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Identifying strategies for mitigating the global warming impact of the EU-25 economy using a multi-objective input–output approach

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HIGHLIGHTS

- We minimize climate change by performing small changes in the consumption habits.
- We propose a tool that combines multiobjective optimization and macroeconomic models.
- Identifying key sectors allows improving the environmental performance significantly with little impact to the economy.
- Significant reductions in global warming potential are attained by regulating sectors.
- Our tool aids policy makers in the design of effective sustainability policies.

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ABSTRACT

Global warming mitigation has recently become a priority worldwide. A large body of literature dealing with energy related problems has focused on reducing greenhouse gases emissions at an engineering scale. In contrast, the minimization of climate change at a wider macroeconomic level has so far received much less attention. We investigate here how to mitigate global warming by performing changes in an economy. To this end, we make use of a systematic tool that combines three methods: linear programming, environmentally extended input output models, and life cycle assessment principles. The problem of identifying key economic sectors that contribute significantly to global warming is posed in mathematical terms as a bi-criteria linear program that seeks to optimize simultaneously the total economic output and the total life cycle CO_2 emissions. We have applied this approach to the European Union economy, finding that significant reductions in global warming potential can be attained by regulating specific economic sectors. Our tool is intended to aid policy makers in the design of more effective public policies for achieving the environmental and economic targets sought.

1. Introduction

The CO_2 atmospheric concentration, which is increasing at a rate of around 2 ppmv every year (Budzianowski, 2013), has become a major environmental problem over the last decades (Raupach et al., 2007). This has led to severe dangers for Earth's climates and ecosystems such as global warming, sea level rise and ocean acidification. In 2009, most of the atmospheric CO_2 emissions were emitted from fossil fuel combustion in various energy related applications (IEA, 2010). Worldwide national governments have placed greenhouse gas emissions mitigation as a high priority and have started to implement stringent measures based on the reorganization of the way in which society develops (work, transport, leisure, city planning, housing, electricity production, etc.) (Carvalho, 2012). A large body of literature has studied different technological alternatives to mitigate global warming by adopting an engineering approach, mainly through carbon sequestration (VijayaVenkataRaman et al., 2012), the use of renewable energy sources (Panwar et al., 2011), and the improvement of energy efficiency in processes and buildings (Huesemann, 2006). In contrast, much less work has been devoted to warming mitigation at a macroeconomic level. There are very few works in the

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literature that deal with this topic (Asafu-Adjaye and Mahadevan, 2013), and almost all of them lack a systematic approach for identifying economic actions leading to environmental savings.

In the area of macroeconomics, input output models (Leontief, 1936) provide an exhaustive description of the economic transactions between final consumers and productive sectors in complex trade networks. Input output models have been widely applied to diverse fields over the last four decades (Miller and Blair, 2009) in order to disclose complex connections between economic sectors and nations. One of the main advantages of input output models is that, in addition to revealing the macroeconomic structure of an economy, they can assess the environmental loads using “pollution intensity” vectors associated with the production technologies. This allows translating the economic output of each sector into tangible environmental loads (e.g. greenhouse gas energy related emissions, energy expenditure, and/or consumption of natural resources).

Environmentally extended input output (EEIO) models are flexible, transparent and accurate, which makes them quite appealing for conducting environmental assessment studies (McKenzie and Durango-Cohen, 2010). The very first approaches based on EEIO models that assessed environmental loads (Leontief, 1970; Leontief and Ford, 1972) focused their attention on quantifying air emissions. EEIO models were later applied to study energy related emissions in different areas, including the estimation of the level and composition of greenhouse gas emissions as a function of the final demand of the economies (Butnar and Llop, 2007; Tarancón and del Rio, 2007); the assessment of CO_2 emissions related to specific sectors and/or regions (Alcántara and Padilla, 2009; Wiedmann et al., 2010; Zheng et al., 2007); the assessment of the CO_2 emissions embodied in international trade (Davis and Caldeira, 2010; Davis et al., 2011; Hertwich and Peters, 2009; Lenzen et al., 2004; Peters et al., 2011; Wiebe et al., 2012a, 2012b); and the assessment of other toxic emissions to air (e.g. sulphur oxides, nitrogen oxides, ammonia, particulate matter and other hazardous materials) (Chang et al., 2010; Roca and Serrano, 2007).

The approaches described above provide valuable quantitative information on the anthropogenic environmental loads of economic activities, but offer no guidelines on how to reduce such environmental pressures. Some authors have taken one step further on the application of EEIO models and have used them to identify aprioristic strategies leading to greenhouse gas emissions reductions. These strategies are based on readjusting the economic flows so as to minimize the associated impact (Baiocchi and Minx, 2010; Facanha and Horvath, 2007; Golub and Strukova, 2004; Rosenblum et al., 2000). Other works have studied the implications of alternative environmental policies and future economic scenarios on global warming mitigation (Acquaye and Duffy, 2010; Acquaye et al., 2012; Barrett and Scott, 2012; Bright et al., 2010; Llop and Pié, 2008). Unfortunately, the aforementioned studies are based on a “what if” analysis. That is, they explore only a set of scenarios defined beforehand, which restricts the analysis to a reduced number of alternatives. This type of approaches may eventually result in suboptimal solutions that do not fully exploit the capabilities of EEIO models.

