the assessment of the external cost-benefit ratio of NOx emission reductions in the cement industry, two scenarios were calculated, one on the basis of an external damage of 5.000 ECU per Mg NOx, the second one on the basis of 10.000 ECU damage per Mg NOx.[5] For these two scenarios, the externalities were calculated for two kilns, "Variant A" with an initial emission level of 1.300 mg NOx / Nm^3 (European average), "Variant B" with an initial NOx emission of 2.000 mg NOx /Nm^3.

As can be seen from Table 6, a reduction of NOx emissions from the cement industry will significantly reduce the external damage caused by these emissions. For two typical cases, the costs and benefits from NOx reduction measures are plotted in graphical form in Figures 5 and 6. The ratio between these benefits and the costs which are necessary to achieve is calculated in Table 7.

Starting from the European emission average of 1.300 mg NOx /Nm^3, every ECU that is spent for NOx reduction will yield external benefits worth between 2 and 31 ECU, depending on the detailed conditions of the single case. Because of the maximum reduction of external damages, the largest cost-benefit ratio of 1:31 is achieved by an optimum application of the SCR technique (i.e. target emission level < 200 mg /Nm^3) if the external damage of NOx is assumed to be 10.000 ECU/Mg NOx (Table 7).

For an initial emission level of 2.000 mg NOx per Nm3, the cost-benefit ratio of NOx reduction measures will lie between 1:4 and 1:42. Again, the SCR technique is able to yield the highest benefits.

Implementation of a legal NOx emission limit of 800 mg / Nm^3 on all European cement kilns will yield cost-benefit ratios between 1:3 and 1:33, depending on the circumstances of the individual case.

These cost-benefit ratios will decrease slightly (between four and seven per cent) when they are based on the alternative calculating model of annual equivalent costs instead of annual costs by the static method. On the other hand, cost-benefit ratios will be higher by 50 per cent when the damage costs are assumed to be 15.000 ECU/Mg NOx instead of 10.000 ECU/Mg NOx.

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[5] Both scenarios will presumably underestimate the external benefit that will arise from the reduction of NOx emissions from the cement industry. However, a more detailed analysis would have to be based on a detailed assessment of one or several specific sites, which would have been clearly beyond the scope of this study.

6. Commercial advantages from using wastes as fuel substitutes

By taking in wastes as secondary fuel, an economic advantage is given for the operator of a cement kiln for two reasons: On the one hand, he can save expenses for regular fuel, on the other hand he can charge a disposal fee for the wastes (Figure 7).

Based on data about fuel costs and disposal fees that was obtained from various industries, the economic net revenue from the substitution of 5% of regular fuel by wastes as secondary fuel is estimated at circa 0,7 ECU per Mg of clinker produced.

In practice, many European kiln operators are presently substituting between 25% and 50% of their energy demand by secondary fuels, corresponding to an economic advantage of often more than 5 ECU/Mg clinker.

Depending on the kiln size, the proportion of wastes whose co-incineration can cover the costs of NOx reduction measurements, will lie between 5 and 7% of the overall energy demand for both primary measures and the SNCR technique. Substitution of 5-10% of the energy demand can finance the same emission reduction (from 1.300 to 500 mg NOx / Nm³) by applying the SCR technique.

Between 6 and 12% of regular fuel have to be substituted by wastes in order to finance a reduction of NOx emissions from 2.000 to 800 mg / Nm³ by either the SNCR or the SCR technique.

In a medium-size or large kiln equipped with a cyclone preheater, for achievement of the same emission reduction the costs of SCR can be equal or even lower than the costs for SNCR (Table 4 and Figures 3-4).

7. Summary and Recommendation

A variety of techniques have been developed that allow cement kilns to reduce their emissions of nitrogen oxides to levels below 800 mg NOx /Nm³. The most relevant techniques to be mentioned here are several primary measures, staged combustion, selective non-catalytic reduction (SNCR), and the rather new technique of selective catalytic reduction (SCR).

Although not every one of these techniques is applicable to each kiln type, for every kiln there is at least one technical option feasible that enables the operator to control the NOx emissions below the above-mentioned level.

