Optimizing Production in Greece under Particulate Pollution Constraints with cross-Regional Transport Effects

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Abstract

Particular matter (PM10) pollutants, generated from combustion-based processes largely attributed to economic activity, are known to cause serious adverse effects on human health, including respiratory and heart related effects. PM10 pollutants are a significant problem in Greece, and especially in the Attica region, which includes Athens and about half of the country's population. Some studies report that a PM10 increase of 10 μg/m3 could increase daily death rates by 0.6%. We propose an input-output model for optimizing production in Greece under constraints on the PM10 concentrations which are deposited in Attica. Production is optimized on a regional, sector-by-sector basis. Our analysis uses the Greek environmental input-output matrix and takes into account PM10 concentrations which are "deposited" in the Attica region but may have originated in any region of Greece. The percentage contributions of each region and economic activity (identified in a regional Greek NAMEA) are determined via high-resolution atmospheric simulations, taking into account weather conditions in Greece, using the WRF-inverse HYSPLIT model combo. Besides pollution constraints, we require that the resulting sectoral/regional production levels satisfy constraints on overall demand, energy use, and maximum sectoral variations over current-baseline levels. We use our model to determine (via linear programming) economically optimal policies (sectoral production targets) that lead to desired reductions of PM10 in the Attica region, and examine whether those reductions can be achieved without worsening the PM10 concentrations in other regions. To our knowledge, this study represents the first approach to consistently integrate high resolution atmospheric models with NAMEA. This study also paves the way for extending our model to a broader setting where regional production is optimized with pollutant transfers from and to all regions being taken into account.

JEL codes: Q51, C67, Q53.

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1. Introduction

In recent years, epidemiological studies have demonstrated a clear association between population mortality, morbidity and ambient air pollutants (e.g. Katsouyanni et al. 2001). It is well established nowadays that short- and long-term exposure to ambient PM concentrations causes adverse health effects and reduction in the life expectancy of urban populations in both developed and developing countries (e.g. WHO Report, 2005). For Europe, in particular, it has been estimated that the life expectancy is reduced by an average of 9 months as a result of exposure to anthropogenic PM particles (Amann et al., 2005). A number of toxicological and epidemiological studies have also reported that health problems ranging from respiratory to cardiovascular illnesses could be caused by exposure to PM (e.g. Pope and Dockery, 2006; EPA, 2008; Perez et al., 2009). The particulate pollutants, as inducers of oxidative stress, they may impact allergic inflammation and also induce acute asthma exacerbations.

To date, various research approaches have attempted to investigate factors that attribute sources to exposure concentrations or estimate population exposure. The approach of attribution relies on statistical tools such as principal component analysis (e.g. Sindosi et al. 2003; Vardoulakis and Kassomenos, 2008) while estimation is based on extrapolation of data or surrogate information such as air quality networks, satellite imaging techniques, regression analysis, dispersion and emission modelling. Of course, air emissions are typically linked to economic activity, and one consolidated framework for assessing and analyzing the relationships between air emissions and economic structure is that of Environmental input-output (EEIO) models. EEIO models have been applied, for instance, in estimating the atmospheric levels and concentration of GHG as a function of economic demand in a given region (Butnar & Llop 2007, Tarancón & del Rio 2007) and in assessing CO2 emissions related to specific sectors and/or regions (e.g. Alcántara & Padilla 2009). Recently this approach has been integrated with optimization tools for minimizing the environmental impact of economic processes.

The present work proposes a method for mitigating PM10 pollution in Greece, using an input-output approach to "attribute" pollution to the various sectors of an economy. Based on this attribution and on the interdependence of sectors with respect to changes in final demand, we can then seek to adjust the level of economic activity in each sector (subject to various practical constraints to be discussed shortly) so as to maximize total economic output while capping PM10 pollution. We expand upon our previous work (Hristu-Varsakelis et al 2010, 2012), by introducing into the analysis transport effects on pollution patterns, based on prevailing meteorological patterns and the application of high resolution dispersion models. This allows us to account not only for the amount of PM10 pollution that is produced as a result of economic activity in each sector, but also for the amount that is *deposited* in a particular region of interest (in our case Attica, home to roughly 50% of the country's population – see Fig. 1) which may be heavily populated or otherwise burdened with pollution.

