Macro-economic multi-objective input-output model for minimizing CO_2 emissions: Application to the US economy

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Abstract

Designing effective environmental policies for mitigating global warming is a very challenging task that requires detailed knowledge of the international channels through which goods are traded. This work presents a decision-support tool that minimizes the impact at a global macroeconomic scale by performing changes in the economic sectors of an economy. Our tool combines multi-objective optimization, environmentally extended input-output tables and life cycle assessment within a unified framework. Our results on the US economy to minimize CO_2 emissions identify sectors that should be regulated first to reach a given environmental target while maximizing the demand satisfaction. The impact of shale gas is also studied. Our findings show that the application of process systems engineering tools at a macroeconomic level can provide valuable insight for public policy makers into problems of general interest.

Topical Heading: Process Systems Engineering

Keywords: Input-Output Analysis, multi-objective optimization, linear programming, global warming potential.

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Introduction

In today's globalized market, countries must face the challenge of reducing their greenhouse gas (GHG) emissions while remaining economically competitive. To accomplish this goal, it is necessary to identify critical hotspots across economic sectors so the proper actions can be undertaken. Environmental policies, like the “cap and trade” system in EU, have focused on reducing the direct emissions of nations in an attempt to mitigate global warming on time by allocating permits or allowances to discharge a specific quantity of carbon dioxide. These policies allow countries willing to increase their emissions to buy permits from others countries willing to sell them. By imposing regional bounds, all the nations will keep the emissions below their desired limits. This “cap and trade” approach, however, provides no insight into the ultimate sources of impact and the regulations that should be put in place in order to control the most polluting sectors of an economy. Hence, while “cap and trade” might reduce the total emissions by fixing limits on countries, the way in which these limits are met might not be optimal as countries might prefer to buy emissions permits rather than promoting cleaner technologies within their boundaries.

Another limitation of “cap and trade” is that it focuses on production-based (i.e., territorial-based) emissions, as opposed to consumption-based ones, which reflect a fairer scenario by which the environmental responsibility is allocated to the final consumer instead of the producer. The production-based impact is caused by the facilities operating within the boundaries of a country. In practice, some of these facilities might produce goods that are exported overseas, and for this reason the associated environmental responsibility of the impact they cause should be assigned to the final consumer rather than to the original producer. Conversely, consumption-based impact refers to the impact caused by all of the facilities (located anywhere in the world) that produce those goods demanded by a region. By defining environmental policies based on consumption, final customers are held accountable for the impact associated with the goods they consume, thereby ensuring fairness (as then the potential masking of impact via displacement of production facilities is prevented). This fair allocation of environmental responsibility would eventually prevent countries from masking their environmental impact by displacing the manufacturing tasks to regions with softer environmental regulations [1–6].

It seems clear that in a globalized international market the impact should be assessed on a life cycle basis and across nations (i.e., on a consumption-based basis). Unfortunately, the calculation of the consumption-based impact of a region at a global scale requires large amounts of data that are difficult to collect in practice. The theory underlying consumption-based calculations, however, was developed in economics long time ago through the use of input-output models (IO) [7]. IO models are used to study economic flows between sectors of the same or different nations. They predict how changes in the demand of a sector affect other sectors by solving systems of linear equations based on the technological structure of an economy. The first IO models focused on a single economic region, but were later enlarged in scope in order to deal with several regions simultaneously, thereby covering international transactions between sectors of different nations[8]. The latter models, referred to as multi-regional input-output models (MRIO), are difficult to construct because they require extensive information from national accounting systems that might not be consistent with each other, so further analysis and processing is needed to harmonize and express such information in a common basis.

IO models can also be used to analyze the impact of economic flows on the environment. To this end, environmentally extended input-output models (EEIO)[9] can be constructed from standard IO tables by incorporating an additional column that displays the impact associated with monetary flows between economic sectors. The integration of environmental aspects into IO models gives rise to EEMRIO models. In the recent past, several international bodies have focused on gathering data to build environmentally extended multi-regional input-output tables (EEMRIO) at a global scale [10,11]. These EEMRIO models attribute pollution or resources depletion (quantified considering all the stages in the life cycle of a product/service) to the final demand following a consistent holistic approach[12], which makes them very useful for policy making at the national and international levels.

EEIO models have been integrated recently with multi-objective optimization in order to improve macroeconomic systems. Examples of this approach include the minimization of the environmental impact in the economies of Korea [13], Taiwan [14], Portugal [15], Spain [16], Greece [17] and Japan [18]. The aforementioned works have focused on optimizing single economies (without considering international economic transactions). This narrow scope may lead to suboptimal solutions, as it neglects the impact that changes in the economy of one region may have on other overseas economies.

This work integrates multi-objective optimization and multi-regional input-output models within a unified framework to identify key sectors that contribute marginally to the wealth of an economy but significantly to the total environmental impact. The main novelty of our approach is that it makes use of a multi-regional model that predicts the effects that changes in the economic sectors of a region will have on other nations. This approach leads ultimately to solutions that decrease the impact globally rather than locally. The capabilities of our approach are illustrated through its application to the US economy using information retrieved from the World Input-Output Database (WIOD)[19]. Our final aim is to develop a process systems engineering tool to assist public policy makers in the development of more effective environmental regulations.

The paper is organized as follows. In section 2 the problem of interest is formally defined, while section 3 introduces the mathematical formulation and the solution method. Section 4 summarizes the main results, including a preliminary analysis of the IO data, a discussion of the optimization results produced by the model, and an analysis of the environmental effects (in terms of CO_2 emissions) of replacing coal by shale gas. Finally, section 5 summarizes the conclusions of our work.

Problem statement

The problem we aim to solve can be formally stated as follows. We are given macroeconomic information of a set of economic regions. This information covers the economic transactions (sales and purchases of goods and services) taking place between economic sectors (located in different nations as well as within the same country) that produce goods and services demanded by the global population. The impact associated with each economic transaction is expressed using pollution intensity vectors that indicate the impact caused per unit of money traded. The goal of the analysis is to find key sectors that should be regulated in the first place in order to simultaneously minimize the CO_2 emissions at a global macroeconomic scale and the extent to which the region's economy must be altered for achieving such reductions. As will be discussed in more detail later in the article, the second objective is represented through the maximization of the demand satisfaction of the economy.

