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Environmental damage costs from airborne pollution of industrial activities in the greater Athens, Greece area and the resulting benefits from the introduction of BAT

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Abstract

Attributing costs to the environmental impacts associated with industrial activities can greatly assist in protecting human health and the natural environment as monetary values are capable of directly influencing technological and policy decisions without changing the rules of the market. This paper attempts to estimate the external cost attributable to the atmospheric pollution from 'medium and high environmental burden' industrial activities located in the greater Athens area and the benefits from Best Available Techniques (BAT) introduction. To this end a number of typical installations were defined to be used in conjunction with the Impact Pathway Approach developed in the context of the ExternE project to model all industrial sectors/sub-sectors located in the area of interest. Total environmental externalities due to air pollutants emitted by these industrial activities were found to reach 211 M€ per year, associated mainly with human mortality and morbidity due to PM_{10} emissions, as well as with climate change impacts due to CO_2 emissions for which non-metallic minerals and oil processing industries are the main sources. The results obtained can be used as the basis for an integrated evaluation of potential BAT, taking into account not only private costs and benefits but also the environmental externalities, thus leading to policy decisions that maximize social welfare in each industrial sector/sub-sector.

Keywords: External cost; Industrial activities; Air pollution; BAT

1. Introduction

Despite many years of environmental regulation, atmospheric emissions and other effluents from either industrial processes or fuel combustion in industrial

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units impose risks and cause serious impacts on human health and on the natural and social environment (e.g. crops, forests, water resources, natural ecosystems, buildings, historical monuments, etc.). These impacts induce costs on society, which are, to a large extent, external costs as they are not reflected in the market price of the commodities and are not taken into account in the allocation of economic resources. Nowadays, it is increasingly recognised that in order to effectively incorporate environmental concerns in the planning and decision-making process, it is necessary to take into account all relative costs and benefits (i.e. both private and external) and to develop ways for the internalization of externalities. To this end, the Integrated Pollution Prevention and Control (IPPC) Bureau issued a specific Best Available Techniques Reference Document (BREF) for ranking Best Available Techniques (BAT) in the various industrial sectors on the basis of their cost effectiveness and environmental performance, considering the availability of relevant external cost estimates as a powerful tool to assist policy and decision-making process (European Commission, 2005a).

The estimation of the several types of externalities and the attribution of monetary values to a number of non-tradable goods such as human health, ecosystems, biodiversity, human amenity, etc., has been the subject of substantial effort for many years resulting in the development of a number of techniques based on welfare economics theory, namely Contingent Valuation Method, Travel Cost Approach, Hedonic Pricing Approach, etc. (see for example Pearce and Turner, 1990; Freeman, 2003). The implementation of most of these approaches requires significant human and economic resources, and the results obtained are to a large extent site-specific. This is more so when one attempts to estimate externalities associated with the production of a specific commodity (e.g. electricity, industrial products, transport activity, etc.), which takes part in a specific site and affects several third parties causing various external effects. Toward this, since the early 1990s, significant progress has been made through the utilization of results from various fields, namely environmental economics, epidemiology, agronomy, etc.

The ExternE project, initiated in 1992 and funded by the European Commission, was one of the first attempts aiming at establishing a consistent accounting framework for the assessment of externalities associated with various energy related activities. This accounting framework, based on a detailed bottom–up impact pathway approach, was first implemented in the power generation sector in order to estimate the external costs associated with the various electricity generation technologies used in all member states of the EU (European Commission, 1999a). In a second stage, this framework was extended to quantify the external costs of transport, which is another sector with significant contribution to air pollution (European Commission, 1999b). Environmental externalities of the industrial sector have only been partly addressed in the context of ExernE, mainly through the ECOSIT project, which focuses on the external costs associated with innovative industrial technologies (European Commission, 2003; Holland et al., 2002). A similar bottom–up methodology was also applied to estimate the environmental externalities caused by SO_2 and O_3 emitted from industrial and transport activities in Madrid (Lechon et al., 2002) and to evaluate the environmental performance of some specific industrial projects in Taiyuan City in China (Mestl et al., 2005).

This relative dearth of analytical studies aiming at estimating environmental externalities associated with the production of industrial commodities could be partly attributed to the complexity of the problem. The large number of industrial units that usually operate in a specific region, the diversity of industrial activities, the several stages that each industrial process is divided in and the variation in the importance of specific pollutant emissions between industrial sectors, technologies and plants, are the most important aspects that hinder the development of a comprehensive methodological framework for estimating the externalities of the industrial sector. The results strongly depend on the nature of the product, the technologies used and the location of the industrial unit under consideration and cannot be generalised or extrapolated to other situations (European Commission, 2003).

Air pollution constitutes one of the most significant environmental problems for the greater Athens area with its 4,000,000 inhabitants and over 9000 industrial installations. In an attempt to address environmental policy difficulties in the greater Athens area, this paper aims at exploiting the framework developed in the context of the ExternE project to quantify in a consistent and sound way, the environmental externalities of industrial activities located therein. More specifically, the aim of this paper is to give, to the extent possible, robust estimates of the total amount of the environmental external costs associated with atmospheric pollution from industrial activities located in the wider area of Athens and legally characterized as of 'medium and high environmental burden' disaggregated per industrial sector and impact category. Additional environmental impacts associated with industrial activities (e.g. the impacts of wastewater on the local water resources, the transportation and disposal of solid wastes, the aesthetic impacts, the noise emissions, etc.) are not included in the context of this study, since they are very site-specific or are covered by existing legislation so that possible impacts would be the result of inadequate enforcement; we thus consider their importance for this particular case study to be secondary. The study also seeks to formulate a detailed calculation basis to assist the assessment of the potential benefits from the introduction of BAT to the industrial sectors/sub-sectors in the Athens region. The analysis focuses mainly on conventional air pollutants (PM_{10}, SO_2, NO_x, CO_2) but takes also into account the various micro-pollutants that may be emitted by particular processes (toxic metals, etc.), and VOCs mainly as precursor to O_3 formation. It should be noted that the implementation of any accounting framework for estimating environmental externalities involves many uncertainties related to the exposure-response functions used, the monetary values attributed to the non-tradable goods, etc. It is outside the scope of this study to validate the appropriateness for Greece of the form of the exposure-response functions and monetary values adopted in the context of ExternE for all European Union countries. However, a statistical analysis of the results obtained shows an overall picture of these uncertainties.

The structure of this paper is as follows: Section 2 describes the approach used in this paper. In Section 3 methodologies formulated previously are applied to estimate the environmental externalities associated with industrial activities as well as the potential benefits that could be arise from the introduction of BAT. Finally, in Section 4, the main findings of the study are summarized and conclusions are drawn.

2. Methodological background

2.1. The typical installation approach

In trying to estimate the environmental externalities associated with industrial activities in a region and the potential benefits that result from the application of BAT, one has to deal with the large number of industrial sectors/sub-sectors and the even larger number of installations that are located in this region, the different characteristics (size, capacity, production process, equipment, fuels, raw materials etc.) of the various industrial units, and the existence of a great variety of potential BAT applicable at installation level. It is obvious that the implementation of an analytical bottom–up methodology for estimating the environmental externalities of the very high number of combinations that result would require considerable human and economic resources and powerful computational tools. To reduce the problem to a more manageable size, aggregation is required, which in this case will be implemented through the utilization of a 'typical' (or reference) installation for appropriately identified groups of installations for each industrial sector/sub-sector, as suggested by Geldermann and Rentz (2004). The concept of typical installation rests on the assumption that the environmental burdens (i.e. mainly air emissions for this particular case study) from the typical installation of a group times the number of installations in this group equals the environmental burden of the whole group.

