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Criteria for limits on the emission of dust from cement kilns that burn waste as fuel

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Abstract

This note performs a cost-benefit analysis of proposed limit values for the emission of dust from cement kilns that use waste as fuel (currently under discussion between the European Council and the European Parliament as part of the new Directive to regulate the emissions by facilities that incinerate waste). The estimation of benefits is based on the most recent results of the ExternE Project of the European Commission, taking into account the typical sites where cement kilns are located. The benefits are found to be significantly lower than the costs. The conclusion that the proposed limit values are not justified by a net benefit is robust even in view of the uncertainties. A cost-effectiveness criterion does not provide a justification either.

1. Introduction

The European Council and the European Parliament are in the final process of formulating a new Directive to regulate the emissions by facilities that incinerate waste. One of the clauses concerns a lowering of the limit values for the emission of dust from cement kilns that use waste as fuel. The new values under discussion are 15 and 30 mg/m^3, compared to the 50 mg/m^3 imposed on cement kilns in most countries of the EU. [1].

Since new Directives are supposed to pass a social cost-benefit analysis (CBA), the proposed emission limits have been examined in a CBA by ETSU [1996] regarding municipal solid waste (MSW) incinerators. The specific emission limits for dust from cement kilns that use waste as fuel have been examined by Ökopol [1999]. Based on the CBA by ETSU [1996], and transferring certain assumptions from MSW incineration to cement kilns, Ökopol found that a reduction of the emission limits for kilns would be cost-effective.

There are, however, several reasons why this conclusion needs to be reexamined. First, the estimation of environmental benefits has evolved considerably since the study by ETSU [1996]. Second, additional data have become available for the abatement costs. Third, the analysis is complemented by a look at cost-effectiveness. To address these points is the purpose of the present note, by one of the authors of ETSU [1996] (and of ExternE [1995, 1998, 2000] on which the ETSU study was based).

2. Characteristics of the Technology

2.1. Cement Production

The raw materials for cement production [Alsop 1998] are
- limestone or other source of $CaCO_3$ (about 80 to 85% of input),
- clay (about 15 to 20% of input),
- other (a few % of input) to provide Si, Fe and Al.

After blending and grinding this material is heated in a cement kiln to produce clinker. The clinker is ground and further minerals (about 10 to 20% of the mass) are added to make cement. One needs approximately 1.5 kg of input material for 1 kg of cement output, the loss of mass being emitted as CO_2 to the atmosphere. The fuel energy requirement is around 3700 MJ (1028 kWh) per tonne of clinker.

Cement production in the EU totalled 172 million tonnes in 1995 and consumption 168 million tonnes. The demand for cement in Europe has been undergoing a slow long term decline since 1973, approximately 0.4 % per year [CEMBUREAU]. Since there is no structural reason for a change in this trend, essentially no new cement kilns will be constructed in the EU, except as replacement for kilns that have reached the end of their life. This implies that the costs of adapting kilns to the new Directive are relatively high, since retrofits are much more expensive than implementation in new plants.

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[1] All emissions are stated as concentration in the exhaust gas under standard conditions of temperature, pressure and oxygen content. Instead of “dust” we use the more technical term particulate matter (PM). Dust from cement kilns is assumed here for simplification to be PM_{10}, i.e. particulate matter with diameter smaller than 10 μm.

2.2. Utilization of Waste

Clinker production is very energy intensive, about a third of total production cost being due to energy input. To reduce the cost, there has been an increasing tendency in recent decades to replace part of the fuel by wastes such as saw dust, waste oil, solvents, and tires. Currently the fraction replaced by wastes is typically in the range of 10 to 50%, and it continues to increase as kiln operators learn how to best use different kinds of waste. The main technical limitation is the need for homogeneous waste of constant composition, in order to maintain the uniform steady combustion necessary for good clinker quality.