Note that the outcome of this optimization provides valuable insight for public policy makers, which may use it in different ways. The most straightforward one is to define taxes for CO_2 emissions on the most polluting sectors so as to reduce their demand, and therefore the corresponding environmental impact. Decreasing the demand will in turn reduce the economic flows and consequently the country's gross domestic product (GDP), which might have negative effects on the unemployment rate, and therefore be perceived as an unpopular strategy. Hence, a more appealing alternative to decrease the impact (with minimum changes in the economy) is to foster research on cleaner technologies that could eventually improve the environmental efficiency of the target sectors. In fact, environmental savings attained in one sector may eventually propagate to other economic sectors via trade, thereby enhancing the overall level of sustainability.

Mathematical formulation

Figure 1 summarizes the overall approach presented here to solve the problem stated above. In this example, two countries and three sectors per country are considered. An input-output table, discussed in more detail in the ensuing sections, is constructed in the first place with data on economic transactions between sectors. In this table, rows represent sales of goods/services from one sector to other sectors and final consumers, while columns denote purchases from one sector to other sectors. As an example, sector 1 of country A sells 75 monetary units of goods/services to sector 2 of country A, and purchases 87 monetary units of goods/services from sector 1 of country B.

Input-output tables allow us to quantify the impact of a region following either a production-based (territorial-based) or consumption-based accounting approach. Figure 2 illustrates the differences between the two approaches for an illustrative example with four countries. From a production based approach, countries A and D show low environmental impacts, country B is highly polluting and C does not pollute at all. Following the consumption-based approach, A and C become the most polluting countries, while country B is now totally clean (as the territorial impact of B is now allocated to the final consumers of the goods/services it produces, that is, to A, C and D).

Taking the IO table as starting point, a linear programming (LP) model is formulated next and efficiently solved. The outcome of the bi-objective model (minimization of

CO_2 emissions and maximization of demand satisfaction) consists of a Pareto set of alternatives, each representing a different economic plan. The analysis of these Pareto points provides information on the sectors that should be regulated in the first place to achieve a given environmental target, while causing minimum impact on the economy (i.e., while maximizing the satisfaction of the current demand).

The approach presented here, therefore relies on a bi-objective linear programming model that contains the basic equations of an environmentally extended multi-regional input-output (EEMRIO) table. Before presenting the mathematical formulation, this section starts by introducing IO models, a topic that is typically not covered in the standard chemical engineering literature.

Input-Output (IO) Model

In its basic form, an input-output model is based on a system of linear equations that describe the distribution of the outcome of an economic sector throughout the economy. Table 1 shows a generic IO table, in which the rows represent the sales between sectors and the columns the purchases.

For an economy with sectors *i*, the equations of an IO model can be expressed in compact form as follows (see Appendix for an example):

$$X_i = \sum_j a_{ij} X_j + y_i \qquad \forall i \tag{1}$$

where:

X_i, X_j are variables denoting the total output in currency units (e.g. US$) of sector *i*/*j*.

y_i is a parameter representing the final demand (end user) of sector *i*.

a_{ij} are parameters denoting the technological coefficients, which are calculated with Eq 2 (note that this equation contains only parameters, so it can be left out of the pure IO model).

$$a_{ij} = \frac{\bar{x}_{ij}}{\bar{X}_j} \qquad \forall i, j \qquad (2)$$

where, $\bar{x}_{ij}$ is the current output of sector *i* acting like an input for sector *j*, while $\bar{X}_j$ is the current total output in currency units (e.g. US$) of sector j. The coefficients a_{ij} represent the amount (in US$) of output of sector *i* necessary to produce one dollar of output of sector j. The IO model assumes that there is a direct proportionality between the total output of sector j and the inputs that this sector acquires from its supplying sectors. Accepting this premise, the technological coefficients a_{ij} can be considered constant for a certain period, assuming that the technological conditions in an economy remain unchanged. IO tables are typically used for predicting how changes in the demand of a single (or several) sectors affect the economic flows between sectors. This analysis is carried out by fixing in the IO model the demand to the desired value and then solving the resulting system of linear equations to obtain the new economic flows (corresponding to sectorial transactions) required to satisfy that demand.

As will be explained in more detail later in this article, our IO model is based on the WIOD[19] database, which covers a wide range of transactions of goods and services between several world economic regions [7,20].

Environmental extension of the IO Model

The purely economic IO table can be modified so as to include environmental aspects, which gives rise to an environmentally extended input-output table (EEIO). To this end, additional rows denoting the pollution intensity of each sector (i.e., impact per unit of money traded) are added to the original table. These new rows contain environmental coefficients for each sector and impact. For an economy with sectors i, the following equation is used to build the EEIO model:

$$Imp_i = X_i e_i \qquad \forall i \qquad (3)$$

$$TImp = \sum_i Imp_i = \sum_i X_i e_i \tag{4}$$

where Imp_i is the environmental impact (i.e., global warming potential) associated with sector *i*, while e_i is the environmental pollution intensity for sector *i* (i.e., impact per monetary unit traded in sector *i*). Finally, *TImp* is the total environmental impact generated by all of the sectors of the economy.

Multi-regional IO Model

Multi-regional IO tables cover transactions of goods and services between economic sectors of different countries. For an economy with regions *r* and sectors *i* in each region, Eq. 1 should be rewritten as follows:

$$X_i^r = \sum_j \sum_{r\prime} X_j^{r\prime} a_{ij}^{rr\prime} + y_i^r \qquad \forall i, r \tag{5}$$

The following notation is used here:

X_i^r, $X_j^{r\prime}$ are variables denoting the total output in currency units (e.g. US$) of sector *i/j* in region *r/r'*.

$a_{ij}^{rr\prime}$ are parameters representing the technological coefficients, which are calculated via Eq. 6.

y_i^r is a parameter denoting the final demand (end user) of sector *i* of region *r*.

