Regional optimization of air pollution in Greece via input-output analysis

D. Hristu-Varsakelis[a*], S. Karagianni[b], M. Pempetzoglou[c], A. Sfetsos[d]

[a] Department of Applied Informatics, University of Macedonia, 156 Egnatia St., Thessaloniki 54006, Greece, dcv@uom.gr

[b] Department of Economics, University of Macedonia, 156 Egnatia St., Thessaloniki 54006, Greece, stelkar@uom.gr

[c] Department of Social Administration, Democritus University of Thrace, 1 Panagi Tsaldari St., Komotini, 69100, Greece, mariap@socadm.duth.gr

[d] Environmental Research Laboratory, INT-RP, NCSR Demokritos, Patriarhou Grigoriou, Agia Paraskevi, 15310, Greece, ts@ipta.demokritos.gr

Abstract

This paper explores the use of a multi-region input-output based model for optimizing production on a per-sector basis, while taking into account regional environmental constraints on air pollution and economic impact. The basic model, informed by recently published empirical and environmental data for Greece (which is partitioned into five regions), is used to accomplish two things. First, we determine the regional economic impact of reducing each of a set of major air pollutants (including particulates, and gasses that contribute to global warming and acidification). This is done by solving an optimization problem where we ask to maximize regional GVP subject to constraints on energy use, final demand, and air pollution. Second, we explore the effects on the national and regional economies from localizing environmental policy to target the pollutant deemed most problematic in each region. Our analysis considers two pollution reduction scenarios which entail a 9% and 4.5% reduction, respectively, in the volume of each region's "priority" pollutant.

Depending on the pollutant under consideration, our analysis suggests that significant reductions may be possible with minimal effect on the regional or national gross value of production. Moreover, depending on the level of reductions sought, regulating a single pollutant may be sufficient to induce reductions in other pollutants as well, leading to more concise environmental policies. More specifically, at the aggregate level, the most intense fluctuations in both economic and environmental variables are observed under the more restrictive (9%) scenario. At the sectoral level, under both scenarios, secondary production sectors are subject to the most significant reductions in all regions, in contrast to the tertiary production sectors which are favoured the most by the optimal solution.

JEL codes: Q51, C67, Q53.
Keywords: optimization, input-output models, air pollution, Greek economy.

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[*] Corresponding author. Tel.: +30-2310-891721, Fax: +30-2310-891290

1. Introduction

During the last two decades, academic research has contributed to a steady raising of awareness with respect to the impact of economic activity on the environment. Two of the themes that feature prominently in that effort include: i) studying the "channels" through which the economy alters the environment (e.g., intermediate byproducts, pollution associated with production and consumption), and ii) quantifying the (sometimes global) environmental consequences of a regional economy together with the infrastructure required to support it. The growing realization that the environmental effects of the economy can no longer be safely ignored has placed the environment-economy link firmly in the agenda of most nations, and in some cases has led to important global initiatives, such as the Kyoto Protocol.

This work considers the regional environmental effects of economic activity in Greece and explores the problem of restructuring production on a regional basis, taking into account local priorities such as the air pollutant(s) that affect each area most significantly. Greece, which has long struggled with environmental management issues including solid waste, water and air pollution, has a history of a "one-size-fits-all" centralized approach to policy-making. This may be adequate for certain pollutants with global impact, such as greenhouse gasses (GHG). However, other air pollutants regulated under EC Directives (e.g. Directive 2008/50/EC on ambient air quality and cleaner air for Europe), including ozone, particulate emissions and emissions contributing to acidification, tend to have "local" effects, in the sense that their greatest impact is felt in areas near the source. As a result, policy that addresses such "localized" pollutants should take into account regional differences in concentrations, as well as the economic impact of reducing emissions.

We explore an input-output (IO) based optimization problem for restructuring production on a per-region and per-sector basis, in order to quantify the macroeconomic and sectoral effects that arise (both regionally and nationally) by attempting to satisfy air quality targets. Our approach is based on combining the input-output model by Hristu-Varsakelis et al. (2010) with recently available data on Greece's regional air pollution (Economidis et al. 2011). The basic model is adapted to a multi-region setting in order to maximize an (regional or national) economy's Gross Value of Production (GVP) subject to regional constraints on energy use, final demand, and air pollution. What is described here may be viewed as a computational tool for decision support and for asessing environmental policy before it is implemented. We are specifically interested in a) determining the regional economic impact of four major air pollutants (e.g., find which are "cheapest" to reduce in terms of GVP), and b) exploring policy scenarios in which each region optimizes its production while reducing a single pollutant which it considers most problematic according to some criterion which is to be specified. Among the issues this work is concerned with is whether regional environmental policies should actively address multiple pollutants, or whether simpler policies that focus on a single target pollutant could have the same effect.

The model used here is based on Leontief's analysis (Leontief and Ford, 1972) and is calibrated with empirical data for Greece. These consist of regional environmental IO tables, which were obtained by downscaling existing country-level data, and are used to capture the production characteristics of each region and their linkages to air pollution. IO analysis is used to allocate production of air pollutants to the various sectors of each region’s economy, to account for the interdependence of sectors with respect to changes in final demand, and to link pollution and energy usage to economic production on a sectoral and regional basis. We have chosen the IO approach mainly because of our interest in accounting for the intersectoral couplings previously mentioned, and because of a lack of the empirical data needed to support more complex models (such as CGE, for example).

The remainder of the paper is structured as follows. Section 2 contains a brief literature review covering multi-region input-output models. Section 3 discusses the data sources used in this work. A multi-region input-output model for Greece is discussed in Section 4. In Section 5 the model is used to calculate the regional economic importance of four major air pollutants, and to explore the consequences of two policy scenarios that involve meeting regional pollution reduction targets.

2. Related Work

Regional input-output models were originally introduced in Miller and Blair (1985); however, their practical use was severely impaired at the time, due to lack of the required statistical data. An extensive discussion on the construction of regional and interregional input-output tables can be found in Boomsma and Oosterhaven (1992), and Lahr (1993). Several authors have discussed the issue of downscaling national coefficients to the regional level using differences in production levels and composition of activities in the regional economy (e.g. Richardson, 1985; Flegg et al., 1995; McCann and Dewhurst, 1998). Turner (2006) identified consumption behaviour and production technology as two key indicators for downscaling national data so as to minimize loss of information. Jiang et al. (in press) compared the performance of different approaches for constructing regional IO tables using cross-regional methods. That work employed existing non-survey methods, building and updating the coefficients of a single IO table based on regression analysis. A comparison of 27 regional IO tables from China in 1997 and 2002 indicated that data volume and quality, as well as the volatile nature of the economy in rapidly growing regions, are important factors to consider when developing the regional tables.