When the allowed NOx emission level for cement kilns is lowered to 800 mg / Nm³, the external benefit from the avoided damage caused by NOx emissions will be between three and 33 times higher than the necessary expenses for the reduction measures.

Depending on the initial emission level before the technical improvement, for the annual costs of the NOx reduction measures the kiln operator will have to spend approximately the revenue which he receives from co-incineration of wastes equivalent to between 5 and 12 per cent of the kilns total energy demand. In many cases, the expenses for NOx reduction measures will even be much lower than this.

For most kilns, more than one technical option is available to achieve the proposed NOx emission reduction below 800 mg/Nm³. Depending on the individual circumstances, some of these options are able to achieve even lower emission levels around 500 mg NOx per Nm³.

There are, however, a number of cement kilns that might face difficulties if the allowed NOx emissions were legally restricted to 500 mg/Nm³, because the well-established technologies are either not applicable to the specific kiln type, or they will not suffice to achieve the required target level of 500 mg/Nm³.

A legal limitation of NOx emissions to a level below 200 mg/Nm³ would force all kiln operators to instal an SCR catalyst. The external cost-benefit ratio for such a reduction will lie between 1:7 and 1:42 and will thus be significantly higher than for the NOx reduction to 800 mg/Nm³. However, no long-term experiences with full-scale SCR installations have been made yet in the cement industry, thus leaving a certain degree of uncertainty about the life-time of the catalyst and the subsequent overall costs of this technique.

At present, it may therefore be too early to justify an emission limit of 200 mg/Nm³ for every cement kiln in Europe. Because of the optimum cost-benefit ratio, but depending on the future experiences with the SCR technique, in a medium-term perspective a legal emission limit of 200 mg/Nm³ maybe appropriate for those European cement kilns that are co-incinerating wastes on a large scale.

8. Evaluated Literature

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Further consultations for this project were held with:

Austrian Energy and Environment, Elektro Mark AG, Elex AG, KHD Humboldt-Wedag, Kirchdorfer Zementwerk Hofmann GesmbH, Krupp-Polysius AG, Lurgi Umwelt GmbH, Noell-KRC Energie- und Umwelttechnik GmbH, Readymix Zementwerke GmbH, Spenner Zement GmbH& Co. KG, Umweltbundesamt Berlin, Umweltbundesamt Wien.

The contribution of competent persons from these companies and institutions to this study is gratefully acknowledged.

Annex

Tables

Figures

Table 1 Technical options for NOx reduction

Technical measure	NOx reduction achieved in practice	Comments
Primary measures	Optimum emission level: < 500 mg/Nm3	only by combination of several measures (at new kilns)
Process control optimisation	0 to 20% reduction potential	automatic process control is state of the art today at numerous cement kilns in the EU.
LowNOx - burner	0% to 30% reduction potential	exchange of conventional burners is state of the art at numerous cement kilns in the EU.
Ionisation	0%	supplier claims a reduction potential up to 25% of total NOx.
Fuel selection	circa 50% in combination with other measures; circa 25% NOx reduction potential by fuel selection alone	e.g. switch from pit-coal to lignite or secondary fuels with high proportion of volatile constituents
shift of energy input from main burner to secondary firing	10 to 30% reduction	not applicable to all kiln types
staged combustion	10 to 40% reduction	not applicable to all kiln types; success depends on initial NOx level
fluidized bed combustion	50% reduction (only in combination with other primary measures)	expensive for small and medium-size kilns; only feasible for new kilns (not for all kiln types)
Secondary measures	Optimum 100 - 200 mg/m3 (with SCR technique)	
SNCR	reduction potential 60%	risk of NH3 escape
SCR	reduction potential 90%	NOx emission can be safely kept below 200 mg/m3
Lurenox	reduction potential 60-70%	technique in R&D state only; special catalyst required

Table 2 Cost comparison of various NOx reduction measures at optimumreduction efficiency and an initial emission level of 2.000g/Nm3 [in ECU]

