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Optimizing production with energy and GHG emission constraints in Greece: An input–output analysis

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ABSTRACT

Under its Kyoto and EU obligations, Greece has committed to a greenhouse gas (GHG) emissions increase of at most 25% compared to 1990 levels, to be achieved during the period 2008–2012. Although this restriction was initially regarded as being realistic, information derived from GHG emissions inventories shows that an increase of approximately 28% has already taken place between 1990 and 2005, highlighting the need for immediate action. This paper explores the reallocation of production in Greece, on a sector-by-sector basis, in order to meet overall demand constraints and GHG emissions targets. We pose a constrained optimization problem, taking into account the Greek environmental input–output matrix for 2005, the amount of utilized energy and pollution reduction options. We examine two scenarios, limiting fluctuations in sectoral production to at most 10% and 15%, respectively, compared to baseline (2005) values. Our results indicate that (i) GHG emissions can be reduced significantly with relatively limited effects on GVP growth rates, and that (ii) greater cutbacks in GHG emissions can be achieved as more flexible production scenarios are allowed.

1. Introduction

The European Union's Sixth Environment Action Programme (EAP), "Environment 2010: Our future, Our choice", includes Environment and Health as one of the four main target areas requiring greater effort. Air pollution is one of the issues featuring prominently in that area, in addition to being the focus of increasing global interest. In the EU, member-states are required to comply with the Clean Air for Europe (CAFÉ) objectives and new directives on air quality. The relationship between economic activity and air pollution emissions in the EU overall as well as on an individual country level is well documented (EEA, 2008), and is to be employed as a general policy framework in order to minimize environmental pressures. One of the tools available for work in that direction is the National Accounting Matrix Environmental Accounts (NAMEA). NAMEA is a statistical information system that combines conventional national accounts and environmental accounts, but includes no modelling assumptions or estimates of money value imputed to natural flows and assets. NAMEA was identified by the EU as a relevant part of the framework for environmental satellite accounts which are "attached" to national accounts (EC, 1994). The environmental accounts show the interactions between producer and consumer (household) activities, and the natural environment. These interrelationships occur as a consequence of the environmental requirements of these activities, including natural resource inputs and residual outputs.

By providing economic and environmental data in a consistent Leontief-type framework (Leontief and Ford, 1972), the NAMEA is well suited for analytical purposes, and we will make use of it here in order to model the relationship between sector-level production and GHG emissions in the Greek economy. At current rates, Greece will fail to meet its Kyoto obligations, which prescribe a maximum 25% increase over 1990 levels some time during 2008–2012 (an increase of 28% had already taken place between 1990 and 2005). This paper's main contribution is to explore the problem of reallocating production in Greece, in order to meet various GHG emissions, production, and demand constraints. We will do this by posing an appropriate constrained optimization problem, in an input–output analysis context. On an empirical level, our goal is to assess the effects of emission

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alleviation policies on basic macroeconomic and sectoral indicators in Greece. At the same time, this work could be viewed as a tool for decision makers and planners engaged in addressing economical, environmental and energy sustainability issues collectively. In particular, our approach determines combinations of optimal production and emissions reduction levels that policy makers may choose to target. For the various scenarios examined here—involving modifications in production output and energy usage under the Kyoto restrictions—our results indicate that there exist production configurations which achieve significant GHG emissions reductions with limited "sacrifices" made in terms of final demand to be met.

1.1. Related work

A NAMEA-based approach has been frequently used to connect greenhouse gases, regulated under the Kyoto protocol, with economic activity on a consistent basis. De Haan (2001) reported on the NAMEA of Netherlands, assessing macro-economic developments, industry-level results, and the origin and destination of pollution with respect to consumption and international trade. Moll and Acosta (2006) examined the German NAMEA matrix and derived the production-cycle-wide resource use and environmental impact potentials of final-demand product groups. The Turkish NAMEA is discussed byIpek Tunç et al. (2007), using an extended input–output model for 1996 data, thus identifying CO_2 sources and sectoral impact. The Finnish NAMEA was studied byMäenpää and Siikavirta (2007) where GHG emissions were attributed with respect to international trade and final consumption. The Spanish NAMEA for 2000, including water and air emissions, is discussed by Roca and Serrano (2007). Tarancón Morán et al. (2008) analyzed the primary factors behind CO_2 emissions in the Spanish electricity generation sector in order to propose effective mitigation policies aimed at tackling those emissions. The authors report structural rigidities that lead to the electricity sector's emissions, as a result of demand from several other sectors, whereas the electricity generation sector receives criticism for its energy and carbon intensity.

In this work we will take an input–output approach in "attributing" pollution to the various sectors, and in calculating the interdependence of sectors with respect to changes in final demand. Input–output matrices have been recently employed as a decision making tool for sustainable development and planning in models incorporating the impact of air pollution and energy usage on a national or regional level. In the literature there exist a number of studies that perform multicriteria optimization using variations of the input–output matrix, with particular emphasis on the macroeconomic variables of an economic entity (e.g., a country or region). A series of models has focused on the impact of water pollution. A combined three-criteria model is proposed by Cho (1999) for maximizing employment, and minimizing water pollution and energy consumption in the Cungbuk Province of South Korea, an economy with 12 sectors. Sánchez-Chóliz and Duarte (2005) examined the relationships between production processes and water pollution for seven major sector blocks of the Spanish economy. Spörri et al. (2007) developed an input–output model to predict the impact of the river Thur (northern Switzerland) rehabilitation activities on the local economy. This impact was accounted for through immediate effects, such as planning and construction activities, and through long-term effects such as changes in land use and recreational activity resulting from the modified riverscape.

The linkages between the economy, energy, and air pollution, with emphasis on production at the sectoral level, have been explored in various works proposing viable solutions consistent with sustainable energy usage, continuous growth, social welfare and reduced environmental degradation. A three-criterion model involving GDP and foreign-trade balance maximization, and fuel-and-energy minimization, was studied by Kravtsov and Pashkevich (2004) for the purpose of analyzing and choosing between alternative versions of development for the real sector of the national economy of Belarus. Olivera and Antunes (2002, 2004) constructed a model for the Portuguese economy, using 45 activity sectors, coupling the maximization of the employment, minimization of energy imports, maximization of GDP, and minimization of CO_2 emissions. Hsu and Chou (2000) proposed a multi-objective programming approach integrated with a Leontief inter-industry model to evaluate the impact of energy conservation policy on the cost of reducing CO_2 emissions and undertaking industrial adjustment in Taiwan.

The remainder of this paper is structured as follows. Section 2 discusses the compilation of the Greek NAMEA, focusing on the energy and environmental intensity coefficients. The specification of the main optimization problem, including objective function and constraints are detailed in Section 3. Section 4 discusses the optimal solutions under two possible scenarios with respect to the maximum production fluctuations that any sector is allowed to undergo.

2. The Greek environmental input–output matrix

In the next section, we will formulate a production optimization problem which will incorporate energy and pollution constraints. For this reason, we must know how energy and pollution are to be attributed to each unit of production in each sector. Towards that end, we discuss the calculation of the environmental input–output matrix for Greece, as well as the energy and pollution coefficients that will be required. These will be based on the NAMEA, which is briefly discussed next.

The NAMEA consists of a National Accounting Matrix (NAM) extended with Environmental Accounts, all presented in a matrix format that reconciles supply-use tables and sector accounts into a comprehensive accounting framework that can be presented at various levels of detail. 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, and output of residuals for the national economy. These inputs and outputs can be viewed as the environmental requirements of the economy. Environmental requirements generally are not related to market transactions, and therefore are not represented in the standard national accounts.

