

Integrated pollution prevention and control: choosing the best available technique by using a cost-benefit approach

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Abstract

European directive 96/61/CE concerning integrated pollution prevention and control was completely received in Italy at the beginning of 2005 by D.Lgs. 59/2005. The contents of the directive are now widely applied within the authorization procedure of many industrial activities in Italy, such as pulp and paper production, cement factories, foundries, chemical installations and so on. The hardest decision that competent authorities have to take within the procedure relates to the definition of the emission limit values; these limit values and the equivalent parameters and technical measures shall be based on the so-called “best available techniques (B.A.T.)”. The directive 96/61/CE, art. 9, says that the emission limit values should be decided “taking into account the technical characteristics of the installation concerned, its geographical location and the local environmental conditions. In all circumstances, the conditions of the permit shall contain provisions on the minimization of long-distance or transboundary pollution and ensure a high level of protection for the environment as a whole.”

In the present paper we try to define the proper emission limit values for nitrogen oxides emitted by a cement factory in Italy by comparing the costs of the techniques applied to control emissions with the environmental benefit arising from the reduction of the emissions. The assessment of the external costs associated to the impact of pollutants deriving from cement production has been carried out by using the ExternE approach, a research program of the European Commission based on atmospheric dispersion modelling, exposure-response functions and monetary valuations. On the other hand, the costs of the abatement technologies are assessed on the basis of the investment and operating costs reported for the cement industry.

Keywords: I.P.P.C., B.A.T., cost-benefit, ExternE, NO_x, cement kiln, exposure-response functions, nitrates, regional scale.



1 Introduction

In the present paper we basically analyse the technical features and the possibilities of containing the atmospheric emissions of a cement kiln placed in North Western Italy. The kiln is a typical long dry rotary kiln which can produce 150.000 tonne/year of clinker and it is part of an industrial complex with 3 cement kilns. We focus our attention on the emissions of nitrogen oxides, probably the main environmental impact of the cement industry.

The flow emitted by the analysed kiln is approximately 55.000 Nm³/h, with a humidity volume of 10% and a oxygen content near 11% (vol/vol for dry smoke). The flue gas temperature measures 170 °C, the stack height is 67 m and the stack diameter is 2,6 m. The yearly mean concentration for NO_x is around 1250 mg/Nm³ for wet gases (approximately 1527 mg/Nm³, expressed as NO₂, dry gas, O₂ @ 10%). The cement factory falls within the European directive 96/61/CE concerning integrated pollution prevention and control (I.P.P.C.) and consequently it is forced to apply best available techniques (B.A.T.) in order to limit its impact on the environment, reducing, in particular, NO_x emissions. Obviously, every B.A.T. means different investment and operating costs in order to obtain lower emission levels. On the other hand, the avoided emissions represent environmental benefits which are rarely determined with a consistent approach: in the following pages we try to describe a reliable cost-benefit approach, applied to a real case, so as to determine the proper abatement technique and the corresponding reduction efficiency.

2 B.A.T. costs and emission levels

The Reference Document on best available techniques in the Cement and Lime industries [1] gives a satisfactory overview of the present emission levels associated with cement production and the techniques (feasibility, emission levels, costs) that may have a positive effect on (i.e. reduce) emissions arising during the manufacture of cement. Table 1 reports a summary of the B.A.T. for cement kilns: the reported emissions refer to daily averages, dry gas, 273 K, 101.3 kPa and 10% O₂, the investment costs are expressed in 10⁶ euros (normally referring to a kiln capacity of 3000 tonne clinker/day, so that they are largely overestimated with respect to the analysed kiln) and the operating costs in euros/tonne of clinker.

As one can easily notice, the B.A.T. for reducing NO_x emissions from a long dry rotary kiln are essentially:

- Primary measures to control NO_x emissions
 - Flame cooling
 - Low-NO_x burner
- Selective catalytic reduction (SCR).