Specifically, with respect to PM10 emissions deposited into Attica, the percentage contributions of each region and economic activity (identified in a regional Greek NAMEA) were determined via high-resolution atmospheric simulations, taking into account weather conditions in Greece, using the WRF-inverse HYSPLIT model combo. Besides applying PM10 constraints, we will also require that the resulting sectoral/regional production levels

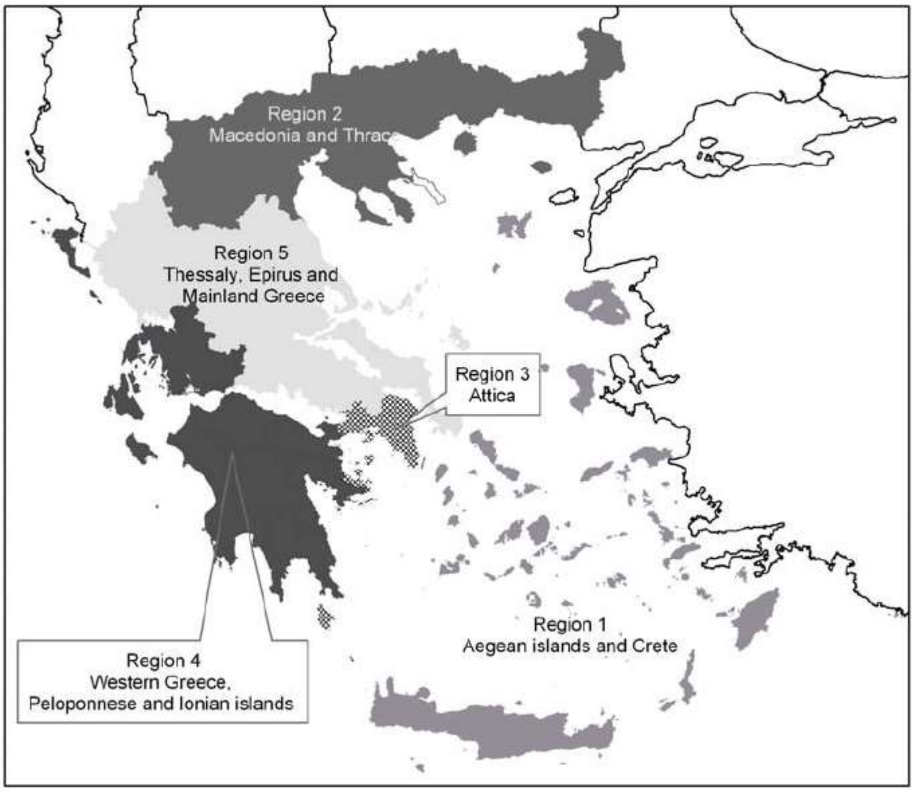

Figure 1. Regional map of Greece.

satisfy constraints on overall demand, energy use, and maximum sectoral variations over current-baseline levels. We use our model to determine (via linear programming) economically optimal policies (i.e., sectoral production targets) that lead to desired reductions of PM10 in the Attica region, and examine whether those reductions can be achieved without worsening the PM10 concentrations in other regions. To our knowledge, this study represents the first approach to consistently integrate high resolution atmospheric models with NAMEA. This study also paves the way for extending our model to a broader setting where regional production is optimized with pollutant transfers from and to all regions being taken into account.