A possible manner to overcome such limitation consists on integrating systematic optimization techniques with EEIO models. In particular, linear programming is an optimization approach well suited to minimize the environmental impact of different economic activities in a systematic manner. Linear programming models have been already coupled with input output analysis for solving environmental problems (Vogstad, 2009). Numerous approaches coupling optimization and EEIO models are limited to the optimization of one single objective; such as the minimization of air emissions in a waste water plant (Lin, 2011); the minimization of CO_2 emissions in household insulation, (Hondo et al., 2006); the maximization of the eco efficiency of a waste management system (Kondo and Nakamura, 2005), or the minimization of the costs given a set of alternative technologies (Duchin and Lange, 1995). Other studies have combined EEIO models with multi-objective optimization to simultaneously optimize environmental and economic objectives. This latter approach has been applied to the economies of Taiwan (Hsu and Chou, 2000), Korea (Cho, 1999), Portugal (Oliveira and Antunes, 2004), Greece (Hristu-Varsakelis et al., 2010), Spain (San-Cristobal, 2012) and Japan (Lin, 2011).

This paper presents a systematic multi-objective optimization approach for simultaneously minimizing the global warming potential (assessed through a life cycle assessment methodology) and maximizing the total economic output of the European Union (EU-25). The calculations are performed using an EEIO model based on a Comprehensive Environmental Data Archive-EU25 ($CEDA_{EU25}$) database (Huppes et al., 2006; Heijungs et al., 2006), which considers 487 sectors (including household activities) for the EU-25 economy in 2006. The use of a highly disaggregated EEIO model allows identifying specific economic activities that are ultimately responsible for the overall environmental impact. In addition, the database incorporates environmental information quantified according to life cycle assessment (LCA) principles. Note that LCA-based EEIO models cover the upstream production stages, thereby avoiding the limitations imposed by conventional system boundary selection (Lenzen, 2001). The integration of LCA and EEIO models with systematic linear programming methods allows for the systematic generation and assessment of a very large number of alternatives that could potentially lead to significant environmental savings. Moreover, EEIO models require less input data than equilibrium models (e.g. product prices), yet they provide valuable information into the economic flows between industrial sectors along with the associated environmental impact.

To the best of our knowledge, this is the first contribution that applies multi-objective optimization to input output models of the whole European Union economy. There are few works that follow a similar integrated approach (i.e., multi-objective optimization applied to EEIO models), but they typically restrict the analysis to single countries or small regions, and in addition to this, they tend to employ highly aggregated data that provides little information on the ultimate source of impact. Furthermore, in this article we present a detailed study of the extent to which the satisfaction of the demand of a single sector (rather than the economic activities performed by a single sector itself) contribute to the total impact. This type of analysis is typically missing in the aforementioned articles. Our analysis allows identifying sectors with low direct greenhouse gas emissions but large indirect ones. This valuable information should be taken into account when formulating more effective environmental policies.

The outline of this article is as follows. Section 2 explains the methodology that we followed, and is divided into two subsections. In Section 2.1 we briefly introduce the EEIO models, focusing on the EU-25 economy in 2006. Then, in Section 2.2 we formally state the multi-objective optimization problem that aims to minimize the greenhouse gas emissions while simultaneously maximizing the economic output of the EU-25 economy. The corresponding linear programming formulation then follows. In Section 3 we present a preliminary analysis of the EU-25's EEIO model based on both a production-based and a consumption-based perspective. We also present in this section the results of the multi-objective optimization approach. Section 4 discusses the results obtained and the main policy implications. The main conclusions drawn from the results are finally presented.

2. Methods

2.1. Standard EEIO model of the EU-25 economy

We consider the European economy in 2006 as described in the environmentally extended input output table $CEDA_{EU25}$, which covers 25 nations within the European Union. This database provides a high resolution input output table that covers the environmental effects of household consumption in the European Union. The database considers 487 sectors and 10 different environmental impact categories. In addition to the productive sectors, the database includes a series of private household consumption activities with direct and indirect greenhouse gas emissions, such as automobile driving, cooking and heating, and a number of postconsumer waste management sectors (for details on the data provided in the $CEDA_{EU25}$ database, refer to Huppes et al., 2006; Heijungs et al., 2006).

In its basic form, a quantity oriented input output model consists of a system of linear equations, each of which describes the distribution of the output of an economic sector among the remaining sectors of the economy (Miller and Blair, 2009). For an economy with n sectors, the total output of the i sector of an economy is given by

$$x_i = \sum_{j=1}^{n} z_{ij} + y_i \tag{1}$$

where x_i is the total output of sector i, z_{ij} are the intermediate sales from sector i to sector j, and y_i is the demand from the final consumers to sector i (the final demand of sector i), all of them expressed in currency units (e.g. Euros).

Input output models often assume a direct proportionality between the total output of a given sector and the inputs that this sector acquires from its supplying sectors. Under this premise, the technical coefficients ($a_{i,j}$) denote the total output from sector i that is required to produce one unit of output in sector j (i.e., the amount of goods produced by sector j purchased by sector i in order to produce one unit of i). The technical coefficients are related to the production technologies and they can be considered constant during a short time frame (e.g. one year). This simplification is based on the assumption that the technological conditions of an economy remain unchanged in the short-term. The technical coefficients are calculated via the following equation:

$$a_{i,j} = z_{i,j}/x_j \tag{2}$$

By replacing the intermediate sales from Eq. (2) in Eq. (1), the output of one sector could be reformulated as a function of the technical coefficients as given in the following equation:

$$x_i = \sum_{j=1}^{n} a_{ij}x_j + y_i \tag{3}$$

Environmentally extended input output models are constructed by adding pollution intensities vectors for each sector. The pollution intensity is the amount of a given environmental load that emerges when generating one unit of economic output. To this end, we consider the pollution intensity (PI) representing the environmental load per Euro of output in each sector. We focus specifically our attention on the global warming potential (GWP). The GWP index is based on the time-integrated global mean radiative forcing of a pulse emission of 1 kg of a given compound relative to that of 1 kg of the reference gas CO_2. Such definition of GWP was developed by the IPCC in 1990 (IPCC, 1990) and was adopted for use in the Kyoto Protocol (IPCC, 2007). In particular, the Kyoto protocol adopts the impact for a 100-years time integration period, which is the one adopted in this work and denoted by the continuous variable GWP_{100}. Then, for a given economy, the GWP_{100} associated to the production technologies of a sector i is given by

$$GWP_{100\,i} = x_i \; PI_i \tag{4}$$

And the total GWP_{100} of the whole economy is given by the summation of the GWP_{100} from all its sectors, as given in the following equation:

$$GWP_{100} = \sum_{i=1}^{n} x_i \, PI_i \tag{5}$$

2.2. Multi-objective optimization problem

2.2.1. Problem statement

The optimization problem we aim to solve can be formally stated as follows. We are given the macroeconomic data and the corresponding environmental extensions of the EU-25 in 2006, including the transactions taking place between economic sectors and the associated global warming potential (this information is retrieved from the $CEDA_{EU\text{-}25}$ database). We assume that the final demand of each economic sector can vary within lower and upper bounds defined beforehand (in practice, the demand can be controlled by imposing taxes on goods and services). The goal is to identify the economic sectors that should be regulated firstly in order to minimize the environmental impact and maximize the total output. Since tradeoffs will naturally exist between both objectives, the solution of the problem will consist of a set of Pareto optimal points (for details on Pareto optimality see for instance Ehrgott, 2005), each achieving a unique combination of total economic output and global warming potential.

2.2.2. Mathematical formulation of the optimization problem

Our approach is based on a multi-objective linear programming formulation that is constructed on the basis of an EEIO model. Hence, our mathematical formulation takes the form of the following linear programming model:

$$\min \left\{ -\sum_{i} x_i, \; GWP_{100} \right\}$$

S.t:

$$x_i = \sum_{j=1}^{n} a_{ij}x_j + y_i$$

$$GWP_{100} = \sum_{i=1}^{n} x_i \, PI_i$$

$$\underline{y}_i \le y_i \le \overline{y}_i \quad \forall \; i$$

As observed, the model contains the basic input output equations, one equation that determines the environmental impact (i.e., global warming potential), and a series of inequality constraints that impose lower and upper bounds on the final demand of each sector. Hence, the key assumption of the model is that the demand can be changed so as to decrease the global warming potential. By defining the demand as a free variable (constrained within realistic lower and upper bounds represented by $\underline{y}_i$ and $\overline{y}_i$, respectively), the model has the flexibility to leave part of it unsatisfied, reflecting the application of environmental policies based on imposing taxes on industrial sectors.

As already mentioned, we expect to find a tradeoff between total economic output and global warming potential. Hence, the solution of the problem will be given by a set of Pareto optimal points, each achieving a unique combination of economic output and environmental impact. These so called Pareto solutions feature the property that it is impossible to improve their performance in one objective without necessarily worsening the other. Fig. 2 shows an example of a Pareto front.

In this work, we solve the bi-criteria model via the epsilon constraint method, which is based on calculating a series of single objective sub problems, where one criterion is kept as main objective while the others are transferred to auxiliary constraints that impose limits on them (Bérubé et al., 2009). The multi-objective formulation contains 1940 variables and 970 equations. It was implemented in the modelling system GAMS (GAMS Development Corporation, 2011), and solved with CPLEX 12.2.0.2. We generated 10 Pareto optimal solutions using the epsilon constraint method and solving 10 auxiliary problems. The solution of each sub problem took around 0.156 CPU seconds on an AMD Phenom Triple-core 2.29 GHz processor. Once the Pareto optimal solutions are calculated, it is possible to choose the most appropriate one by modulating our goals and bearing always in mind the applicable legislation as well as the preferences of the stakeholders. Our final goal is to identify solutions that mitigate the global warming potential at a marginal decrease in economic performance.

3. Results

3.1. Preliminary analysis of direct and indirect contribution to global warming potential of each economic sector

We start by analyzing the direct (production based) and indirect (consumption based) environmental impacts of the sectors of the European economy. The direct contribution to global warming potential is obtained by multiplying the total economic output of each sector by its corresponding pollution intensity according to Eq. (5). In contrast, to estimate the indirect impact of a sector we assume that the whole EU-25's economy works with the unique purpose of covering the final demand of that sector. Hence, in the later case, we consider all the intermediate economic transactions associated with the supply chain of the sector of interest.