Kiln A	Prim.M	(PM+)SC	SNCR	SCR
Repayment	210.000	50.000	85.000	210.000
Interest	105.000	25.000	42.500	105.00
Operation costs	270.00	10.000	383.140	366.605
Annual costs	585.000	85.000	510.640	681.605
Kiln B	Prim.M	(PM+)SC	SNCR	SCR
Repayment	22.000	55.000	90.000	230.000
Interest	110.000	27.500	45.000	115.000
Operation costs	505.000	10.000	933.350	795.012
Annual costs	835.000	92.500	1.068.350	1.140.012
Kiln C	Prim.M	(PM+)SC	SNCR	SCR
Repayment	230.000	60.000	100.000	260.000
Interest	115.000	30.000	50.000	130.000
Operation costs	890.000	10.000	1.850.699	1.890.025
Annual costs	1.235.000	100.000	2.000.699	1.890.025
NOx reduction costs in ECU/Mg clinker				
	Prim.M	(PM+)SC	SNCR	SCR
Kiln A	1,60	0,23	1,40	1, 87
Kiln B	0,92	0,10	1,17	1,25
Kiln C	0,68	0,05	1,10	1,04
Achievable emission level [mg NOx / Nm3]				
	Prim.M	(PM+)SC	SNCR	SCR
Kiln A - C	1.100	900	800	200

Explanatory remark: Staged combustion (SC) is technically feasible only in combination with Primary Measures (PM). Costs for SC therefore have to be taken in addition to costs for PM while the achievable emission level is to be seen in combination of PM+SC.

Table 3 Cost comparison of various NOx reduction measures at optimumreduction efficiency and an initial emission level of 1.300 mg/Nm3[in ECU]

Kiln A	Prim.M	(PM+)SC	SNCR	SCR
Repayment	210.000	50.000	85.000	210.000
Interest	105.000	25.000	42.500	105.000
Operation costs	270.000	10.000	254.991	270.493
Annual costs	585.000	85.000	382.491	585.493
Kiln B	Prim.M	(PM+)SC	SNCR	SCR
Repayment	220.000	55.000	90.000	230.000
Interest	110.000	27.500	45.000	115.000
Operation costs	505.000	10.000	612.977	554.733
Annual costs	835.000	92.500	747.977	899.733
Kiln C	Prim.M	(PM+)SC	SNCR	SCR
Repayment	230.000	60.000	100.000	260.000
Interest	115.000	30.000	50.000	130.000
Operation costs	890.000	10.000	1.209.955	1.019.466
Annual costs	1.235.000	100.000	1.350.000	1.409.466
NOx reduction costs in ECU/Mg clinker				
	Prim.M	(PM+)SC	SNCR	SCR
Kiln A	1,60	0,23	1,05	1,60
Kiln B	0,92	0,10	0,82	0,99
Kiln C	0,68	0,05	0,75	0,77
Achievable emission level [mg NOx / Nm3]				
	Prim.M	(PM+)SC	SNCR	SCR
Kiln A - C	1.100	800	500	130

Explanatory remark: Staged combustion (SC) is technically feasible only in combination with Primary Measures (PM). Costs for SC therefore have to be taken in addition to costs for PM while the achievable emission level is to be seen in combination of PM+SC.

Table 4 Costs of NOx reduction measures for various target emission levels (in ECU/Mg clinker)