2. Data and methodology

2.1 Regional NAMEA data

The regional National Accounting Matrix with Environmental Accounts (NAMEA) for Greece, consists of five tables in total (one for each region), which were last compiled with data from the year 2005 using the methodology described in the work of Economidis et al. (2011). For the Regional Input-Output Table (IOT) the two main steps include a) regionalization of national input-output coefficients, and b) calculation of the quadrants of final demand, intermediate inputs and initial inputs. Similarly, the air emissions data set, on a country level, was attributed down to the regional level, using the following approach:

a) Obtain emissions data from the Large Point Sources, European Pollutant Emission Register database (EPER) and the national total per NFR type of activity from the European

Monitoring and Evaluation Programme (EMEP) and assigned the facility on the corresponding region and NACE code.

b) Convert the NFR based emissions on a country level to a NAMEA based estimation using the conversion proposed by EUROSTAT (2013). The number of economic activities was set at 25.

c) For each economic activity containing large point sources (LPS), deduce the LPS total from the country total.

d) Any emissions remaining after the previous step are assigned to each region using ancillary data, such as the number of enterprises, gross value added, and gross domestic product of the region, depending on the economic activity level.

e) The finally estimated air emissions for each region are estimated as the sum of the previously estimated quantity and the total of LPS for each activity code.

2.2 Percentage attribution of pollution in Attica.

The next step in the analysis is the determination of the percentage attribution of particulate pollution in the region of Attica, using a detailed coupled meteorological – dispersion modeling system. We employed the backward trajectory modelling procedure, using the Hybrid-Single Particle Langrangian Integrated Trajectory (HYSPLIT, v4.9) model (Draxler & Hess, 1998). The HYSPLIT model is the newest version of a complete system for computing simple air parcel trajectories to complex dispersion and deposition simulations. The required meteorological data (vertical distribution of wind speed and direction, temperature, mixing layer height, humidity, precipitation, etc) were extracted from the NCSR Demokritos high-resolution operational forecasting weather model for Greece. The numerical simulations of the present study were conducted with the application of the MM5 meteorological model setup for Greece (Fig. 2), with a spatial resolution of the domain at 3x3 km^2, and 231 cells in each direction.

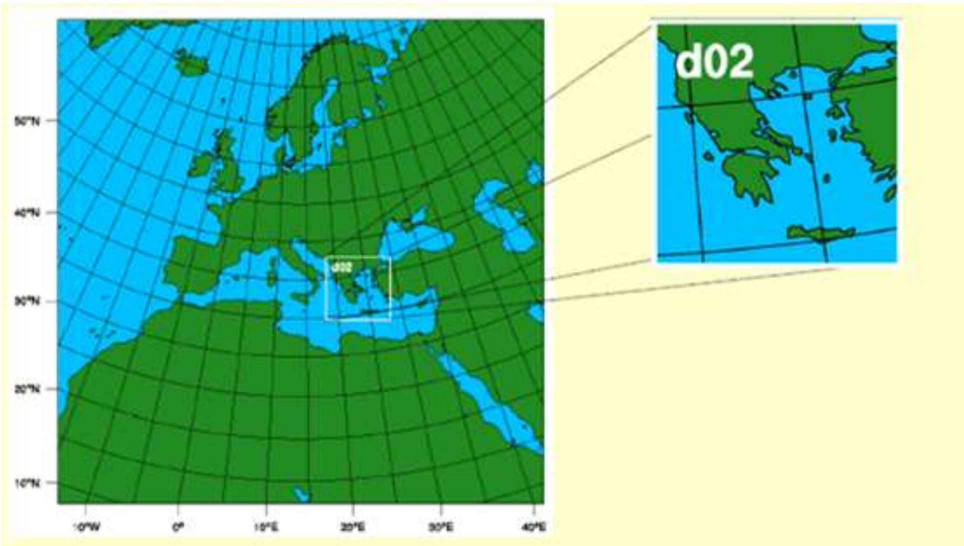

Figure 2. Meteorological model setup for Greece. Spatial resolution was 3x3 km2,

In the vertical, the domain was based on 27 full σ levels to the top at 50 hPa. Initial and boundary conditions for all model runs were based on the 6-hours re-analysis meteorological data available from the National Centres for Environmental Prediction (NCEP) reanalysis data set (FNL) for the period of interest. For the purposes of this study, backward trajectories computed in 12-hour time steps, covering the entire 2010, were estimated from Athens city center (receptor at 37.58 N, 23.43 E) at 10 m height above sea level. The trajectories endpoints that reached an emission height level, for each of the performed runs, were then locally attributed to the Greek national "economic" regions of Figure 1. The application of the Potential Source Contribution (PSC) method (e.g. Heo et al, 2008) estimated the percentage contribution of PM10 pollution in Attica for the year in question.