By presenting economic accounts in monetary terms and environmental accounts in the most relevant physical units, the NAMEA system maintains a strict distinction between the economic sphere and the natural environment. The NAMEA table links environmental and economic data, and allows for direct comparison between the environmental and the economic data. The table allows us to analyze variations of emissions in their time span, caused by: (i) variations in the economic structure, (ii) variations in emissions volume, (iii) variations in the efficiency of the "ecosystems" of producers and consumers and (iv) variations in the energy supply (Mylonas et al., 2000).

2.1. Energy consumption in Greece

Energy consumption in Greece was shown to be a key underlying parameter of economic growth and social welfare (Diakoulaki et al., 2006) and is tightly coupled with air emissions.

Energy usage is continuously increasing during the last decade, and planned changes in the country's energy mix are not deemed adequate to meet the GHG emissions restriction imposed by the Kyoto protocol. Thus, it appears necessary to examine the future sustainability prospects of the Greek economy in a "holistic" coupled economic–energetic–environmental approach, based on the NAMEA framework.

Data used to record the energy consumption patterns for the Greek economy were obtained from the Eurostat New Cronos and PRODCOMS database, the Greek Ministry of Development, and United Nations Production Statistics. The data were assigned into the economy's producing sectors using factors (production and activity data) derived from those databases. The final energy consumption for each energy consuming sector of the Greek economy is portrayed in Fig. 1. According to historical time series data, the energy consumption of the manufacturing sector remains rather stable for the period covered in the databases used, whereas energy consumption in the transportation, domestic and tertiary sectors is increasing. An in-depth examination shows that the manufacturing sector (Fig. 1) is dominated by the non-ferrous metals and the non-metallic minerals sectors; this is also reported in Salta et al. (2009). Industrial energy demand in Greece appears to be rather inelastic, while there is strong evidence of a substitutability relationship between fuels (oil and electricity) (Polemis, 2007).

The total energy consumption in the Greek economy is a key determinant of economic growth (see Fig. 2, and Hondroyiannis et al., 2002) and duly associated with air emissions. Diakoulaki et al. (2006, used a bottom-up approach leading from sectoral to country-level figures, to decompose energy usage and obtain better insight into the origin of the various factors influencing CO_2 emissions. That study concluded that economic growth and the ensuing social welfare are strongly coupled to energy consumption and atmospheric emissions.

2.2. Environmental data and impact

The air emissions data were estimated using the so-called 'air emissions inventory first approach'. Presently, international agreements on air emissions include the Convention on Long-Range Transboundary Air Pollution (CLRTAP) with reporting to UNECE/EMEP and the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC Common Reporting Format (CRF) covers six categories of greenhouse gases (CO_2, N_2O, CH_4, HFCs, PFCs and SF_6) plus four indirect greenhouse gases

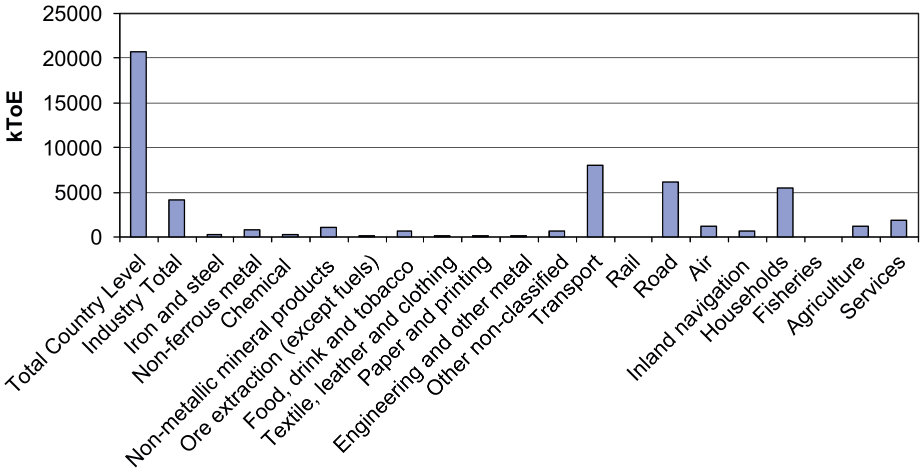

Fig. 1. Final energy consumption per sector in the Greek economy for 2005, in kilotons of oil equivalent (kTOE).

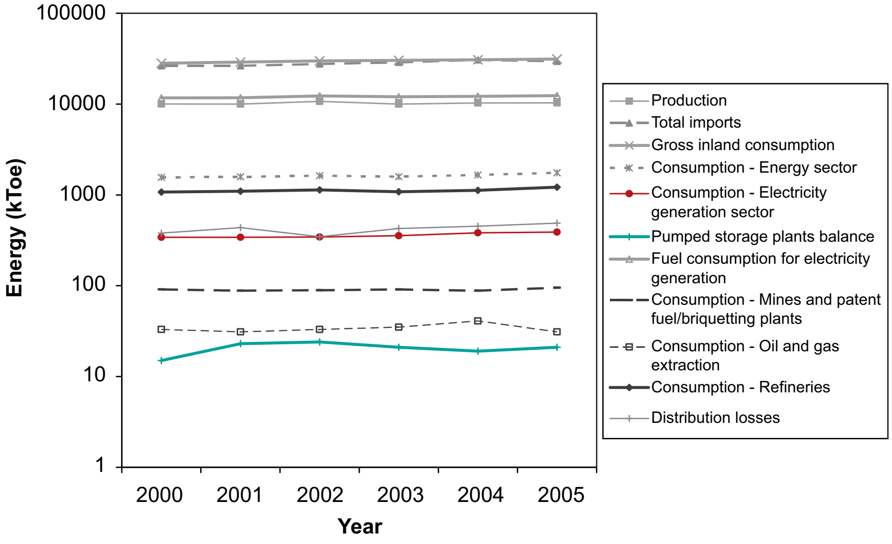

Fig. 2. Total energy production and consumption (in kilotons of oil equivalent) in energy-related sectors.

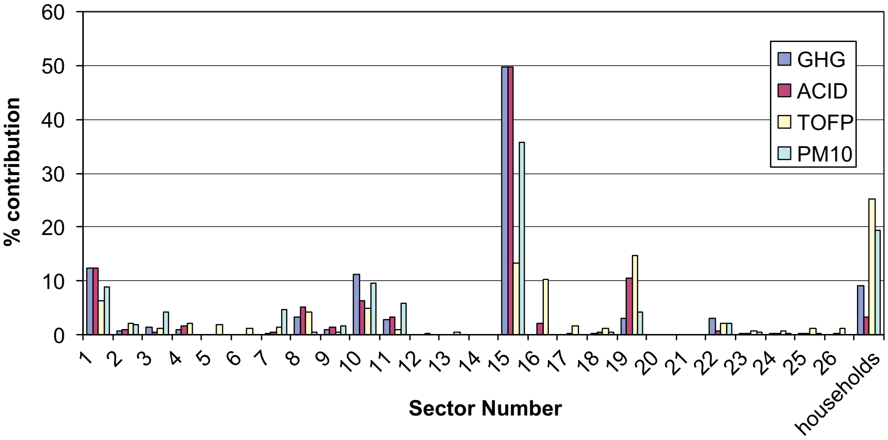

Fig. 3. Percentage contribution of environmental stressors by economic activity. See Table A1 in Appendix for the Sector names corresponding to the numbers 1–26, shown on the horizontal axis.