Variant A: initial emission level 1300 mg NOx/Nm3 (EU average)					
target emissons level	1300	1000	800	500	200
Kiln A (1000t clinker/d)					
Primary+MSC	0	1,84	1,84	1,84	n.p.
SNCR	0	0,61	0,78	1,05	n.p.
SCR	0	1,24	1,32	1,44	1,58
Kiln B (2500t clinker/d)					
Primary+MSC	0	1,02	1,02	1,02	n.p.
SNCR	0	0,39	0,55	0,82	n.p.
SCR	0	0,62	0,70	0,82	0,75
Kiln C (5000 t clinker/d)					
Primary+MSC	0	0,73	0,73	0,73	n.p.
SNCR	0	0,31	0,47	0,75	n.m.
SCR	0	0,41	0,49	0,61	0,75
Variant B: initial emission level 2000 mg NOx/Nm3 (EU upper level)					
target emissons level	1300	1000	800	500	200
Kiln A (1000t clinker/d)					
Primary+MSC	0	1,84	1,84	1,84	n.p.
SNCR	0	0,61	0,78	1,05	n.p.
SCR	0	1,24	1,32	1,44	1,58
Kiln B (2500t clinker/d)					
Primary+MSC	0	1,02	1,02	1,02	n.p.
SNCR	0	0,39	0,55	0,82	n.m.
SCR	0	0,62	0,70	0,82	0,75
Kiln C (5000 t clinker/d)					
Primary+MSC	0	0,73	0,73	0,73	n.p.
SNCR	0	0,31	0,47	0,75	n.m.
SCR	0	0,41	0,49	0,61	0,75

Table 6: Annual equivalent costs at optiminm reduction efficiency
(Kiln B, initial level 2.000 NOx/Nm3)

Primary Measures
(Target level 1.100 mg NOx/Nm3)

Year	Expenditure	Operating cost s	Sum	Discount factor	Present value	Net present value	Annual equivalent costs
0	2.200.000	505.000	2.705.000	1.00	2.705.000	5.859.678	873.265
1	0	505.000	505.000	0,93	467.593		
2	0	505.000	505.000	0,86	432.956		
3	0	505.000	505.000	0,79	400.885		
4	0	505.000	505.000	0,74	371.190		
5	0	505.000	505.000	0,68	343.695		
6	0	505.000	505.000	0,63	318.236		
7	0	505.000	505.000	0,58	294.663		
8	0	505.000	505.000	0,54	272.836		
9	0	505.000	505.000	0,50	252.626		

Primary Measures and Staged Combustion
(Target level 900 mg NOx/Nm3)

Year	Expenditure	Operating cost s	Sum	Discount factor	Present value	Net present value	Annual equivalent costs
0	2.750.000	515.000	3.265.000	1.00	3.265.000	7.663.883	1.142.145
1	0	515.000	515.000	0,93	476.852		
2	0	515.000	515.000	0,86	441.529		
3	0	515.000	515.000	0,79	408.824		
4	0	515.000	515.000	0,74	378.540		
5	0	515.000	515.000	0,68	350.500		
6	0	515.000	515.000	0,63	324.537		
7	0	515.000	515.000	0,58	300.498		
8	0	515.000	515.000	0,54	278.238		
9	0	515.000	515.000	0,50	257.628		

SNCR
(Target level 800 mg NOx/Nm3)

Year	Expenditure	Operating cost s	Sum	Discount factor	Present value	Net present value	Annual equivalent costs
0	900.000	933.350	1.833.350	1.00	1.833.350	7.663.883	1.142.145
1	0	933.350	933.350	0,93	864.213		
2	0	933.350	933.350	0,86	800.197		
3	0	933.350	933.350	0,79	740.923		
4	0	933.350	933.350	0,74	686.040		
5	0	933.350	933.350	0,68	635.222		
6	0	933.350	933.350	0,63	588.169		
7	0	933.350	933.350	0,58	544.601		
8	0	933.350	933.350	0,54	504.260		
9	0	933.350	933.350	0,50	466.907		

SCR
(Target level 200 mg NOx/Nm3)

Year	Expenditure	Operating cost s	Sum	Discount factor	Present value	Net present value	Annual equivalent costs
0	2.550.000	732.512	3.282.512	1.00	3.282.512	8.028.578	1.196.495
1	0	732.512	732.512	0,93	678.252		
2	0	732.512	732.512	0,86	628.011		
3	0	732.512	732.512	0,79	581.492		
4	0	732.512	732.512	0,74	538.418		
5	250.000	732.512	982.512	0,68	668.681		
6	0	732.512	732.512	0,63	461.607		
7	0	732.512	732.512	0,58	427.414		
8	0	732.512	732.512	0,54	395.753		
9	0	732.512	732.512	0,50	366.438		