If a trajectory end point of the air parcel happened to lie in a geophysical grid cell, the trajectory was assumed to collect particulates emitted in that cell. Once the particle was incorporated into the air parcel, it was assumed to be transported along the trajectory to the region of interest. We let PSC_{ij} denote the conditional probability that an air parcel that passed through the (i,j)-th cell had a high concentration upon arrival to the Region of Attica, and

$$PSCF_{ij} = m_{\mathrm{ij}} / n_{ij}$$

where n_{ij} is the total number of end points that fall in the (i,j)-th cell, and m_{ij} is the number of end points in the same modeling cell. Based on the conditional probabilities PSC_{ij}, we calculated the percentages of PM10 emissions which are deposited in Attica after originating in regions 1 thru 5 to be 0.13%, 0.19%, 66.84%, 1.37% and 5.98%, respectively.

3. Model and Main Optimization Problem

In this section we formulate an optimization problem where overall production is to be maximized on a sector-by-sector basis, subject to overall energy and demand constraints, as well as constraints on the total PM10 pollution in the country's most populous Attica region. 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, $\boldsymbol{u} = [1,\dots,1]'$ 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:

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

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:

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

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

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

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:

$$\boldsymbol{t} = \mathrm{diag}(\boldsymbol{a_T})\mathbf{X}'\boldsymbol{u} = \mathrm{diag}(\boldsymbol{a_T})\mathrm{diag}(\boldsymbol{x})\mathbf{A}'\boldsymbol{u} \tag{7}$$

$$\boldsymbol{v} = \mathrm{diag}(\boldsymbol{a_V})\mathbf{X}'\boldsymbol{u} = \mathrm{diag}(\boldsymbol{a_V})\mathrm{diag}(\boldsymbol{x})\mathbf{A}'\boldsymbol{u}, \tag{8}$$

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

The PM10 air pollutant discussed in Section 2 is assumed to be emitted in quantities which are directly proportional to the total output of the corresponding sectors. Thus,

$$\boldsymbol{p} = \mathrm{diag}(\boldsymbol{a_p})\boldsymbol{x} \tag{9}$$

will denote the vector of per-sector emissions of PM10, where $\boldsymbol{a_p}$ is a vector containing the corresponding emission coefficients. Those coefficients 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,

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

where $\boldsymbol{a_e}$ is a vector of energy coefficients. Finally, total emissions of PM10 and total energy consumption are obtained by summing over all sectors:

$$p = a_p' x, \tag{11}$$

$$T_{ce} = a_e' x \tag{12}$$

3.1 Accounting for Inter-regional pollution transport into Attica

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,…,k, so that for example, $\boldsymbol{x}^{(r)}$ will be the production vector in region r, $\boldsymbol{p}^{(r)}$ the vector of PM10 emissions in region r, etc. PM10 particles are not necessarily "deposited" near the source, but are carried by prevailing winds. The 5-vector $\boldsymbol{q}$ will contain the proportion of the PM10 emissions of region r=1,…,5, which are deposited in Attica. Therefore, the overall PM10 concentrations in Attica will be

$$P_{attica} = \sum_{r=1}^{5} q_r p^{(r)} = \sum_{r=1}^{5} q_r a_p^{(r)}{}' x^{(r)} \tag{13}$$

3.2 Optimization Problem

Based on the definitions of the previous section, we are interested in solving the following optimization problem:

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

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: $P_{attica} \leq b$, j=1,…,4, r=1,…,5, where b is a (scalar) upper limit on PM10 emissions deposited in Attica[1], and P_{attica} is as per (13).