(NO_x, CO, NMVOC, SO_2). The UNECE/EMEP reporting only includes NO_x, CO, NMVOC and SO_2 plus NH_3 plus nine heavy metals as well as 17 persistent organic pollutants (POPs).

The data utilized in this study are official data reported by the Greek Ministry of Environment and Public Works to fulfil the country's obligations to the organizations mentioned above. The data are based on the CORINAIR methodology and are classified according to the Selected Nomenclature for sources of Air Pollution (SNAP). The original data were processed, to deriving a NAMEA-consistent total and to arrange process-oriented data in order to fit into the NACE[4]-based classification, presently adopted for NAMEA. A hybrid approach combining simple (direct) and complex allocations, was followed in order to attribute the SNAP-classified emissions to NACE-based economic activities or households' consumption functions. Concerning the complex allocations, some SNAP processes emissions had to be split into several NAMEA activities. These emissions were attributed to NACE codes or households' consumption functions using fuel consumption data, technical data contained in CORINAIR and the NSSG, expert knowledge, or other data.

Air-emissions were further grouped and aggregated into four environmental pressure variables, following the recommendations by the European Environment Agency (Moll et al., 2006). Those were: greenhouse gases (GHG) that collectively contribute to global warming and quantified based on the global warming potential (GWP) index, acidification (ACID), tropospheric ozone forming potential (TOFP) and concentrations of particulate matter (PM_{10}) with diameter less than 10 μm. They are defined via the following set of equations (see for example, Moll et al., 2006):

$$GHG = CO_2 + 310{*}N_2O + 21{*}CH_4 \tag{1}$$

$$ACID = SO_2 + 0.7{*}NO_x + 1.9{*}NH_3 \tag{1}$$

$$TOFP = NMVOC + 1.22{*} + 0.11{*}CO + 0.014{*}CH_4, \tag{1}$$

where chemical quantities are measured in ktons.

Fig. 3 shows the percentage attribution of the environmental stressors to the Greek production sectors (there are 26 sectors, identified by numerical code in the horizontal axis—see Table A1 in Appendix for the corresponding names). In absolute terms, the most severe pressure appears in GHG, especially in electricity production (sector 15), where ACID and PM_{10} are also major concerns. Household consumption appears to have the highest TOFP impact among all sectors.

The impact of the environmental stressors on the economy production levels is assessed (as in Economidis et al., 2008) from:

1. The vector of direct coefficients, a_k, of the kth pollutant's air intensity, where $k=1,\ldots,4$, denotes the environmental pressure variable (i.e., GHG, TOFP, ACID, and PM_{10}, in that order); the jth entry ($j=1,\ldots,26$) of each a_k is computed as emissions of pollutant k in the jth sector, E_{kj}, per gross output, x_j, for that sector:

   $a_{kj} = E_{kj}/x_j$.
2. The indirect coefficients, ε_{kj}, which depend on the direct effects and the matrix of technology coefficients for domestic production, A (the latter was computed from the Greek input–output matrix for 2005, using data from Skountzos et al., 2007—see Section 3):

   $\varepsilon_{kj} = a_{kj}(I - A^T)^{-1}$

These were further used to estimate: (a) the elasticity of the emissions' intensity with respect to final consumption, e_j^c, that shows the unitary expansion of the final demand of the specific industry, and (b) the elasticity with respect to final production, e_j^p, which estimates the unitary increase of a given industry's production. Table 1 shows the estimated coefficients by sector for the four environmental stressors examined.

Concerning the direct emission intensity coefficients, a_{kj}, the most important environmental stressor appears to the GHG, and in particular CO_2, which dominates the emissions in this category. The energy production sector (sector 15) exhibits the highest direct emission intensity coefficient, as expected, and in agreement with other similar studies (e.g., Tarancón Morán et al., 2008). Other significant parameters are found in sector 10 (non-metallic mineral products, NACE activity 26) and sector 3 (mining, NACE activities 10–14), that involve fuel combustion in the transformation process, and mining activities. From the other stressors, TOFP and ACID exhibit lower values mainly associated with domestic services and agriculture. Based on the elasticity coefficients, e_j^c and e_j^p, GHG appears to be the most important stressor. The highest values are found in the electric energy, non-metallic mineral products, mining, agriculture, basic metals, and petroleum sectors. However, the largest indirect effect is from the manufacturing and construction industries, due to their extensive

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[4] NACE: Nomenclature statistique des Activités économiques dans la Communauté Européenne.

Table 1
Emission intensity coefficients by industry and pollutants. Sector numbers refer to the industries shown in Table A1 in Appendix.

Sector no.	GHG			TOFP			ACID			PM10		
	a_{1j}	e_j^p	e_j^c	a_{2j}	e_j^p	e_j^c	a_{3j}	e_j^p	e_j^c	a_{4j}	e_j^p	e_j^c
1.	1.180817	1.65	2.1096	0.008247	0.0104	0.0145	0.010332	0.0142	0.0184	0.000359	0.0005	0.0006
2.	0.285558	0.3418	0.2533	0.008244	0.008	0.0073	0.002958	0.0035	0.0027	0.000758	0.0007	0.0007
3.	1.333808	0.3947	0.5694	0.021351	0.0043	0.0091	0.00654	0.0024	0.0023	0.00176	0.0003	0.0006
4.	0.063389	0.8019	0.071	0.001255	0.0054	0.0012	0.000276	0.0066	0.0003	7.12E−06	0.0003	0
5.	0.024523	0.5094	0.0167	0.002952	0.0041	0.002	0.000245	0.0043	0.0002	1.79E−05	0.0001	0
6.	0.027891	0.3936	0.0225	0.007466	0.0071	0.0059	0.000158	0.0031	0.0001	5.28E−05	0.0001	0
7.	0.091502	0.3498	0.102	0.002271	0.0028	0.0022	0.00115	0.0032	0.0011	0.000697	0.0007	0.0007
8.	0.551182	0.6983	0.7445	0.004719	0.0059	0.0062	0.005583	0.0061	0.0078	3.25E−05	0.0002	0
9.	0.499915	0.4632	0.3579	0.003234	0.0023	0.0022	0.004901	0.0042	0.0032	0.000181	0.0002	0.0001
10.	3.679021	3.6759	3.5111	0.016011	0.0154	0.015	0.0143	0.0168	0.0135	0.001535	0.0015	0.0014
11.	0.630604	1.403	0.7845	0.002258	0.0043	0.0027	0.00635	0.0124	0.0077	0.000635	0.0008	0.0007
12.	0.360382	0.7318	0.3806	0.000862	0.0022	0.0008	0.00213	0.0055	0.002	8.12E−05	0.0003	0.0001
13.	0.439045	0.2322	0.1846	0.000881	0.0006	0.0003	0.00317	0.0017	0.001	1.73E−05	0	0
14.	0.266535	0.4495	0.2587	0.000374	0.0014	0.0003	0.000292	0.0022	0.0002	6.65E−06	0.0002	0
15.	11.49947	12.4758	17.1902	0.026879	0.0301	0.0403	0.096393	0.1044	0.144	0.003717	0.0041	0.0055
16.	0.011035	0.5693	0.0132	0.002101	0.0044	0.0023	0.000334	0.0037	0.0003	7.35E−05	0.0003	0.0001
17.	0.012418	0.1674	0.0277	0.000487	0.0014	0.0005	5.75E-05	0.0015	0.0001	1.22E−06	0	0
18.	0.011062	0.3845	0.0108	0.00032	0.0022	0.0003	0.000111	0.0031	0.0001	7.95E−06	0.0001	0
19.	0.210795	0.3994	0.3107	0.005609	0.0062	0.0084	0.003889	0.0052	0.0056	9.25E−05	0.0001	0.0001
20.	0.002492	0.2045	0.005	0.000272	0.0013	0.0004	5.45E−05	0.0017	0.0001	0	0.0001	0
21.	0.0021	0.0648	0.0043	5.04E−05	0.0003	0	9.75E−06	0.0004	0	1.53E−06	0	0
22.	0.183601	0.3967	0.1836	0.001014	0.0018	0.001	0.000356	0.0021	0.0004	5.28E−05	0.0001	0.0001
23.	0.028036	0.1157	0.0272	0.000685	0.001	0.0007	0.000247	0.0008	0.0002	1.94E−05	0	0
24.	0.014712	0.1654	0.0148	0.000448	0.0008	0.0004	0.000131	0.0013	0.0001	1.13E−05	0	0
25.	0.02143	0.1423	0.027	2.71E−05	0.0003	0	2.63E−05	0.001	0	1.56E−05	0	0
26.	0.078288	0.0783	0.0783	0.011111	0.0111	0.0111	0.001472	0.0015	0.0015	5.51E−05	0.0001	0.0001