The key feature is the fact that the emissions from the kiln are the same whether waste is burned or not: no statistically significant differences have been detected, neither in the air emissions nor in the leachability of the resulting concrete [Colucci 1993, Germaneau 1993]. In fact, a cement kiln is an excellent means for disposing of toxic organic waste because the long residence time at high temperature (approximately 5 s between 1500 and 2000 C [Italcementi 2000], compared to only 2 s at 1200 C in dedicated toxic waste incinerators) guarantees good destruction, and there are neither liquid nor solid residues. The dust collected by the stack gas filter is mixed with the raw material or the cement. Thus any toxic metals from raw material or waste (with the exception of Hg and to some extent other metals with low melting point) are integrated into the resulting concrete. Note that stabilization in concrete is considered one of the safest methods for disposing of toxic fly ash from incinerators.

Finally dust from kilns and dust from incinerators have a very different composition, the former more like the input limestone and clay, the latter more carbonaceous, and epidemiologists tend to believe that soil particles are less harmful than carbonaceous particles. However, lacking firm data, we do not take this possibility into account. One should also note that the composition of dust from cement kilns remains essentially unchanged when waste is used as fuel.

3. Cost-Benefit Analysis

3.1. Methodology for Calculation of Benefits

The benefit of pollution abatement is the avoided damage. The damage cost per kg of pollutant has been estimated by the ExternE ("External Costs of Energy") Project of the EC. The ExternE methodology takes into account the specific conditions (source location, stack height, meteorology, population density, etc) of the pollution source. This involves an analysis of the impact pathway for each pollutant, from source to receptors (population, crops, buildings, etc.):

- specification of the emissions source (e.g. kg/yr of PM from kiln at such and such site);
- calculation of increased pollutant concentration in all affected regions (e.g. $\mu g/m^3$ of PM, using models of atmospheric dispersion and chemistry);
- calculation of physical impacts (e.g. number of asthma attacks due to PM using dose-response functions);
- economic valuation of impacts (e.g. multiplication by cost of asthma attack).

The damage is summed over all affected receptors. For details of this analysis, the reader is referred to publications by the ExternE [1995, 1998] Project; shorter accounts can be found in Rabl, Spadaro & McGavran [1998] and Rabl & Spadaro [2000].

It turns out that most of the damage cost of PM is due to mortality. The key parameter is the so-called value of statistical life VSL (= willingness to pay for reducing the risk of premature death). In ExternE [1998], a European-wide value of 3.1 M€ was chosen for VSL, close to similar studies in the USA. There are, however, problems in applying such a VSL value because it has been determined by studies of accidental deaths. Accidents involve a large loss (on average 40 to 50 years per accident) with low probability, air pollution a small loss (a few months per case, typically at high age) with high probability. This difference is likely to affect the willingness to pay (WTP) for reducing the risk of a premature death.

The studies before 1997 simply multiplied the number of premature deaths by VSL, an approach that most people now recognize as inappropriate. The 1998 and 2000 versions of ExternE have therefore calculated the cost of mortality as the product of the years of life lost and the value of a life year VLY, taking VLY as 0.08 to 0.15 M€, depending on the lag between exposure and death. This VLY has been derived on theoretical grounds as the prorated annual equivalent of the VSL of 3.1 M€.. That has been the only possible approach since no other VSL studies had ever been carried out. Only in the last few years has the need been recognized for studies that explicitly determine the willingness to pay for reducing air pollution mortality, and the first reliable results [Krupnick et al 2000] did not become available in time for ExternE [2000].

3.2. Evolution of Damage Cost Estimates since 1996

In addition to the different valuation of mortality several other developments have occurred since the study by ETSU [1996]. In the field of epidemiology a major study by a team at Harvard University [Pope et al 1995] measured the total increase in mortality due to exposure to PM, by contrast to previous studies that were able to measure only health effects observable within a few days after exposure. The total includes mortality due to slow acting diseases such as cancer and emphysema, and is of course much larger than the short term effects. ExternE has applied the results of Pope et al [1995] since 1997. Numerically the resulting increase of damage costs happens to cancel approximately the decrease due to the shift from a VSL to a VLY valuation. In the latest phase of ExternE [2000] the estimates have been further refined.