Multi-region input–output (MRIO) models allow for the integration of inter-sectoral connections (in monetary terms) with multiple environmental data, so that environmental impacts can be accurately and comprehensively reflected in production profiles (Wiedmann, 2009). The application of MRIO models in problems of environmental interest is an emerging area, with the majority of the recent literature focusing on determining the impact of pollution from trade (e.g., Chung and Rhee, 2001; Nijdam et al., 2005; Wiedmann et al., 2009). Ahmad and Wyckoff (2003) estimated the percent contribution of emissions due to trade to be approximately 14% in OECD countries. Separate works by Lenzen et al. (2004) and Peters and Hertwich (2004) introduced a consistent theoretical framework for MRIO analysis for the purpose of calculating pollution from trade in the receiving economy. A central conclusion of the SKEP-ERA network[1] is that MRIO analysis is a promising methodology for accounting for trade-related impacts from a consumption perspective, forming a robust basis upon which more detailed methods may be built (Wiedmann et al., 2009).

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[1] http://www.skep-network.eu

There are a limited number of works applying input-output analysis in an interregional setting within a country, while at the same time addressing the economy’s environmental impact. Bertini and Paniccià (2008) augmented an existing interregional IO table for Italy (20 regions) with data for air pollution emissions, such as Global Warming Potential (GWP) and Potential Acid Equivalent (PAE). That work examined the discrepancies in environmental efficiencies between regions as well as the environmental impact of interregional economic activity. Liang et al. (2007) divided China into eight economic regions and established an MRIO model for energy requirements and CO_2 emissions. Hallegatte (2008) used IO tables to investigate the consequences of hurricane Katrina and the subsequent reconstruction phase. Recently, IO analysis has been used to set priorities for environmental policy and in particular policies addressing consumer products. Two of the relevant studies addressing the environmental impact of production and consumption sectors are the Environmental Impacts of Products (EIPRO) study which has been very influential in shaping EU product policy (Tukker et al., 2009), and Larsen and Hertwich (2010) which applied a carbon-footprint–based calculation tool to Norwegian municipalities in order to improve the local GHG inventory.

3. Data and methodology

This section discusses the empirical data that will be used to calibrate the optimization model to be formulated shortly. They consist of i) regional economic data, including the Greek regional IO matrices, from which one can calculate the effect of a change in production in any one sector on the remaining ones as regional GVP is maximized, ii) data on energy consumption by each sector, and iii) data on air pollution. The economic and environmental data used here[2] are referenced to year 2005 levels which will thus be considered as the “baseline” for all comparisons made in the sequel. In the following, Greece’s regional structure is described, and each set of data is discussed briefly.

Greece is formally partitioned in five regions (shown in Figure 1), in a way which is consistent with the European National Strategic Reference Framework (NSRF) 2007-2013 (Skountzos and Stromplos, 2007). The five regions correspond to five Regional Operational Programmes (ROP): 1) Aegean islands and Crete, 2) Macedonia and Thrace, 3) Attica, 4) Western Greece, Peloponnese and Ionian islands and 5) Thessaly, Epirus and Mainland Greece. For simplicity, the five regions will henceforth be referred to by number. Regional

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[2] All figures are available upon request from the authors but are not included here because of space considerations.

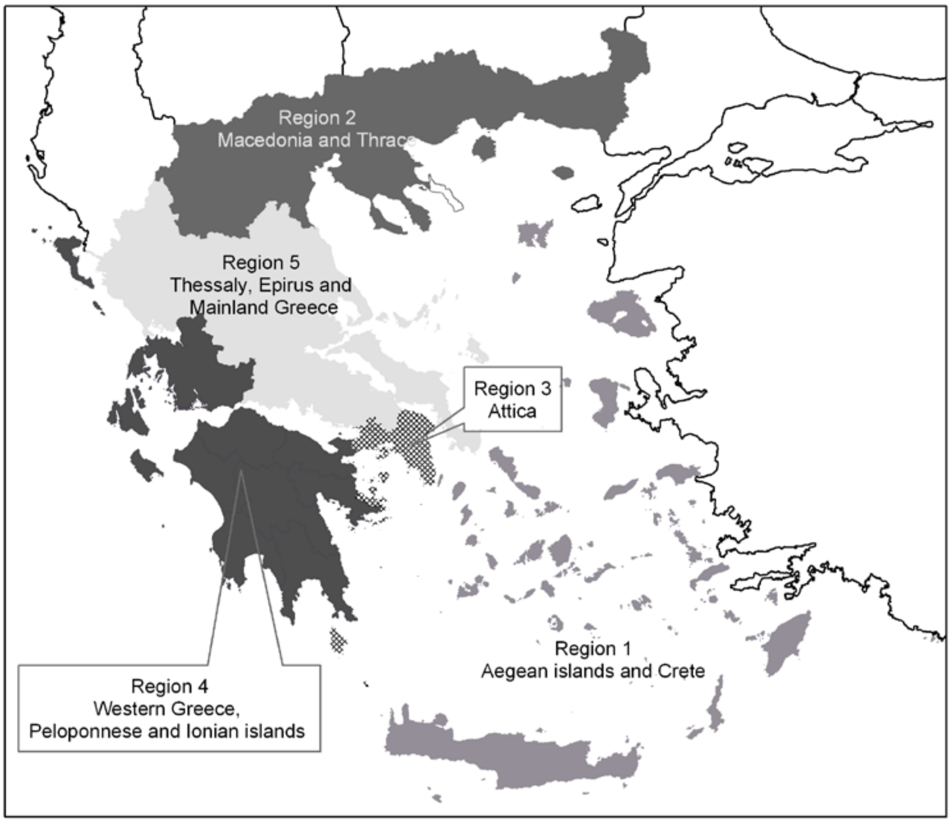

Figure 1. Regional map of Greece.