intermediate inputs. The impact of other environmental parameters does not seem to influence economic activities significantly.

3. Problem setup

Armed with the pollution coefficients discussed in the previous section, we proceed to formulate the constrained optimization problem central to this work. Our formulation follows the "standard" Leontief treatment (Leontief, 1966; Yan, 1969). For an economy with n sectors, let $x \in \mathbb{R}_*^n$ be the gross value of production vector, Y the final demand, M imports, and X the $n \times n$ input–output matrix. These satisfy the basic relationship:

$$x = X\mathbb{E} + Y - M, \tag{2}$$

where $\mathbb{E}^T = [1, 1, \ldots, 1]^T$ (so that $X\mathbb{E}$ is the column-sum of the input–output matrix), and Y is assumed to be constant at this point. The matrix of technology coefficients is obtained from the input–output matrix and the production vector (assuming $x > 0$) as follows:

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

Via some algebraic manipulation, the last relationship can be written as[5] $X = A\,diag(x)$, so that $X\mathbb{E} = Ax$. Based on this, we can rewrite (2) as

$$x = Ax + Y - M \Rightarrow (I - A)x = Y - M \tag{4}$$

which is the basic linear Leontief model (Leontief, 1966; Yan, 1969).

The total intermediate consumption at market prices can be written as be the total value of inputs in basic prices (the row-sum of the input–output matrix) plus taxes, T, VAT, V, and subsidies, S, all written as column-vectors in $\mathbb{R}^n$ (e.g., Mylonas et al., 2000):

$$x_T = X^T\mathbb{E} + T + S + V = diag(x)A^T\mathbb{E} + T + S + V \tag{5}$$

with S assumed constant. Taxes and VAT are taken to be directly proportional to the total value of inputs in basic prices (Karagianni et al., 2004; Pempetzoglou, 2003). In our notation, this can be expressed as

$$T = diag(a_T)X^T\mathbb{E} = diag(a_T)diag(x), A^T\mathbb{E}$$

and

$$V = diag(a_{VAT})X^T\mathbb{E} = diag(a_{VAT})diag(x)A^T\mathbb{E},$$

where the vectors a_T, a_{VAT} correspond to the model's tax and VAT proportionality constants, respectively.

Based on the above relationships, the vector form of the gross value added (GVA) (the difference between production and total intermediate consumption) can be computed as

$$\begin{aligned} GVA &= x - x_T \\ &= x - diag(x)A^T\mathbb{E} - diag(a_T)diag(x)A^T\mathbb{E} \\ &\quad - diag(a_{VAT})diag(x)A^T\mathbb{E} - S \\ &= x - diag(x)(I + diag(a_T + a_{VAT}))A^T\mathbb{E} - S \end{aligned} \tag{6}$$

GHG pollution emanating from each sector will be assumed to be linearly related to that sector's production. Thus, we may define a GHG pollution production vector corresponding to x:

$$P = diag(a_{GHG})x, \tag{7}$$

where a_{GHG} is a vector of pollution coefficients, whose choice we will discuss shortly. The energy consumption vector corresponding to a production of x will be similarly defined as

$$C = diag(a_e)x, \tag{8}$$

where a_e is a vector containing the energy coefficients for all sectors (i.e., their energy use per unit of production), calculated

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[5] For a vector x, $diag(x)$ denotes the diagonal matrix whose diagonal elements are those of x.

from the data discussed in Section 2.1. We note that the total pollution and total energy consumption corresponding to a production vector x are: $\sum_i P_i = \mathbb{E}^T diag(a_{GHG})x = a_{GHG}^T x$, and $\sum_i C_i = \mathbb{E}^T diag(a_e)x = a_e^T x$, respectively.

Finally, the economy's total GVP is the sum of elements in the production vector:

$$GVP = \mathbb{E}^T x. \tag{9}$$

3.1. Optimization problem

We will consider maximizing total GVP, which in the notation used in the previous section, and assuming imports remain constant, is equivalent to

$$\max J = \mathbb{E}^T x$$

subject to the following (linear) constraints:

- $\sum_i C_i = a_e^T x \leq e_u$, where e_u is a (scalar) upper limit on energy used. This will ensure that we only consider production vectors that do not exceed some energy usage threshold (e.g., 2005 levels).
- $\sum_i P_i = a_{GHG}^T x \leq p_u$, where p_u is a scalar upper limit on pollution. Any feasible solution must not exceed this threshold, which we will lower progressively.
- $\mathbb{E}^T (I-A)x \geq \mathbb{E}^T (Y_l - M)$, where Y_l is a lower bound on the total sum of demand met across all sectors. By comparing with (4), we observe that this constraint forces solutions that will meet a demand vector of at least Y_l. We will discuss the choice of Y_l shortly.
- $x_l \leq x \leq x_u$, where x_l, $x_u \in \mathbb{R}^n$ are lower and upper bounds on production. Production fluctuations in any sector should be kept within reasonable limits. The specific choices of upper and lower bounds will be addressed in the next section.
- $x \geq 0$ (gross value of production must be non-negative in every sector).

We have chosen to place a single constraint (third on the above list) on the *total* production. The fourth constraint is placed in order to avoid solutions which boost production to unrealistic levels for some sectors (e.g., those which contribute most to total final demand, or those who pollute least) and eliminate it in others. An alternative would be to replace our third constraint with a series of similar constraints, one for each sector, and place upper and lower bounds on the final demand of each sector. If that approach is taken, it would be necessary to also include inequality constraints on the final demand in order for the optimization to be meaningful. This is because, in our case, the matrix $(I-A)$ will turn out to be nonsingular; thus, if one insists on specifying a final demand, Y, there will be a unique solution, x, satisfying $(I-A)x = Y-M$, and there is no optimization to be done.

We note that our model is static and therefore does not specify the time over which it is to be applied. Therefore, the constraints considered here (and the corresponding solutions which can be achieved by applying them) are to be viewed as policy targets. This means that the various bounds introduced in the model, as well as the time frame in which they are to be attained must be feasible and realistic. We will have more to say about this in the next section.