Another major development has been a greatly improved understanding of the variability of the damage with the site where a pollutant is emitted. This variability is very pronounced for the health damage of primary pollutants such as PM: within central Eupope the damage per kg of PM_{10} emitted by industrial sources (with stack height of 50 m or more) can vary by an order of magnitude, depending on whether the source is in a metropolis or in a rural area. At the time of the ETSU study only a handful of sites had been analyzed, not enough to permit extrapolation to other sites.

Concerned with MSW (municipal solid waste) incinerators, ETSU [1996] chose three urban sites because incinerators tend to be very close to or even within cities. In retrospect the three cities chosen (Paris with 11 million, Birmingham with 1.1 million, and Stuttgart with 0.6

million in a densely populated region) were so large that they could not even be considered representative of MSW incinerators.

For cement kilns, by contrast, the prime siting criterion is close proximity to a quarry of limestone or chalk; therefore kilns are located in far more rural settings than MSW incinerators. Thus a certain amount of judgement is required in applying the ETSU numbers to cement kilns. The values for the primary pollutant PM_{10} chosen by Ökopol [1999], even though they excluded Paris, now appear about two to ten times too high, after systematic investigations of the variation of damage cost with site and stack height of the source [Rabl & Curtiss 1996, Spadaro & Rabl 1999, Spadaro 1999].

A comparison of damage costs is shown in Table 3.1. The numbers chosen for the present note are in bold face. They are based on the ExternE [2000] results for the average PM emissions from industrial sources in the EU. Since cement kilns are in more rural areas than most industries, we take a value halfway between the numbers shown in the "average" and "rural" lines, the latter having been estimated from the "average" line by rural/average ratios of Spadaro & Rabl [1999] and Spadaro1999].

The last column in Table 3.1 shows how the numbers of ExternE [2000] would change if the valuation of mortality were reduced by a factor of 5, as suggested by recent studies mentioned above in Section 3.1. and carried carried out by Krupnick et al [2000] in Japan, Canada and the USA. The results, just published, suggest that VLY due to air pollution is about a factor 5 smaller than VLY due to accidents. This reduction of VLY multiplies the damage by a factor 0.41 rather than 0.2 because the other contributions such as chronic bronchitis remain unchanged.

Table 3.1. Estimates of damage cost per kg of PM_{10}. Numbers in bold face are used for the CBA in Figs.3.1. Uncertainties are large: upper and lower limits are estimated to be for 0.7 to 15€/kg for PM_{10} cement kilns.

€/kg of PM_{10} site	**Ökopol [1999]**	**ExternE [1998]**	**ExternE [2000]**	**ExternE [2000]** if 1/5 VLY [a]
[b]	10 to 75			
"average"		14.1	8.2 [c]	3.4
"rural"			4.0 [d]	1.6
cement kilns			**6.1** [e]	**2.5**

[a] if VLY for air pollution mortality is 1/5 VLY for accidents [Krupnick et al 2000].
[b] Extrapolation of ETSU [1996] results for Birmingham and Stuttgart.
[c] average for industrial sources in EU, recommended by ExternE [2000] for life cycle assessment.
[d] adapted form average ExternE [2000] by rural/average ratios of Spadaro & Rabl [1999] and Spadaro1999].
[e] average of "average" and "rural".

When talking about cement kilns, it is convenient to state the results per t of clinker. To calculate the benefit per ton of clinker, we multiply the€/kg of pollutant in Table 3.1 by the annual average emission reduction in mg/m^3 and by a typical exhaust flow of 2000 m^3/t of clinker. The results are shown in Table 3.2.

It is important to note the difference between limit values and annual average emissions. The damage cost is proportional to the annual average emissions. Because of the inevitable fluctuations of the operation of real equipment, the daily averages emissions of PM are much higher than the annual average. An installation must be designed with sufficient margin in order not to exceed the limit values of the Directive which are stated in terms of daily average. Based on measurements by TA Luft, Ökopol [1999] estimates that the limit values in column one of Table 3.2 correspond to the annual averages listed in column two.