IO tables for the Greek economy were obtained from the study by Skountzos and Stromplos (2007), which used data from the National Statistical Service of Greece (NSSG). The tables include regional data for 26 sectors, corresponding to the Classification of Economic Activities in the European Community (NACE) codes, listed in Table A1 in the Appendix. Sector 26 (recreational, cultural and sporting activities, activities of households, extra-territorial organizations) was excluded from the analysis that follows, because the economic activities contained therein are outside the scope of this study. Energy consumption data for the Greek economy were obtained from the Eurostat and PRODCOMS3 databases, the Greek Ministry of Development[4,] and the United Nations Production Statistics[5]. That data were assigned

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[3] http://epp.eurostat.ec.europa.eu/portal/page/portal/prodcom/introduction
[4] http://www.cres.gr/kape/pdf/datainfo/2005_gr.pdf
[5] http://unstats.un.org/unsd/industry/

to the economy's individual sectors using factors (production and activity data) derived from those databases.

The main source of air pollution data was the Greek National Accounting Matrix with Environmental Accounts (NAMEA) from Economidis et al. (2008). The NAMEA is structured in a composite matrix format that reconciles supply-use tables and sectoral accounts into a comprehensive accounting framework (de Haan and Kee, 2004). The economic accounts in the NAM-part of the NAMEA contain the complete set of accounts in the System of National Accounts (SNA). The environmental accounts in the NAMEA are denominated in physical units and focus on the consistent presentation of material input of natural resources, i.e., energy demand and output of residuals for the national economy; in this work, the latter are GHG contributing to global climate change and measured via the Global Warming Potential (GWP) index, pollutants contributing to acidification (ACID), Tropospheric Ozone Forming Potential (TOFP), and particulate emissions smaller than 10 micron (PM10) (Mylonas et. al., 2000). The first three residuals are calculated as follows:

$$\begin{aligned} \mathrm{GWP} &= \mathrm{CO_2} + 310 * \mathrm{N_2O} + 21 * \mathrm{CH_4} \\ \mathrm{ACID} &= \mathrm{SO_2} + 0.7 * \mathrm{NO_x} + 1.9 * \mathrm{NH_3} \qquad (1) \\ \mathrm{TOFP} &= \mathrm{NMVOC} + 1.22 * \mathrm{NO_x} + 0.11 * \mathrm{CO} + 0.014 * \mathrm{CH_4}\,, \end{aligned}$$

where NMVOC stands for "non-methane volatile organic compounds".

An analysis of these environmental stressors and their decomposition on a regional scale are described in detail in Economidis et al. (2011). The breakdown of national-level data to the regional level took into account Large Pollution Sources (LPS), based on data from the European Pollutant Emission Register (EPER) for Greece. Briefly, LPS were "placed" in their respective regions based on existing geo-referenced information. Emissions from LPS were then deducted from the country's total values; the remaining amounts were allocated to each region using relative production levels as percentage attribution factors.

4. Model and Main Optimization Problem

In this section we formulate an optimization problem where production is to be maximized regionally and on a sector-by-sector basis, subject to energy and pollution constraints. The model described here is from Hristu-Varsakelis et al (2010), and is presented mainly for the sake of completeness, before being applied to a multi-region setting.

Consider an economy with n sectors and k geographical regions (k=5 for Greece). For any given region, the standard linear input-output model (Leontief, 1966) is given by:

$$\boldsymbol{x}=\mathbf{X}\boldsymbol{u}+\boldsymbol{y}-\boldsymbol{m} \tag{2}$$

where $\boldsymbol{x} \in R^n$ stands for the region's GVP vector, $\mathbf{X}$ is the region's nxn intermediate input-output matrix, $\boldsymbol{u} = [1,\ldots,1]'$ with prime denoting transpose, $\boldsymbol{y}$ is the final demand vector, and $\boldsymbol{m}$ are imports. Technical coefficients are calculated as the ratio of each element of the intermediate input-output matrix to the total output of the corresponding activity branch:

$$A_{ij} = X_{ij} / x_j, \qquad i, j = 1,...,n. \tag{3}$$

Observe that (3) can be written as $\mathbf{X}=\mathbf{A}\cdot\mathrm{diag}(\boldsymbol{x})$ (where diag($\boldsymbol{x}$) denotes the diagnoal matrix formed from the elements of the vector $\boldsymbol{x}$), which implies that $\mathbf{X}\boldsymbol{u}=\mathbf{A}\boldsymbol{x}$. Thus, the basic model can be expressed as:

$$\boldsymbol{x} = \mathbf{A}\boldsymbol{x} + \boldsymbol{y} - \boldsymbol{m} \Rightarrow (\mathbf{I} - \mathbf{A})\boldsymbol{x} = \boldsymbol{y} - \boldsymbol{m}. \tag{4}$$

Summing the total intermediate inputs at basic prices, $\mathbf{X}'\boldsymbol{u}$, tax revenues, $\boldsymbol{t}$, subsidies, $\boldsymbol{s}$, VAT revenues, $\boldsymbol{v}$, and the gross value added (GVA), $\boldsymbol{g}$, for each sector, one obtains the GVP vector as:

$$\boldsymbol{x} = \mathbf{X}'\boldsymbol{u} + \boldsymbol{t} + \boldsymbol{s} + \boldsymbol{v} + \boldsymbol{g} = \boldsymbol{x}_{\boldsymbol{T}} + \boldsymbol{g}, \tag{5}$$

with the sum of the first four variables being the value of total inputs in market prices, $\boldsymbol{x}_{\boldsymbol{T}}$. The GVA is obtained indirectly by subtracting the value of total inputs in market prices from the gross value of production:

$$\boldsymbol{g} = \boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{T}}. \tag{6}$$

Subsidies are assumed to be exogenously determined and remain constant, while tax, $\boldsymbol{t}$, and VAT revenues, $\boldsymbol{v}$, are calculated as ratios of total intermediate inputs in basic prices:

$$\boldsymbol{t} = \text{diag}(\boldsymbol{a}_{\boldsymbol{T}})\mathbf{X}'\boldsymbol{u} = \text{diag}(\boldsymbol{a}_{\boldsymbol{T}})\text{diag}(\boldsymbol{x})\mathbf{A}'\boldsymbol{u} \tag{7}$$

$$\boldsymbol{v} = \text{diag}(\boldsymbol{a}_{\boldsymbol{V}})\mathbf{X}'\boldsymbol{u} = \text{diag}(\boldsymbol{a}_{\boldsymbol{V}})\text{diag}(\boldsymbol{x})\mathbf{A}'\boldsymbol{u}, \tag{8}$$

where $\boldsymbol{a}_{\boldsymbol{T}}$ and $\boldsymbol{a}_{\boldsymbol{V}}$ stand for the (constant) technical coefficients between tax and VAT revenues, respectively, and total intermediate inputs in basic prices.