For the sake of simplicity, and because the impact of the various sectors on TOFP, ACID and PM_{10} is small or negligible compared to GHG, we will concentrate on this latter variable in the optimization problem posed above. Thus, the coefficient a_{GHG} will be the vector of GHG direct coefficients (a_1, from Table 1), when calculating the pollution, $a_{GHG}^T x$, that would be produced by a particular production vector, x. Of course the analysis could be performed including the other pollutants via a treatment similar to that of GHG. Finally, we will exclude sector 26 (recreational, cultural and sporting activities, activities of households, extra-territorial organizations—see Table A1) from the analysis, because the economic activities contained therein are outside the scope of this study.

3.2. Policy scenarios and choice of parameters

Our analysis uses the 2005 input–output matrix for the Greek economy, denoted by X in (2), as a baseline for making comparisons with a set of policy scenarios which we describe briefly next. The matrix itself, as well as data on final demand, Y, and imports, M, for 2005 were obtained from Skountzos et al. (2007). We will consider optimizing the total production value by reallocating sectoral product, for varying levels of greenhouse emission cutbacks starting from no cutbacks at all (i.e., at 2005 levels), and progressing by reducing allowable GHG emissions gradually. Of course, the production levels one arrives at in this fashion will depend on the allowable fluctuations in sectoral production and the overall demand that must be satisfied.

As we have already mentioned, based on our latest available data (2005) Greece had already surpassed its year 2012 allowed increase by 3%. Given the time frame, and after taking into account expert opinion (Stromplos, 2009), it appears that a 9–15% GHG reduction is a reasonable current target for Greece that will enable it to meet its Kyoto obligations. As we will see shortly, GHG reduction at this range is possible by allowing variations of 10–15% in sectoral production and of 3% in total demand that can be met. These variations are estimated to be within "reasonable" limits for the Greek economy for a time frame of 3–5 years (Stromplos, 2009). Thus, in our model we will allow up to a 3% reduction in total demand (Y_l=0.97Y); constraints in sectoral production will be either ±10% (we will call this the *restrictive* scenario) or ±15% (termed the *flexible* scenario) compared to their baseline values. Of course, additional scenarios can easily be examined using the same methodology.

4. Solutions

Using the Greek environmental matrix for 2005, we calculated the technology matrix, A, and the coefficients a_e, and a_{GHG}=a_1. We set the energy upper bound e_u to be 100% of the 2005 usage and the minimum total demand met, Y_l, to be 97% of its nominal (2005) value. The next sections describe the results for each of the two scenarios under consideration. We will refer to each sector by name in the text and by its corresponding number (as per Table A1 in Appendix) in the various graphs and figures.

4.1. Results under the restrictive scenario

The production lower (x_l) and upper bounds (x_u) were set to be 90% and 110% of the nominal production vector, respectively. We computed the optimal total production (by solving the problem in Section 3.1 and using (8)) and the corresponding sectoral production values, as we gradualy reduced GHG emissions. Fig. 4 shows the resulting curve that represents the relationship between GVP and GHG emissions levels, under the ±10% (restrictive) scenario. We observe that the reallocation of sectoral production without the implementation of any GHG emission mitigation policies or other constraints, such as domestic demand limitations, allows an increase of 9.7% in total GVP compared to the baseline (2005) status. Gradual cutbacks in emissions restrict the production increases that are possible through production reallocations, from 9.7% down to 4.3% (as we move from 0% to 9% GHG emissions reduction). The optimization problem was infeasible for an emissions reduction of 10% or more under the restrictive scenario. The combination of optimal production and emissions reduction that policy makers may choose to implement would of course depend on the desired growth level, on the particular binding emissions targets and on the effects of the chosen policy on other economic variables; for example if the government is obliged to reduce GHG emissions by 5%, it will have to sacrifice 1.2% in terms of economic growth.

Overall, the 10% allowable fluctuations in sectoral production permit a maximum GHG emissions cut of approximately 9.9%. Here, we have chosen to present data for a less-than-maximal, but viable, reduction of 9%. We have done this because demanding optimality in GHG emissions (e.g., moving from a 9% cut to the maximum, 9.9%), is accompanied by a precipitous—on the order of 8%—drop in all major economic variables examined here, and is thus considered too severe.

Table 2 shows the changes (over the nominal values) of our main economic variables, including GVP, GVA, total GHG emissions, total tax revenues, VAT and total energy use, at the aggregate level. Percentage changes are shown in parenthesis and brackets, indicating that the reallocation of sectoral production allows for a 9.7% increase in GVP (with no emissions reduction), while the adoption of emission mitigation policies may reduce those gains by a maximum of 5.4%; thus if production levels are optimized, a 9% reduction in total GHG emissions still permits a 4.3% increase in GVP. Equivalent effects are observed in the GVA; without environmental restrictions, GVA may increase by 9.5%, whereas policies that lead to 9% emission cutbacks restrict the GVA increase to 4.8%. Emissions mitigation policies seem to have significant effects on taxation; the Ministry of Finance may forgo an approximate 7.3% tax revenue increase that could be achieved with 0% GHG cutbacks. In terms of VAT, the potential increase lost is limited to 3.5%. We also note that under the optimal solution with 0% GHG changes, energy use is reduced by 0.7% compared to baseline. Under the maximum possible emissions limitation, energy use is restricted far more (8.2%).

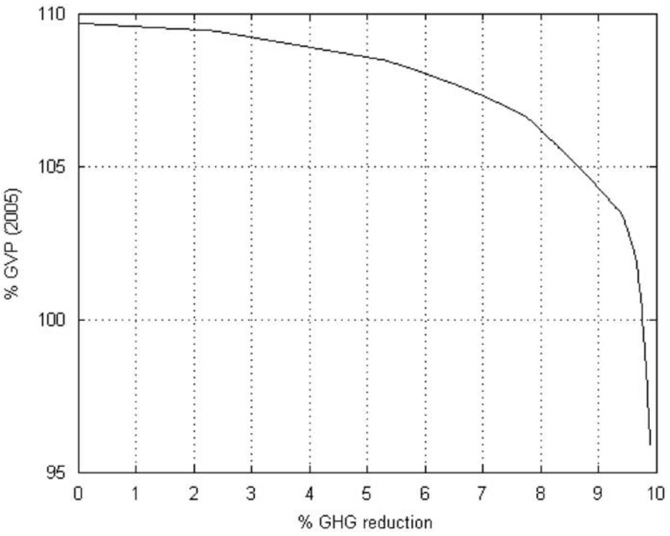

Fig. 4. Optimal production level vs. GHG emissions reduction targets under the restrictive scenario.

Table A2 (see Appendix) indicates the percentage changes in the value of all variables at the sectoral level, under the restrictive scenario. In the absence of any environmental policy, compared to the baseline case, the reallocation mainly reduces the sector of electricity generation, and increases all other sectors by the maximum 10% allowed. GHG emissions and tax revenues behave in the same way, as one would expect due to their linear relationship with production in our model. With respect to changes in sector GVAs, there are a few differences in percentage changes compared to the behavior of production levels, such as in agriculture (+9%), manufacture of food products, beverages and tobacco (+7.4%), manufacture of textiles and textile products (+8.5%), and energy use in fisheries (0%). VAT increases by 10% in about half of the sectors, including agriculture, fisheries, manufacture of food products, beverages and tobacco, manufacture of pulp, paper and paper products, publishing and printing, construction, hotels and restaurants, transport, storage and communication, financial intermediation, real estate, renting and business activities, public administration and defence, sewage and refuse disposal, education, health and social work and activities of membership organizations.