The configuration of each typical installation comprises all the basic production stages, from the processing of raw materials to the storage of products, which allows the analytical estimation of the air pollutants emitted by the typical installation. Technical parameters that primarily influence the impacts of air pollutants on the environment and human health and thus constitute substantial elements for the configuration of the typical installation unit are the type of processes included in the typical industrial unit under consideration, the conversion technologies used, the fuel characteristics, the raw materials used, the environmental protection measures implemented, the installed capacity of the unit and the mean annual load factor of the unit. In addition, the configuration also includes the installation's characteristics such as the height, diameter, flue gas volume etc. of its stack. On the basis of these parameters, the total quantities of emissions of the typical industrial unit under consideration can be determined including the fraction of fugitive emissions. The aggregation level of the typical installation must be such as to allow for the incorporation of BAT in the process, so that the environmental impacts from their introduction can be examined. It should be noted that since the methodology invokes the concept of the 'typical' installation for estimating the total amount of environmental externalities of the industrial sector, it is particularly important to choose correctly the location of this 'typical' installation or installations. Thus the geographic distribution pattern of the actual installations, as well as the terrain features of the area of interest need to be taken into account. In selecting the location of the typical units, the geographical spread of the installations of each sector/sub-sector was examined and a decision was made, taking into account also topographic barriers, as to the need of more than one unit per sector/sub-sector, not to exceed three. Then for each group, the unit was sited so as to minimize the sum of distances between the typical unit and the existing installations of this group. An example of such siting selection for the group of

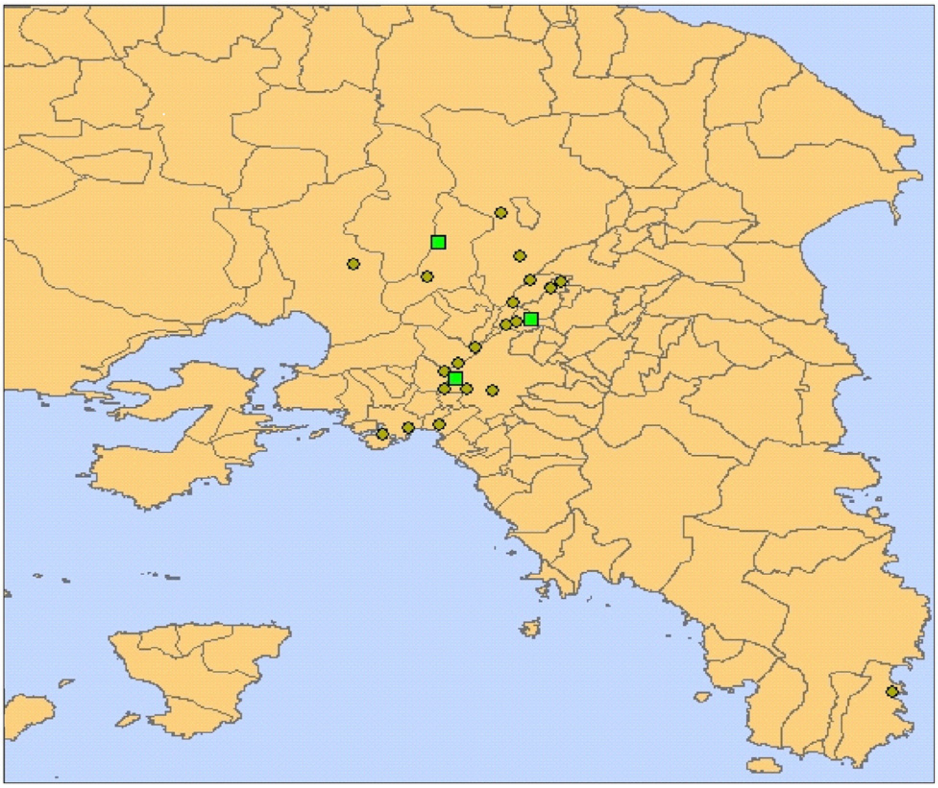

Fig. 1. Siting of the 3 'typical' installations (squares) and the location of actual industrial installations (circles) of the textiles sector in the greater Athens area. The boundaries of the municipalities affected and taken into account in this study to calculate externalities are also shown.

installations of the textiles sector in the region of Attica is shown in Fig. 1.

The above characteristics and structural elements of each typical installation defined in the context of this study are based on an analysis of all the industrial units of medium and high environmental burden of the relevant sectors/sub-sectors in the region of interest, for which the operational characteristics were available from a census carried out in 2001 (Epem et al., 2001). The number of groups inside the sector/sub-sector depends on whether there are significant differences between the installations mainly in terms of the process use (for example type of furnace used). In view of the extremely large number of combinations of BAT to be applied to the over 800 industrial units of medium and high environmental burden in the greater Athens area, every effort has been made to keep the number of groups (and consequently of typical installations) within a sector/sub-sector as low as possible (e.g. three or less) so that the computational time needed for the analysis of trade-offs in a later stage remains within reasonable limits. Table 1 shows the number of typical installations defined in each industrial sector and specifies the most important characteristics that led to the categorization adopted in this study.

2.2. The impact pathway approach

To calculate damages to the environment and to human health from the industrial activities under consideration, the Impact Pathway Approach (IPA), developed within the ExternE project has been chosen (European Commission, 2005b). IPA is a detailed bottom–up methodology which follows the sequence of processes through which emissions or other burdens associated with a particular polluting source result into environmental damages. It has been chosen because it has been judged better suited compared to earlier top–down approaches, because in this situation external costs are highly site-dependent and are estimated on a marginal basis. The basic steps included in the IPA comprise the: (i) identification of the reference site and technology, including the main environmental burdens released, (ii) calculation of changes in the ambient conditions due to the operation of the industrial unit under examination, (iii) estimation of impacts, and (iv)

Table 1
Typical installations defined in each industrial sector/sub-sector

	Industrial sector	Number of typical units	Reasoning for typical units discrimination
15	Food and drinks	11	Products differentiation Spatial distribution
17	Textiles	2	Products differentiation
19	Leather tanning	1	–
20	Wood processing	1	–
21	Paper and pulp	1	–
22	Printing	1	–
23	Petroleum industry	6	Products differentiation Type of production process Capacity differentiation
24	Chemical industry	7	Products differentiation Capacity differentiation Spatial distribution
25	Plastic products	1	–
26	Non-metallic minerals	7	Products differentiation Type of furnace
27	Metal processing	11	Products differentiation Capacity differentiation Spatial distribution
28	Electroplating	1	–
31	Batteries	1	–
36	Furniture	1	–

monetization of impacts and damages. These methodological steps have been incorporated in the Ecosense computational tool (IER, 2004). Ecosense is an integrated modeling framework, developed in the framework of ExternE and used worldwide (e.g. Brazil, China, Russia and Ukraine, see European Commission, 2005a) for estimating the environmental externalities of air pollution. It combines local and regional dispersion models with dynamic databases of exposure-response functions to compute the impacts of increased concentrations of air pollutants to the various receptors and hence the monetary values for the different impact categories. A more analytical description of these steps is presented below.

2.2.1. Specification of technology and location

Technology is specified on the basis of the typical installation approach, while the estimation of externalities is done at group of installations level by multiplying the concentration of the air pollutants in the flue gas volume of the typical installation by the number of installations in the corresponding group rather than estimating the externalities for a single typical unit and then multiplying the results with the number of installations of the group. This aggregation scheme results to more accurate estimations of the relevant externalities for small industrial units, as the Ecosense model was originally designed to estimate the impacts and damages of the large quantities of air pollutants released by large power plants (European Commission, 2003). In addition, this aggregation at a group of installations level, models in a better way the non-linear effects that the increased concentrations of air pollutants cause to some receptor categories (e.g. the influence of increased SO_2 concentrations to agricultural production).

Location is specified with respect to the density and distribution of the various receptors (population, crops, buildings, natural ecosystems, etc.) as well as to the meteorological data affecting the dispersion of effluents. The level of detail that the spatial distribution of the receptors is incorporated in the modeling framework depends upon the geographical range of analysis, with local analysis requiring data at a higher level of geographical resolution compared to those required for the regional or global level of analysis.