Note that, as in the previous case, for a given fixed demand and set of technical coefficients (given by the current technologies in the economy), the model takes the form of a system of linear equations with the same number of equations and unknowns. The values of the technical coefficients are obtained from the current values of the economic flows as follows (again, note that this equation contains parameters only, so it can be left out of the pure IO model):

$$a_{ij}^{rr\prime} = \frac{\bar{x}_{ij}^{rr\prime}}{\bar{X}_j^{r\prime}} \qquad \forall i, j, r, r\prime \tag{6}$$

In Eq. 6, $\bar{x}_{ij}^{rr\prime}$ is a parameter denoting the current output of sector *i* of region *r* acting like an input for sector *j* of region *r'*, while $\bar{X}_j^{r'}$ is another parameter that represents the total current output in currency units (e.g. US$) of sector *j* in region *r'*. Note again that we assume here that the relationship between the amount purchased from a sector to its neighboring sectors, and the total output of the sector, is constant in a given time period. Hence, current values of economic flows are used to calculate the technical coefficients, which are then employed to predict economic flows for any other given demand (see the Appendix for an illustrative example of IO models). Hence, the reader should not confuse the current economic flows (i.e., parameters $\bar{x}_{ij}^{rr'}$ and $\bar{X}_j^{r'}$) corresponding to the current demand, with those calculated for a different demand (i.e., variables $x_{ij}^{rr'}$ and $X_j^{r'}$). The technical coefficients $a_{ij}^{rr'}$ represent the amount (in US$) of output of sector *i* in region *r* necessary to produce one dollar of output of sector *j* in region *r'*. Taking this into account, the environmental equations can be rewritten as follows:

$$Imp_i^r = X_i^r e_i^r \qquad \forall i, r \tag{7}$$

$$TImp = \sum_i \sum_r Imp_i^r = \sum_i \sum_r X_i^r e_i^r \tag{8}$$

where e_i^r is the environmental pollution intensity for sector *i* of region *r* (i.e., impact per monetary unit traded). Finally, *TImp* is the total environmental impact generated by all of the sectors of the economy.

Multi-objective optimization problem based on linear programming.

As already mentioned, an IO table leads to a system of linear equations in which the total output of each sector is unknown, while its demand is fixed (parameter). The system of linear equations is typically solved for different demand values (y_i^r) to generate insight into how demand changes affect the economic and environmental performance of the overall economy.

Bearing all this in mind, we use the basic EEMRIO table to develop a multi-objective LP model that will be used to optimize the economic flows and demand values so as to reduce the environmental impact. Since it is assumed that the technologies (and therefore the corresponding pollution intensities) are given, the only way we can accomplish this goal is by reducing the economic flows (X_i^r), that is, by modifying the economic activity of each sector. Unfortunately, this will have the side effect of reducing in turn the demand satisfaction level. Hence, the goal of the optimization must be twofold: to minimize the environmental impact and to minimize the extent to which the economy is modified to reduce this impact. The latter objective is here modeled through the maximization of the demand satisfaction (i.e., maximization of the demand values, y_i^r). In our case, the environmental impact is quantified via the total CO_2 emissions (although any other impact indicator could be easily optimized). Finally, our approach leads to the following bi-criterion optimization problem:

$$\min\left\{-\sum_i \sum_r y_i^r,\ TImp\right\} \tag{9}$$

$$s.t.\quad X_i^r = \sum_j \sum_{r'} X_j^{r'} a_{ij}^{rr'} + y_i^r \qquad \forall i,r$$

$$TImp = \sum_i \sum_r Imp_i^r = \sum_i \sum_r X_i^r e_i^r$$

$$\underline{y0}_i^r \leq y_i^r \leq \overline{y0}_i^r \qquad \forall i,r$$

$$X_i^r,\ y_i^r,\ TImp,\ Imp_i^r \in \mathbb{R}^+$$

where Imp_i^r denotes the environmental impact (i.e., CO_2 emissions) produced by sector *i* of region *r*, while e_i^r is the environmental coefficient for sector *i* of region *r*. Finally, *TImp* is the total impact generated by all of the sectors of the economy.

This LP model seeks to optimize simultaneously the demand satisfaction and the associated CO_2 emissions (*Timp*) at a global scale (i.e., across the world), subject to the standard equations of the input output tables, the environmental equation that quantifies the CO_2 emissions and a flexible demand constraint. Thus, the model minimizes the total CO_2 emissions regardless of the place where the emissions occur. This approach avoids solutions in which the emissions of a country are minimized by displacing the manufacturing tasks to other regions. Note that the LP could be modified in order to include constraints on the production-based (territorial) emissions of the countries, which together with slack variables and penalties would enable the modeling of "cap and trade" policies. This was not done as we are considering global CO_2 emissions following a consumption-based perspective (instead of a territorial-based one), and in addition we treat the emissions as an additional objective rather than as a constraint.

In the LP, the demand is represented by the continuous variable y_i^r, which is constrained within realistic lower and upper bounds. Hence, as opposed to standard IO tables where y_i^r is a parameter, here it is defined as a variable. This mathematical approach makes the LP flexible enough to leave part of the demand unsatisfied (if required) and allows modeling the effects of potential environmental regulations on sectors' demands. The LP identifies key sectors whose demand needs to be modified to achieve a given environmental target (while maximizing demand satisfaction). This information provides valuable insight for public policy makers seeking to improve the environmental performance. Specifically, the solution calculated by the optimization algorithm can be implemented in practice by: (i) imposing taxes on these key sectors so as to reduce their demand; (ii) improving the environmental efficiency of their technologies; (iii) combining both strategies simultaneously.

Solution method

The solution of the bi-criterion optimization problem described above is given by a set of Pareto solutions representing the optimal trade-off between the conflicting objectives. At these Pareto points it is impossible to improve simultaneously all of the objectives without necessarily worsening at least one of them. There are several methods available for solving multi-objective optimization problems. This work applies the epsilon constraint method, which solves a series of single objective sub-problems where one objective is selected as main criterion while the others are transferred to auxiliary constraints that impose bounds on them[21].

Results

The approach presented was applied to the US economy in order to minimize the CO_2 emissions at a global scale by regulating US economic sectors. This part of the paper is organized as follows. Section 4.1 describes the database used in this work. Section 4.2 provides a preliminary analysis that assesses the CO_2 emissions embodied in the trade of goods and services within US sectors, and between US sectors and other foreign sectors. Section 4.3 summarizes the results obtained with the bi-objective model. Finally, section 4.4 analyzes the effect of replacing coal by shale gas, an emerging trend in the US economy, will have on the outcome of the optimization.

Data source

The World Input-Output Database (WIOD) was used in our calculations. This database was originally developed to analyze the effects of globalization on trade patterns, environmental pressures and socio-economic development across a wide set of countries[19]. The WIOD describes the economic inputs and outputs (in monetary terms) of 35 manufacturing sectors, covering 27 EU countries and 13 other major countries in the world for the period 1995 to 2009. The level of disaggregation, chosen based on initial data-availability exploration, ensures a maximum level of detail without relying on additional information typically lacking in national accounts. The 35-industry list is identical to the list used in the EUKLEMS database[22], but shows an additional breakdown of the transport sector. The list of countries covered by the database is given in Table 2, while the list of manufacturing sectors is given in Table 3. The preliminary analysis is simplified by grouping the 35 manufacturing sectors into 6 main sectors according to the type of activity (see Table 3). In the calculations, we omitted the emissions under the category "final consumption expenditure by households", as they are not disaggregated by sectors and therefore would not affect the outcome of the optimization (they would represent a fixed term in the objective function).