Table A2 also indicates the effects of a reallocation in sectoral production with a 9% GHG emissions reduction. In this case, almost half of the sectors face the maximum reduction (−10%) in GVP value, tax revenues and GHG emissions. The remaining sectors show an increase of 10%, except for public administration and defence and sewage and refuse disposal, whose increase is limited to 2%. The situation is similar for energy use, with the exception of fisheries that remain unchanged. GVA increases by 10% in 10 sectors, by 8.5% in manufacture of textiles and textile products, by 7.4% in manufacture of food products, beverages and tobacco and by 2% in public administration and defence and sewage and refuse disposal, while it decreases by 10% in all other sectors, except for agriculture that declines by 9%. VAT is reduced by 10% in agriculture, fisheries and transport, storage and communication, whereas it increases by 10% in nine sectors. In public administration and defence, as well as in sewage and refuse disposal, VAT increases are limited to 2%, while in all other sectors VAT remains unchanged.

Table 2
Nominal, optimal values and percentage changes of main economic variables under the restrictive scenario.

	Nominal (2005) values (baseline)	Optimal values with 0% change in total GHG emissions (*restrictive scenario*)	Optimal values with 9% reduction in total GHG emissions (*restrictive scenario*)
Total GHG emissions (ktons)	102,705	102,705 (0%)[a]	93,462 [−9%][b]
Total GVP (M$)	265,712	291,390 (9.7%)	277,117 [4.3%]
Total GVA (M$)	160,394	175,696 (9.5%)	168,116 [4.8%]
Total tax revenues (M$)	2726	2978 (9.2%)	2778 [1.9%]
Total VAT (M$)	3227	3550 (10%)	3436 [6.5%]
Total energy use (TJ)	950	943 (−0.7%)	872 [−8.2%]

[a] The percentages in parenthesis '( )' indicate the percentage changes in values with 0% change in total GHG emissions (restrictive scenario compared to baseline).

[b] The percentages in brackets '[ ]' indicate the percentage changes in values with 9% reduction in total GHG emissions (restrictive scenario compared to baseline).

4.1.1. *A note on the relationship between optimal GVP and GHG reductions*

The GVP vs. GHG reduction curve depicted in Fig. 4, could also be viewed in the context of multi-objective optimization, where one seeks to maximize both GVP and GHG cuts. In that case, Fig. 4 shows the Paretto front on which various trade-offs may be sought. We observe that the front appears to piecewise-linear (which is to be expected in a linear problem such as ours), with a progressively negative slope. Intuitively, as the GHG constraint becomes "tighter", maintaining an optimal solution to the original (linear) problem means cutting back on the sector with the highest GHG production to GVP contribution ratio. In the upper part of the curve, the relationship is more "horizontal", so that we can achieve relatively significant reductions in GHG without sacrificing too much GVP. The opposite is true as we approach the end of the lower part of the curve. A relatively simple way to explore the trade-off represented in the Pareto front is to examine its slope. A piecewise linear approximation obtained via least-squares indicates the intervals on which the relationship is linear, along with the corresponding (see Table 3), with slopes corresponding to the marginal cost in GVP for reducing GHG emissions one additional percentage point.

We have also calculated the optimal solution at a few intermediate points of the GVP vs. GHG reduction curve shown in Fig. 4. Table A3 shows the values of the main economic variables at 3% and 6% GHG reduction. Because of space considerations, we have not included detailed figures for each sector here; they are available from the authors upon request, or online (Hristu-Varsakelis et al., 2009).

4.2. *Results under the flexible scenario*

We repeated the optimization procedure, this time allowing for a ±15% change in the production of each sector, compared to its 2005 levels. The resulting GVP for varying levels of pollution allowed is shown in Fig. 5. This time, it was possible to reduce GHG emissions up to approximately 14.5% before the problem became infeasible. The curve in Fig. 5 indicates that the optimal production level that can be achieved, with an allowable 15% fluctuation in sectoral product reallocation and the lack of emissions restriction policies, may boost GVP up to 14.5% compared to the initial (2005) status of production. This increase defines the base case of the flexible scenario. We observe that gradual emission cutbacks lower the GVP increases made possible by optimizing production, from 14.5% to approximately 5.5%, for a GHG reduction of 14%, at which point further GHG reductions cause a precipitous drop in GVP. As in Section 4.1 we will choose to discuss a less-than-optimal reduction of 14%, in order to avoid the large reductions (approximately 10%) in all economic variables values generated by demanding the maximum feasible cutback in emissions.

Table 3
Piecewise linear approximation to the GVP vs. %GHG reduction curve shown in Fig. 4 (restrictive scenario). The least-squares fit obtained was such that the R^2 coefficient for all linear segments was better than 0.99, while the mean percentage regression error was no worse than 0.061%.

%GHG reduction interval	*Slope*
0–2.56	−0.1087
2-56–5.99	−0.3548
5.99–7.97	−0.8464
7.97–9.55	−2.0559
9.55–9.65	−6.2650
9.65–9.77	−16.5326
9.77–9.9	−30.5992

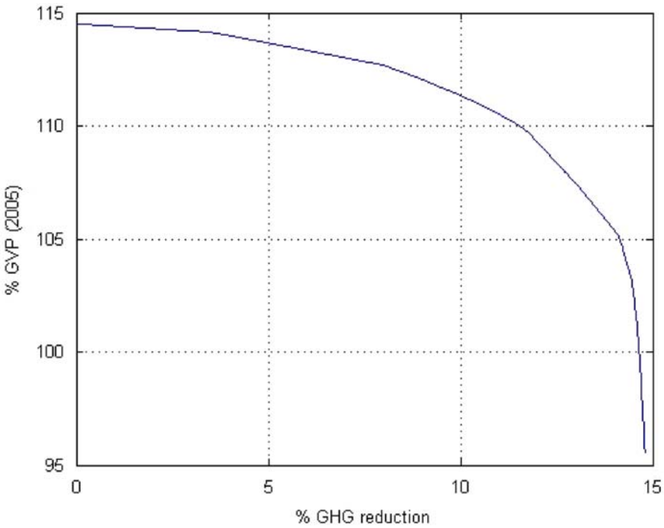

Fig. 5. Optimal production level vs. GHG emissions reduction targets under the flexible scenario.

Table 4 shows the changes (over the nominal values) of the main economic variables at the aggregate level and lists their percentage changes. If, under the flexible scenario, emissions cutbacks reach 14%, there is an opportunity cost of 9% in GVP compared to what can be achieved with optimal production allocation but no GHG reduction. Specifically, the implementation of emissions mitigation policies will restrict the GVP increase to 5.5% under optimal allocation, while production can increase by 14.5% in the absence of environmental policies. There are similar effects on GVA (14.3% increase over baseline with 0% GHG reduction and 6.1% with 14% GHG reduction) as well as VAT (a 15% increase with no environmental policy in place, versus 7.8% with 14% GHG reduction). The total taxation undergoes an increase of 13.9% compared to its 2005 level if emissions remain at baseline levels as well, and an increase of just 2.4% in the case of the maximum (14%) emissions reduction considered here. The corresponding energy use levels are 1% and 12.4% lower than their baseline values.

The percentage changes in the value of all variables at the sectoral level, under the flexible scenario (±15% fluctuations in sectoral production compared to baseline values and 14% emissions cutbacks) are shown in Table A2 in Appendix. The results differ from those in the restrictive scenario mainly in the magnitude of their fluctuations, which is much greater under the flexible set-up. The sectoral movements reach +15% for all sectors except for electricity generation (which is reduced by −15%). The same percentage changes occur for GVP, GHG emissions and tax revenues. In the GVA case, results are slightly different, in the sense that agriculture, manufacture of food products, beverages and tobacco and manufacture of textiles and textile products increase by 13.5%, 11% and 12.8%, respectively. Energy usage remains unchanged in fisheries, and VAT increases by 15% in 13 sectors; in all other sectors, VAT remains unchanged over its 2005 levels.