2.2.2. Calculation of changes in the ambient concentrations

Taking into account the quantities of air pollutants released on an annual basis at a group of installations level as well as the technological and structural characteristics of the corresponding typical installation, the incremental concentrations of air pollutants due to the operation of the industrial units under consideration are calculated by using the appropriate dispersion models. The Ecosense tool used in this study integrates three different models for the calculation of the dispersion of air pollutants in the atmosphere:

- The Industrial Source Complex Model (ISC), which is a Gaussian plume model used for transport modeling of primary air pollutants (PM_{10}, SO_2, NO_x, etc.) on a local scale (i.e. at distances up to 50–100 km from the source) using a grid of 10×10 km.
- The Windrose Trajectory Model (WTM), which models the chemical reactions of primary pollutants in the atmosphere and is used to estimate the concentration of primary and secondary air pollutants as well as acid deposition on a regional scale (covering all Europe and part of Asia using the EMEP[2] 50 km grid).
- The Source-Receptor Ozone Model (SROM), which estimates on a regional scale (originally the EMEP 150 km grid is used and then the results are adjusted to EMEP 50 km grid) the concentrations of ozone formed due to atmospheric chemical reactions between NMVOCs and NO_x in the presence of sunlight.

[2] EMEP is a Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air pollutants in Europe.

2.2.3. Estimation of impact effects

In the context of this study we consider the impacts of air pollutants emitted by the various industrial activities on human mortality and morbidity, agriculture, materials and climate change. The effect of the enhanced concentrations on the different receptor categories is estimated by using appropriate dose- or exposure-response functions. So, for example, impacts on human health result from a series of exposure-response functions developed on the basis of epidemiological studies of the relationship between pollutant concentration and health parameters of specific risk groups. In a similar way, effects on agriculture and on materials are calculated through functions relating crop yield changes or material degradation with changes in pollutants concentrations.

In the context of the present analysis the exposure-response functions proposed by the ExternE project (European Commission, 2005b) have been used. The proposed exposure-response functions for estimating the impacts on human health are linear without threshold. The slopes of these functions are presented in Table 2. Impacts on human health include asthma attacks, hospital admissions, chronic bronchitis, restricted activity days, premature deaths, etc. Mortality impacts are quantified in terms of the reduction in life expectance, expressed as cumulative years of life lost (YOLL) for the population at risk. For agriculture and building materials, the exposure-response functions have non-linear shapes and are presented in Tables 3 and 4. The impacts on agriculture considered in the context of this study result from the changes on crop yields from their exposition to increased SO_2 and O_3 concentrations, from the cost of the additional lime required for the restoration of agricultural soils due to the incremental acidification levels and from the reduction in fertilizer consumption due to the increased nitrogen deposition. As regards impacts on building materials, the surface area that is damaged by pollution on an annual basis is calculated, taking into account the exposure-response functions for each material category presented in Table 4 in combination with the corresponding critical thresholds that define the necessity for restoration or for maintenance.

Table 2
Quantification of human health impacts and damages due to air pollution

Receptor	Impact category	Reference	Pollutant	f_{er} [a]	Unit damage cost (€$_{2000}$)
Asthmatic adults	Bronchodilator usage	Dusseldorp et al. (1995)	PM_{10}	0.163	40
	Cough	Dusseldorp et al. (1995)	PM_{10}	0.335	45
	Lower respiratory symptoms	Dusseldorp et al. (1995)	PM_{10}	0.061	8
Asthmatic children	Bronchodilator usage	Roemer et al. (1993)	PM_{10}	0.078	40
	Cough	Pope and Dockery (1992)	PM_{10}	0.267	45
	Lower respiratory symptoms	Roemer et al. (1993)	PM_{10}	0.103	8
Asthmatics	Asthma attacks	Whittemore and Korn (1980)	O_3	6.01E−3	75
Adults above 65 years	Congestive heart failure	Schwartz and Morris (1995)	PM_{10}	1.85E−5	3260
			CO	5.64E−7	
Children	Chronic cough	Dockery et al. (1989)	PM_{10}	2.07E−3	240
Adults	Restricted activity days	Ostro (1987)	PM_{10}	0.025	110
	Minor restricted activity days	Ostro and Rothschild (1989)	O_3	9.76E−3	45
	Chronic bronchitis	Abbey et al. (1995)	PM_{10}	4.90E−5	169,330
Total population	Chronic mortality [b]	Pope et al. (1995)	PM_{10}	3.90Å−4	50,000
	Acute mortality [b]	Anderson et al. (1996)	SO_2	5.34Å−6	75,000
		Touloumi et al. (1996)	CO	1.08Å−7	
		Sunyer et al. (1996)	O_3	6.13Å−6	
	Respiratory hospital admissions	Dab et al. (1996)	PM_{10}	2.07E−6	4320
		Ponce de Leon et al. (1996)	SO_2	2.04E−6	
			O_3	4.96E−6	
	Cerebrovascular hospital admissions	Wordley et al. (1997)	PM_{10}	5.04E−6	16,730
	Symptom days	Krupnick et al. (1990)	O_3	0.046	45
	Non-fatal cancers	WHO (1987)	As	4.29E−5	450,000
		EPA (1996)	Cd	2.57E−5	
		WHO (1987)	Ni	5.71E−6	
		WHO (1987)	Cr	5.71E−4	

The toxicity of nitrates is taken as equivalent to 1/2 the toxicity of PM_{10} while the toxicity of sulphates is taken equal to the toxicity of PM_{10}. The information presented in this table has been mainly derived by ECOSIT (2003), European Commission (2004), and European Commission (2005b).

[a] The slope f_{er} of the exposure-response functions is expressed in [cases/(year × person × μg/m^3)].

[b] The exposure-response functions for chronic and acute mortality estimate the years of life lost due to air pollution.

Table 3
Exposure-response functions and monetary values used for estimating the impacts of air pollution on agriculture

Impact category	Pollutant	Dose-response functions [a]	Crop	Prices (€$_{2000}$/t)
Yield loss	SO_2	$y=0.74\times[SO_2]-0.55\times[SO_2]^2$ for $0<[SO_2]<13.6$ ppb	Sunflower	273
		$y=-0.69\times[SO_2]+9.35$ for $[SO_2]>13.6$ ppb	Wheat	137
		Baker et al. (1986)	Potato	113
			Rice	200
			Rye	99
			Oats	132
			Tobacco	2895
			Barley	93
			Sugar beet	56
Yield loss	O_3	$y=99.7-1.2\times\text{AOT40}$ Fuhrer, 1996; Mills et al., 2003	Sunflower	273
		$y=99.7-1.7\times\text{AOT40}$ Fuhrer, 1996; Mills et al., 2003	Wheat	137
		$y=99.7-0.6\times\text{AOT40}$ Fuhrer, 1996; Mills et al., 2003	Potato	113
		$y=99.7-0.4\times\text{AOT40}$ Fuhrer, 1996; Mills et al., 2003	Rice	200
		$y=99.7-0.5\times\text{AOT40}$ Fuhrer, 1996; Mills et al., 2003	Tobacco	2895
		$y=99.7-0.6\times\text{AOT40}$ Fuhrer, 1996; Mills et al., 2003	Sugar beet	56
Acidification of agricultural soils	Acid deposition	$\Delta L=50\times A\times\Delta D_A$ (European Commission, 2005b)	Not applicable	33 /t lime required
Fertilization effect	Nitrogen deposition	$\Delta F=14.0067\times A\times\Delta D_N$ (European Commission, 2005b)	Not applicable	525 €/t fertilizer avoided

The information presented in this table has been mainly derived by ECOSIT (2003), European Commission (2004), and European Commission (2005b).

[a] Where y is the relative yield change, $[SO_2]$ is the SO_2-concentration at receptors' site in ppb, AOT40 is the accumulated ozone concentration above a threshold of 40 ppb_V, ΔL is the additional lime requirement in kg/year, ΔF is the reduction in fertilizer requirement in kg/year, A is the agricultural area in ha, ΔD_A is the annual acid deposition at the receptors' site in meq/m^2/year and ΔD_N is the annual nitrogen deposition at the receptors' site in meq/m^2/year.