The four air pollutants discussed in Section 2 (GWP, ACID, TOFP and PM10) are assumed to be emitted in quantities which are directly proportional to the total output of the corresponding sectors. Thus,

$$\boldsymbol{p}_{\boldsymbol{j}} = \text{diag}(\boldsymbol{a}_{\boldsymbol{j}})\boldsymbol{x} \tag{9}$$

will denote the vector of per-sector emissions of pollutant j=1,…,4, where $\boldsymbol{a}_{\boldsymbol{j}}$ is a vector containing the corresponding emission coefficients. The $\boldsymbol{a}_{\boldsymbol{j}}$ are taken to be constant, assuming a constant technical relationship between pollution variables and total output. A similar relation is also assumed between energy consumption, $\boldsymbol{c_e}$, and GVP,

$$\boldsymbol{c_e} = \text{diag}(\boldsymbol{a_e})\boldsymbol{x}, \tag{10}$$

where $\boldsymbol{a_e}$ is a vector of energy coefficients. Finally, total emissions of a pollutant *j*, and total energy consumption are obtained by summing over all sectors:

$$P_j = \boldsymbol{a}_{\boldsymbol{j}}'\boldsymbol{x}, \quad j=1,\dots,4 \tag{11}$$

$$T_{\boldsymbol{Ce}} = \boldsymbol{a}_{\boldsymbol{e}}'\boldsymbol{x} \tag{12}$$

Equations (2)-(12) refer to the economy of a “generic” region, without specifying which one in particular. A superscript $^{(r)}$ will be used for that purpose, where $r=1,\dots,k$, so that for example, $\boldsymbol{x}^{(r)}$ will be the production vector in region *r*, $\boldsymbol{p}_j^{(r)}$ the vector of pollutant *j* emissions in region *r*, etc.

4.1 Optimization Problem

Based on the input-output model described above, we go on to formulate a pair of optimization problems in order to:

i) explore the effects of imposing pollution abatement targets locally (on a regional basis and considering each pollutant separately) on the maximum regional GVP that can be achieved. In effect, this will identify the pollutant that is the “cheapest” to reduce in each region, in the sense that it requires the least reduction in GVP for a given % reduction in emissions

ii) optimize the country’s total GVP (as the sum of the regional GVPs) for a given % reduction in emissions, if each region is allowed to choose which pollutant to reduce locally, based on criteria which will be discussed shortly.

4.2 Regional Economic Importance of each Pollutant

For r=1,...,5, consider the following linear programming problems:

$$\max_{\boldsymbol{x}^{(r)}} \ \mathrm{GVP}^{(\boldsymbol{r})} = \boldsymbol{u}'\,\boldsymbol{x}^{(r)} \tag{13}$$

subject to the constraints

***C1*:** $T_{Ce}{}^{(r)} = (\boldsymbol{a}_{\boldsymbol{e}}^{(r)})'\,\boldsymbol{x}^{(r)} \le e_u^{(r)}$, where $e_u^{(r)}$ is a (scalar) upper limit on energy used. This is to ensure that the only production vectors considered are those that do not exceed some energy usage threshold (e.g., 2005 levels).

***C2*:** $P_j^{(r)} = (\boldsymbol{a}_{\boldsymbol{j}}^{(r)})'\,\boldsymbol{x}^{(r)} \le b_j^{(r)}$, j=1,…,4, where $b_j^{(r)}$ is a (scalar) upper bound on emissions of pollutant j in region r. The four pollutants considered will be GWP, ACID, TOFP and PM10, in that order. The bounds $b_j^{(r)}$ will be “swept” over a range of values to determine the maximum GVP that can be achieved as a function of $b_j^{(r)}$.

C3: $\boldsymbol{u}'(\mathbf{I} - \mathbf{A}^{(r)})\boldsymbol{x}^{(r)} \ge \boldsymbol{u}'(\boldsymbol{y}_{\boldsymbol{l}}^{(r)} - \boldsymbol{m}^{(r)})$, where $\boldsymbol{u}'\,\boldsymbol{y}_{\boldsymbol{l}}^{(r)}$ is a lower bound on the total sum of demand met across all sectors of region r.

***C4*:** $0 \le \boldsymbol{x}_{\boldsymbol{l}}^{(r)} \le \boldsymbol{x}^{(r)} \le \boldsymbol{x}_{\boldsymbol{u}}^{(r)}$, where $\boldsymbol{x}_{\boldsymbol{l}}^{(r)}$, $\boldsymbol{x}_{\boldsymbol{u}}^{(r)} \in R^n$ are lower and upper bounds on production. The specific choices of upper and lower bounds will be addressed in the next section.

By solving (13) while gradually reducing the upper limit $b_j^{(r)}$ on a single pollutant at a time (while ignoring the others), one can obtain a (numerical) relationship between the maximum attainable regional GVP and the % reduction in pollutant j emissions. This will be taken up in Section 5 in order to identify the pollutant whose reduction has the lowest impact on GVP.

4.3 The effects of regional "autonomy" when it comes to reducing pollution

The effectiveness of pollution abatement policies which take into account regional characteristics (as opposed to addressing a single pollutant on a national level), may be assessed by posing the following problem:

$$\max_{\boldsymbol{x}^{(r)}} \text{ GVP} = \sum_{r=1}^{5} \boldsymbol{u}'\,\boldsymbol{x}^{(r)} \tag{14}$$

subject to the constraints

***C1'*:** $\sum_{r=1}^{5} T_{Ce}{}^{(r)} \leq \sum_{r=1}^{5} e_u^{(r)}$, meaning that the country's energy consumption should not exceed the sum of the upper bounds set in constraint *C1* above (e.g., 2005 energy usage),

***C2'*:** $P_j^{(r)} \leq b_j^{(r)}$, j=1,…,4, r=1,…,5, where $b_j^{(r)}$ is a (scalar) upper limit on emissions of pollutant j in region r. Structurally, the constraint is identical to *C2* above, however the bounds $b_j^{(r)}$ will be set based on each region's local priorities, to be discussed shortly.