On a sector level, the majority of kilns in the European Union is said to be able to achieve less than 1200 mg/m³ (dry gas, O₂ @ 10%) with primary measures; this emission level is usually proposed by industrial administrators within the I.P.P.C. authorization procedure, in association with Low NO_x burner.



On the other hand, the B.A.T. reference document reports very low emission levels (400 mg/m^3) associated with the use of primary measures (flame cooling and Low-NO_x burner), so that the BAT emission level associated with the use of these techniques is considered to be in the range $200\text{-}500 \text{ mg NO}_x/\text{m}^3$ expressed as NO₂ on a daily average basis.

Table 1: Overview of techniques for controlling NO_x.

Technique	Kiln systems applicability	Reduction efficiency	Reported emissions		Reported costs	
			mg/m ³	kg/tonne	investment	operating
Flame cooling	All	0-50 %	400-	0.8-	0.0 -0.2	0.0-0.5
Low-NO _x burner	All	0-30 %			0.15-0.8	0
Staged combustion	Precalciner	10-50 %	<500-1000	<1.0-2.0	0.1-2	0
	Preheater				1-4	0
Mid-kiln firing	Long	20-40 %	No info.	-	0.8-1.7	No info.
Mineralised clinker	All	10-15 %	No info.	-	No info.	No info.
SNCR	Preheater and Precalciner	10-85 %	200-800	0.4-1.6	0.5-1.5	0.3-0.5
SCR – data from pilot plants only	Possibly all	85-95 %	100-200	0.2-0.4	ca. 2.5 3.5-4.5	0.2-0.4 No info.

There was also a view that selective catalytic reduction (SCR) is BAT with an associated emission level of $100\text{-}200 \text{ mg NO}_x/\text{m}^3$ (as NO₂), based upon SCR being regarded as an available and economically viable technique. This conclusion is drawn from feasibility studies and successful pilot tests. There are at least three suppliers in Europe that offers full scale SCR to the cement industry with performance levels of $100\text{-}200 \text{ mg/m}^3$.

Based on the described features, within our analysis, we consider 3 different emission levels achievable with B.A.T.; Table 2 reports these levels and the corresponding costs, calculated on the basis of the analysed kiln capacity.

Table 2: NO₂ emission levels considered in the cost-benefit analysis.

mg NO ₂ /Nm ³ (dry gas, O ₂ @ 10%)	mg NO ₂ /Nm ³ (wet gas)	Reported B.A.T. costs		notes
		Investment (€)	Operating (€/y)	
1527	1250	-	-	no B.A.T.
1200	981	150.000- 800.000	-	Proposed level
500	409	0-200.000	0-75.000	Flame cooling
500	409	150.000- 800.000	-	Low-NO _x burner
200	163	2.500.000- 4.500.000	30.000- 60.000	SCR

3 Environmental benefit assessment

Externalities deriving from any production cycle represents the costs imposed on society as well as on the environment that are not accounted for by the producers



and consumers of goods, that is which are not included in the market price; external costs constitute an heavy market failure which justifies strong intervention policies. The ExternE project [2] is the first and, at the moment, the most advanced and reliable attempt to use a consistent methodology to assess the external costs deriving from airborne pollutants since it comprises valuation techniques which integrate technical-scientific and economic analysis. The externalities evaluation techniques are divided into direct and indirect methods: as concerns the external costs due to pollution, the direct techniques characterize the facility to be analysed (technical features, emitted pollutants...), determine the pollutants pathway within a certain distance and measure the impacts on particular receptors. The direct method doesn't perform economic assessments but its technical analysis, based on atmospheric dispersion modelling and exposure-response toxicological functions, can evaluate, in statistical terms, the probability of certain negative events (for example, the probability of some respiratory pathology or the loss of crop quantities). On the other hand, the indirect methods are based on the perception of the damage that people think to receive as a consequence of the atmospheric pollution; consequently, these techniques observe the real behaviours of people who suffer from the impact and obtain from these behaviours a purely economic valuation. The underlying principle in monetary valuation is to obtain the willingness to pay (WTP) of an affected individual to avoid a negative impact, or the willingness to accept (WTA) payment as compensation if a negative impact takes place.