Data analysis

Production-based emissions of US industrial sectors

We first studied the extent to which every sector of the economy contributes to the overall CO_2 emissions. Figure 3 shows a breakdown of the US production-based (territorial) CO_2 emissions according to the sector of origin. Every bar in the figure represents the total emissions of each economic sector quantified following a production-based (territorial-based) approach; that is, the figure shows the emissions released within the limits of US regardless of the final destination of the goods/services. The production-based CO_2 emissions of sector i of country r (denoted by $ImpP_i^r$) are calculated from the sales of the sector and the associated pollution intensity, as follows:

$$ImpP_i^r = XP_i^r e_i^r \qquad \forall i, r = US \qquad (10)$$

where XP_i^r represents the sales of sector i of region r (in this case US), and e_i^r is the pollution intensity of that US sector (environmental coefficient for sector i of region r expressed in Gt CO_2 per US\$).

Note that the CO_2 emissions are associated with economic transactions required to produce goods consumed by either national (dark blue bars in Figure 3) or international (light blue bars in Figure 3) customers.

The total production-based US emissions were 4.2 Gt in 2009 (leaving the emissions associated with "final consumption expenditure by households" out), while the total exported emissions were 0.3 Gt. More than half of the emissions generated within US belong to the sector industry. A more detailed analysis that includes disaggregated data is provided in Fig. A.1. of the Appendix, which shows that activities related to chemical engineering (sectors: *coke, refined petroleum and nuclear fuel, chemicals and chemical products and rubber and plastics*) represent 9% of the total production-based emissions, while the production of utilities (sector *electricity, gas and water supply*) represents a 48%.

Consumption-based emissions of US industrial sectors

The consumption-based emissions of US consider the CO_2 emissions associated with all the facilities located anywhere in the world that cover the demand of every single sector of US, either directly (i.e., sectors sending goods to US customers in order to cover their demand) or indirectly (sectors whose output is used as intermediate input by other sectors that ultimately cover the US demand). The consumption-based CO_2 emissions (denoted by $ImpC_i^r$) are therefore obtained as follows:

$$ImpC_i^r = \sum_{i'} \sum_{r'} XC_{ii'}^{rr'} e_{i'}^{r'} \qquad \forall i, r = US \qquad (11)$$

where $XC_{ii'}^{rr'}$ denotes the economic transactions (in all of the sectors *i'* and economic regions *r'*) required to fulfill the demand of sector *i* of region *r*. Note that, as opposed to the production-based emissions of sector *i*, the consumption-based ones are generated by different sectors *i'* (located either in US or abroad) that produce either the final goods that sector *i* demands, or intermediate products used by other sectors to ultimately cover the demand of *i*. The value of $XC_{ii'}^{rr'}$ is obtained by solving the Leontief system for a vector demand where all the demands except for the one of the US sector being *i* are set to zero.

The total US consumption-based emissions were 4.9 Gt in 2009 (versus 4.2 Gt of production-based emissions), while the total imported emissions were 1.1 Gt (versus 0.3 Gt of CO_2 emissions exported). Hence, around 90% of the total CO_2 emissions (4.2 out of 4.9 Gt) attributed to the US economy (without considering the emissions associated with “final consumption expenditure by households”) are generated internally, while the remaining 10% are imported via trade. This 10% mismatch between production-based and consumption-based emissions evidences that the US is masking part of its impact by importing goods and services from abroad.

Figure 4 shows the results of this analysis, where each bar denotes the total emissions associated with the manufacturing tasks (taking place in any sector of any country) required to fulfill the demand of every US sector. As an example, to fulfill the demand of the sector industry, US needs to emit 1.5 Gt of CO_2 emissions within its boundaries, while other countries need to emit 0.31 Gt that are "imported" by the US economy via trade. On the other hand, this sector produces 2.5 Gt of CO_2, 0.14 Gt of which are exported (see Figure 3).

As observed, the economic activities associated with the sector industry are responsible for a large amount of emissions (2.53 Gt CO_2, which represents 64% of the total US production-based emissions, as shown in Figure 3), while the emissions required for satisfying the demand of the sector are significantly lower (1.51 Gt CO_2, which represents 38% of the total US consumption-based emissions in Figure 4). This means that most of the emissions generated by the sector industry are ultimately associated with other sectors that use its output as intermediate input to cover other sectors' demand. Hence, while the sector industry is indeed the largest ultimate source of impact, it produces outputs to other sectors that should share the corresponding environmental responsibility.

A deeper analysis of the sector industry reveals that 59% of the consumption-based emissions correspond to the subsector *electricity, gas and water supply*, which represents 22% of total consumption-based emissions (see Figure A.2 in the Appendix). Chemical engineering sectors represent 9% of the total production-based emissions, and 7% of the total consumption-based ones.

The mismatch between production-based and consumption-based emissions is further explored in Figure 5, which shows a breakdown of the emissions of the sector industry according to the ultimate destination of its output. As observed, the main sectors that consume the output of sector industry are the same sector itself (54%), followed by services (23%) and commerce (11%).

Figure 6 shows a more detailed comparison between consumption-based and production-based emissions for each of the sectors of the US economy. Those sectors with ratios consumption-based/production-based close to one (black line in Figure 6) have lower mismatches between both accounting methods (e.g., sector transport). In sectors below the line, the production-based emissions exceed the consumption-based ones (e.g., sector industry), while in the sectors above the line, the opposite situation occurs (e.g., sector technology). As already discussed, the overall mismatch between production-based and consumption-based emissions is around 10%. However, this value can be significantly larger on a sector basis. More precisely, consumption-based emissions are significantly higher than production-based emissions in the sectors commerce (ratio of 143%), services (202%) and technology (401%), while they are lower in the sectors industry (32%) and primary sectors (67%). This was expected, as part of the output of industrial and primary sectors is used to provide services, develop technology and run businesses. A more detailed analysis of this issue covering the subsectors within each sector is provided in Figure A.4 of the Appendix. Regarding the chemical engineering activities, we found that the sector *coke, refined petroleum and nuclear fuel* shows a ratio below 1 and it is therefore deemed as net producer of emissions (its consumption-based emissions are 34% lower than its production-based emissions), while the sectors *chemicals and chemical products* and *rubber and plastics* are net consumers of emissions (their consumption-based emissions are 4% and 52% higher than their production-based emissions, respectively).