The consumption based (indirect) approach calculates the global warming potential as follows. We first fix the demand of sector *i* and set the final demand of the remaining sectors to zero. By doing so, we obtain a column vector whose values are all zero except for its component *i*, which will denote the demand of sector *i*. Let us denote this consumption based final demand vector of sector *i* as y_i^C. It is important to note that there are in total *n* y_i^C vectors (one for each sector). Then, we introduce each of these vectors in Eq. (3), and solve the resulting system of linear equations to obtain the consumption based output for each sector *i*, denoted as x_i^C. The consumption based global warming potential of sector *i* is given by Eq. (6). Note that Eq. (6) takes into account all the inter sector economic transactions required to satisfy the demand of sector *i* (regardless of the sector where these transactions take place).

$$GWP^C_{100\,i} = \sum_i x_i^C \ PI_i \tag{6}$$

We focus on CO_2 equivalent emissions (which represent the amount of CO_2 that would have the same global warming potential than a given amount of greenhouse gases). In terms of direct emissions, we find that 4% of the sectors are responsible for 49% of the EU-25's global warming potential, while the remaining 51% of the impact is produced by 96% of the sectors. Table 1, obtained from Eq. (5), shows the percentage breakdown of output contribution and CO_2 equivalent emissions for the sectors causing a 48.6% of the EU-25's GWP_{100}.

Table 1
Top 21 emitting sectors breakdown from the EU-25 in 2006 through a direct (production based) approach.

Sector	Percentage of CO_2 equivalent emissions	Percentage of output
Motor vehicles and passenger car bodies (Driving with)	6.95	4.28
Electric services (utilities)	6.10	1.37
Eating and drinking places	3.39	4.01
Meat packing plants	3.12	1.30
Blast furnaces and steel mills	2.95	1.01
Industrial inorganic and organic chemicals	2.10	0.98
Meat animals	2.03	1.01
Poultry slaughtering and processing	1.99	0.98
New residential 1 unit structures, nonfarm	1.83	3.82
Heating equipment, except electric and warm air furnaces	1.63	0.57
Feed grains	1.41	0.72
Petroleum refining	1.34	1.15
Crude petroleum and natural gas	1.23	1.63
Natural, processed, and imitation cheese	1.18	0.62
Wholesale trade	1.17	3.03
Sausages and other prepared meat products	1.15	0.47
Fluid milk	1.15	0.63
Miscellaneous plastics products, n.e.c.	1.13	0.96
Household laundry equipment	1.04	0.34
Poultry and eggs	1.03	0.56
Trucking and courier services, except air	0.98	1.15

As observed, among the most polluting sectors, there are some with high global warming potential contribution per Euro of output that are not highly demanded, and others with low or medium pollution intensity and very high demand. Particularly, Huppes et al. (2006) found that meats and derived products along with household heating represent a large share of the total environmental impact due to their high impact per Euro and high customer expenditure. In the case of bars and restaurants, clothing, residential construction and services such as telecommunications, the impact per Euro is low or medium, but their sales volume is particularly high.

Our analysis reveals that there are sectors that contribute significantly to the total environmental impact, but whose output is used by other sectors as intermediate flows. That is, their impact is embodied in the supply chains of other goods and services rather than caused by their direct use. To shed light on this issue, we investigate which sectors are ultimately responsible for the total impact. Note that the direct emissions of a sector are those generated by the sector itself, while the indirect ones correspond to the emissions generated by all the activities required to satisfy the demand of the sector (i.e., emissions embodied in the supply chain of the sector).

The indirect (consumption based) assessment of the European GWP_{100} reveals that 66% of the CO_2 equivalent emissions are attributed to 5% of the sectors. Table 2, obtained from Eq. (6), provides details on the output contribution and CO_2 equivalent emissions of the sectors responsible for 66% of the EU-25's GWP_{100} from a consumption based point of view. By comparing both

Table 2
Top 26 emitting sectors breakdown from the EU-25 in 2006 through a indirect (consumption based) approach.

Sector	Percentage of CO_2 equivalent emissions	Percentage of output
Motor vehicles and passenger car bodies	12.35	9.53
Eating and drinking places	8.84	9.04
Meat packing plants	5.40	3.31
Poultry slaughtering and processing	4.21	2.76
New residential 1 unit structures, nonfarm	3.10	4.67
Heating equipment, except electric and warm air furnaces	2.81	2.16
Sausages and other prepared meat products	2.60	1.58
Household laundry equipment	2.48	1.15
Fluid milk	2.35	1.68
Natural, processed, and imitation cheese	2.14	1.50
Household refrigerators and freezers	1.86	0.80
New additions and alterations, nonfarm, construction	1.73	2.41
Apparel made from purchased materials	1.63	2.16
Beauty and barber shops	1.42	1.69
Edible fats and oils, n.e.c.	1.40	0.96
Telephone, telegraph communications, and communications services n.e.c.	1.33	3.06
Automotive repair shops and services	1.29	1.84
Electric lamp bulbs and tubes	1.29	0.48
Household audio and video equipment	1.18	0.59
Insurance carriers	1.14	3.92
Drugs	1.09	1.01
Household appliances, n.e.c.	1.03	0.89
Bottled and canned soft drinks	1.01	0.95
Bread, cake, and related products	0.99	1.03
Household cooking equipment	0.99	0.53

Tables 1 and 2, we find that the most polluting sectors differ from one approach to another. In particular, out of the 21 "top polluting" sectors found with the direct (production based) assessment, there are only 10 appearing in the "top polluting" sectors list of the consumption based approach. This mismatch is due to the fact that there are sectors that generate large emissions, but whose output is mainly used by other sectors. One clear example of such situation is the sector labeled as *Industrial inorganic and organic chemicals*. From a production based assessment, this sector is in the sixth place of the list, being responsible for 2.1% of the global warming potential of the European Union. However, the consumption based approach reveals that the output of this sector is mainly used as input to other sectors rather than to cover the demand of the final consumer. Hence, the environmental impact attributed to this sector is highly embodied in the products and services ultimately consumed by final consumers (e.g. manufactured foods, clothes, etc.).