If we allow for a ±15% fluctuation in sectoral production and simultaneously implement emissions alleviation policies that cut emissions down to 14%, the situation changes as follows: in 12 sectors, GVP, GHG emissions and tax revenues increase by 15%; in all other sectors, emissions are reduced by 15%, except for public administration and defence, and sewage and refuse disposal, which decrease by 12.1%. Similar results occur in GVA and energy usage. As far as GVA is concerned, the main difference over

Table 4
Nominal, optimal values and percentage changes in the values of main economic variables under the flexible scenario.

	Nominal (2005) values (baseline)	Optimal values with 0% change in total GHG emissions (*flexible scenario*)	Optimal values with 14% reduction in total GHG emissions (*flexible scenario*)
Total GHG emissions (ktons)	102,705	102,705 (0%)[a]	88,326 [–14%][b]
Total GVP (M$)	265,712	304,229 (14.5%)	280,023 [5.4%]
Total GVA (M$)	160,394	183,348 (14.3%)	170,176 [6.1%]
Total tax revenues (M$)	2726	3104 (13.9%)	2792 [2.4%]
Total VAT (M$)	3227	3711 (15%)	3478 [7.8%]
Total energy use (TJ)	950	940 (–1%)	832 [–12.4%]

[a] The percentages in parenthesis '( )' indicate the percentage changes in values with 0% change in total GHG emissions (flexible scenario compared to baseline).

[b] The percentages in brackets '[ ]' indicate the percentage changes in values with 14% reduction in total GHG emissions (flexible scenario compared to baseline).

Table 5
Piecewise linear approximation to the GVP vs. %GHG reduction curve shown in Fig. 4 (flexible scenario). The least-squares fit obtained was such that the $R^2$2 coefficient for all linear segments was better than 0.99, while the mean percentage regression error was no worse than 0.09%.

%GHG reduction interval	*Slope*
0–3.85	–0.1089
3.85–8.99	–0.3550
8.99–11.96	–0.8475
11.96–14.33	–2.0590
14.33–14.48	–6.3364
14.48–14.65	–16.3600
14.65–14.9	–30.1420

production levels is in the magnitude of changes in agriculture (–13.5%), in manufacture of food products, beverages and tobacco (+11%) and in manufacture of textiles and textile products (+12.8%). In terms of energy use, fisheries remain unchanged. Finally, VAT increases by 15% in nine sectors; it decreases in agriculture, fisheries and transport, and storage and communication by 15%, and in public administration and defence, and sewage and refuse disposal by 12.1%; it remains constant in all other sectors.

4.2.1. *A note on the Pareto front*

As in Section 4.1, the relationship between the optimal GVP that can be achieved with a given GHG emissions reduction (shown in Fig. 5) can be viewed as a Pareto front. It has similar characteristics as the one obtained for the restrictive scenario. Table 5 shows the corresponding least-squares piecewise linear approximation, indicating the marginal cost in GVP for the various ranges of GHG reduction.

Table A3 shows the values of the main economic variables at two intermediate points (4.8% and 9.6% GHG reduction) on the GVP vs. GHG % reduction curve with the flexible scenario. Detailed sectoral breakdowns are available from the authors upon request, or online (Hristu-Varsakelis et al., 2009).

4.3. *Comparison between scenarios*

As one might expect, the restrictive scenario provides a more limited potential as far as the status of production and emissions mitigation are concerned. The reallocation of sectoral production, without the implementation of emissions alleviation policies, permits a GVP increase of 9.7% under the restrictive scenario instead of 14.5% under the flexible one. The adoption of environmental policies achieves a 9% cutback in emissions under the restrictive scenario—with an opportunity cost of 5.4% in terms of GVP—and a 14% cutback under the flexible one—with an opportunity cost of 9% in GVP. The adoption of the flexible scenario implies greater fluctuations in all economic variables level. As Table 6 indicates, and as one would expect, all indicators values undergo greater variations under the flexible set-up. Thus, comparing the restrictive and flexible scenarios, one may achieve greater emission limitations under the latter one (14% instead of 9%), as well as greater GVP (5.4% instead of 4.3%), GVA (6.1% instead of 4.8%), tax and VAT revenues (2.4% instead of 1.9% and 7.8% instead of 6.5%, respectively), and significantly lower energy use (–12.4% instead of –8.2%).

At the sectoral level (Table A2), electricity, gas and water supply is the sector undergoing the most significant negative effects, at least in the baseline case. Its limitations in GVP, GHG emissions, GVA, energy use and tax revenues vary between 10% and 15% in the base case, depending on the scenario followed. GVA displays increases in all 24 sectors, except for electricity, ranging from 7.4% to 15%. Energy use in fisheries remains unchanged under either scenario. VAT revenues increase by 10% and 15%, under the restrictive and the flexible scenario, respectively, in 13 sectors, and remain constant in all other sectors.

When we depart from the 0% GHG reduction case and implement emissions alleviation policies, effects are spread to additional sectors as well. The main differentiation between the two scenarios considered here rests only upon the magnitude of the percentage changes, except for public administration and defence, sewage and refuse disposal that show an increase of 2% in all variables under the restrictive scenario, but a decrease of 12.1% under the flexible scenario. As far as GVP, GVA, GHG emissions, energy use and tax revenues are concerned, there are 13 sectors that appear to shrink between –9% and –15%, depending on the scenario adopted (see Table A2). For these same variables, all other sectors undergo increases between 2% and 10% under the restrictive scenario and between 11% and 15% under the flexible one. Energy use in fisheries remains unchanged regardless of scenario. Under the restrictive scenario, VAT decreases by –10% in three sectors, increases by 2% in one sector and by 10% in nine sectors and remains unchanged in the rest; under the flexible scenario it decreases by –12.1% in one sector, by –15% in three sectors, it increases by 15% in nine sectors and remains unaffected in the remaining 12 sectors.

5. Conclusions

Because Greece has already surpassed (+28% in 2005) its obligation stemming from the Kyoto Protocol and the EU burden-sharing agreement to limit GHG emissions increases to 25% over 1990 levels, between 2008 and 2012, there is a pressing need to begin restricting emissions in the immediate future. The purpose of the paper was to compute and describe the effects accruing

Table 6
Percentage changes in the values of main economic variables at the aggregate level: comparison between scenarios.

	Optimized with no GHG reductions, compared to baseline (%)		*Optimized with GHG reductions, compared to baseline*	
	Restrictive scenario (%)	*Flexible scenario (%)*	*Restrictive scenario*	*Flexible scenario*
Total GHG emissions (ktons)	0	0	−9	−14
Total GVP (M$)	9.66	14.5	4.29	5.4
Total GVA (M$)	9.54	14.3	4.81	6.1
Total tax revenues (M$)	9.24	13.9	1.91	2.4
Total VAT (M$)	10.01	15	6.48	7.8
Total energy use (TJ)	−0.74	−1	−8.21	−12.4

from the adoption of emissions mitigation policies on main macroeconomic indicators as well as on sectoral production. We formulated and solved a constrained optimization problem, using data from the Greek environmental input–output matrix for 2005, in order to compute the optimal production levels (on a sector-by-sector basis) while meeting various GHG emissions targets. Other constraints concerned the amount of energy utilized, and the overall demand that must be met. We examined two scenarios: a *restrictive* one that permits fluctuations of at most 10% in sectoral production, and a *flexible* one, under which fluctuations may reach 15%, compared to their baseline values.