Obviously, the best approach for an exhaustive valuation of the externalities is the integration of both the techniques: the ExternE methodology applies the indirect analysis downstream from the direct method. The analysis is based on 4 phases and proceeds in a sequential way from emissions towards the impact assessment and the respective monetization. The first phase individuates the main technological features of facility, the pollutant concentrations (mg/Nm^3), the emission rates (g/kWh) and the characteristics of the stacks (number, height and diameter). The second phase consists of the calculation of the year mean concentration of the pollutants at the ground level on the basis of atmospheric dispersion models. The third phase individuates the subjects exposed to the pollutants in the considered area and the correspondent characteristics (the number, the distribution and the age groups of the hit people, types and distribution of crops...). In the same phase, proper exposure-response functions are applied in order to determine the impacts on the receptors (these impacts are quantified as year additional cases of chronic bronchitis or asthma attacks for the human health, yield loss for the crops, etc...). As concerns the analysis of the effects on human health, which generally constitute the main contribute to the total monetary damage, the correspondent exposure-response functions are expressed as $\text{cases}/(\text{year} \cdot \text{person} \cdot \mu\text{g}/\text{m}^3)$; this approach is clearly linear, without thresholds. Finally, the fourth phase monetizes the calculated physical impacts on the basis of the WTP or WTA techniques described before. Table 3 reports the exposure-response functions and the corresponding monetization suggested by the ExternE project [2] for the receptor 'human health'.



Table 3: Exposure-response functions in ExternE for the receptor 'human health'.

	Health end point	Reference	receptor	f_{er} (cases/year/ person/ $\mu\text{g}/\text{m}^3$)	Unit cost (EURO ₂₀₀₀ /case)
FINE DUST (PM ₁₀), NITRATES AND SULPHATES	Bronchodilator usage	Dusseldorp <i>et al.</i> , 1995	Asthmatic adults	1,63E-01	40
	Cough	Dusseldorp <i>et al.</i> , 1995	Asthmatic adults	1,68E-01	45
	Lower Respiratory Symptoms	Dusseldorp <i>et al.</i> , 1995	Asthmatic adults	6,06E-02	8
	Bronchodilator usage	Roemer <i>et al.</i> , 1993	Asthmatic children	7,75E-02	40
	Cough	Pope and Dockery, 1992	Asthmatic children	1,33E-01	45
	Lower Respiratory Symptoms	Roemer <i>et al.</i> , 1993	Asthmatic children	1,03E-01	8
	Congestive Heart Failure	Schwartz and Morris, 1995	Adults over 65	1,85E-05	3.260
	Chronic cough	Dockery <i>et al.</i> , 1989	Children	2,07E-03	240
	Restricted Activity Days	Ostro, 1987	Adults	2,50E-02	110
	Chronic Bronchitis	Abbey <i>et al.</i> , 1995	Adults	2,45E-05	169.330
	Respiratory Hospital Admissions	Dab <i>et al.</i> , 1996	Entire population	2,07E-06	4.320
	Cerebrovascular Hospital Admissions	Wordley <i>et al.</i> , 1997	Entire population	5,04E-06	16.730
	Chronic mortality (YOLL)	Pope <i>et al.</i> , 1995	Entire population	1,57E-04	96.500
SO ₂	Respiratory Hospital Admissions	Ponce de Leon, 1996	Entire population	2,04E-06	4.320
	Acute mortality (YOLL)	Anderson & Toulomi, 1996	Entire population	6,16E-06	165.700
CO	Congestive Heart Failure	Schwartz and Morris, 1995	Adults over 65	5,64E-07	3.260
PAH	Lung cancer	U.S.EPA, 1990	Entire population	0,1/70*0,9	3.400.000
	Non fatal cancer	U.S.EPA, 1990	Entire population	0,1/70*0,1	485.943
PCDD/DF	Cancer	LAI	Entire population	1,4/70	3.400.000
Cadmium	Cancer	LAI	Entire population	1,2/100/70	3.400.000
Chromium	Cancer	WHO	Entire population	4/100/70	3.400.000
Arsenic	Cancer	LAI	Entire population	4/1000/70	3.400.000
Nickel	Cancer	U.S. EPA	Entire population	4/1000/70	3.400.000
Benzene	Cancer	U.S. EPA	Entire population	8/10^6/70	3.400.000