Table 4
Exposure-response functions and monetary values used for estimating the impacts of air pollution on materials

Material	Dose-response functions [a, b]	Critical thickness/ material loss	Maintenance cost (€$_{2000}$/m^2)
Limestone	$R=(2.7\cdot[SO_2]^{0.48}\cdot e^{-0.018T}+0.019\cdot \text{Rain}[H^+])\cdot t^{0.96}$	4 mm	296
Sandstone, natural stone, mortar, rendering	$R=(2.0\cdot[SO_2]^{0.52}\cdot e^{f(T)}+0.028\cdot \text{Rain}[H^+])\cdot t^{0.91}$ with $f(T)=0$ if $T<10$ °C or $f(T)=-0.013\cdot(T-10)$ if $T>10$ °C	4 mm	296 (sandstone, natural stone) 33 (mortar, rendering)
Zinc and galvanized steel	$\text{ML}=1.4\cdot[SO_2]^{0.22}\cdot e^{0.018\text{Rh}}\cdot e^{f(T)}\cdot t^{0.85}+0.029\cdot \text{Rain}[H^+]\cdot t$ with $f(T)=0.062\cdot(T-10)$ if $T<10$ °C or $f(T)=-0.021\cdot(T-10)$ if $T>10$ °C	50 µm	~27 (zinc) ~38 (galvanized steel)
Paint coating on steel	$A=(0.033\cdot[SO_2]+0.013\cdot \text{Rh}+f(T)+0.0013\cdot \text{Rain}[H^+])\cdot t^{0.41}$ with $f(T)=0.015\cdot(T-11)$ if $T<11$ °C or $f(T)=-0.15\cdot(T-11)$ if $T>11$ °C	5 on the basis of ASTM rating index	13
Paint coating on galvanized steel	$A=(0.0084\cdot[SO_2]+0.015\cdot \text{Rh}+f(T)+0.00082\cdot \text{Rain}[H^+])\cdot t^{0.43}$ with $f(T)=0.04\cdot(T-10)$ if $T<10$ °C or $f(T)=-0.064(T-10)$ if $T>10$ °C	5 on the basis of ASTM rating index	13
Carbonate paint	$\Delta R=0.12\cdot(1-\exp(-0.121\cdot \text{Rh}/(100-\text{Rh})))\cdot[SO_2]+0.0174\cdot \text{Rain}[H^+]$	50 µm	13

The information presented in this table has been mainly derived by ECOSIT (2003), European Commission (2004), and European Commission (2005b).

[a] Where R is the surface recession in ìm, $[SO_2]$ the SO_2 concentration at receptors' site in µg/m^3, T is the temperature in °C, Rain the precipitation in mm/year, $[H^+]$ the hydrogen ion concentration in precipitation expressed in mg/l, ML the mass loss in g/m^2, Rh the relative humidity in %, and A is a degradation rating index (originally $A=(10-\text{ASTM})$, with ASTM representing a rating between 1 and 10, assuming that 10 corresponds to an unexposed surface).

[b] The dose-response functions presented here have been proposed by Tidblad and Kucera (1998) and Haynie (1986).

2.2.4. Monetization of impact effects

Monetization is by far the most complicated step of the methodological approach especially when environmental burdens affect non-tradable goods such as human life, ecosystems, etc. To this end, appropriate techniques based on welfare economics theory are used in order to translate the impact effects previously estimated to monetary terms. These techniques are distinguished in: (i) direct approaches, such as the Contingent Valuation Method (CVM), which is based on questionnaire data for individuals' willingness to pay to avoid hypothetical scenarios involving reductions in health and/or environmental risks, is utilized; and (ii) indirect approaches, seek to uncover values for the non-marketed goods by identifying relationships connecting them to marketed goods or to specific behaviors that have a well-defined price and act as substitutes or complements of the goods examined.

To estimate the damage costs for each environmental impact category examined one multiplies the number of impacts that have been calculated in the previous stage of the analysis by the unit cost attributed to each impact category. In the context of this study the following assumptions have been made with respect to unit cost per impact category:

- For *mortality impacts* associated with air pollution, the estimation of relevant damages is based on the value of life year lost as proposed by Rabl (2003) to take into account the fact that the loss of life expectance due to air pollution is relatively short while the total number of premature deaths is almost impossible to be determined. Specifically, for chronic mortality a value of life year lost equal to 50,000 € is used, assuming that the corresponding payments will occur annually over a ten-year period (a 3% discount rate was used in these calculations). For acute mortality damages, the value of life year lost is based on the same approach assuming 75,000 € and 0% discount rate.
- For *morbidity effects*, the unit costs include the medical expenditures, wage and productivity losses as well as various disutility costs associated with reduced enjoyment of desired leisure activities, pain or suffering, anxiety about future, etc. Table 2 gives the unit costs used in this study for various morbidity effects on the basis of the corresponding figures proposed by the NewExt project (European Commission, 2004).
- The unit cost values for estimating damages on *agriculture* are defined on the basis of the international market prices of the crops affected (e.g. wheat, potatoes, rice, rye, barley, etc.) and the additive materials (e.g. lime, fertilizers) used, summarized for convenience in Table 3.
- The unit cost values for estimating damages on building materials are based on their replacement or maintenance costs, which are presented in Table 4.
- Finally, with respect to damages associated with CO_2 emissions and the resulting global warming effect, it should be noted that they do not vary with technological and geographical characteristics of the source. This is explained by the fact that each unit of CO_2 contributes equally to the climate change threat and the resulting cost. The existing estimations for the external cost of climate change vary significantly, reflecting the high uncertainty of these estimations as most of them will occur in the long-run. In the context of this study the monetization of this impact category is based on an estimation of 18 € per ton CO_2 released (European Commission, 1999c) although there is considerable spread in the values to be found in the literature (see for example the recent survey of Tol (2005) who suggests 13.6 \$ per ton CO_2 released as a likely upper value). Lately the European Commission (2005b) recommends a value of 19 € per ton CO_2 released, which is very close to the figure used in the context of this study.

The sum of these damage costs constitutes the external cost of the group of installations modeled through the typical installation under consideration, while the sum of the external costs of all the groups of installations under a sector/sub-sector gives the total damages at a sector/sub-sector level and in turn the sum of external costs of all sectors/sub-sectors represents the total environmental damages associated with industrial activities in the region. This aggregation scheme does not fully take into account the non-linearity of some relevant processes, such as the influence of increased SO_2 concentrations on agricultural production and material deterioration (Lechon et al., 2002). However, given that damages to human health and the impact of climate change, which constitute by far the larger part of external costs associated with air pollution, are estimated on the basis of linear functions, we assume that the non-inclusion of these additional non-linear effects on agriculture and building materials will not affect the estimates of the externalities at a sector/sub-sector level.

2.3. Assessment of BAT benefits

The installation and operation of BAT in an industrial unit will reduce the quantities of one or more of the released pollutants, thus resulting in environmental benefits.

The quantification of these benefits is undertaken on the basis of the following steps:

1. For each group of industrial installations, which is simulated by a unique typical unit, the environmental externalities estimated through the use of the IPA as described in the previous stage of the analysis, are ascribed on a mass unit per each pollutant released. It should be noted that for the same pollutant, the unit external environmental cost differs across typical units of the same sub-sector or across typical units of different sub-sectors, due to differences in the location of installations, the technical characteristics of the stack and the effluents emitted to the atmosphere.
2. The introduction of BAT reduces the quantities of one or more air pollutants released by the typical industrial installation and therefore the group of installations that is modeled through this typical unit. These environmental changes associated with the implementation of each particular BAT are calculated.
3. The resulting external environmental benefits due to the introduction of BAT in one typical installation/industrial sub-sector are the sum of the products of the mass of the air pollutants reduced due to the implementation of the BAT with the corresponding damage values per mass unit estimated in step 1, provided that the exit conditions of the air pollutants from the stack are not altered.

3. Application

3.1. An overview of industrial activities in Athens and BAT examined

The methodological framework described previously was implemented in the greater Athens area where approximately 9200 industrial units are located constituting the 44% of the total number of industrial units in Greece and contributing 38% of the total gross value added by this sector nationally. Industrial sectors and installations are diverse, varying from small handicraft shops up to large industrial units (e.g. refineries, iron and steel plants etc.) out of which, approximately 800 are legally characterized as of 'medium and high environmental burden'. According to recent legislation (Law 3325/2005), all these units have to apply BAT within the next 4 years and switch to natural gas when their connection to the gas pipeline network becomes technically feasible.