Fig. 1 compares the GWP_{100} assessed through the direct (production based) and indirect (consumption based) approaches of all of the sectors. The horizontal axis represents the GWP_{100} contribution per sector through a production based assessment, and the vertical axis represents the GWP_{100} sector contribution from a consumption based point of view. Thereby, sectors under the diagonal line score higher global warming potential from a production based assessment than from the consumption based one (and vice versa).

We found that there are 304 out of 487 sectors below the diagonal, indicating that the majority of the sectors show higher global warming potential through the production based approach. Hence, environmental policies aiming to control the direct greenhouse gas emissions might wrongly penalize the demand of sectors (e.g. by establishing taxes on their products) whose output is largely used by other sectors as intermediate products and services. In other words, production based environmental policies might be ineffective, since they are unable to properly attribute the impacts to the correct sources, thereby hindering the identification and regulation of those sectors which are ultimately responsible for global warming.

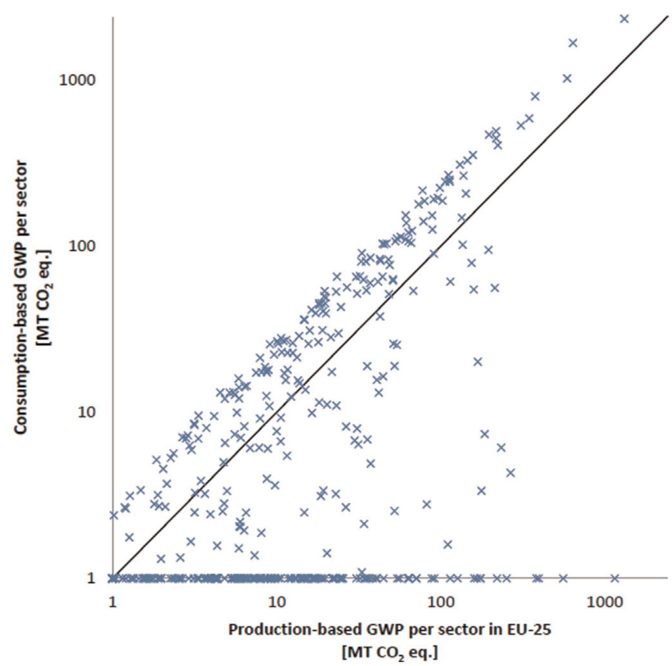

Fig. 1. Comparison of the consumption-based and production-based global warming potential of the economic sectors in the EU-25, in 2006.

3.2. Results of the optimization

Fig. 3 depicts the Pareto front trading off the global warming potential and the total economic output of the European economy. The Pareto solutions are labeled from 1 to 10, being 1 the minimum impact solution and 10 the one with the maximum economic output. Due to the linear nature of the model, the Pareto front is concave, implying that the slope increases when we move to the left in the curve. Hence, as we move from the solution of maximum output to the minimum impact one, we gradually need greater reductions of output in order to achieve the same impact reduction.

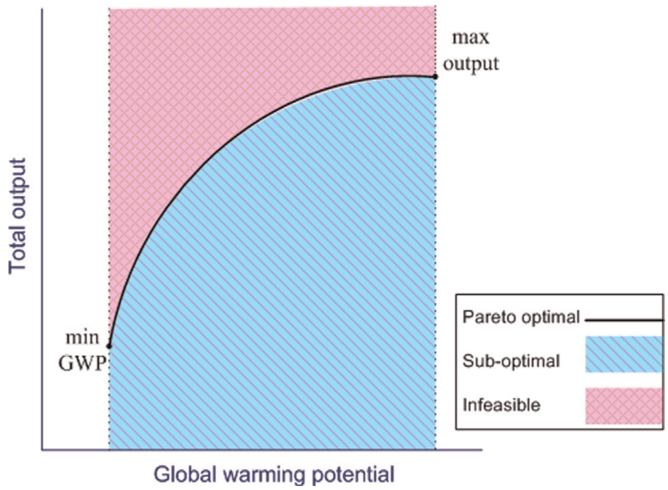

Fig. 2. Example of a bi-criteria Pareto optimal frontier for two conflictive objectives (i.e., total economic output vs. global warming potential).

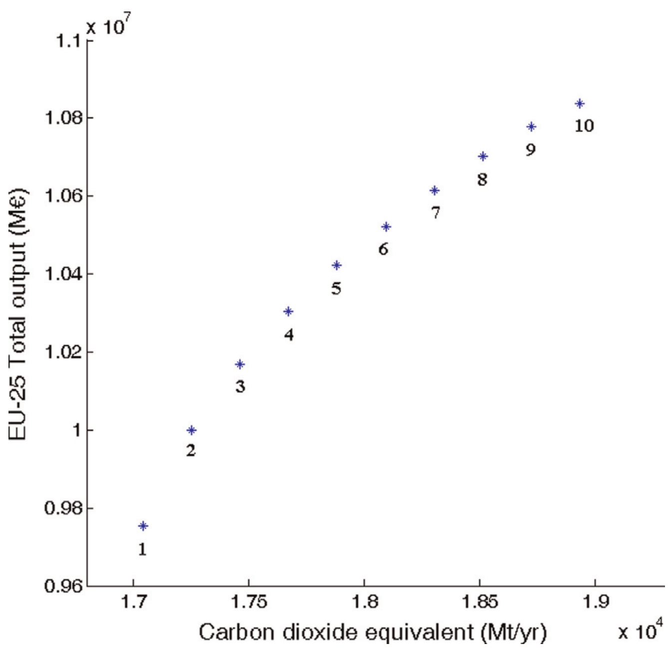

Fig. 3. Pareto optimal frontier for GWP100 vs. the EU-25's total output in the year 2006.