The ExternE methodology can be applied both on the local scale and the regional scale (European-wide). As a matter of fact, the local scale focuses on



distance up to 20 km, where the formation of secondary pollutants, that is nitrates and sulphates deriving from atmospheric chemical reactions, can be neglected.

The ECOSENSE software package [3] has been developed within the ExternE project to support and standardize the assessment of the main environmental impacts deriving from the exposition to the atmospheric pollutants. The ECOSENSE software can calculate the total monetary damage both on a local scale (100 km * 100 km centred on the site of the plant, with a spatial resolution of 10 km) and on a regional scale (the resolution is 100 km). As far as the regional scale is concerned, the concentrations at the ground level are calculated by means of the Lagrangian model Windrose Trajectory Model (WTM), developed by the Harwell Laboratories and included in the ECOSENSE model. The Windrose Trajectory Model employs an air parcel with a constant mixing height of 800 m, moving with a representative wind speed, and considers the atmospheric chemical reactions; as a consequence, it can calculate the concentrations of the acid species formed in atmosphere (i.e. nitrates and sulphates).

Within the present study, it is important to remember that nitrogen oxides are significant precursors to nitrates (secondary particulates) and ozone. Some studies reported epidemiological evidences regarding NO_x but the broad trust was that apparent NO_x effect were best understood not as casual, but as NO_x being a surrogate for some mixture of pollution. The APHEA results reported positive associations between NO₂ and daily mortality or respiratory hospital admissions in several European cities. Consequently it is possible to propose exposure-response function for NO_x. However it is recommended that the E-R functions for NO_x are used exclusively for sensitivity analyses.

On the other hand, the exposure-response functions for secondary pollutants deriving from NO_x, such as nitrates and ozone, are reliable enough to be used without problems. In spite of this, the assessment of the effect of emission reductions on ozone concentrations at the local scale probably represents the most difficult problem within atmospheric transport modelling for ExternE (Friedrich and Bickel [4]). As a consequence, in the present work, in order to define the environmental benefits arising from the reduction of NO_x emissions, we used the ECOSENSE model on the regional scale to determine the total monetary damage due to nitrates derived from nitrogen oxides emitted by the analysed cement kiln. Moreover, since public administrations are very interested in local context, we applied the exposure-response functions for NO_x on the local scale, so as to get some general information.

4 Results

Table 4 reports the monetary damages, corresponding to each health end point indicated by the ExternE project for nitrates, calculated by ECOSENSE on the regional scale for the “no B.A.T.” scenario (i.e., current emission levels, 1527 mg/Nm³, dry gas, O₂ @ 10%). As one can easily observe, the total damage is very large (7.463 €/t of emitted NO₂) due to the high number of individuals hit



by the impact all over Europe. The main contribution to the total damage is constituted by the chronic mortality (77%), followed by the chronic bronchitis (12%) and the restricted activity days (8%); in particular, the calculated nitrates concentration, due to the NO₂ emissions of the analysed kiln, causes respectively 36 YOLL per year (Years Of Life Lost distributed over the resident population), 3,2 additional cases of chronic bronchitis per year and 3.253 restricted activity days per year.

Table 4: Damages on the regional scale for the “no B.A.T.” scenario.