Figure 7 shows a more detailed spatial analysis of the geographical distribution of the emissions traded that covers the top countries (and their industrial sectors) with which US exchanges goods and services. Note that “Rest of World” (ROW) accounts for the joint emissions of several countries.

As observed, trade is larger between countries like China, Canada, Russia, Japan, Mexico, Great Britain and the nations lumped into the aggregated region “Rest of the World”. Regarding the breakdown of emissions by sectors, we found that industry and primary sectors cover 68% and 55% of the USA imported/exported emissions, respectively. These results are consistent with the work by David and Caldeira (2010)[1].

Multi-objective optimization

The multi-objective IO model described previously was applied to minimize the impact of the US economy at a global scale (considering all the emissions required to satisfy the US demand). For convenience in the presentation of the results, the demand satisfaction level is expressed as the percentage of the total demand that is effectively covered. This percentage is obtained as follows:

$$DSat = 100\sum_i \frac{y_i^r}{y\_ini_i^r} \qquad r = US \qquad (12)$$

where demand y_i^r corresponds to the optimized demand of sector *i* in region *r* (i.e., US), and $y\_ini_i^r$ is the current demand of sector *i* in region *r* (i.e., US).

Note, however, that the objective that is maximized is the summation of the demand flows rather than the percentage of demand satisfied. This is because we found inconsistencies using percentage demand in cases where the demand is zero. In the calculations we assume that the optimized demand flows must fall within 90% to 100% of the actual nonzero demands. We defined a 10% variation limit in the demand, because when very high limits are used the model tends to fully eliminate the demand of some sectors (i.e., reductions close to 100%), while keeping the remaining ones unchanged. Therefore, by defining these limits, we ensure a responsible reduction in carbon dioxide emissions with minimum impact in the global economic structure.

The resulting LP model features 4,307 variables and 2,873 equations. It was implemented in the General Algebraic Modeling Software (GAMS v 24.4.1) and solved with CPLEX v12.6.1.0. Using 10 points for the epsilon constraint method to generate the Pareto curve, the CPU time varied between 15.77 and 44.35 CPU seconds depending on the instance being solved.

Figure 8 shows the Pareto curve obtained using the epsilon constraint method. The Pareto frontier, as expected from the nature of the LP model, is concave with the slope increasing as we move to the left. Hence, as we go from the maximum demand satisfaction solution (solution 1) to the minimum impact one (solution 10), greater reductions of demand satisfaction are required for a given reduction of CO_2 emissions.

Each point of the curve corresponds to a different macroeconomic alternative in which sectors are classified into 3 main groups: sectors with a demand hitting their lower bound, sectors with a demand hitting their upper bound, and only one sector with a demand lying between its lower and upper bound. Hence, an important outcome of the optimization is the number of sectors whose final demand is modified to reach a given environmental target. The number of sectors regulated increases as we move from the maximum demand satisfaction solution (all sectors fully cover the final demand) to the minimum impact one (all the demands hit the lower bound of 90%).

Table 4 displays the ratio between the demand unsatisfaction (calculated as 100 minus the demand satisfaction) and the corresponding reduction in CO_2 emissions for every point in the Pareto frontier:

$$Ratio = \frac{\text{demand unsatisfaction } (\%)}{\text{CO}_2 \text{ emissions reduction } (\%)} \tag{13}$$

Note that the values of this *Ratio* are consistent with the concave nature of the Pareto set. In the same table, the *Cut sectors* row indicates the number of productive sectors whose final demand must be modified to reach the corresponding environmental target (note that there are in total 1435 sectors, that is, 35 sectors in 41 countries).

In the maximum demand solution, all of the sectors fulfill the maximum demand. The minimum impact solution (i.e., solution 10) shows the highest ratio (4.13, calculated as 9.99/2.42), but allows for the largest reduction in CO_2 emissions (2.4%) at the expense of reducing the demand by 10% and cutting 1,435 sectors. In contrast, the intermediate Pareto point 6 shows a ratio close to 1.5 with a reduction of 1.35% in CO_2 emissions and a demand satisfaction of 98.1%.

Figure 9 shows the reduction in production-based CO_2 emissions of each country compared to the base case (current situation) in the minimum impact solution (i.e., solution 10), in an intermediate solution (i.e., solution 6), and in the solution with the lowest ratio (i.e., solution 2). As seen, the largest reduction in emissions occurs in United States, followed by Canada and Mexico. These last two countries exchange a large amount of goods/services with US via trade, and for this reason their CO_2 emissions are affected significantly by changes in the US economy.

Figure 10 shows how the US sectors reduce their emissions during the optimization (see Figure A.6. in Appendix for the disaggregated results). As observed, as we move from the maximum impact solution (Pareto point 2) to the minimum impact one (Pareto point 10), the first sector that is cut is industry (0.36%), which shows a low ratio demand satisfaction/CO_2 emissions (see Eq.13). An increasing number of sectors are then gradually cut until the minimum impact solution is reached in which the emissions reductions in all of the sectors are above 8%. A disaggregated analysis of these results shows that the first sector affected by the optimization is *electricity, gas and water supply* (2.6%). Furthermore, the emissions associated with chemical engineering activities are reduced by 8.2% in the minimum impact solution.

Finally, Figure 11 is similar to Figure 10, but shows the changes in emissions of the sectors at a global scale rather than the changes taking place only in US. As seen in Figure 11, the model regulates first those sectors with a low ratio demand satisfaction/CO_2 emissions, with the sector industry being the first to be modified. The analysis of the minimum impact solution shows also that the most affected sector is services (3.5%) followed closely by the commerce sector (3.0%) (see Figure A.7. of the Appendix for the disaggregated results).

Impact of Shale Gas

The interest in shale gas as an available source of natural gas has grown recently in the US, where it has become one of the major sources of energy[23]. This trend has been motivated by different factors, including the existence of large reserves and the fact that it is cleaner than standard fossil fuels in terms of contribution to global warming (see Table 5)[24]. At present, the sector has declined due to the low oil price resulting from geopolitical factors, but will very likely take off again in the future when oil prices will return to higher historical levels.

Bearing this in mind, this section aims to analyze the effect that increasing the share of shale gas in the electricity grid of US will have on its overall environmental performance. Specifically, we study several plausible scenarios, each entailing a different replacement ratio of coal by shale gas (i.e., percentages of replacement of coal by shale gas: 15% scenario Shale +, 25% scenario Shale ++, and 50% scenario Shale +++).