***C3'*:** $\boldsymbol{u}'\sum_{r=1}^{5}(\mathbf{I}-\mathbf{A}^{(r)})\boldsymbol{x}^{(r)} \geq y_{tot} - \boldsymbol{u}'\sum_{r=1}^{5}\boldsymbol{m}^{(r)}$, i.e., the sum total of final demand satisfied across all regions must be at least y_{tot}. The scalar y_{tot} will be set to some fraction of the Greek economy's 2005 total final demand.

***C4'*:** $0 \leq \boldsymbol{x}_l^{(r)} \leq \boldsymbol{x}^{(r)} \leq \boldsymbol{x}_u^{(r)}$, for all r.

5. Parameter Selection and Empirical Results

When solving the optimization problems formulated in Section 4, there was a 10% maximum fluctuation allowed in any sector's production, i.e., $\boldsymbol{x}_l^{(r)} = 0.9\boldsymbol{x}^{(r)}$

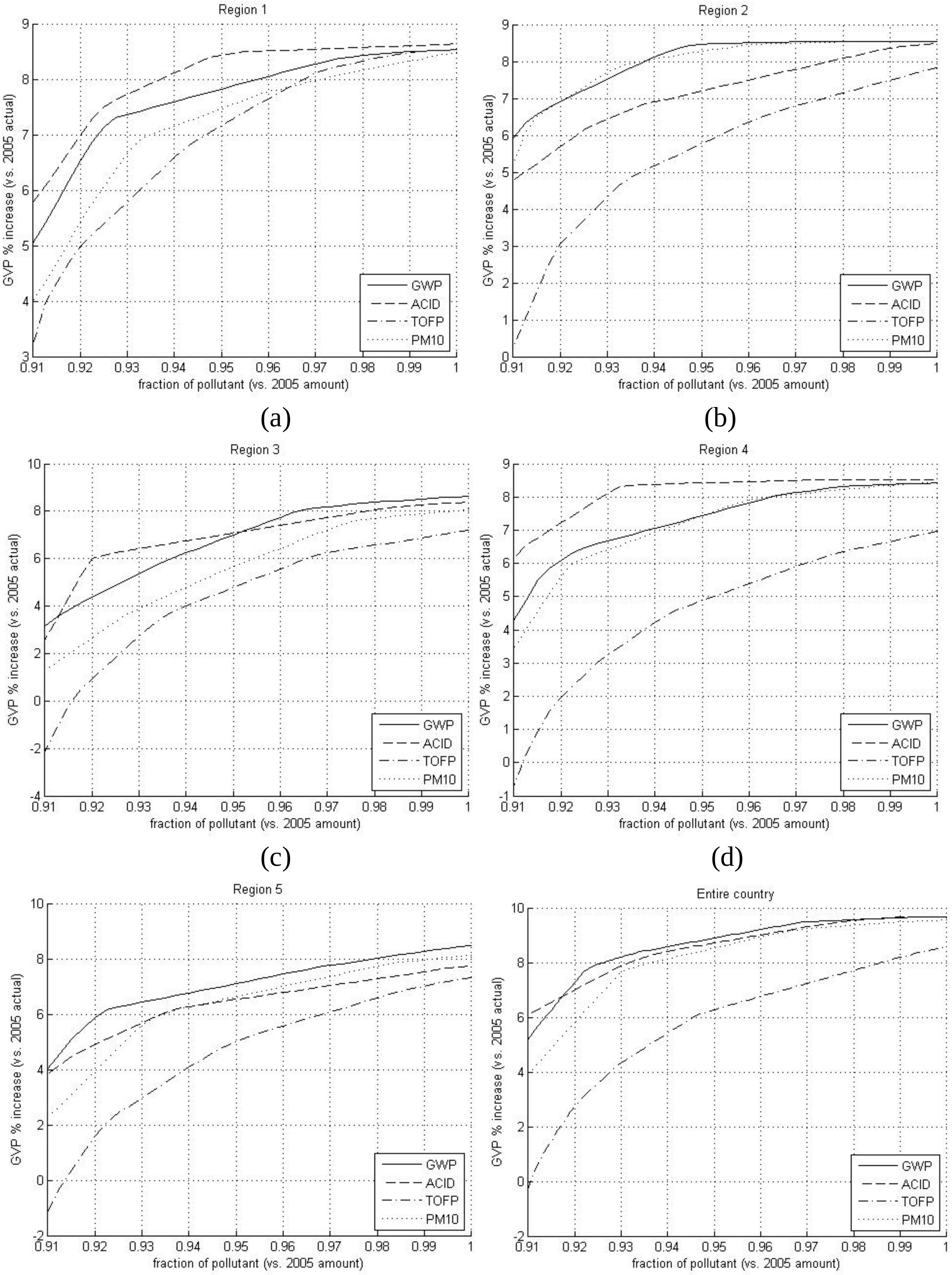
and $\boldsymbol{x}_{\boldsymbol{u}}^{(r)} = 1.1\boldsymbol{x}^{(r)}$ in constraint *C4*. This range, as well as those discussed below, is considered to be realistic for Greece, given the available data and expert opinion (Stromplos, 2010). Sectors with zero activity in some region were required to remain at zero in that same region after optimization (in which case the corresponding elements in $\boldsymbol{x}_l^{(r)}$ and $\boldsymbol{x}_u^{(r)}$ were both set to zero). This choice was based on the assumption that the imposition of environmental policies is not sufficient to provoke the commencement of economic activity in a region where that activity was until recently non-existent. The cost of establishing new activities may be dissuasively high and difficult to be offset by the potential environmental benefits for the region. At the same time, certain activities may be difficult or impossible to establish in particular regions, due to lack of infrastructure, distance from materials, and land morphology.

In constraints *C3* and *C3*', the right-hand side was adjusted to require a total production that can satisfy at least 97% of the total 2005 final demand (thus setting y_{tot} to 97% of the Greek economy's 2005 final demand, for example). Note that constraint *C3'* is equivalent to imposing a lower bound on the total value of final demand across all sectors, as opposed to constraining the demand for each sector separately. This was done in order to avoid restricting the problem too severely, thus allowing more room for meaningful solutions. Constraints *C1* and *C1'* were set to allow no more than the baseline (2005) energy usage ($e_u^{(r)}$ set to the 2005 total energy usage for each region *r*).