NO _x : 1527 mg/Nm ³ dry gas, O ₂ @ 10%					
	Health end point	Reference	receptor	Impacts (cases/year)	Damage (EURO ₂₀₀₀)/y
NITRATES	Bronchodilator usage	Dusseldorp <i>et al.</i> , 1995	Asthmatic adults	742,15	29.679
	Cough	Dusseldorp <i>et al.</i> , 1995	Asthmatic adults	763,17	34.353
	Lower Respiratory Symptoms	Dusseldorp <i>et al.</i> , 1995	Asthmatic adults	275,98	2.208
	Bronchodilator usage	Roemer <i>et al.</i> , 1993	Asthmatic children	148,64	5.945
	Cough	Pope and Dockery, 1992	Asthmatic children	255,93	11.514
	Lower Respiratory Symptoms	Roemer <i>et al.</i> , 1993	Asthmatic children	197,35	1.579
	Congestive Heart Failure	Schwartz and Morris, 1995	Adults over 65	0,55	1.790
	Chronic cough	Dockery <i>et al.</i> , 1989	Children	113,39	27.219
	Restricted Activity Days	Ostro, 1987	Adults	3253,11	357.828
	Chronic Bronchitis	Abbey <i>et al.</i> , 1995	Adults	3,19	539.896
	Respiratory Hospital Admissions	Dab <i>et al.</i> , 1996	Entire population	0,47	2.041
	Cerebrovascular Hospital Admissions	Wordley <i>et al.</i> , 1997	Entire population	1,15	19.251
	Chronic mortality (YOLL)	Pope <i>et al.</i> , 1995	Entire population	35,85	3.459.149
	Total monetary damage				4.492.453

Table 5 shows the comparison cost-benefit for the different scenarios: it has to be noted that the “proposed level”, 1200 mg NO₂/ Nm³, dry gas O₂ @10%, is usually associated with Low-NO_x burner, whereas, according to the reference document on B.A.T., both the flame cooling techniques and the Low-NO_x burner can reach very low emission levels (500 mg NO₂/ Nm³). Moreover, we used the highest costs within the range reported in Table 2 in order to give a clear and univocal interpretation of the comparison. Benefits are calculated with respect to the “no B.A.T.” scenario.

As one can easily observe in Figure 1, which shows the cost-benefit analysis in the time (starting from the investment), all the scenarios have strong positive effects if compared with the B.A.T. costs. In particular, for the primary measures, flame cooling and Low NO_x burners, the break event point (the time at which benefit overcomes cost) is lower than 1 year, even in the case of the “proposed level” scenario. As far as the most expensive scenario is concerned, that is the selective catalytic reduction (SCR), the break event point occurs after

1 year but the environmental benefits have a large slope factor so that, in the long term, SCR could be the best choice.

Table 5: Cost-benefit analysis.

Emission level mg NO ₂ /Nm ³ dry gas, O ₂ @ 10%	Calculated environmental damage (€/y)	Benefit (€/y)	B.A.T. costs		notes
			Investment (€)	Operating (€/y)	
1527	4.492.453	0	-	-	no B.A.T.
1200	3.525.114	967.339	800.000	-	Proposed level
500	1.469.066	3.023.387	200.000	75.000	Flame cooling
500	1.469.066	3.023.387	800.000	-	Low-NO _x
200	585.816	3.906.637	4.500.000	60.000	SCR