C3: $\boldsymbol{u}' \sum_{r=1}^{5} (\mathbf{I} - \mathbf{A}^{(r)}) \boldsymbol{x}^{(r)} \geq y_{\boldsymbol{tot}} - \boldsymbol{u}' \sum_{r=1}^{5} \boldsymbol{m}^{(r)}$, 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: $0 \leq \boldsymbol{x}_{\boldsymbol{l}}^{(r)} \leq \boldsymbol{x}^{(r)} \leq \boldsymbol{x}_{\boldsymbol{u}}^{(r)}$, for all r, where $\boldsymbol{x}_{\boldsymbol{l}}^{(r)}$ and $\boldsymbol{x}_{\boldsymbol{u}}^{(r)}$ are lower and upper bounds on production in region r.

4. 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., $\boldsymbol{x}_{\boldsymbol{l}}^{(r)} = 0.9\boldsymbol{x}^{(r)}$ 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 constraint *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

[1] We will use the term "PM10 deposited into Attica" to refer to PM10 which may originate in any region but is transported by weather phenomena ending up in Region 3 (Attica).

economy's 2005 final demand, for example). Constraint *C1* was 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*). The PM10 upper bound b in constraint *C2* varied in the range of 0%-9% lower than the baseline (2005) PM10 level in Attica. Finally, the vector *q* containing the percentages of regional PM10 emissions being deposited into Attica from each of the five regions was $q = [0.13\ 0.19\ 66.84\ \ 1.37\ 5.98]'$, as per the PM10 transport computational model discussed in Section 2.2. The remaining emissions are deposited in other regions, with a large percentage ending up at sea and not accounted for in this study, although one could augment the model to include a cost (or constraint) for that quantity as well.

4.1. Optimal (aggregate) production levels versus PM10 deposition reduction targets

Figure 3 illustrates the relationship between the maximum achievable production level (computed by solving the optimization problem of Section 3.2) and the PM10 deposition reduction targets in Attica. Both are measured against the baseline levels (2005). The vertical axis indicates the percentage increase in optimized GVP at the aggregate (country) level and the horizontal axis the percentage reduction in PM10 pollutants deposited in Attica. As one would expect, higher levels of production are associated with higher levels of pollution. The curve shown in Fig. 3 is concave, implying an increasing opportunity cost in production, when stricter environmental targets are imposed. The right-most point of the curve corresponds to the maximum attainable GVP percentage increase (compared to 2005 levels)