On the basis of data and environmental factors collected in the framework of a recent project (Epem et al., 2001), it has been estimated that the 800 industrial installations identified as being of high and medium environmental burden emit approximately 3.1 kt PM_{10}, 17.4 kt SO_2, 6.0 kt NO_x, 28.0 kt VOC and 3.7 Mt CO_2 annually. These emissions constitute a significant part of the total quantities of air pollutants emitted in the greater area of Athens (Fig. 2a), corresponding to 57% for PM_{10}, 54% for SO_2, 41% for VOC, 29% for CO_2 but only 9% for NO_x, of the total emissions. Most of the rest is emitted by road transport.

The contribution of particular industrial sectors to the total emissions from industrial activities in the wider area of Athens is shown in Fig. 2b. The oil processing sector, comprising two major refineries located in the area and a number of smaller units producing asphalt products and mineral oils, is responsible for the majority of SO_2 (79.4%) and for half of NO_x and CO_2 emissions in Athens; its contribution to VOC emissions is also significant (29.8%) due to leakage from the fuel storage tanks located within the boundaries of the refineries. In addition to the VOC emissions from the tanks at refinery installations, fuel storage is responsible for a further 38% of total VOC emissions. Almost 67% of PM_{10} emissions comes from the sector of non-metallic minerals (cement, ceramics and lime), which emits also significant quantities of NO_x and CO_2 (34% and 33% of total emissions respectively). Considerable quantities of PM_{10} are also emitted by metal processing installations (13.6% of the total). Chemical industry installations generate emissions of limited scale except for VOC (9%), while the contribution of the rest sectors to air pollutants ranges from 6% of SO_x to 11% of VOC.

In the context of this study, approximately 900 individual BAT have been identified as applicable to the installations of the industrial sectors/sub-sectors in the greater Athens area. This number becomes much larger if combinations of BAT that are technically feasible are taken into account. A first screening based on effectiveness was carried out that reduced the number to about 340. This screening was also aided by the fact that a number of installations, in particular some large industrial units, where BAT are already in place so that further application of BAT is unproductive, were excluded from further BAT assessment. It is also noted that if some BAT are already implemented by the majority of the actual units, they are included in the description of the typical unit resulting in a corresponding reduction the total number of additional BAT combinations that can be implemented. The basic BAT categories analyzed in this study are: (i) the introduction of natural gas or other environmental friendly energy sources; (ii) the implementation of energy conservation interventions; (iii) the implementation of techniques for reducing wastewater

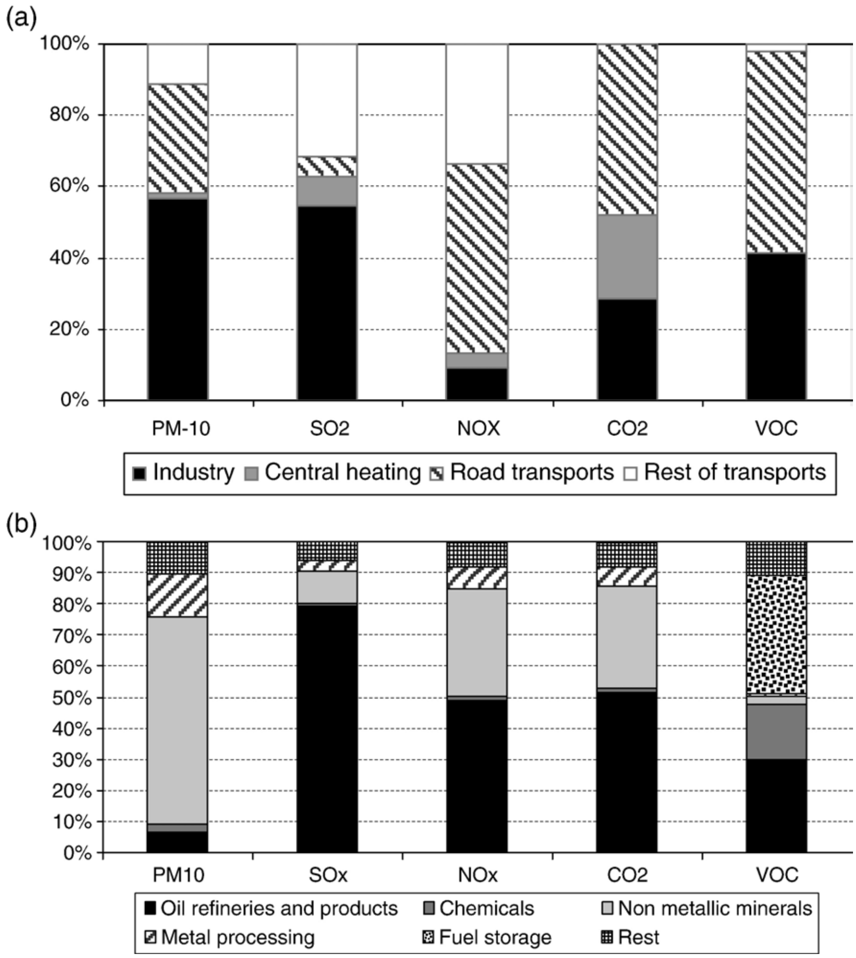

Fig. 2. Contribution of total emissions of air pollutants in the greater Athens area, disaggregated by (a) sector of economic activity and (b) sector/sub-sector of industrial activity.

quantities; (iv) the installation of end-of-pipe equipment for reducing air pollutants; (v) the re-organization of industrial processes; (vi) the exploitation of advanced technologies; (vii) the substitution of specific raw materials, etc.

3.2. Environmental externalities of industrial activities

The application of the methodological framework in the wider Athens area resulted in an estimate for the external cost attributed to the industrial air pollution of about 211 M€ per year. Of that 153 M€ (72% of total externalities) is due to emissions from stacks, while fugitive sources are responsible for the rest 58 M€ (28%). Of the total cost 43% is incurred at a local scale (i.e. in the greater Athens area due to increased concentrations of primarily PM_{10} and secondarily SO_2, CO and heavy metals), 26% at regional level (due to increased concentration of sulphates, nitrates, O_3, and PM_{10}), and the rest 31% at a global scale from the contribution of CO_2 emissions to climate change impacts.

As regards sectoral disaggregation of the total estimated external cost, Fig. 3a clearly shows that industrial activities of oil refineries and non-metallic minerals cause the most serious damages to the environment accounting for 34% and 48% respectively of the total external cost. It should be pointed out that these specific sectors include in the area under consideration some large installations (e.g. two refineries, two cement units, etc.), but also a significant number of smaller units, which produce ceramics, bricks, asphalt products, etc. In the case of the oil refineries sector, the major part of external costs incurred originate from stacks while non-metallic minerals show an approximately equal division of damages originating from point sources and from fugitive sources, because of the significant dust emissions from raw