Table 7: External damage from NOx emissions and benefit from NOx reduction measures

NOx [mg/Nm3]	2.000	1.300	1.000	800	500	200
NOx kg/Mg clinker]	4,27	2,77	2,13	1,71	1,07	0,43
Reduction [kg/Mg]						
Variante A	0,00	0,00	0,64	1,07	1,71	2,35
Variante B	0,00	1,49	2,13	2,56	3,2	3,84
External costs [ECU/mg NOx]						
Scenario 1	5.000	5.000	5.000	5.000	5.000	5.000
Scenario 2	10,000	10,000	10,000	10,000	10,000	10,000
External benefit (Kiln 1 [ECU/Mg clinker])						
Scenario 1	0,00	0,00	3,20	5,33	8,53	11,73
Scenario 2	0,00	0,00	6,40	10,67	17,07	23,47
External benefit (Kiln 2 [ECU/Mg clinker])						
Scenario 1	0,00	7,47	10,67	12,80	16,00	19,20
Scenario 2	0,00	14,93	21,33	25,60	32,00	38,40
External damage [ECU/Mg clinker]						
Scenario 1	21,33	13,87	10,67	8,53	5,33	2,13
Scenario 2	42,67	27,73	21,33	17,07	10,67	4,27

Variant A: 1.300 mg/Nm3 initial level (EU average)(equivalent to 2,77 kg NOx/mg clinker)
Variant B: 2.000 mg/Nm3 initial level (equivalent to 4,27 kg NOx/mg clinker)

Table 8:Ratio between benefits and costs

NOx target level mg/Nm3]		1300	1000	800	500	200
Variant A:		External damage 5.000 ECU/Mg NOx				
KilnA 1000 t clinker/d	Primary +MSC		1,7	2,9	4,6	n.p.
	SNCR		5,9	6,9	8,1	n.p.
	SCR		2,6	4,0	5,9	7,7
Kiln B 2500 t clinker/d	Primary +MSC		3,1	5,2	8,4	n.p.
	SNCR		8,3	9,7	10,4	n.p.
	SCR		5,1	7,6	10,4	12,2
Kiln C 5000 t clinker/d	Primary +MSC		4,4	7,3	11,7	n.p.
	SNCR		10,3	11,3	11,5	n.p.
	SCR		7,8	10,9	14,0	15,7
Variant A:		External damage 10.000 ECU/Mg NOx				
KilnA 1000 t clinker/d	Primary +MSC		3,5	5,8	9,3	n.p.
	SNCR		10,4	13,7	16,3	n.p.
	SCR		5,2	8,1	11,8	14,9
Kiln B 2500 t clinker/d	Primary +MSC		6,3	10,5	16,8	n.p.
	SNCR		16,6	19,5	20,8	n.p.
	SCR		10,3	15,2	20,7	24,5
Kiln C 5000 t clinker/d	Primary +MSC		8,7	14,6	23,3	n.p.
	SNCR		20,6	22,5	22,9	n.p.
	SCR		15,7	21,8	28,0	31,5
Variant B:		External damage 5.000 ECU/Mg NOx				
KilnA 1000 t clinker/d	Primary +MSC	4,1	5,8	7,0	n.p.	n.p.
	SNCR	7,6	13,1	9,1	n.p.	n.p.
	SCR	5,3	8,1	7,9	9,2	10,3
Kiln B 2500 t clinker/d	Primary +MSC	7,3	10,5	12,6	n.p.	n.p.
	SNCR	9,9	18,2	10,9	n.p.	n.p.
	SCR	9,5	15,1	12,8	14,2	15,4
Kiln C 5000 t clinker/d	Primary +MSC	10,2	14,6	17,5	n.p.	n.p.
	SNCR	11,0	20,9	11,7	n.p.	n.p.
	SCR	12,7	21,7	16,3	17,6	21,1
Variant B:		External damage 10.000 ECU/Mg NOx				
KilnA 1000 t clinker/d	Primary +MSC	8,1	11,6	13,9	n.p.	n.p.
	SNCR	15,2	26,2	18,3	n.p.	n.p.
	SCR	10,6	16,1	15,8	18,4	20,6
Kiln B 2500 t clinker/d	Primary +MSC	14,7	21,0	25,2	n.p.	n.p.
	SNCR	19,8	36,4	21,9	n.p.	n.p.
	SCR	18,9	30,2	25,6	28,5	30,7
Kiln C 5000 t clinker/d	Primary +MSC	20,4	29,2	35,0	n.p.	n.p.
	SNCR	22,0	41,7	23,4	n.p.	n.p.
	SCR	25,4	43,3	32,6	35,2	42,2