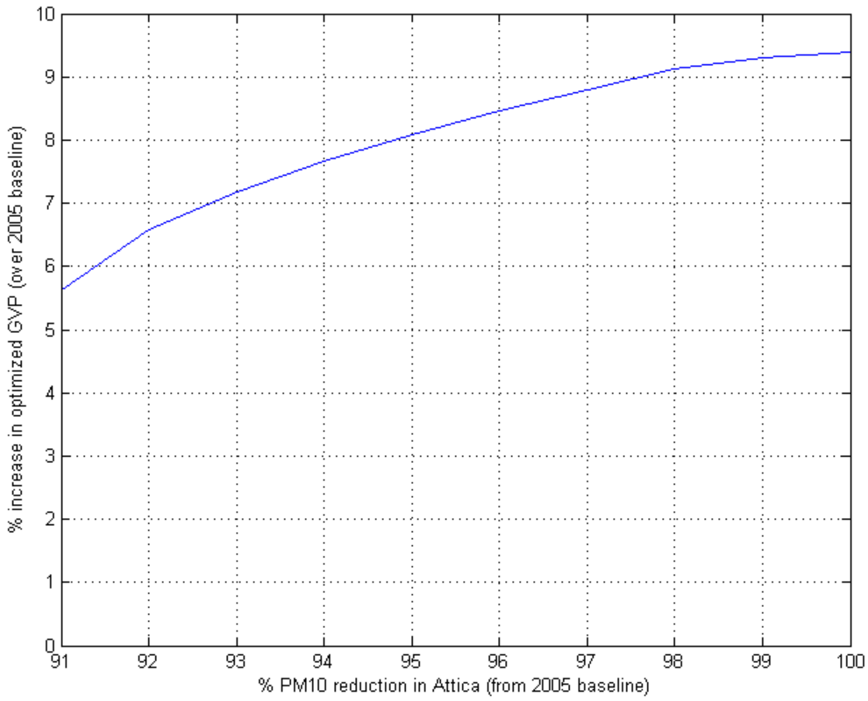

Figure 3. Optimal GVP versus PM10 deposition reduction targets

where a restructuring of economic activity –without any pollution mitigation measures - stimulates production by approximately 9.4%.

In the following, two optimization scenarios were explored: a so-called “restrictive” scenario that entailed a 9% reduction in the volume of PM10 concentrations deposited in Attica, and a “flexible” one that set a 4.5% PM10 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, 2010). As indicated in the figure, the maximum possible GVP increase for the entire country under the “restrictive” scenario is 5.63%, whereas under the “flexible” 8.28%.

4.2 Results under the restrictive scenario (9% reduction in PM10 deposited in Attica)

In the restrictive scenario, the aim was to optimize regional production (GVP) on a sector-by-sector basis by curtailing PM10 concentrations deposited in Attica, by 9%. This reduction should ideally be achieved without worsening the PM10 concentrations in other regions. The maximum allowed reduction in total demand was 3% and sectoral fluctuations were kept within ±10% compared to the baseline 2005 values, for sectors with non-zero regional activity. Sectors with zero regional production were constrained to remain at zero. Energy consumption at the aggregate (country) level was constrained to be no higher than baseline (2005) values.

Table 1 shows the percent changes in the economic variables of interest, namely GVP, GVA, tax and VAT revenues, as well as the percent changes in the volumes of the main environmental variables, namely energy use and PM10 emissions, both at the regional and aggregate levels. The results indicate that a 9% reduction in PM10 concentrations in Attica

Table 1: Percent changes in main economic variables under the restrictive (9%) scenario.

	Region 1 (Aegean)	**Region 2 (Macedonia)**	**Region 3 (Attica)**	**Region 4 (Mainland)**	**Region 5 (Western Greece)**	**Entire country**
GVP	9.99	9.54	0.96	9.02	6.79	5.63
GVA	9.95	9.42	1.35	8.95	6.56	5.78
TAX	9.97	8.94	-2.10	8.10	5.37	4.12
VAT	10.00	10.00	-5.27	10.00	6.21	3.00
Energy use	3.97	-1.32	-7.54	-3.58	-10.94	-4.39
PM10 emitted	6.72	-3.55	-9.33	-3.38	-6.56	-4.29

can be accompanied by increased GVP and GVA in all regions, increases in tax and VAT revenues in all regions -except for Attica- and significant reductions in the environmental variables in all regions -except for region 1. As one might expect, the most “severe” consequences in terms of production occur in the target region, Attica, while the least affected region is the one with the lowest percentage of PM10 transfer in Attica (region 1). Increases in GVP vary between 0.96% (Attica) and 9.99% (region 1). Energy consumption fluctuations range between -10.94% (region 5) and 3.97% (region 1). The maximum PM10 emissions reduction is achieved in Attica (-9.33%); however, optimization may well induce emissions' increases (6.72% in region 1). Additionally, this solution satisfies 105.76% of original demand.

The results signify an inverse relation in the effects on economic and environmental variables; that is, the most severe economic effects keep pace with the mildest effects on environmental variables. In this sense, the restrictive scenario favors region 1 with respect to economic variables (production, value added, tax and VAT revenues), while it entails the greatest disadvantages for the environmental variables (energy usage and PM10 emissions) in that same region. On the contrary, the worst outcomes in all economic variables, which involves Attica, are offset by the most favorable consequences on the environment. In terms of policy, this means that environmental targets can be achieved at a -more or less significant- regional economic cost, although this cost can be offset at a country level by appropriately rearranging production in other regions. Furthermore, the greater the environmental goals to be achieved, the higher the economic cost.