To model these scenarios, we made the following calculations. The pollution intensity parameter of the US sector *Electricity, gas and water supply* (subsector S17 belonging to the sector industry, as shown in Table 3) was modified, keeping the remaining parameters constant. The amount of energy required per unit of money traded (denoted by parameter $energy_{s17}^{US}$) was first obtained as follows:

$$energy_{s17}^{US} = \frac{e_{s17}^{US}}{\sum_n PI_n \cdot w_n} \quad (14)$$

where PI_n is the pollution intensity of technology *n* (i.e., CO_2 emissions per kWh), w_n is the share of technology *n* (that can be coal, petroleum, shale gas, natural gas, geothermal, solar, nuclear, wind and hydroelectric) in the US electricity grid (which falls in the interval 0-1), and e_{s17}^{US} is the pollution intensity factor of the sector *Electricity, gas and water supply* (S17) of the US expressed in $kgCO_2$/\$. Note that here we assume that all the emissions of sector S17 are due to electric power.

After determining the amount of energy required per monetary unit traded in sector S17, we next modified the share of coal and shale gas (w_{coal} and $w_{shale\ gas}$) according to the forecasted scenarios displayed in Table 6. The modified impact per monetary unit traded in sector S17 was therefore calculated as follows:

$$e'^{US}_{s17} = energy_{s17}^{US} \sum_n PI_n \cdot w'_n \quad (15)$$

where $energy_{s17}^{US}$ denotes the amount of energy required per unit of money traded in sector S17, PI_n is the pollution intensity of technology *n* (i.e., CO_2 emissions per kWh) and w'_n represents the new share of technology *n*.

The LP was solved again for the new modified environmental coefficients of sector 17 (Eq. 9).

Figure 12A shows the 10 Pareto points (global CO_2 emissions vs demand satisfaction) for the base case, scenario Shale+ (15% of coal replaced by shale gas), scenario Shale++ (25% of coal replaced by shale gas) and scenario Shale+++ (50% of coal replaced by shale gas). These points were solved following the same procedure as before; that is, by maximizing demand satisfaction for different targets on the total emissions. Figure 12B is equivalent to Figure 12A, but shows the US production-based emissions instead of the world production-based emissions. Note that the points have been projected here onto the subspace “US production-based emissions vs US demand satisfaction” despite being generated in the subspace “Global emissions vs US demand satisfaction”.

The analysis of the extreme scenario Shale+++ (50% of coal replaced by shale gas) shows that US CO_2 production-based emissions can drop by more than 10% compared to the base case, while the world emissions can drop by up to 2% in all of the Pareto points (the Pareto frontier shifts to the left) when replacing coal by shale gas.

An in-depth analysis of the Pareto frontier shows that the most affected countries and sectors are the same that in the base case (Figures 9-11). However, when shale gas is included in the electricity grid, the CO_2 emissions are significantly reduced.

Conclusions

This work has presented an approach for minimizing the CO_2 emissions at a macroeconomic level by modifying the sectors of an economy. Our approach combines multi-objective optimization and multi-regional input-output models within a single unified framework that allows identifying key economic sectors whose regulation leads to larger reductions in environmental impact, while keeping demand satisfaction as high as possible. The proposed model was applied to the US economy in order to identify the best policies to be implemented in practice for mitigating global warming.

A preliminary analysis of the IO data reveals that consumption-based US emissions are higher than production-based ones, thereby evidencing that part of the impact caused by the US is currently being masked by the displacement of the manufacturing tasks to other countries. This effect is also observed when the analysis is carried out on a sector basis, which shows that the life cycle emissions of several sectors exceed their emissions taking place within the limits of US. More than half of the production-based emissions belong to the industrial sector, while sectors related to chemical engineering activities represent 9% of the total emissions (i.e., sectors *Coke, Refined Petroleum and Nuclear Fuel, Chemicals and Chemical Products* and *Rubber and Plastics* shown in the Appendix). Most of these emissions, however, are ultimately associated with other sectors that use the output of the former ones to produce final goods (i.e., the emissions are originated in one sector, but the corresponding responsibility should be assigned to other sectors). As for the spatial distribution of emissions, we found that the trade of emissions is larger with China, Canada, Russia, Japan, Mexico and Great Britain.

The optimization model identified key sectors that should be regulated in order to attain a given environmental target while maximizing the demand satisfaction. The global sectors that would be more affected by a potential environmental regulation of the US economy would be services and commerce, with a reduction of 3.5% and 3.0% of their demand, respectively, in the minimum impact solution. These changes in the economy would also have a significant impact on Mexico and Canada, countries with which the US maintains a more intensive commercial activity.

Finally, replacing coal by shale gas can lead to reductions of up to 2% in global CO_2 emissions and up to 10% in US production-based CO_2 emissions.

Our analysis provides valuable insight for decision makers during the development of more effective environmental regulations. This approach, which can be easily extended to include other economic regions and environmental impacts, opens new avenues for the application of process systems engineering tools in macroeconomic problems. This work can be regarded as a first step towards the development of an equilibrium model, including prices elasticities with respect to supply and demand, to assist in the optimization of environmental regulations.

Acknowledgments

The authors wish to acknowledge the financial support received from the University Rovira i Virgili and from the Spanish Ministry of Education and Science (CTQ2012-37039 and DPI2012-37154).

Nomenclature

Acronyms

EEIO	Environmentally extended input-output
EEMRIO	Environmentally extended multi-regional input-output
EU	European Union
GHG	Greenhouse Gas Emissions
IO	Input-output
LP	Linear programing
Shale+	Case study 1: 15% of coal replaced by shale gas
Shale++	Case study 2: 25% of coal replaced by shale gas
Shale+++	Case study 3: 50% of coal replaced by shale gas
US	United States
WIOD	World Input-Output Database

Index

i	Economic sector
j	Economic sector
n	Energy technology
r	Region
r'	Region

Parameters

a_{ij}	Amount (in US$) of output of sector *i* required to produce one dollar of output of sector *j*
$a_{ij}^{rr'}$	Amount (in US$) of output of sector *i* of region *r* required to produce one dollar of output of sector *j* of region *r'*
e_i	Environmental pollution intensity of sector *i* (i.e., impact per monetary unit traded)
e_i^r	Environmental pollution intensity of sector *i* of sector *r* (i.e., impact per monetary unit traded)
$energy_{s17}^{US}$	Amount of energy required per unit of money traded in sector S17 of US
$ImpC_i^r$	Consumption-based CO_2 emissions
$ImpP_i^r$	Production-based CO_2 emissions