Variant A: initial emission level 1.300 mg NOx/Nm3 (EU average)
Variant B: initial emission level 2.000 mg NOx/Nm3 (EU upper level)
n.p.: not possible

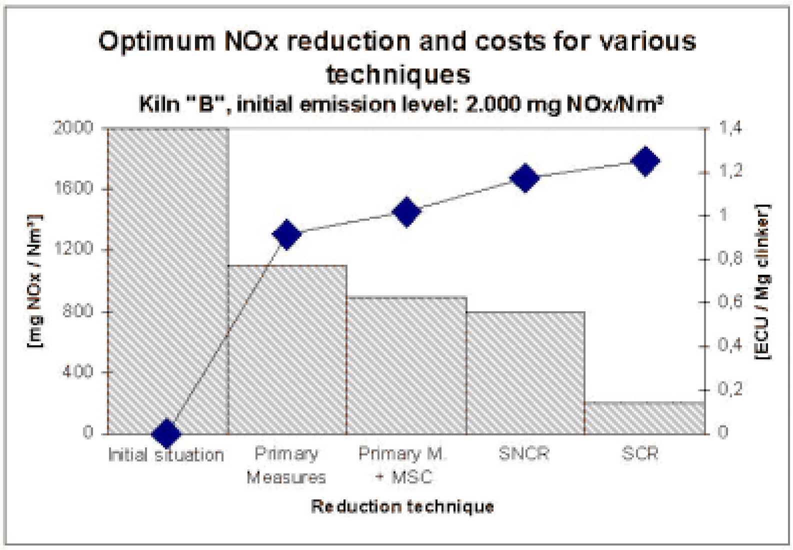

Figure 1 Optimum NOx reduction and costs for various techniques (initial emission level 2.000 mg NOx/Nm³)

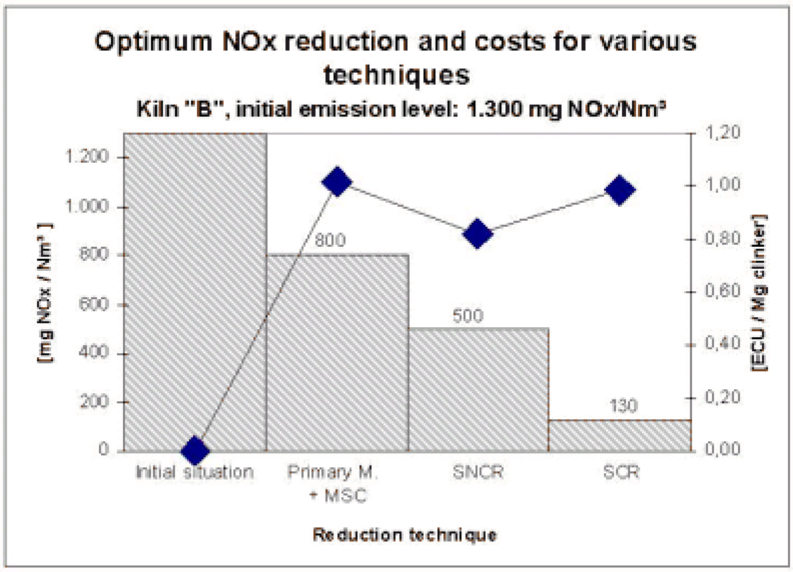

Figure 2 Optimum NOx reduction and costs for various techniques (initial emission level 1.300 mg NOx/Nm³)