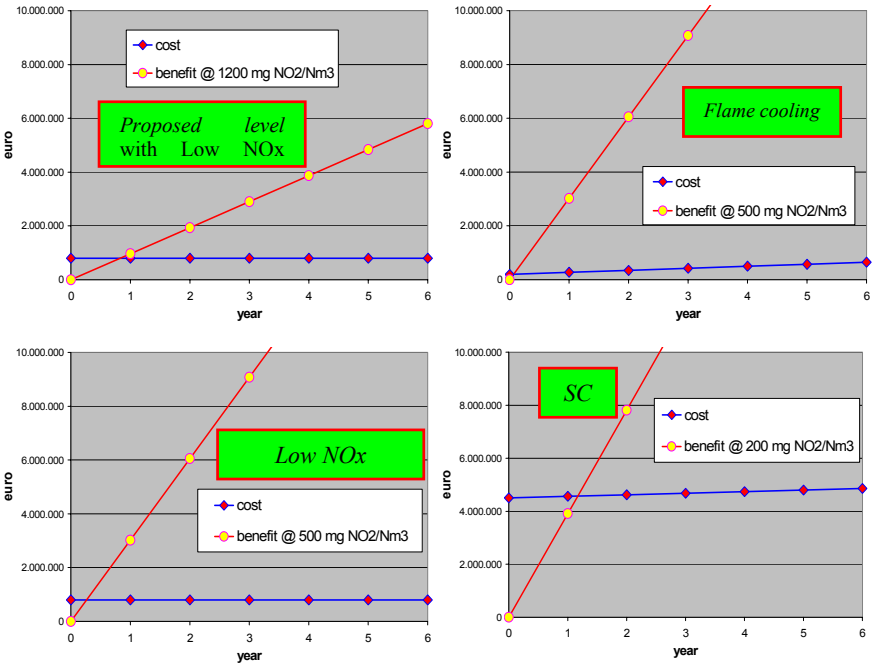


Figure 1: Cost-benefit analysis for the B.A.T. scenarios.

4.1 The local scale

So far, we carried out the cost-benefit analysis on the regional scale, which is the approach that gives the most complete information about the impact due to an industrial plant. At the same time we are usually very interested in the damage at



the local scale, where NO_2 has not undergone chemical transformations yet. This way, we determined the NO_2 yearly mean concentration at the ground level in a very local scale by means of the Industrial Source Complex Short Term Model, version 3 (ISCST3), by U.S. EPA [5], and then we calculated the impact on human health; to do this, we applied the exposure-response functions for NO_2 (Table 6), which are recommended exclusively for sensitivity analyses. In order to carry out the present part of analysis, we investigate 2 different areas: Cuneo, a town of 53.000 inhabitants, placed downwind of the cement factory during the night hours and Roccavione, a village of 2.800 inhabitants, impacted during the day. Figure 2 shows the isoconcentration map of the investigated areas on the basis of the “no B.A.T.” emission level (1527 mg/Nm^3 , expressed as NO_2 , dry gas, $\text{O}_2 @ 10\%$) whereas Table 7 reports the corresponding calculated damages. The first comment on these results is that local impact due to NO_2 is negligible if compared with the regional damages due to nitrates; this can be explained by the larger number of receptors on a European-wide scale.

Table 6: Exposure-response functions for NO_2 .

Health end point	Reference	receptor	f_{er} (cases/year/person/ $\mu\text{g}/\text{m}^3$)	Unit cost (EURO ₂₀₀₀ /case)
Respiratory Hospital Admissions	Ponce de Leon, 1996	Entire population	1,40E-06	4.320
Acute mortality (YOLL)	Anderson & Toulomi, 1996	Entire population	2,91E-06	165.700

Table 7: Damages on the local scale for the “no B.A.T.” scenario.

$\text{NO}_x: 1527 \text{ mg/Nm}^3$ dry gas, $\text{O}_2 @ 10\%$					
	Health end point	Reference	receptor	Impacts (cases/year)	Damage (EURO ₂₀₀₀)/y
NO_2 Cuneo	Respiratory Hospital Admissions	Ponce de Leon, 1996	Entire population	0,0088	38
	Acute mortality (YOLL)	Anderson & Toulomi, 1996	Entire population	0,0184	3.041
NO_2 Roccavione	Respiratory Hospital Admissions	Ponce de Leon, 1996	Entire population	0,0067	29
	Acute mortality (YOLL)	Anderson & Toulomi, 1996	Entire population	0,0138	2.293
Total monetary damage					5.401