Our results indicate that greater cutbacks in GHG emissions can be achieved as more flexible production scenarios are allowed. Specifically, emissions restrictions can be significant, ranging from approximately 9% under the restrictive scenario to over 14% under the flexible one. These targets (along with the necessary fluctuations in sectoral production discussed previously) are viewed as realistic for the Greek economy, provided that action is taken now. As one would expect, however, the implementation of pollution mitigation policies induces adverse effects on GVP growth rates and other economic indicators values. GVP increases may be 5.4% (restrictive scenario) to 9.1% (flexible scenario) below what can be achieved in the base case, with no GHG reductions; this still corresponds to growth rates of 4.3% and 5.4%, respectively, compared to the 2005 status. All other economic indicators decline between 3.5% (VAT under the restrictive scenario) and 11.5% (tax revenues under the flexible scenario). Total energy savings may reach 8.2% under the restrictive scenario and 12.4% under the flexible one, compared to the 2005 levels. The sectors most affected in terms of production losses are agriculture, fisheries, mining and quarrying, manufacture of coke, refined petroleum products and nuclear fuel, manufacture of chemicals, chemical products and man-made fibres, manufacture of other non-metallic mineral products, manufacture of basic metals and fabricated metal products, manufacture of fabricated metal products, except machinery and equipment, manufacture of machinery and equipment, recycling, electricity, gas and water supply transport, storage and communication and public administration and defence, sewage and refuse disposal. In other words, the adoption of pollution alleviation policies tends to restrict secondary production sector activities and supports the expansion of tertiary production sector activities. We have included a brief analysis of the Pareto front associated with the problem of maximizing GVP and GHG emissions reductions simultaneously, showing the economic sacrifice needed to achieve various GHG emissions targets.

Apart from the differentiated results accruing from the various assumptions governing the scenarios examined here, interesting results arise from the reallocation of sectoral product, without the adoption of any pollution mitigation policies. Our model allows for a 9.7–14.5% increase in GVP, according to the 10% and the 15% scenario, respectively. Energy use falls slightly, by −0.7% and −1%. However, in this case only development targets can be achieved—no environmental goals are attained.

Table A1
Sector numbers, Nomenclature statistique des Activités économiques dans la Communauté Européenne (NACE) codes and activities in the 2005 Greek Input-Output Matrix.
Source: Economidis et al., 2008, p. 5.

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[a]

[a] 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.

Although environmental policy decisions will depend on additional variables, our work helps to identify combinations of optimal production and emissions reduction levels that policy makers may choose to implement. The results presented here

Table A2
Percentage changes in GVP, GHG emissions, tax revenues, GVA, energy use, and VAT at the sectoral level, for the restrictive and flexible scenarios of Section 4.

Sector no.	**Restrictive scenario**								**Flexible scenario**							
	Optimized with no GHG reductions, compared to baseline				*Optimized with GHG reductions (9%), compared to baseline*				*Optimized with no GHG reductions, compared to baseline*				*Optimized with GHG reductions (14%), compared to baseline*			
	GVP, GHG emissions and tax revenues (%)	GVA (%)	Energy use (%)	VAT (%)	GVP, GHG emissions and tax revenues (%)	GVA (%)	Energy use (%)	VAT (%)	GVP, GHG emissions and tax revenues (%)	GVA (%)	Energy use (%)	VAT (%)	GVP, GHG emissions and tax revenues (%)	GVA (%)	Energy use (%)	VAT(%)
1.	10	9	10	10	−10	−9	−10	−10	−10	−9	−10	−10	−15	−13.5	−15	−15
2.	10	10	0	10	−10	−10	0	−10	−10	−10	0	−10	−15	−15	0	−15
3.	10	10	10	0	−10	−10	−10	0	−10	−10	−10	0	−15	−15	−15	0
4.	10	7.4	10	10	10	7.4	10	10	10	7.4	10	10	15	11	15	15
5.	10	8.5	10	0	10	8.5	10	0	10	8.5	10	0	15	12.8	15	0
6.	10	10	10	0	10	10	10	0	10	10	10	0	15	15	15	0
7.	10	10	10	10	10	10	10	10	10	10	10	10	15	15	15	15
8.	10	10	10	0	−10	−10	−10	0	−10	−10	−10	0	−15	−15	−15	0
9.	10	10	10	0	−10	−10	−10	0	−10	−10	−10	0	−15	−15	−15	0
10.	10	10	10	0	−10	−10	−10	0	−10	−10	−10	0	−15	−15	−15	0
11.	10	10	10	0	−10	−10	−10	0	−10	−10	−10	0	−15	−15	−15	0
12.	10	10	10	0	−10	−10	− −10	0	−10	−10	−10	0	−15	−15	−15	0
13.	10	10	10	0	−10	−10	−10	0	−10	−10	−10	0	−15	−15	−15	0
14.	10	10	10	0	−10	−10	−10	0	−10	−10	−10	0	−15	−15	−15	0
15.	−10	−10	−10	0	−10	−10	−10	0	−10	−10	−10	0	−15	−15	−15	0
16.	10	10	10	10	10	10	10	10	10	10	10	10	15	15	15	15
17.	10	10	10	0	10	10	10	0	10	10	10	0	15	15	15	0
18.	10	10	10	10	10	10	10	10	10	10	10	10	15	15	15	15
19.	10	10	10	10	−10	−10	−10	−10	−10	−10	−10	−10	−15	−15	−15	−15
20.	10	10	10	10	10	10	10	10	10	10	10	10	15	15	15	15
21.	10	10	10	10	10	10	10	10	10	10	10	10	15	15	15	15
22.	10	10	10	10	2	2	2	2	2	2	2	2	−12.1	−12.1	−12.1	−12.1
23.	10	10	10	10	10	10	10	10	10	10	10	10	15	15	15	15
24.	10	10	10	10	10	10	10	10	10	10	10	10	15	15	15	15
25.	10	10	10	10	10	10	10	10	10	10	10	10	15	15	15	15

Table A3
Percentage changes in the values of main economic variables at the aggregate level, for intermediate points on the GVP vs. GHG reduction curve.

	Restrictive scenario (Fig. 4)		**Flexible scenario** (Fig. 5)	
	Optimized with 3% GHG reductions, compared to baseline (%)	*Optimized with 6% GHG reductions, compared to baseline (5) (%)*	*Optimized with 4.8% GHG reductions, compared to baseline*	*Optimized with 9.6% GHG reductions, compared to baseline*
Total GHG emissions	−3	−6	−4.8	−9.6
Total GVP	9.2	8	13.7	11.6%
Total GVA	9.2	8.3	13.7	12.3%
Total tax revenues	8.5	7.1	12.6	10.1%
Total VAT	9.7	7.8	14.3	11.7%
Total energy use	−2.2	−4.4	−3.4	−7.5%

offer an empirical assessment of the effects of emission alleviation policies on basic macroeconomic and sectoral indicators in Greece. Of course, the same methodology could be applied to other economies as well. Our findings may prove useful to theoretical and empirical research on specifying economic and environmental effects of policies with the use of environmental input–output tables. Finally, this work may also serve to inform policy makers regarding potential targets of emissions mitigation achievability, and provide a kind of 'warning' on the accompanying shocks that may arise in the economy. Opportunities for future work include relaxing some of the constraints present in our current model, including the requirement for a decrease in final demand, by considering variations in the energy mix used by each sector.

Appendix

See Tables A1–A3

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