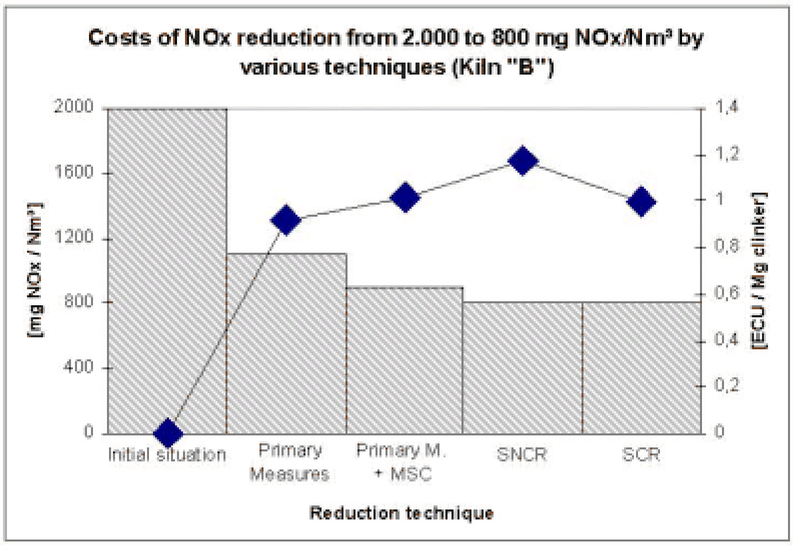

Figure 3 Costs of NOx reduction from 2.000 to 800 mg NOx/Nm³

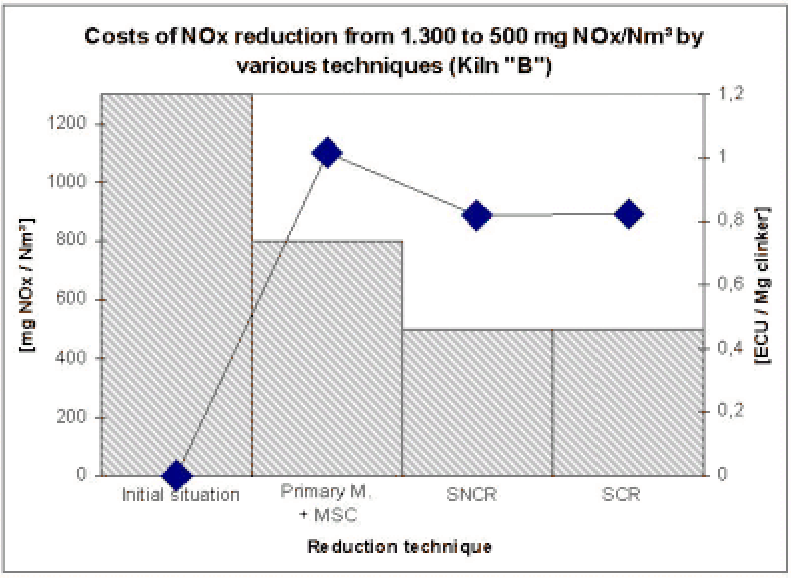

Figure 4 Costs of NOx reduction from 1.300 to 500 mg NOx/Nm³

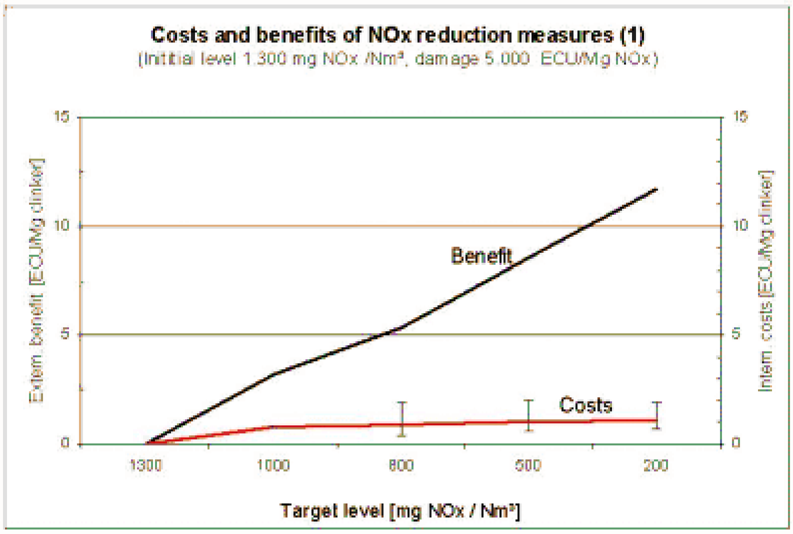

Figure 5 Costs and benefits of NOx reduction measures