As expected, in the extreme point corresponding to the maximum output, the demand of all of the sectors hit the upper bound; while in the extreme solution with minimum impact, the demand of all of the sectors reaches the lower bound. Note that the demand of each sector is allowed to vary between a lower bound (90% of the current demand), and an upper bound (the current demand). Hence, the Pareto optimal solutions between the extreme points are unique combinations of totally and partially satisfied demands of sectors.

Particularly, as we reduce the global warming potential, the number of sectors that are regulated increases. Table 3 shows, for each Pareto point, the number of sectors that are regulated (i.e., whose demand is not totally met) along with the ratio between the variations of the total output and GWP_{100} (%GWP_{100} reduction/%output reduction). This can be interpreted as an elasticity output of the reduction in emissions. A high value in this elasticity indicates a high sensibility of the emissions under a decrease in output, whereas a low value indicates that the reduction in emissions is rigid to changes in output.

Table 3
Optimal solutions found for the GWP-100 minimization.

	Pareto points									
	1	2	3	4	5	6	7	8	9	10
GWP reduction (%)	10.0	8.9	7.8	6.7	5.6	4.4	3.3	2.2	1.1	0.0
Output reduction (%)	10.0	7.7	6.2	4.9	3.8	2.9	2.0	1.2	0.5	0.0
Elasticity-output	1.00	1.15	1.26	1.36	1.46	1.53	1.63	1.79	2.07	–
Number of capped sectors	282	214	175	116	88	46	43	21	11	–

A detailed analysis of the results reveals that the model first identifies the sector that reduces the impact the most for a given drop in total output. The model then reduces the demand of that sector until it hits its lower bound. The algorithm proceeds in a similar manner with the following sectors until the environmental target imposed by the epsilon constraint is reached. The sector that is being reduced when the algorithm meets the epsilon target is not decreased any further, so its demand finally falls between its upper and lower bounds. Hence, in each Pareto point, we find three types of sectors: those whose demand hits the lower bound, those whose demand hits the upper bound and only one with a demand lying between its upper and lower bound. The complex interactions between sectors make it difficult to identify at a first glance the sectors that should be firstly regulated. For instance, sectors with small production based emissions might consume intermediate goods and services from very polluting sectors. In this context, the input–output model uncovers these complex relationships, allowing for the identification of the ultimate source of impact.

An important outcome from the optimization problem concerns the number of sectors whose final demand is restricted to reach a given environmental target. This information is quite valuable for governments and public policy makers, as it pinpoints the sectors to be more severely regulated to attain significant environmental benefits. As observed, solution 9 shows the highest elasticity (2.07) of GWP_{100} reduction per output reduction, allowing for a reduction of GWP_{100} of 1.1% at the expense of a drop in the output of 0.5%. In this solution, only 11 sectors are restricted. In point 8, the impact is halved with respect to point 9, at the expense of reducing the output by more than double and restricting 21 sectors. Such trend of reducing more the output than the impact by moving to the left of the curve tends to increase due to the concavity of the curve. Point 9 is for example an appealing solution for policy makers due to its high ratio value. Table 4 provides detailed information on the sectors that are capped in the Pareto

Table 4
Affected activities final demand reduction for optimal solution 9 (GWP minimization).

Sector	$\frac{y(i)-y_0(i)}{y_0(i)}$
Household cooking equipment	– 10.0%
Household refrigerators and freezers	– 10.0%
Household laundry equipment	– 10.0%
Electric housewares and fans	– 10.0%
Electric lamp bulbs and tubes	– 10.0%
Household audio and video equipment	– 10.0%
Chemical and fertilizer minerals	– 10.0%
Sausages and other prepared meat products	– 9.6%
Nonwoven fabrics	– 10.0%
Fabricated textile products, n.e.c.	– 10.0%
Boot and shoe cut stock and findings	– 10.0%

point 9, and the extent to which their demand should be reduced with respect to the original one.

Among the sectors that are regulated in solution 9, we find industrial sectors such as *Chemical and fertilizer minerals*, *sausages and other prepared meat products*, *Nonwoven fabrics*, *Fabricated textile products and Boot and shoe cut stock and findings*. Note that the $CEDA_{EU25}$ database considers domestic activities. Particularly solution 9 requires reducing 10% the consumption of energy related domestic appliances (e.g. refrigerators, light bulbs, fans, and equipment related to laundry, cooking, video and audio). These activities are restricted in first place, and this is achieved by defining taxes on the corresponding products. For example, reducing the energy consumption in households does not harm the European economy as much as it would affect reducing the energy expenditure of the industrial sector, but still leads to significant reductions in CO_2 equivalent emissions. Regarding the industrial sectors restricted in point 9, we observe that their economic contribution to the European economy is low in comparison to their associated global warming potential. Hence, small reductions in the demand of such sectors result in a positive impact on global warming mitigation at minimum economic impact (e.g. acting on the consumption of energy and alimentary habits in Europe contributes in an efficient manner to mitigate global warming; Tukker et al., 2011).

By comparing the preliminary analysis and the optimization results, we find that the sectors capped firstly in the optimization problem are not necessarily the same appearing in the list of the top polluting sectors (in both approaches, consumption based and production based), except for a few of them (i.e. sausages and other prepared meat products and household laundry equipment). This is explained by the fact that our optimization model considers both objectives (environmental and economic) simultaneously.