When solving (13), the regional emissions bounds $b_j^{(r)}$ in constraint *C2* varied in the range of 0%-9% lower than the *j*-th pollutant's baseline (2005) level in region *r*. On the other hand, for the problem in (14), the $b_j^{(r)}$ were set by assuming that each region, *r*, selects a single "most problematic" pollutant, $j_*^{(r)}$, and sets out to reduce its emissions, without raising those of the remaining pollutants. The choice of $j_*^{(r)}$ was based partly on data from the European Environmental Agency showing which pollutant is locally in higher concentrations compared to other regions. Thus, the bounds, $b_j^{(r)}$, were set to the *j*-th pollutant's baseline value in region *r* if $j \neq j_*^{(r)}$, and to some fraction of the baseline value if $j = j_*^{(r)}$.

5.1 Determining the most "economic" pollutant in each region

The five regional optimization problems (13) and their "global" counterpart (where the various parameters, input-output table, etc, referred to the national economy), were solved to produce the graphs shown in Figure 2. Each of the four curves (one per pollutant) obtained for each region (a)-(e) illustrates the relationship between the maximum achievable GVP and the reduction in the corresponding pollutant, both measured against baseline levels, assuming that regional production is optimally rearranged as per (13) and that the other three polutants are ignored. As one might expect, GVP and pollution are positively related; thus, pollution mitigation implies production restrictions. The resulting curves are concave, indicating an increasing opportunity cost – in production terms -- when seeking to achieve greater restrictions on pollutant volumes; that is, the stricter the pollution abatement targets, the greater the losses in production. In addition to identifying the pollutants which are least (or



(a) (b) (c) (d) (e) (f)

Figure 2. Optimal production levels versus pollutants reduction targets in the five Greek regions (a)-(e), and the country overall (f). The right-most point of each curve corresponds to the maximum attainable GVP % increase (compared to 2005 levels) when the corresponding pollutant is kept at its 2005 levels and the regional economy is optimized as per equation (13).

most) expensive to reduce in each region, Figure 2 also indicates that there are some pollutants for which significant reductions can be achieved with minor losses in GVP. These are briefly discussed next.

In region 1 (Aegean Islands and Crete), pollutants contributing to acidification (ACID) can be reduced with the least economic impact, as shown by the fact that the ACID-reduction curve in Figure 2(a) lies above all others. Observe also that ACID can be reduced by almost 5% with negligible effect on the regional GVP, since the corresponding curve is almost flat in the 0.95-1 range on the horizontal axis. In region 2 (Macedonia – Thrace), both GWP and PM10 are significantly cheaper to reduce than either ACID or TOFP. Furthermore, a reduction of GWP or PM10 by approximately 5% can be obtained with a minor economic sacrifice of less than 0.2% in GVP compared to the maximum level attainable when no pollutant is reduced. In region 3 (Attica), GWP is least costly to mitigate if the reduction is up to approximately 5% compared to 2005 levels, whereas for a 5-8% reduction the choice would be ACID. The pollutant which is most cost-effective to reduce in region 4 (Western Greece – Pelloponese – Ionian islands) is ACID, and its reduction comes at almost no cost up to almost 7%. Finally, in region 5 (Thessaly-Epirus-Mainland), GWP is the least costly pollutant to reduce. Note that in all regions, TOFP (mainly associated with agricultural activities) is the pollutant whose reduction entails the greatest economic cost, as indicated by the fact that the corresponding curve lies below all others in Figure 2(a)-2(f).

5.2 Optimizing production with regional priorities on air pollution

Consider now the problem of optimizing production nationally (as the sum of regional productions) with regional constraints in pollution, as described in Section 4.3. In constraint *C2'*, the choice of the "priority" pollutant which is to be reduced in each region was made by considering pollutant concentrations relative to other regions as well as each pollutant's impact on quality of life. GWP was excluded from consideration because gasses contributing to global warming tend to diffuse globally and thus are not expected to have a significant local impact. The remaining pollutants were analysed using a) monitoring data, and b) dispersion models and the corresponding country-level concentration maps[6] (available from the European Environmental Agency web site and reports contained therein). The resulting selection of priority pollutants was: ACID in regions 2 and 4 (Macedonia and Western Greece, respectively), PM10 in regions 2 and 3 (Aegean and Attica, respectively), and TOFP in region 5 (Mainland Greece).

Two scenarios were explored: a so-called "restrictive" scenario that entailed a 9% reduction in primary pollutant volume, and a "flexible" one that set a 4.5% reduction target. These choices were made after taking into account the country's production profile combined with recent estimates of achievements and expert opinion (Stromplos, 2009). In both cases, emissions of non-priority pollutants were constrainted to be no higher than baseline (2005) values.

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[6] Available at http://www.eea.europa.eu

5.2.1 Results under the restrictive scenario

In the restrictive scenario the aim was to optimize regional production (GVP) by curtailing each region's priority pollutant by 9%. As before, the maximum allowed reduction in total demand was 3% and sectoral fluctuations were kept within ±10% compared to baseline, for sectors with non-zero regional activity. Table 1 shows the percent changes in the economic variables of interest (GVP, GVA, tax and VAT revenues), as well as the percent changes in the volumes of the main environmental variables, i.e., energy use, GWP, ACID, TOFP and PM10, both at the regional and agregate levels. All percentages are relative to year 2005 values. For comparison, note that the maximum possible GVP increase for the entire country with pollutants remaining at baseline levels is 9.68% (calculated by solving (14) with energy, pollution and final demand bounds set to their 2005 values).

Notice that a 9% reduction in each region's priority pollutant can be accompanied by increased GVP and GVA in most regions (with the exception of region 5), and significant reductions in all environmental variables. Most of the losses in economic

Table 1: Percent changes in main economic variables under the restrictive (9%) scenario. * indicates a region's priority pollutant.