(initial level 1.300 mg NOx/Nm³, damage 5.000 ECU/Mg NOx)

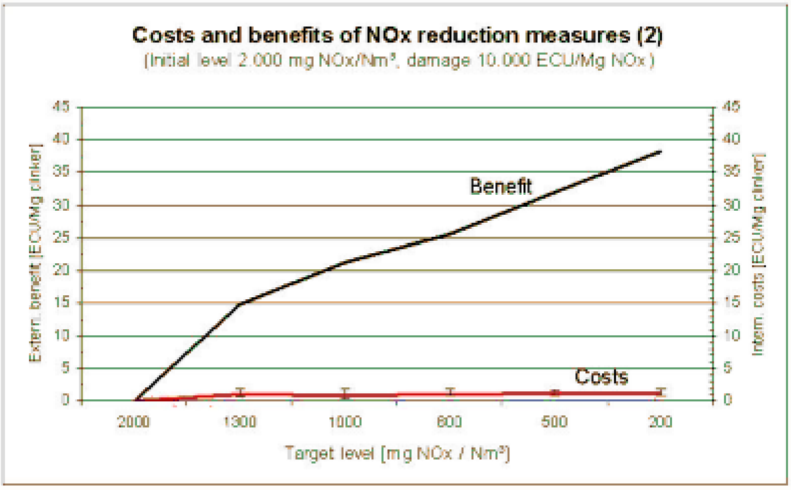

Figure 6 Costs and benefits of NOx reduction measures
(initial level 2.000 mg NOx/Nm³, damage 10.000 ECU/Mg NOx)

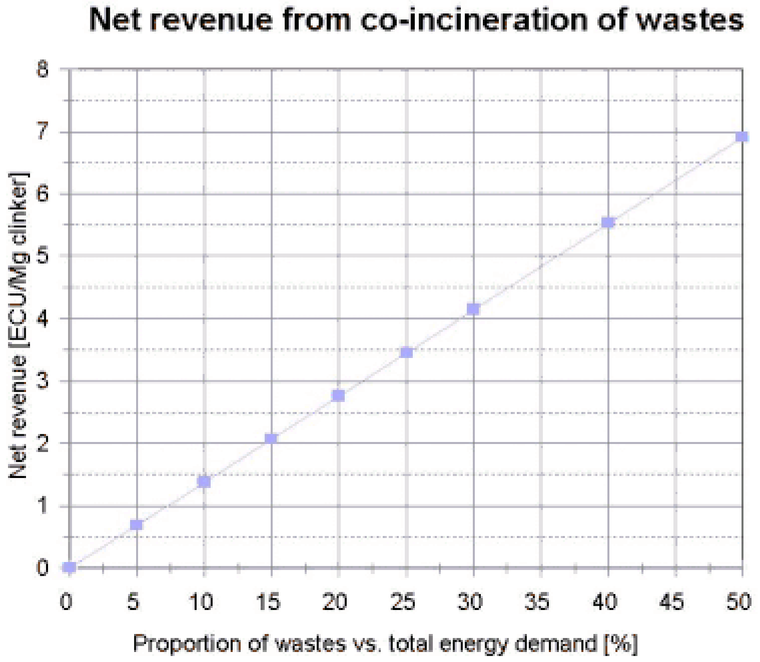

Figure 7 Net revenue from co-incineration of wastes

Contact

Dirk Jepsen jepsen@oekopol.de