The output of one sector is employed to satisfy the final demand along with the intermediate sales. There are sectors that keep their original demand constant, but manage to reduce their total output by reducing intermediate transactions. Fig. 4 shows the cumulative distribution of the percentage of economic output reduction associated with the intermediate Pareto optimal solutions. That is, the y axis of the curve displays the percentage of sectors whose economic output is reduced by a percentage less or equal to what is shown in the horizontal axis.

Fig. 4 shows how more sectors are progressively restricted when moving from solution 9 to solution 2. That is, in solution 9 the overwhelming majority of sectors have an output reduction of less than 2%, while in solution 2, most of the sectors are restricted by more than 6%. As an example, in Table 5 we provide details of the sectors with output restrictions above 2% in solution 9.

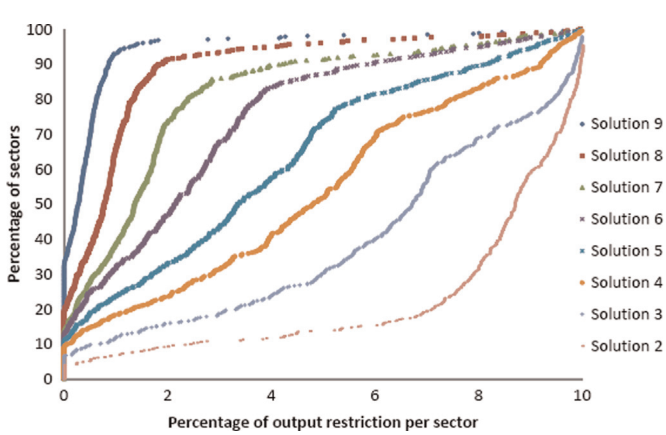

Fig. 4. Cumulative distribution of the output reduction per-sector in the intermediate Pareto optimal solutions.

Table 5
Sectors whose total output is reduced by more than 2% in the selected optimal solution (i.e. solution 9).

Sector	$\frac{x(i)-x_0(i)}{x_0(i)}$
(Washing with) household laundry equipment	10.0%
(use of) Household refrigerators and freezers	10.0%
(use of) Household cooking equipment	10.0%
(use of) Electric lamp bulbs and tubes	10.0%
(use of) Household audio and video equipment	8.45%
Sausages and other prepared meat products	8.01%
(use of) Electric housewares and fans	7.90%
Fabricated textile products, n.e.c.	7.01%
Wood television and radio cabinets	5.40%
Electric services (utilities)	4.70%
Electron tubes	4.27%
Nonwoven fabrics	4.18%
Turbines and turbine generator sets	4.15%
Coal	3.16%
Power, distribution, and specialty transformers	2.78%

Comparing Tables 4 and 5, we observe that 9 of the 11 sectors with restrictions over the final demand in Table 4 appear also in Table 5 (i.e., not only their final demand is reduced, but also their economic output drops by more than 2%). In contrast, 6 of the sectors appearing in Table 5 reduce their output without manipulating the demand (e.g. *Wood television and radio cabinets*, *Electric services (utilities)*, *Electron tubes*, *Turbines and turbine generator sets*, *Coal*, *Power*, *distribution*, *and specialty transformers*). This occurs mainly because part of the output of these sectors is used to fulfill the intermediate demand of other sectors or activities. As an example, the reduction in the consumption of energy in households affects the output of sectors belonging to the supply chain of energy, such as coal and turbines (which are both used for energy generation).

It is worth noting that as the slope of the Pareto front increases (as one moves towards solution 1); it is more difficult to obtain substantial impact reductions, so we need to reduce further the economic output to attain the same impact reduction.

4. Discussion

Valuable policy implications are derived from our results. Mitigation of greenhouse gas emissions in the European economy should mainly focus on making the economic activities less energy intensive (either by improving the production technologies, or by increasing the use of renewable energy), and on the rational use of energy (both in the direct utilization of electricity and the indirect consumption of energy embodied in the demanded products). Our findings suggest that EU-25's public energy policies should take into account simultaneously economic concerns along with environmental priorities to guarantee long term sustainability. Sustainability policies should be integrated in the European Union for simultaneously improving the socioeconomic development and environmental performance. From our results we could extract three main strategies that are closely related with the current European agreement 20-20-20 target (European Comission, 2009), which establishes that by 2020 the European Union should reduce the GHG emissions by 20%; should improve the energy efficiency in order to save 20% of the European Union energy consumption; and should reach a 20% share of renewable energy sources with respect to the total energy consumption. The three strategies as well as their relation with the 20-20-20 targets are described below.

4.1. Encouraging technology improvement

The fast economic growth and industrialization of today's economies has led to a general increase of energy consumption. Energy efficiency improvement in the productive sectors can play a key role in terms of greenhouse gas savings. Increasing the efficiency of the production technologies is not the only measure to stabilize the growing energy related greenhouse gas emissions. In fact, it should be accompanied by a general decline in the per capita energy consumption. This policy implication is in line with the goal of the 20-20-20 agreement that indicates that energy efficiency in the European countries should be promoted in order to save 20% of the energy consumed in the European countries by 2020.

One of the main outcomes from the multi-objective optimization is the identification of sectors whose regulation leads to major greenhouse gas savings at a marginal decrease in economic performance. This information is rather valuable for governments and public policy makers when establishing effective sustainability policies, as it pinpoints the sectors with a better potential for reducing the greenhouse gas emissions (larger reductions in emissions at a marginal drop in economic performance). A high disaggregation of sectors facilitates the precise identification of such key economic sectors.