Table 3.2. Estimates of benefits per tonne of clinker

Emissions mg/m^3		kg_{PM10}	Benefit €/$t_{clinker}$	
Limit value daily average	Real emission annual average	per $t_{clinker}$	ExternE [2000]	ExternE [2000] if 1/5 VLY
Current 50	20	0.04		
30	15	0.03	0.061 [a]	0.025 [b]
15	5	0.01	0.183 [c]	0.075 [d]

[a] 6.1€/kg × (20 – 15) mg/m^3 × 2000 m^3/t = 0.061€/$t_{clinker}$.
[b] 2.5€/kg × (20 – 15) mg/m^3 × 2000 m^3/t = 0.025€/$t_{clinker}$.
[c] 6.1€/kg × (20 – 5) mg/m^3 × 2000 m^3/t = 0.183€/$t_{clinker}$.
[d] 2.5€/kg × (20 – 5) mg/m^3 × 2000 m^3/t = 0.075€/$t_{clinker}$.

3.3. Comparison of Costs and Benefits

Table 3.3 shows estimates of abatement cost, i.e. the incremental cost per t of clinker for reducing the emissions from current levels to the levels under consideration for the new Directive. We show the costs only for retrofits of existing kilns, since little construction of new kilns can be expected in the EU.

It is important to note that even the estimation of abatement costs is plagued with uncertainties. Costs tend to be highly site specific, and are generally not known with precision until an installation is complete. Estimates based on typical numbers can easily differ from real costs by a factor of two, especially in retrofit situations. This is further compounded by uncertainties about the performance of the technologies in practice.

Table 3.3. Estimates of abatement cost for PM_{10}. Columns three to ten indicate the cost per t of clinker, the choice for this paper being shown in columns nine and ten. Column 11 shows the $kg_{PM10}/t_{clinker}$ for the respective annual average emission. The last two columns express the abatement cost in € per kg of PM_{10}.

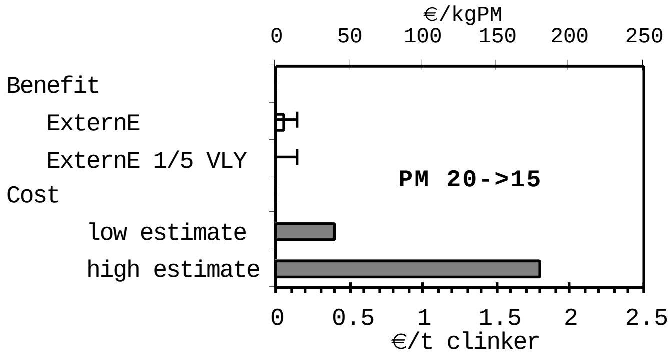
Emissions mg/m^3		Abatement cost €/$t_{clinker}$								kg_{PM10}	Abatement cost €/kg_{PM10} This paper	
Limit value	Real emission	Ökopol [b]		VDZ [c]		Recent data [e]		This paper		per		
daily average	annual average	low	high	low	high	low	high	low [f]	high	$t_{clinker}$ [g]	low	high
Current 50 [a]	20									0.04		
30	15	0.15	1.22	0.44	1.06	0.55	1.83	0.4	1.8	0.03	40	180
15	5	0.25	1.56	[d]		0.70	2.34	0.7	2.3	0.01	23	77

[a] Present limit values (simplified): 50 mg/m^3 for the majority of kilns in the EU
[b] Ökopol [1999]
[c] VDZ [2000]
[d] VDZ [2000] imply that such an emission limit is not realistic.
[e] recent experience with 5 retrofits in France and Belgium [Italcementi 2000].
[f] we disregard the low costs of Ökopol because they correspond to kilns much larger than the typical size in the EU.
[g] assuming a typical exhaust gas flow of 2000 $m^3/t_{clinker}$.