	Region 1 (Aegean)	**Region 2 (Macedonia)**	**Region 3 (Attica)**	**Region 4 (Mainland)**	**Region 5 (Western Greece)**	**Entire country**
GVP	4.73	5.58	1.88	6.94	-0.90	3.20
GVA	4.97	5.58	2.42	7.00	-0.09	3.58
TAX	-0.11	2.41	-1.55	5.14	-5.05	-0.17
VAT	-2.47	6.53	-4.95	5.30	-6.60	-1.22
Energy	-7.36	-7.48	-7.05	-5.87	-8.65	-7.26
GWP	-9.01	-9.19	-7.48	-7.96	-9.46	-8.79
ACID	-9.64	-9.00*	-7.87	-9.00*	-9.47	-8.96
TOFP	-8.68	-5.77	-7.13	-1.75	-9.00*	-6.53
PM10	-9.00*	-8.89	-9.00*	-6.88	-9.61	-8.71

variables concern tax and VAT revenues. Fluctuations in GVP range between -0.90% (region 5) and 6.94% (region 4). Energy use is lower in all regions. The restrictive scenario affects region 5's ecomony the most and, to a lesser extent, those of regions 3 and 1. With respect to pollution mitigation, the restriction in each region's priority pollutant has the effect of reducing energy use as well as the other, non-priority pollutants. From an optimization viewpoint, this means that the constraints (*C2'*) corresponding to the non-priority pollutants were slack and could be ignored. This is due to the fact that pollutants are not produced 'independently' of one another; thus, a reduction in one pollutant induces reductions in the others as well. In terms of policy, this suggests that if a sufficiently ambitious target it adopted, only a single pollutant per region may need to be addressed, and that one need not worry about possible increases in the other pollutants as a result of optimization.This implies potentially simpler policies with less bureaucracy. The situation is reversed under the flexible scenario, as shown in the next section.

Sectoral fluctuations under the restrictive scenario are shown in Table 2. Regions 5, 3 and 1 are those most severely affected, with nearly 15 sectors facing the maximum allowed reduction of 10%. This result is consistent with the figures obtained at the aggregate level. Sectors 1, 3, 9, 10 and 11 (primary and secondary production) undergo decreases in all regions. On the other hand, tertiary sectors, which involve mainly services, show an increase across the board, with few exceptions mostly in regions 5 and 3. The sectors which are consistently assigned the maximum 10% rise in all regions are 17, 18, 20, 21, 24 and 25 -- all involving tertiary sector activities.

Table 2: Percentage changes of sectoral production under the restrictive (9%) scenario. The correspondence between sector numbers and NACE activities can be found in the Appendix. NA is used to denote that a sector has no activity in a particular region.

Sector No.	**Region 1 (Aegean)**	**Region 2 (Macedonia)**	**Region 3 (Attica)**	**Region 4 (Mainland)**	**Region 5 (Western Greece)**
1	-10	-10	-10	-10	-10
2	-10	10	-10	10	-10
3	-10	-10	-10	-10	-10
4	-10	10	10	10	-10
5	-10	10	-10	10	-10
6	-10	10	10	10	-10
7	-10	-10	-10	10	-10
8	NA	-10	-10	-10	NA
9	-10	-10	-10	-10	-10
10	-10	-10	-10	-10	-10
11	-10	-10	-10	-10	-10
12	-10	10	-10	10	10
13	-10	-10	9.79	0.64	-1.3
14	-10	-10	-10	NA	-10
15	NA	-10	-10	-10	NA
16	-10	10	-10	10	-10
17	10	10	10	10	10
18	10	10	10	10	10
19	-9.14	-9.8	-10	10	-10
20	10	10	10	10	10
21	10	10	10	10	10
22	10	10	-10	10	-10
23	10	10	10	10	-10
24	10	10	10	10	10
25	10	10	10	10	10

5.2.2 Results under the flexible scenario

Under the flexible scenario, total GVP was maximized through the restriction of each region’s priority pollutant by 4.5%. The same constraints regarding the lower bound in total demand and fluctuations of sectoral production were applied as in Section 5.2.1. Table 3 contains the percent changes in the main economic and environmental variables. Again, under the optimal

Table 3: Percent changes (vs. 2005 levels) in main variables under the flexible (4.5%) scenario. * indicates the region's priority pollutant

	Region 1 (Aegean)	**Region 2 (Macedonia)**	**Region 3 (Attica)**	**Region 4 (Mainland)**	**Region 5 (Western Greece)**	**Entire country**
GVP	8.56	8.26	6.74	7.77	6.03	7.27
GVA	8.55	8.29	6.55	7.81	5.82	7.19
TAX	7.03	6.91	3.77	6.22	3.07	5.00
VAT	7.83	7.23	9.75	6.60	6.20	8.06
Energy	-3.95	-4.16	-5.29	-4.55	-6.04	-4.80
GWP	-3.66	-7.26	-4.10	-6.30	-6.32	-6.29
ACID	-5.87	-4.50*	-5.72	-8.27*	-4.96	-6.26
TOFP	-3.36	-0.46	-1.87	0.00	-4.50*	-1.82
PM10	-4.50*	-5.75	-4.50*	-5.04	-3.90	-5.10

solution there are increases in all economic variables and decreases in energy use and non-priority environmental variables. Specifically, changes in GVP range from 6.03% (region 5) to 8.56% (region 1). Pollutant volumes change between 0% (TOFP in region 4) and -8.27% (ACID in region 4). At the regional level, region 5 -- and to a lesser extent region 3 -- are most severely affected in terms of economic performance.

In this case, there is a qualitative difference compared to the restrictive scenario. Specifically, the constraints *C2'* corresponding to the non-priority pollutants are sometimes tight (see TOFP in region 4). In this case, the 4.5% rate of reduction in the target variables is not sufficient to reduce the remaining pollutants, as was the case in the restrictive scenario. The implication is that, in general, it may be necessary to impose bounds on one or more non-priority pollutants (depending on the % reduction one is aiming for) to prevent them from rising above their nominal levels as priority pollutants are reduced. The above results suggest that aiming for more moderate pollution abatement targets does not always imply a simpler environmental policy.

The percent changes in sectoral production under the flexible scenario are shown in Table 4. In this case, the adverse effects are less significant compared to those in the restrictive scenario; they are centred mostly in regions 1 and 3, where ten sectors undergo the maximum 10% reduction. The lowest number of sectors undergoing reductions occurs in region 2. The sector most severely affected in all regions is 10 and to lesser extent sectors 8, 14 and 15, all of which involve secondary production. Sectors undergoing increases in all regions are 4, 13, 16-18, and 20-25. Overall, the imposition of moderate pollution abatement targets favours tertiary production as well as a few secondary sectors.