Policy makers have different alternatives to achieve the target reductions shown by the Pareto solutions. Two of them are: (i) implementing policies that reduce the activity of key polluting sectors (e.g. through the increase of environmental taxes); and/or (ii) fostering research on ways to improve the technological efficiency of those sectors. Policy makers should in either case concentrate efforts on the key sectors identified by the optimization model (those showing a better ratio of potential environmental savings per unit of economic drop).

4.2. Following optimal paths

Improving simultaneously the socioeconomic development and environmental performance is in line with the principles of sustainability, where a balance is established between such competitive objectives. One of the aims of the 20-20-20 European agreement is to reduce the GHG emissions by 20% in 2020. However, stricter environmental regulations are sometimes unpopular because they might compromise the economic competitiveness. In this context, the Pareto optimal front establishes the ideal path to be followed bearing in mind the principles of sustainability. Hence, the economic policies adopted by national governments willing to improve their environmental performance should follow the guidelines obtained from the analysis of the Pareto front. This would avoid implementing suboptimal solutions.

The main advantage of heeding the path established by the Pareto front is that it allows policy makers to consider the direct and indirect greenhouse gas emissions in the whole production chain of the demanded products. Consumption-based policies are more effective than those based on production, since they prevent nations from displacing their manufacturing tasks to countries with softer production based regulations (Peters and Hertwich, 2008).

4.3. Greening the final demand

The rapid growth of population and economies has led to greater resources consumption and greenhouse gas emissions. Then, the success of greenhouse effect mitigation is strongly dependent on the consumption habits of the global population. According to the optimization results, household utilization of energy is among the first activities to be regulated. In addition, the regulation of other industries such as those producing some meat derived products and clothes and apparels can lead to significant environmental savings. European governments should therefore pay more attention to energy use in household consumption, by encouraging lifestyle changes entailing the use of more green-labeled products and products manufactured with renewable energy sources, and promoting as well more efficient electric appliances. Such encouraging policies are in line with the goals of the 20-20-20 agreement, in particular with that aiming to reach a 20% of renewable energy in the total European Union energy consumption. The implementation of massive green consumption habits will translate into the use of less energy intensive products, which will in turn decrease energy consumption.

5. Conclusions and policy implications

Based on EEIO tables, this paper addressed the simultaneous optimization of the economic and environmental performance of the EU-25 economy in 2006 at a macroeconomic scale by applying a great level of disaggregation of the industrial and domestic activities. A preliminary analysis of the data reveals that consumption based and production based emissions differ substantially, which can lead to a misallocation of impacts and subsequent concentration of efforts on sectors which are not the ultimate source of environmental damage.

From the production based assessment the impact is allocated proportionally to each sector involved in the supply chain of a product; whereas, through the consumption based approach, the environmental responsibility of the whole life cycle of the process (from cradle to grave) falls on the products addressed to final consumers. A consumption based analysis reveals that there are sectors developing simple daily activities that show very high global warming potential values (e.g. *bars and restaurants*). This is because these sectors carry the environmental burdens of other more polluting sectors (e.g. electric services, food industries, fertilizers, paper, and other sectors involved). The allocation of environmental responsibilities has major effects in the development of effective and equitable environmental policies. That is, by penalizing the consumers of products with a large impact embodied in them (individuals and households), we could make gradual changes in consumption patterns leading to significant environmental savings.

The present study explores in quantitative terms the way in which the European economy should proceed to optimally reduce the global warming potential without significantly compromise the economic performance. A detailed sector by sector analysis identifies the sectors (or activities) that lead to major environmental savings with the least economic impact in the economy. We provide a Pareto front in which each intermediate solution reduces the global warming potential with respect to the previous solution, at the expense of restricting progressively the total output of the economy. Numerical results showed that, with the existing technology and the current international trade network; the GWP_{100} indicator could be lowered in greater proportion than the economic output by restricting adequately the demand of certain sectors. As an example, the GWP_{100} can be reduced by 1.1% by only reducing the economic output in 0.5%. This could be achieved by reducing 10% the final demand in 11 economic activities out of the 487 studied.

In addition, we found that the economic activities that should be firstly restricted are those with a high ratio between the amount of greenhouse gases emitted and the contribution to the EU-25's total output. Through the application of the presented methodology, we found that the use of household appliances, the consumption of certain apparels, and the consumption of sausages and other prepared meat products are listed first among the activities to regulate in order to attain global warming potential reductions with the least impact to the European economy. Some minor changes in the basic consuming habits in households could lead to significant environmental savings without modifying the overall economic structure of the EU-25. We conclude that the multi-objective environmental and economic optimization of EEIO models are powerful tools that could contribute to develop effective environmental policies by pinpointing sectors embedded in intricate trading networks to be firstly regulated in order to attain specific environmental savings.

We are aware that not all the economic sectors are "elastic", and their demand cannot be reduced by 10%. This limitation could be overcome by coupling our approach with a detailed economic analysis on the elasticity of each sector's demand in order to set more realistic limits on the demand variables of our model.

Other aspects out of the scope of our study include the possible changes in consumers' behavior in terms of sector substitution processes in final consumption (e.g. reducing the demand from the sector of bars and restaurants might be traduced in an increase in household cooking). Additionally, the input–output quantity oriented model assumes that prices are constant, and for this reason our approach cannot show the effects on sector prices of production.

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