The comparison of costs and benefits is presented in Fig.3.1. To explain the €/kg_{PM} scale, note that in Fig.3.1a the emission is reduced by 0.01 $kg_{PM}/t_{clinker}$ as already indicated in column 11 of Table 3.2; thus the 2.5 €/$t_{clinker}$ at the right end of the scale correspond to 2.5 €/$t_{clinker}$/(0.01 $kg_{PM}/t_{clinker}$) = 250€/kg_{PM}.

Fig.3.1. Comparison benefits, last two columns of Table 3.2, and of costs, columns nine and ten of Table 3.3. Error bars indicate uncertainty of benefit. Costs and benefits are shown on two scales: per $t_{clinker}$ (bottom) and per kg_{PM10} (top).

a) reduction of average emission from 20 to 15 mg/m^3 (of emission limit from 50 to 30 mg/Nm^3).



b) reduction of average emission from 20 to 5 mg/m^3 (of emission limit from 50 to 15 mg/Nm^3).

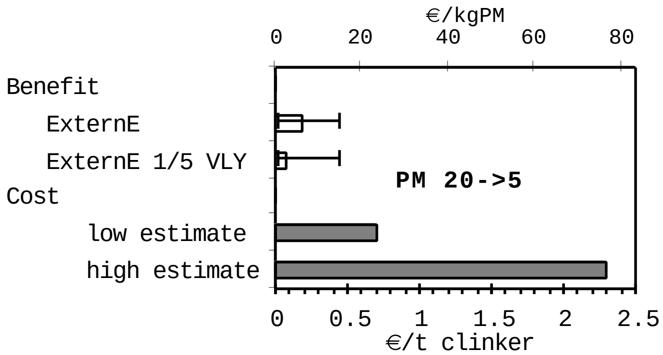


Fig.3.1 shows that the abatement costs are so much larger than the benefits that the proposed emission limits cannot be justified by a cost-benefit criterion. This conclusion holds even if one takes into account the uncertainties.

4. Cost-Effectiveness Analysis

It is also interesting to obtain another perspective of the problem by looking at cost-effectiveness. An analysis of cost-effectiveness compares the abatement costs per kg of pollutant avoided in different sectors to identify the measures that buy the greatest emission reduction for a given expenditure. The abatement cost per kg of PM_{10} for cement kilns has already been calculated in Figs.3.1; it is in the range of 23 to 180€/kg.

As for abatement cost estimates for PM in other sectors, one of the difficulties lies in the fact that some of the evaluated techniques reduce the emission of several pollutants together [for example the data of AutoOil 1996], hence there is no clear allocation to PM as needed here.

Another difficulty lies in the lack of information about the rate at which the various techniques are being implemented in practice. For these reasons a useful concept is perhaps the one proposed by de Jonge [2000] who states what he calls reference values, i.e. guidelines such that a technique should be implemented if and only if it costs less than the reference value.

For PM abatement de Jonge cites a reference value of 2.5 €/kgPM. This reference value is based only on a limited number of existing Dutch industrial operations and may not be representative for the whole EU. This said, even the lowest estimates of PM abatement for cement kilns are so much higher that this approach yields the same conclusion as the CBA in Section 3: limit values of 30 or 10 mg/m3 for PM10 emissions are not justified.

Let us also take the case of new plants, for which we have no practical data, but only the Ökopol assumptions. When the limit goes from 50 to 15 mg/Nm3, Ökopol estimates the additional cost to be 0.1 to 0.44 €/$t_{clinker}$, or 0.1 €/0.03 kg_{PM10} = 3.3 €/kg_{PM10} to 0.44 €/0.03 kg_{PM10} = 15 €/kg_{PM10}. Even in this case, the reduction of the emission limit to a level lower than 50 mg/Nm3 is not justified either, compared to a reference value of 2.5 €/kg_{PM10}.