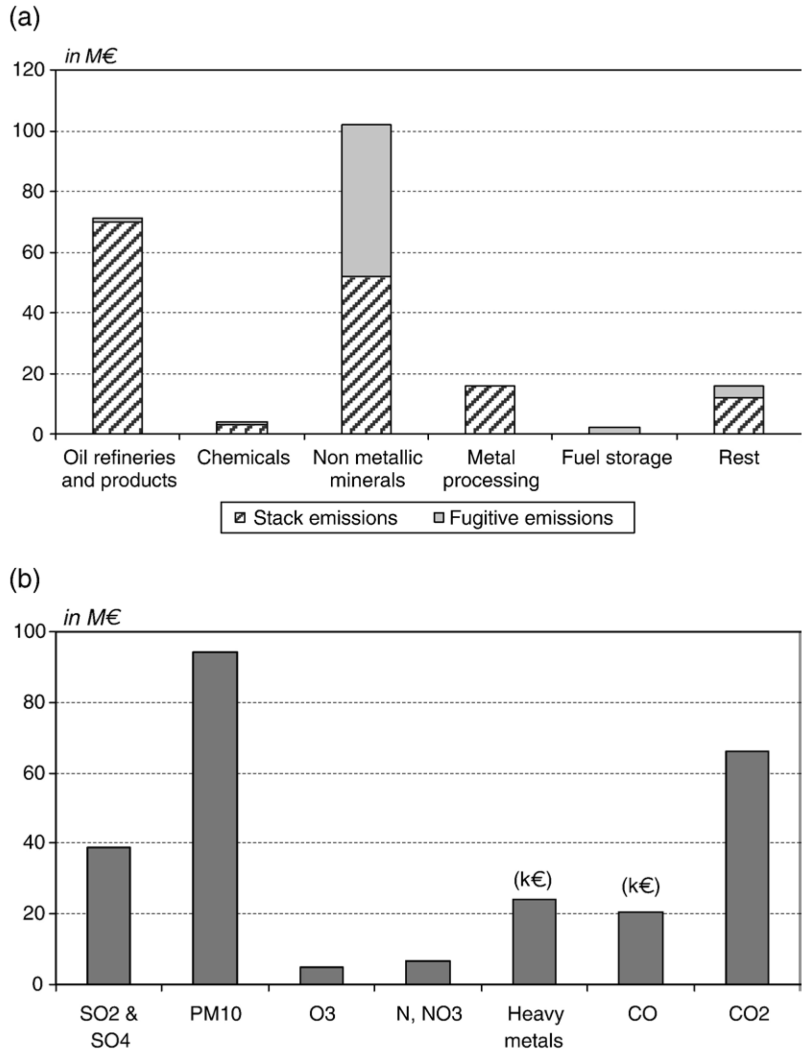

Fig. 3. External cost of emissions from industrial installation of medium and high environmental burden, located in the greater Athens area, by (a) sector and (b) pollutant. Note that, the external cost for CO and heavy metals in (b) is given in thousands rather than millions of €.

materials handlings and products storage in this sector. Metal processing activities are responsible for 8% of the total external cost, while the contribution from chemical industries and fuel storage is less than 3%. Finally, installations from the rest sectors generate emissions that result in about 7% of the total environmental external cost. As for air pollutants the major contribution to the total external cost due to air pollutants comes from PM_{10}, which are responsible for half of externalities associated with industrial activity in Athens reaching 94.3 M€ per year (Fig. 3b). Sulphur oxide and sulphates contribute 18.5% of the external costs that corresponds to 39 M€ annually and are primarily related with public health. Additionally, climate change damages from CO_2 reach almost 66 M€ per year or 31% of the total. Finally external costs due to nitrogen oxides — nitrates and ozone account for the rest and are much lower.

As shown in Fig. 4, damages to public health (increase of morbidity and mortality rates) and global warming are the effects that generate the major part of externalities associated with air pollutants emitted by industrial activities in Athens area. Specifically, impacts associated with mortality caused by particulates, SO_2, CO, heavy metals and the secondary produced aerosols (sulphates and nitrates) and O_3 account for the loss of approximately 1900 life years annually, which corresponds to 93.7 M€ per year, with morbidity effects adding another 48.3 M€ per year. In summary, the contribution of air pollution damages to public health is about 67% of the total estimated external cost mostly from recipients in the

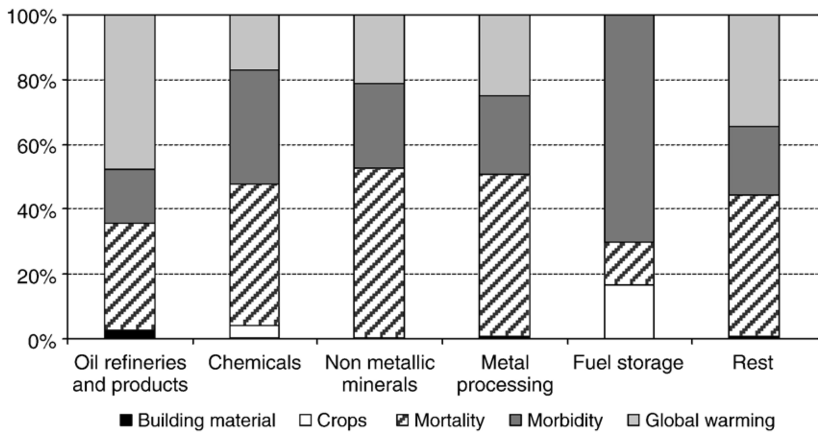

Fig. 4. Disaggregration of the total external cost estimates attributed to the air pollutants emitted by the various sectors of industrial installations located in the greater Athens area per impact category.

vicinity of the industrial installations. Global warming damages are 31% of the total external cost. Impacts on building material and crops represent less than 2%, which is explained by the fact that the area of interest is mostly urban with quite limited agricultural activity and by the fact that the positive impacts (benefits) of SO_2 and nitrogen deposition on plants moderate the negative impacts of O_3 on agriculture.

The total amount of estimated externalities attributable to industrial activities of ‘high and medium environmental burden’ that are located in the greater Athens area (i.e. 211 M€) represents 0.5% of the GDP and 4.1% of the Gross Value Added by industrial sectors in the reference area in 2000. These figures are even larger in real terms as the estimated externalities do not include: (i) the external costs of electricity that is consumed in the industrial units examined, (ii) the environmental damages from the additional 8400 small industrial units located in the area of interest, which are characterized by law as of ‘low environmental burden’ (since most of them use electricity to cover their energy needs), and (iii) specific impact categories that were not quantified in the context of the present analysis.

When the estimated external costs are expressed on a per mass unit of specific pollutant basis, released from all the typical units under consideration, a wide range of values results as shown in Table 5. In Fig. 5, this is further broken down focusing on unit external environmental cost from the emissions of PM_{10}, the most important pollutant from industrial sources of the relevant sectors. The estimated damages for PM_{10} range approximately from 8000 to 50,000 €/t PM_{10}, with the majority of typical installations falling in the interval 20,000–30,000 €/t PM_{10}. The spread of the unit price evident in Fig. 5, but also in Table 5 in general, is caused by the different technical characteristics of each typical installation (source type and characteristics of release including if applicable height and diameter of stack, volume and temperature of flue gases at the exit of the stack, geographical location) and is seen to be considerable for some sectors.

3.3. Uncertainties

Despite the considerable progress made in the assessment of environmental externalities, the accounting procedure still involves many uncertainties introduced in each step of the IPA. Specifically, limited availability of data on the performance of the technology used in installations and on actual emissions combined with dispersion modeling parameterization introduces uncertainty in the level of environmental burdens and their

Table 5
Variation of the estimated external costs per unit mass of pollutants released from the industrial sectors/sub-sectors in the greater Athens area

Pollutant	External cost (€/t pollutant)		
	Minimum value	Weighted average	Maximum value
PM_{10} (stack)	8018	23,721	42,139
PM_{10} (fugitive)	21,502	38,932	49,563
SO_2	1926	2252	27,722
NO_x	−2872	1321	16,202
NMVOC		195	
CO_2		18	
CO	1.5	3.7	10.8
As	3455	6651	24,880
Cd	2077	5981	15,098
Ni	461	877	3324
Cr	92605	93042	249,239