PI_n	Pollution intensity of technology *n*
w_n	Share of energy technology *n* in the electricity grid of US
XC_i^r	Total economic transactions required to fulfill the demand of sector *i* of region *r*
XP_i^r	Total sales of sector *i* of region *r*
x_{ij}	Output of sector *i* acting like an input for sector *j*
$\bar{x}_{ij}$	Current output of sector *i* acting like an input for sector *j*
$x_{ij}^{rr'}$	Output of sector *i* of region *r* acting like an input for sector *j* of region *r'*
$\bar{x}_{ij}^{rr'}$	Current output of sector *i* of region *r* acting like an input for sector *j* of region *r'*
$\bar{X}_j$	Current total output in currency units (e.g. US$) of sector *j*
$\bar{X}_j^{r'}$	Current total output in currency units (e.g. US$) of sector *j* in region *r'*

Variables

DSat	Demand satisfaction
Imp_i	Environmental impact (i.e., global warming potential) produced by sector *i*
Imp_i^r	Environmental impact (i.e., global warming potential) produced by sector *i* of region *r*
RATIO	Ratio between the demand unsatisfaction and the corresponding optimal reduction in CO_2 emissions for every point of the Pareto frontier
Timp	Total environmental impact generated by all of the sectors of the economy
X_i	Total output in currency units (e.g. US$) of sector *i*
X_i^r	Total output in currency units (e.g. US$) of sector *i* in region *r*
X_j	Total output in currency units (e.g. US$) of sector *j*
$X_j^{r'}$	Total output in currency units (e.g. US$) of sector *j* in region *r'*
y_i	Final demand (end user) of sector *i*
y_i^r	Final demand (end user) of sector *i* of region *r*
$y\_ini_i^r$	Current final demand (end user) of sector *i* of region *r*

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Figures and captions

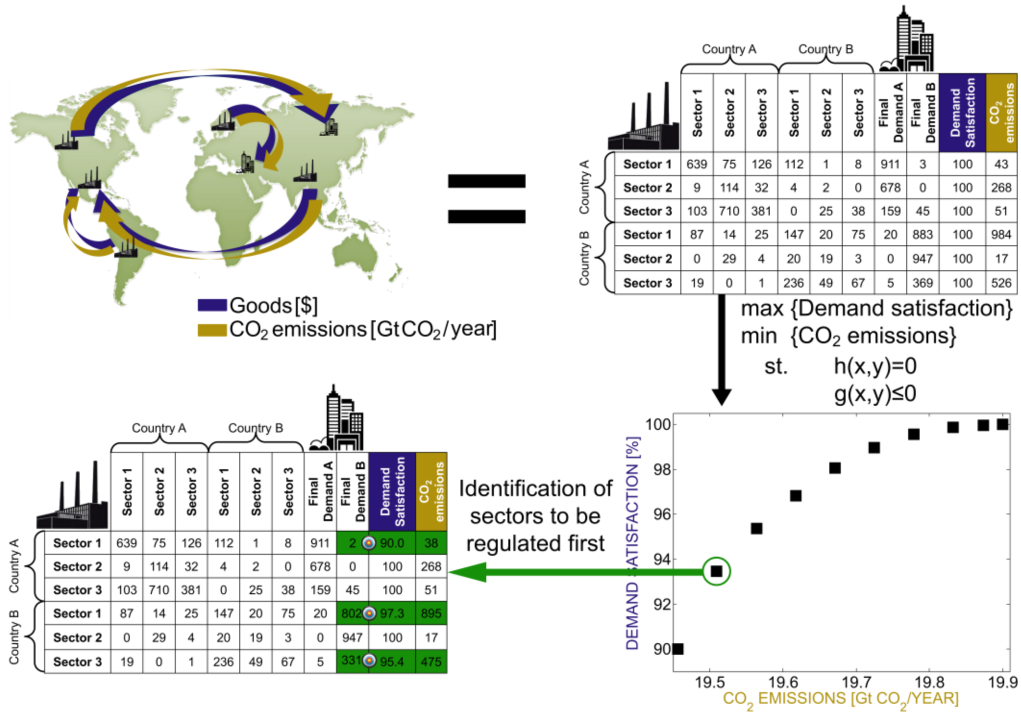

Fig. 1. Outline of the approach. Environmental impacts are embodied in the flows of goods and services. Input-output tables describe the economic transactions taking place between sectors of an economy. The solution of a multi-objective model based on input-output tables identifies the sectors that need to be regulated first so as to attain significant improvements in environmental performance with little impact on the economy.

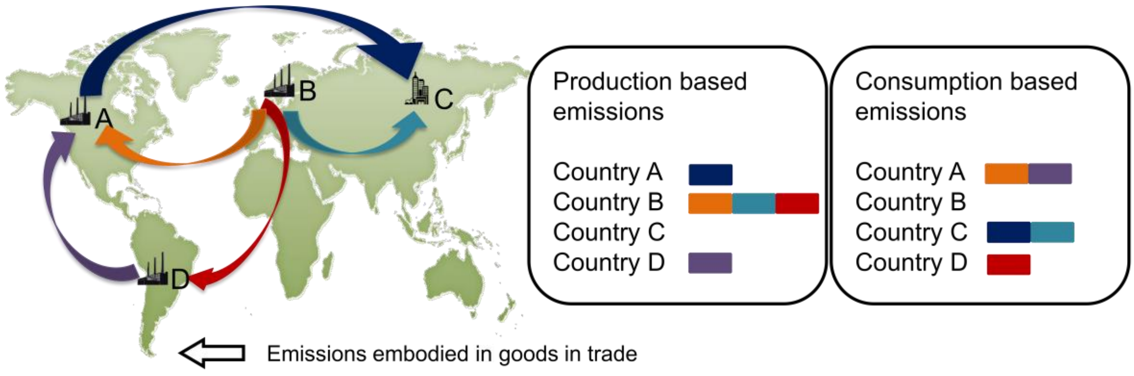

Fig. 2. Illustrative example of the differences in the quantification of impacts between the production-based (territorial) and the consumption-based accounting approaches. The arrows represent the emissions embodied in goods in trade between countries. Production-based emissions are those released within the boundaries of a country, while consumption-based ones refer to those associated with the generation of the goods and services consumed by the country regardless of the location where they take place.