Table 4: Percent changes in sectoral production under the flexible (4.5%) scenario. The correspondence between sector numbers and NACE activities can be found in the Appendix. NA is used to denote that a sector has no activity in a particular region.

Sector No.	Region 1 (Aegean)	Region 2 (Macedonia)	Region 3 (Attica)	Region 4 (Mainland)	Region 5 (Western Greece)
1	4.88	-6.05	-10	-4.46	-10
2	-10	10	-10	10	-10
3	-10	10	-10	-10	-10
4	10	10	10	10	10
5	-10	10	10	10	10
6	-10	10	10	-10	-10
7	-10	10	-10	10	10
8	NA	-10	-10	-10	NA
9	-10	10	-10	10	10
10	-10	-10	-10	-10	-10
11	-10	10	-10	10	7.92
12	-10	10	10	10	10
13	10	10	10	10	10
14	-10	-10	-10	NA	-10
15	NA	-10	-10	-10	NA
16	10	10	10	10	10
17	10	10	10	10	10
18	10	10	10	10	10
19	10	10	NA	10	-10
20	10	10	10	10	10
21	10	10	10	10	10
22	10	10	10	10	10
23	10	10	10	10	10
24	10	10	10	10	10
25	10	10	10	10	10

6. Conclusions

This work addressed the problems of quantifying the regional economic impact of reducing each of a set of four major air pollutants (GWP, ACID, TOFP, PM10) in Greece, and of optimizing sectoral production with regional constraints on energy and air pollution. The proposed approach involved the formulation of a linear optimization problem whose parameters were informed by regional IO and environmental data for Greece. The resulting model links sectoral regional economic activity and air pollution and was used to i) compute the relative cost-effectiveness of reducing each pollutant in each region, and ii) explore two production reallocation scenarios in which each region is allowed to reduce a single "priority" pollutant.

In the two scenarios considered, the economy's GVP was optimized under a 9% and a 4.5% reduction in each region's priority pollutant, with other pollutants kept no higher than their baseline (2005) levels. The choice of air pollutant considered most important in each region was made by examining available air pollution maps to locate regional "peaks" in concentrations, and by considering each pollutant's impact on local quality of life. The approach followed here is consistent with policies which promote greater regional autonomy and a cleaner environment for local societies, without excessive economic sacrifices. Other constaints imposed while optimizing the GVP included a fluctuation range of ±10% for sectoral production and a lower bound of -3% for total demand.

Based on the numerical experiments detailed here, and on the fact that pollutants are often generated jointly, a policy that aims to reduce one pollutant may induce a drop in the others as well. However, the analysis has shown that these changes are not always proportional to the reduction of the priority polllutant. In fact, when one pollutant is reduced while maximizing GVP, other pollutants may rise unless they are specifically constrained not to. This was the case in the "flexible" (4.5% reduction) scenario examined here. In light of this, the model described in this paper could be used to support policy formation, and in particular to distinguish between scenarios where it is sufficient to regulate a single pollutant versus those where additional pollutants must be considered explicitly.

Overall, the imposition of emission mitigation policies entails reductions or lower increases than would otherwise be achievable in the aggregate economic variables studied here, across all regions. As expected, these effects were much more pronounced under the restrictive scenario. Under both the restrctive and flexible scenarios, the regions most severely affected in economic terms were regions 5 and 3. Region 5 also had the most significant drop in energy consumption and the greatest reductions in air pollution under the restrictive scenario. At the sectoral level, the restrictive scenario leads to production fluctuations in a larger number of sectors, compared to the flexible one; regions 5, 3 and 1 had the largest number of sectors with reduced production under the optimal solution. This ranking changed slightly under the flexible scenario, with region 5 coming in third. Sectors 8, 10, 14 and 15 (all secondary production sectors) were subject to the most significant reductions in all regions under either scenario. Tertiary production sectors were favoured the most by the optimal solution.

Opportunities for future work include revisiting the problem by linking pollution levels to both economic and health costs. This is of interest because high concentration levels of a pollutant in a certain region may not necessarily render that pollutant as the most dangerous for human health. In that sense, pollutants should be weighted accordingly to the effects they induce on the health of the local population and the costs of dealing with the health consequences of each pollutant should be incorporated into the objective function to be optimized.

Appendix

Table A1: Sector numbers, NACE (Nomenclature statistique des Activités économiques dans la Communauté Européenne) codes and activities in the 2005 Greek Input-Output Matrix.

Sector No	NACE Code	NACE Activity Rev. 1
1.	**01 & 02**	Agriculture
2.	**5**	Fisheries
3.	**10,11&12 / 13-14**	Mining and quarrying
4.	**15-16**	Manufacture of food products, beverages and tobacco
5.	**17-19**	Manufacture of textiles and textile products
6.	**20A**	Manufacture of wood and wood products
7.	**21-22**	Manufacture of pulp, paper and paper products; publishing and printing
8.	**23**	Manufacture of coke, refined petroleum products and nuclear fuel
9.	**24-25**	Manufacture of chemicals, chemical products and man-made fibres
10.	**26**	Manufacture of other non-metallic mineral products
11.	**27**	Manufacture of basic metals and fabricated metal products
12.	**28**	Manufacture of fabricated metal products, except machinery and equipment
13.	**29-36**	Manufacture of machinery and equipment
14.	**37**	Recycling
15.	**40-41**	Electricity, gas and water supply
16.	**45**	Construction
17.	**50-52**	Wholesale and retail trade; repair of motor vehicles, motorcycles and personal and household goods
18.	**55**	Hotels and restaurants
19.	**60-64**	Transport, storage and communication
20.	**65-67**	Financial intermediation
21.	**70-74**	Real estate, renting and business activities
22.	**75&90**	Public administration and defence; Sewage and refuse disposal
23.	**80-84**	Education
24.	**85**	Health and social work
25.	**91**	Activities of membership organizations n.e.c.
26.	**92, 93, 95 & 99**	Recreational, cultural and sporting activities; Activities of households; Extra-territorial organizations[7]

Source: Economidis et al., 2008, p.5.

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[7] Sector 26 (Recreational, cultural and sporting activities, activities of households, extra-territorial organizations) has been excluded from the analysis because the economic activities contained therein are outside the scope of this study.

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