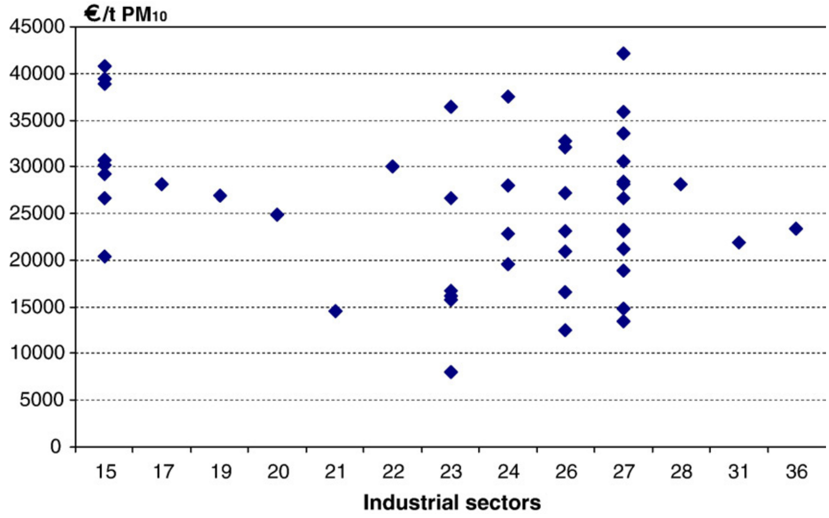

Fig. 5. External environmental cost from PM_{10} emissions per industrial sector/sub-sector from the medium to high environmental burden installations in greater Athens area per mass unit of PM_{10} released (in €/t PM_{10}). The code numbers of the industrial sectors correspond to: 15 — food & drinks, 17 — textiles, 19 — leather tanning, 20 — wood processing, 21 — paper and pulp, 22 — printing, 23 — petroleum industry, 24 — chemical industry, 25 — plastic products, 26 — non-metallic minerals, 27 — metal processing, 28 — electroplating, 31 — batteries and 36 — furniture.

spatial distribution, inadequate knowledge of receptor size hinder the precise estimation of the type and intensity of the associated environmental impacts and questions on the accuracy and local applicability of exposure-response functions add to the uncertainty. It is worth mentioning that uncertainties are different for different pollutants (e.g. for secondary pollutants the uncertainties of chemical reactions need to be considered) and for different impact categories for each pollutant (subject to the availability and reliability of the corresponding epidemiological studies). Also, the monetization of the estimated environmental impacts which is associated with subjective factors and policy or ethical choices defining the human attitude with respect to the valuation of the non-marketed goods further increases the possible uncertainty. In addition, the concept of "typical installation" and the resulting aggregation of releases adopted in this study increases the uncertainties of the calculation framework, since it assumes that the release of air pollutants from the industrial activities occurs in representative locations (i.e. the location of the corresponding typical unit) rather than from the actual geographical site of each industrial unit.

To address this, Rabl and Spadaro (1999) proposed a quantitative analysis, which assumes that the environmental impacts and damages follow a lognormal distribution and as a result the uncertainty associated with the externalities caused by air pollutants can be described through a geometric standard deviation (σ_g). Then, if a 68% confidence interval is assumed, the total external cost of industrial air pollution will range in the interval:

$$\left(\frac{\mu_g}{\sigma_g}, \mu_g \cdot \sigma_g\right) \qquad ((1))$$

where μ_g is the median value (=geometric mean for lognormal distribution) of the external costs under consideration, which can be obtained from the mean value (μ) resulting from the IPA, via the following equation:

$$\mu/\mu_g = \exp[0.5 \cdot (\ln\sigma_g)^2] \qquad ((2))$$

As the geometric standard deviation (σ_g) of the externalities under consideration is estimated by the uncertainties of each step of the pathway analysis, it would vary on the basis of the pollutant considered, the impact category analyzed, the unit monetary value used, etc. (for an analytical discussion see European Commission, 2005b). As an example, for mortality damages, which were found to be the most significant external cost component associated with the industrial air pollution, geometric standard deviations are estimated to be 2.65 for primary PM, 3.13 for SO_2 via sulphates and 3.26 for NO_x via nitrates (European Commission, 2005b).

It is out of the scope of this paper to undertake an analytical estimation of the uncertainties associated with the adopted methodological framework. However, in view of the individual estimates mentioned above and in an attempt to provide at least an initial assessment of the uncertainty a value of 3 was chosen for the geometric

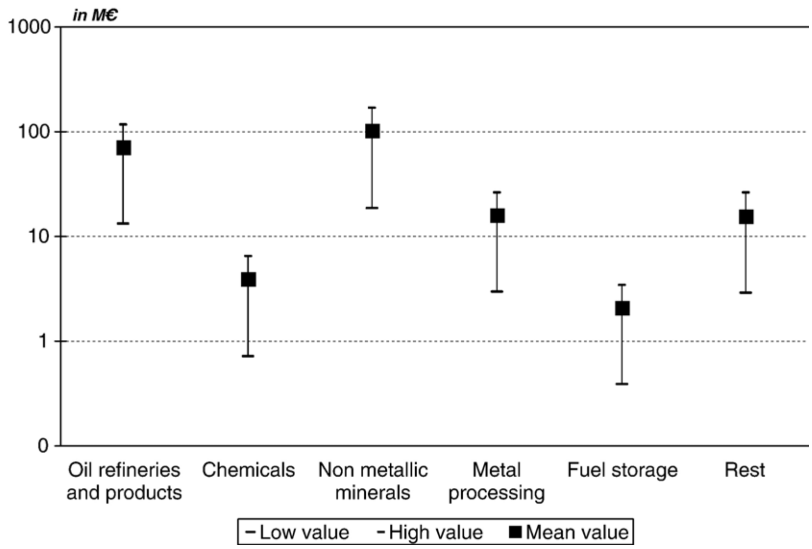

Fig. 6. An estimation of the uncertainties associated with the external cost of emissions from industrial installation of medium and high environmental burden, located in the greater Athens area.

standard deviation (σ_g) for the total externality value estimated for each industrial sector/sub-sector. The resulting range interval for the external cost estimated for each industrial sector/sub-sector in Athens area, is shown in Fig. 6. The total external cost attributed to the industrial air pollution in Athens could be ranging between a high value of 346 M€/year and a low of 39 M €/year. It should be underlined that this is only a rough and indicative estimation of the uncertainties associated with the calculation framework implemented in this study, as it does not differentiate between uncertainty factors for different pollutants and different impacts and does not include the additional uncertainties introduced through the 'typical installation' approach.

3.4. External benefits from BAT introduction

As already mentioned previously, according to a recent law (Law 3325/2005), all industrial units that are located in the wider Athens area and are legally characterized as of 'medium and high environmental burden', have to apply BAT within the next 4 years, thus extending substantially (i.e. from 45 to 802 installations) the field of application of the IPPC Directive. The environmental externalities of BAT are considered to be an essential element in the evaluation of alternative techniques, as suggested by the relevant BREF of the IPPC on the economics and cross-media effects of BAT (European Commission, 2005a). In the context of this study we have assessed at a sectoral

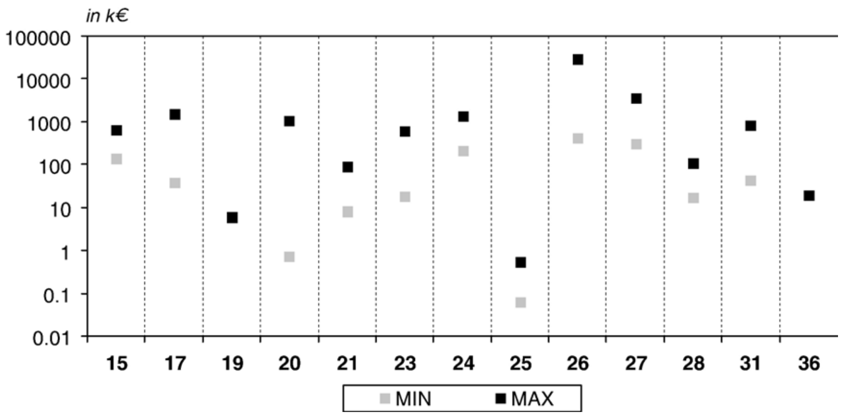

Fig. 7. Range of external benefits due to BAT implementation on the installations of medium and high environmental burden located in the greater Athens area. The code numbers of the industrial sectors correspond to: 15 — food & drinks, 17 — textiles, 19 — leather tanning, 20 — wood processing, 21 — paper and pulp, 22 — printing, 23 — petroleum industry, 24 — chemical industry, 25 — plastic products, 26 — non-metallic minerals, 27 — metal processing, 28 — electroplating, 31 — batteries and 36 — furniture.

level the environmental externalities of 342 different BAT combinations that could be implemented in the industrial installations located in the wider Athens area. Fig. 7 gives an overall picture of the range interval of these externalities for all the industrial sectors analyzed, while Table 6 presents those BAT combinations that result in the most significant environmental benefits in each industrial sector/sub-sector in the wider Athens area. It should be noted that the variation of external benefits in each industrial sector/sub-sector is exclusively attributed to the different BAT combinations and does not take into account the potential uncertainties presented in Section 3.3.