It is also interesting to look at the total emissions to see whether the proposed emission reduction in the cement industry would bring about a significant improvement in environmental quality. Table 4.1 shows the emissions of PM_{10} in the EU15, as well as the contribution of the cement industry. Even with the current limit value of 50 mg/m^3 cement kilns contribute only 0.2% of the total PM burden of the EU.

Table 4.1. Contribution of cement kilns in EU15 to total PM_{10} emissions in EU15.

Clinker production [a]	150	Mt/yr
exhaust flow	2000	m^3 per t clinker
average PM_{10} (for limit value 50 mg/m^3)	20	mg/m^3
PM from kilns, EU	6	kt/yr
total PM, EU [b]	2610	kt/yr
% of total PM_{10} EU	0.2	%

[a] for typical ratio of 1.15 t cement per t clinker.
[b] PM_{10} Emissions for 1990, from Environmental Data Compendium [OECD 1995], extrapolated in proportion to population from 72% of EU15 population.

6. Conclusions

We find that the proposed limits for PM_{10} emissions (15 and 30 mg/m^3) from cement kilns that burn waste as fuel cannot be justified by the social benefits, since the costs are significantly higher than the benefits. Neither can they be justified in terms of cost-effectiveness.

Misallocation of expenditures due to excessive regulations hurts rather than protects the environment because that money will not be available for other more cost-effective measures. To avoid such negative effects, we recommend that the limits be left at 50 mg/m^3, for existing and for new kilns.

References

Alsop PA 1998. The Cement Plant Operations Handbook. 2nd edition. Tradeship Publications, Dorking, Surrey RH4 1AR, UK.

AutoOil 1996. "The European AutoOil Programme". Report XI/361/96 by Directorate General for Environment. European Commission. And “A cost-effectiveness study of the various measures that are likely to reduce pollutant emissions from road vehicles for the year 2000” final report, Touche Ross & Co, 39 George St, Edinburgh EH2 2HZ.

Bontoux L 1999. “The incineration of waste in Europe: issues and perspectives”. Report EUR 18717 EN, Institute for Prospective Technological Studies, Seville.

CEMBUREAU 1997. “Best Available Techniques for the Cement Industry”. A contribution from the European cement industry to the exchange of information and preparation of the IPPC BAT Reference Document for the cement industry. CEMBUREAU Report, 1997.

CEMBUREAU. The European Cement Association. Rue d’Arlon 55, B-1040 Brussels.

Colucci M, P Epstein and B Bartley 1993. “A comparison of metal and organic concentrations in cement and clinker made with fossil fuels to cement and clinker made with waste derived fuels”. NSF International, POBox 130140, Ann Arbor, MI 48113-0140.

De Jonge L 2000. “Establishing cost effectiveness of environmental measures in industries”. In Proceedings of VITO [2000].

EPA 1997. “National Air Pollutant Emission Trends, 1900 – 1996”. Report EPA-454/R-97-011 (Dec.1997). S. V. Nizich et al.

ERPURS 1997. "Analyse des liens à court terme entre pollution atmosphérique et santé" (Analysis of short term correlations between air pollution and health). Evaluation des Risques de la Pollution Urbaine sur la Santé. Observatoire Régional de Santé d'Ile-de-France, 21-23 rue Miollis, F-75015 Paris.

ETSU 1996. “Economic Evaluation of the Draft Incineration Directive”. Report produced by ETSU, Harwell Laboratory, Didcot, Oxfordshire OX11 0RA, for the European Commission DGXI, contract number B4 3040/95/001047/MAR/B1. Published by the European Commission, Directorate-General XII, Science Research and Development. L-2920 Luxembourg.

ExternE 1995. ExternE: Externalities of Energy. Vol. 1: Summary; Vol. 2: Methodology; Vol. 3: Coal and Lignite; Vol. 5: Nuclear. ISBN 92-827-5210-0. Published by the European Commission, Directorate-General XII, Science Research and Development. L-2920 Luxembourg.