With respect to pollution mitigation, it should be noted that PM10 emissions and energy use move in the same direction. Particularly, in all regions restrictions in PM10 emissions keep up with energy use reductions and vice versa. This suggests that the adoption of a particular environmental measure may affect other environmental parameters as well and positively impact environmental performance in general.

Sectoral fluctuations under the restrictive scenario are listed in Table 2. Attica is the most severely affected region, with 18 sectors facing reductions that, in almost all cases, reach the maximum allowed reduction of 10%. The second most severely hit region is 5, with 7 sectors facing decreases. This result is consistent with the outcome at the aggregate level. Sector 15 (electricity) undergoes decreases in all regions, while sector 10 in 4 out of 5 regions. Sectors 3 and 11 production is restricted in 3 regions. All of the previously mentioned sectors involve primary and secondary production. Tertiary production is strengthened with the maximum 10% rise - with few exceptions in Attica, where production drops.

4.3 Results under the flexible scenario (4.5% reduction in PM10 deposited in Attica)

Under the flexible scenario, aggregate and regional GVP was maximized while imposing the restriction of PM10 concentrations in Attica by 4.5%. The allowable fluctuation range in sectoral production and aggregate demand was set as in the previous section. Table 3 contains the percent changes in the main economic and environmental variables. At the regional level, increases are observed in all economic variables and decreases in energy use and PM10 emissions in two regions, Attica and its neighboring region 4. Once again, Attica faces the most significant changes, while region 1 the least. Particularly, increases in GVP range from 6.36% (Attica) to 9.97% (region 1). PM10 emissions fluctuate between -4.99% (Attica) and 5.65% (region 1). This optimization scenario satisfies 108.23% of the original demand. Comparing with the "strict" scenario, we conclude that in terms of economic performance, the flexible scenario leads to higher increases in production and tax revenues. However, the restrictive scenario appears more appealing in terms of environmental quality.

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	10.00	10.00	-10.00	10.00	-10.00
2	10.00	10.00	-10.00	10.00	-10.00
3	10.00	10.00	-10.00	-10.00	-10.00
4	10.00	10.00	10.00	10.00	10.00
5	10.00	10.00	-10.00	10.00	10.00
6	10.00	10.00	-10.00	10.00	10.00
7	10.00	10.00	-10.00	10.00	-10.00
8	NA	10.00	-10.00	10.00	NA
9	10.00	10.00	-10.00	10.00	10.00
10	-10.00	10.00	-10.00	-10.00	-10.00
11	10.00	10.00	-10.00	-10.00	-10.00
12	10.00	10.00	-10.00	10.00	10.00
13	10.00	10.00	-10.00	10.00	10.00
14	10.00	10.00	-10.00	NA	-10.00
15	NA	-10.00	-10.00	-10.00	NA
16	10.00	10.00	-10.00	10.00	10.00
17	10.00	10.00	10.00	10.00	10.00
18	10.00	10.00	10.00	10.00	10.00
19	10.00	10.00	-10.00	10.00	10.00
20	10.00	10.00	10.00	10.00	10.00
21	10.00	10.00	10.00	10.00	10.00
22	10.00	10.00	-10.00	10.00	10.00
23	10.00	10.00	-5.38	10.00	10.00
24	10.00	10.00	10.00	10.00	10.00
25	10.00	10.00	10.00	10.00	10.00

Table 3: Percent changes (vs. 2005 levels) in main variables under the flexible (4.5%) scenario.