The most significant external benefits are expected from BAT implementation to the sectors of non-metallic minerals and metal processing, especially because of the fact that the respective BAT combinations perform well in reducing PM_{10}, which impose risks on and cause serious problems to human health and natural environment. In addition, these sectors comprise large industrial units that also present a high emissions reduction potential. By implementing, in each industrial sub-sector or group of installations examined, the BAT combination that maximizes the environmental gains, the overall external benefits attributable to the introduction of BAT in the industrial activities in the wider Athens area could reach 39 M€/year. BAT or combinations of BAT that contribute substantially to the maximization of the total external benefits (by 19%, 46%, 19% and 10% respectively) are the following: a) natural gas implementation, b) natural gas in combination with abatement techniques, c) good housekeeping and abatement techniques and d) techniques for wastewater minimization and

Table 6
BAT or combinations of BAT that maximize the external benefits due to their implementation on the installations of medium and high environmental burden located in the greater Athens area

Industrial sector/sub-sector		BAT or combination of BAT that maximize external benefits
15	Food and drinks	▪ Natural gas and cooling system (technique for wastewater minimization)
		▪ Natural gas and closed CIP (Clean-In-Place) system for cleaning equipment
		▪ Natural gas, cooling system and CIP system
17	Textiles	▪ Natural gas and recycling in dyeing processes
		▪ Natural gas, recycling of rinsing baths and printing pastes
		▪ Good housekeeping and recycling in dyeing processes
19	Leather tanning	▪ Good housekeeping
		▪ Good housekeeping and control techniques for water use (e.g. valves, flow gauges)
20	Wood processing	▪ Good housekeeping, spraying technique (in finishing) and bag filter (in drying)
		▪ Good housekeeping, scrubbing and bag filter (in drying)
		▪ Good housekeeping, total enclosure (in finishing) and abatement techniques (e.g. biofilter, bag filter)
21	Paper and pulp	▪ Natural gas
		▪ Specific compression techniques (nip press or shoe press)
23	Petroleum industry	▪ Natural gas
		▪ Good housekeeping
		▪ Natural gas, wastewater reuse and scrubbing
24	Chemical industry	▪ Good housekeeping, procurements scheduling (based on production) and water-based products
		▪ Good-housekeeping, closed vessels and biofilters
		▪ Natural gas
25	Plastic products	▪ Natural gas and closed vessels
		▪ Natural gas
		▪ Natural gas and spraying (in casting)
26	Non-metallic minerals	▪ Good housekeeping and wet scrubbing
		▪ Good housekeeping and bag filter
		▪ Natural gas
27	Metal processing	▪ Natural gas, bag filter and electrostatic precipitator
		▪ Natural gas and afterburning
		▪ Natural gas and bag filter
28	Electroplating	▪ Natural gas and wet scrubbing
		▪ Natural gas, bag filter, cyclone and biofilter
		▪ Natural gas, cleaning water recycling, bag filter, cyclone and biofilter
31	Batteries	▪ Natural gas and bag filter
		▪ Natural gas
		▪ Good housekeeping
36	Furniture	▪ Good housekeeping
		▪ Good housekeeping and scrubbing
		▪ Good housekeeping, total enclosure and biofilter

abatement techniques. It is obvious that the substitution of mainly oil products with natural gas is of primary importance to achieving the significant environmental benefits estimated above. In recognition of this, significant economic incentives are provided to industrial installation operators to implement such fuel switching and expansion of the NG distribution network is given high priority.

Viewed sector by sector, BAT effectiveness varies. For installations producing ceramics and bricks and tiles, the combined use of natural gas and wet scrubbing systems gives significant profits, while energy conservation measures ("good house-keeping") such as pipe insulation seem to be less profitable. This latter technique is likely to also result in lower environmental benefits for cement and lime installations but the penetration of natural gas per se, the combination of natural gas and end-of-pipe technologies, and also the combined use of selective non-catalytic reduction systems (SNCR) and energy conservation measures could be quite effective in environmental terms. For steel processing installations significant benefits arise from techniques related to optimization of furnace operation in combination with end-of-pipe technologies. In addition, for secondary metal production and metal foundries, maximum external benefits result from use of natural gas combined with the use of cyclone scrubbers or fabric filters, while the introduction of simple horizontal techniques (e.g. house-keeping) looks less effective. For units that produce food and batteries, natural gas penetration or the combination of natural gas penetration with abatement techniques could result in maximization of the external benefits. Respectively, natural gas and techniques related to wastewater minimization (through recycling, etc.) provide significant environmental profits in the textile manufacturing sector where though good housekeeping measures are not effective. In the wood processing sector, a wide range of benefits results from BAT application, with dust abatement from wood drying presenting the most benefits. The implementation of energy conservation measures in leather tanning and furniture manufacturing installations seems also quite profitable. For units producing paper, the maximum environmental benefits emanate from the use of natural gas despite the already significant natural gas penetration in the sector. Due to the large number and differentiation among units that belong to oil refineries & products and chemical industry, it is quite difficult to decide the choice of effective BAT that contributes to external benefits maximization. Finally, the plastic products and electroplating activities contribute very limited amounts to the environmental burdens and consequently the emissions reduction potential is likely to be quite limited.

4. Concluding remarks

In this work, the IPA for estimating the environmental externalities associated with air pollution emitted by an industrial installation has been modified to cover the numerous industrial activities of 'medium and high environmental burden' located in the greater Athens area by introducing the concept of typical installation, appropriately defined taking into account common features of the majority of units. This typical installation approach and the estimation of externalities at group of installations level, seems to be an effective tool for generating aggregated results including those that accrue from the introduction of BAT, which are particularly important for decision-making at a sectoral/regional level.

Attributing monetary values to environmental improvements, associated with the realization of BAT, seems to form a powerful tool for incorporating environmental and social issues in the decision-making process. Specifically, expressing all costs and benefits (whether private or external) into a common measuring unit (i.e. monetary value), provides the advantage of using a single measure of the attractiveness of an alternative option, compared to other assessment techniques such as multi-criteria analysis, etc. The evaluation of the various BAT on the basis of an integrated cost benefit analysis, can bring out the difference in rank, highlighting those policy actions that minimize the financial cost and maximize the social welfare. Furthermore, the estimation of net external benefits associated with the implementation of each of the examined interventions shows an indicative picture of the level of subsidies that can be implemented as a means of promoting the corresponding BAT.

The results of the analysis clearly show that external costs associated with industrial activities located in the wider Athens area are very high and amount to 211 M€ per year, representing 0.5% of the GDP and 4.1% of the Gross Value Added by the industrial activities in the area of interest in 2000. These externalities are associated mainly with human mortality and morbidity primarily due to PM_{10} emissions, as well as with climate change impacts due to CO_2 emissions. Non-metallic minerals and oil processing industries are the main sources of these environmental burdens and thus constitute the main contributors to the total environmental damages attributed to industrial air pollution.

Based on these findings, an effective environmental policy in the industrial sector of the wider Athens area should focus mainly on interventions that reduce PM_{10} and CO_2 emissions particularly in the sectors of non-metallic minerals and metal processing, without of course ignoring the rest of pollutants and industrial sectors/sub-sectors. It is also important to note that since nearly half of the total external cost is incurred at a local scale due to increased concentrations of primarily PM_{10} and secondarily SO_2, CO and heavy metals, a more detailed analysis is required with a finer geographic resolution so as to capture better the differences in population density, the effect of topography, the impact on sensitive segments of population and buildings of high value, thus leading to more accurate estimates of environmental externalities, which can be of great value to policy makers.

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