ExternE 1998. ExternE: Externalities of Energy. New results, published by ExternE Program of European Commission, Directorate-General XII, Science Research and Development. Available at http://ExternE.jrc.es/publica.html.

ExternE 2000. ExternE: Externalities of Energy. New results, to be published by ExternE Program of European Commission, Directorate-General XII, Science Research and Development.

Germaneau B, B Bollotte and C Defossé 1993. “Leaching of heavy metals by mortar bars in contact with drinking and deionized water”. Emerging Technologies Symposium on Cement and Concrete in the Global Environment. Portland Cement Association, 10-11 March 1993, Chicago, IL.

IPPC 1999. “Integrated Pollution Prevention and Control (IPPC): Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries”. European Commission, Directorate General JRC, Institute for Prospective Technological Studies, Seville.

Italcementi 2000. Personal communication. P. Ronsin, Italcementi, Tour Ariane, 92088 Paris La Défense.

Krupnick A, A. Alberini, M. Cropper, N. Simon, B. O'Brien, R. Goeree and M. Heintzelman 2000. "What are Older People Willing to Pay to Reduce Their Risk of Dying?" Resources for the Future, 1616 P Street, NW, Washington, DC 20036. Paper presented to the AERE Sessions, ASSA Meetings, Boston, Mass., January 7, 2000.

OECD 1995. Environmental Data Compendium. OECD, 2 rue André-Pascal, 75775 Paris.

Ökopol 1999. "Economic evaluation of dust abatement techniques in the European cement industry", report for EC DG11, contract B4-3040/98/000725/MAR/E1; and "Economic evaluation of NO_x abatement techniques in the European cement industry", report for EC DG11, contract B4-3040/98/000232/MAR/E1. Ökopol GmbH, Hamburg.

Peyrelongue J-P 1997. GEC ALSTHOM Stein Industrie. "Variations et différences de référentiels: influence sur les coûts" (Variations and different references: influence on the costs). Présentation EUROFORUM, Paris. 3 juin 1997.

Pope, C. A., M. J. Thun, M. M. Namboodri, D. W. Dockery, J. S. Evans, F. E. Speizer, and C. W. Heath. 1995."Particulate air pollution as a predictor of mortality in a prospective study of US adults". Amer. J. of Resp. Critical Care Med. vol.151, 669-674Rabl A, JV Spadaro & PD McGavran 1998. "Health Risks of Air Pollution from Incinerators: a Perspective". Waste Management & Research, vol.16, pp.365-388.

Rabl A & JV Spadaro 1999. "Environmental Damages and Costs: an Analysis of Uncertainties". Environment International, 25(1): 29-46.

Rabl A & JV Spadaro 2000. "Public Health Impact of Air Pollution and Implications Energy Systems". To be published in Annual Review of Energy and the Environment.

SFSP 1999. *L'Incinération des déchets et la Santé Publique* (Waste Incineration and Public Health). Collection Santé et Société, No.7. Société Française de Santé Publique, 2 av. Du Doyen J. Parisot, BP 7, F-54501 Vanoeuvre-lès-Nancy.

Spadaro JV 1999. "Quantifying the Effects of Airborne Pollution: Impact Models, Sensitivity Analyses and Applications". Doctoral thesis, Ecole des Mines, 60 boul. St.-Michel, F-75272 Paris, France.

Spadaro JV and A Rabl 1999. "Estimates of real damage from air pollution: site dependence and simple impact indices for LCA". International J. of Life Cycle Assessment. Vol.4 (4), 229-243.

VITO 2000. International workshop on economic aspects of BAT. Feb 10-11, 2000, Brussels. http://www.emis.vito.be/BBT/Workshop.

Wilson R & JD Spengler, editors 1996. Particles in Our Air: Concentrations and Health Effects. Harvard University Press, Cambridge, MA.

VDZ 2000. Verein Deutscher Zementwerke. M Schneider , G Hirth and P Magel. "The economic effect of BAT on the production of cement". In Proceedings of VITO [2000].