	Region 1 (Aegean)	Region 2 (Macedonia)	Region 3 (Attica)	Region 4 (Mainland)	Region 5 (Western Greece)	Entire country
GVP	9.97	9.77	6.36	9.47	9.13	8.28
GVA	9.93	9.64	6.18	9.36	8.85	8.14
TAX	9.96	9.48	3.19	8.84	8.90	6.94
VAT	10.00	10.00	9.74	10.00	10.00	9.89
Energy use	3.40	4.43	-5.68	-2.08	1.67	0.00
PM10 emitted	5.65	3.33	-4.99	-0.04	0.14	1.12

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	10.00	10.00	-10.00	10.00	10.00
2	10.00	10.00	-10.00	10.00	10.00
3	10.00	10.00	-10.00	10.00	-10.00
4	10.00	10.00	10.00	10.00	10.00
5	10.00	10.00	10.00	10.00	10.00
6	10.00	10.00	10.00	10.00	10.00
7	10.00	10.00	-10.00	10.00	10.00
8	NA	10.00	-10.00	10.00	NA
9	10.00	10.00	-10.00	10.00	10.00
10	-10.00	10.00	-10.00	10.00	-10.00
11	-10.00	10.00	-10.00	10.00	-5.42
12	10.00	10.00	-10.00	10.00	10.00
13	10.00	10.00	10.00	10.00	10.00
14	10.00	10.00	-10.00	NA	10.00
15	NA	0.15	-10.00	-10.00	NA
16	10.00	10.00	10.00	10.00	10.00
17	10.00	10.00	10.00	10.00	10.00
18	10.00	10.00	10.00	10.00	10.00
19	10.00	10.00	-10.00	10.00	10.00
20	10.00	10.00	10.00	10.00	10.00
21	10.00	10.00	10.00	10.00	10.00
22	10.00	10.00	10.00	10.00	10.00
23	10.00	10.00	10.00	10.00	10.00
24	10.00	10.00	10.00	10.00	10.00
25	10.00	10.00	10.00	10.00	10.00

Table 4 shows the percentage changes in the value of sectoral production under the flexible scenario. In this case, the adverse effects are less significant compared to those in the restrictive scenario and they occur in Attica, where 12 sectors face curtails of 10% in their production. In region 2, all sectors display increases. The rest of the regions face marginal cuts in their sectoral production. The most energy intensive activities, sectors 10 and 11, undergo major reductions in 3 out of 5 regions. The least affected activities belong to the tertiary sector of production – with the exception of sector 19 in Attica, which faces a drop of 10%.

5. Conclusions

This paper examined the macroeconomic and sectoral effects of two policy scenarios aiming at restricting PM10 concentrations – a particularly harmful pollutant - transferred (by weather patterns) from all Greek regions and deposited into Attica, the country’s capital region. For the purposes of the study, an input-output model has been constructed for optimizing production in Greece on a regional, sector-by-sector basis, subject to constraints on pollution, energy usage and final demand to be satisfied. The PM10 contributions of each region and economic activity were determined with the use of the WRF-inverse HYSPLIT model combo. Our results suggest that the achievement of high-level environmental objectives implies significant economic sacrifices at a regional level, although those sacrifices can be “offset” by appropriate production changes in other regions so that the country’s entire economy performs better overall in terms of the economic variables examined here. In addition, PM10 pollution is strongly connected to energy usage. At the aggregate level, output increases may vary between 5.63% and 8.28%, depending on the PM10 abatement policy. At the sectoral level, the imposition of pollution mitigation targets favors tertiary production. The primary and secondary sectors of production suffer the greatest fluctuations. The most energy intensive activities, which correspond to sectors 10, 11 and 15, undergo major reductions in most cases.

Of the two PM10 reduction scenarios examined here, the “flexible” one (4.5% reduction in PM10 deposited in Attica) appears to be advantageous in terms of economic performance, with modest gains in terms of environmental effectiveness. Opportunities for future work include revisiting the problem by considering a full model where pollution transport to/from all regions is considered (not just into Attica). It is also of interest to consider an objective function that includes the health consequences of multiple pollutants, linking pollution levels to both economic and health costs, and weighting each pollutant according to the effects they induce on the health of the local population.

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**	FiNAcial 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[2]

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

[2] 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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