Moreover, one can observe that, in spite of the difference of population in the two analysed areas on the local scale, the damages are quite similar; this effect is due to the different NO_2 concentrations at the ground level (the yearly mean concentration over Cuneo is $0,12 \mu\text{g}/\text{m}^3$, $1,70 \mu\text{g}/\text{m}^3$ over Roccavione). As a matter of fact, the ExternE methodology consist of a multiplicative approach ($\text{Damage} = \text{pollutant Concentration (C)} \times \text{Population (P)} \times \text{Exposure-Response function} \times \text{Unit cost}$); once the exposure-response functions and the corresponding unit cost are assumed, the main parameter to assess the total monetary damage is $\sum C_i \times P_i$ (the sum takes into account the different population density and the inhomogeneous concentration level in the calculation area). In

the present study, the larger mean concentration calculated for Roccavione compensates the smaller population, so that the parameter $\sum C_i \times P_i$ is almost the same in the 2 analysed areas.

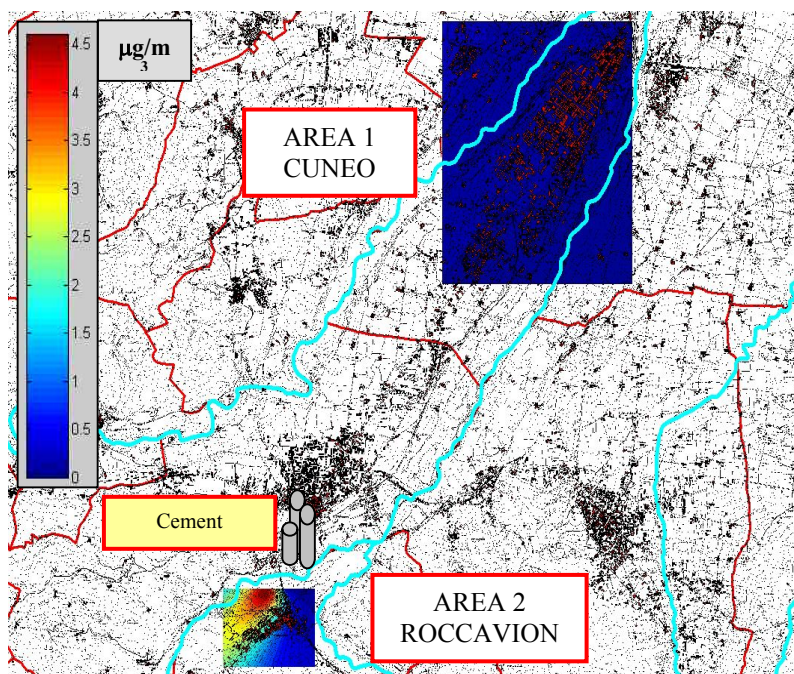


Figure 2: NO_2 yearly mean concentrations in the analysed areas.

5 Conclusions

The ExternE methodology enables to carry out cost-benefit analysis within the I.P.P.C. authorization procedure; in the present paper we verify that all the B.A.T. proposed to reduce NO_2 emissions for long dry rotary cement kiln (flame cooling, Low NO_x burners, Selective Catalytic Reduction) implicate environmental benefits, due to the reduction of nitrates concentration on a regional scale, which overcome B.A.T. costs after 1 year or less. The benefit deriving from the reduction of NO_x emissions could be reasonably larger than the calculated one when taking into account the ozone formation or considering that the mixing height assumed by the Windrose Trajectory Model could be lower than 800 m, that is plausible for European areas such as Northern Italy, when temperature inversion phenomena occurs. Another effect that could enlarge the environmental benefit is the stagnation of pollutants at the ground level, due to the very low wind speed of Northern Italy, which is not considered by ordinary dispersion models; this way, the concentration of pollutants, both primary and secondary, can be underestimated.

As far as the air quality is concerned, the main problem for Northern Italy and large part of Europe comes from particulates (PM_{10} or smaller) and ozone; since nitrogen oxides are partly responsible for both the pollutants, any possible effort should be done to reduce their emissions.

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