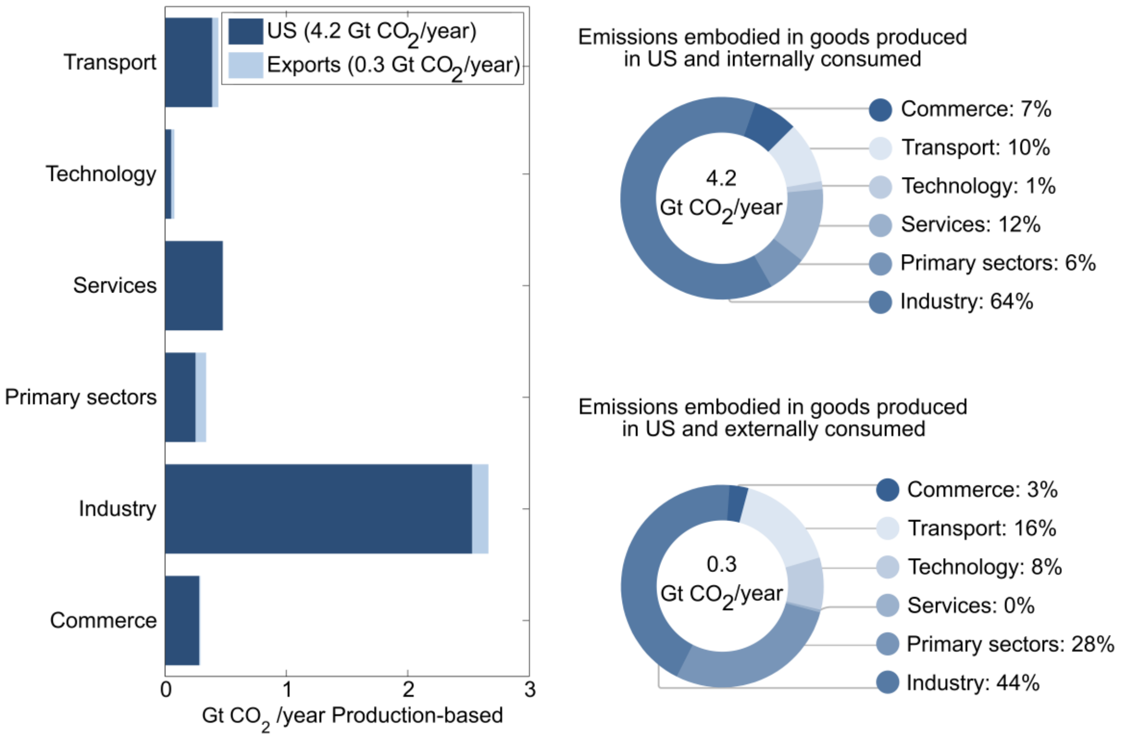

Fig.3. Dark blue bars represent the breakdown of total production-based CO_2 emissions generated within the limits of US (total emissions equal 4.2 Gt CO_2/year). Light blue bars show the breakdown of CO_2 emissions exported via trade (total exported emissions equal 0.3 Gt CO_2/year).

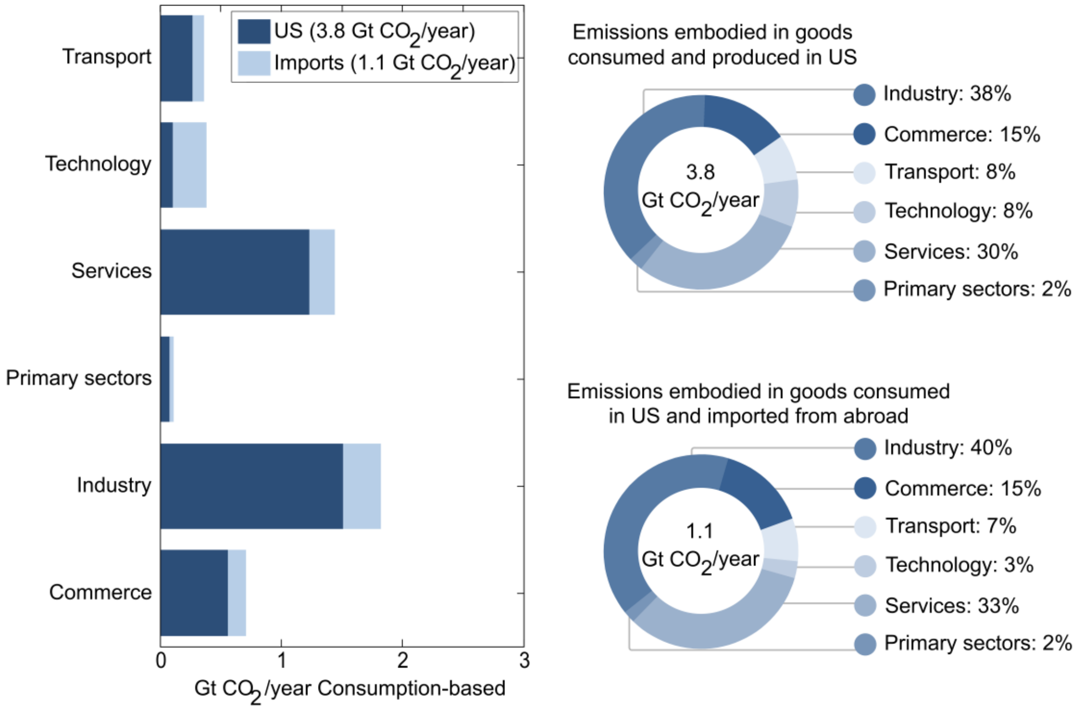

Fig. 4. Dark blue bars represent the breakdown of total consumption-based CO_2 emissions generated to satisfy the demand of each US sector (total emissions equal 3.8 Gt CO_2/year). Light blue bars are the sectorial breakdown of CO_2 emissions imported via trade (total imported emissions equal 1.1 Gt CO_2/year).

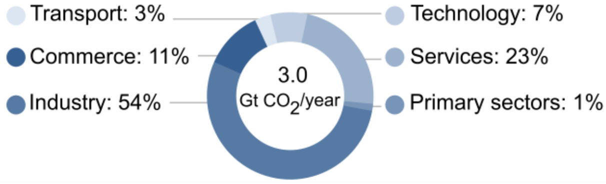

Fig. 5. Breakdown of the emissions of the sector industry in 2009 according to the final destination of the goods/services provided. Each portion represents the percentage of production-based CO_2 emissions generated by the sector industry that are attributed to the intermediate demand of each US sector.

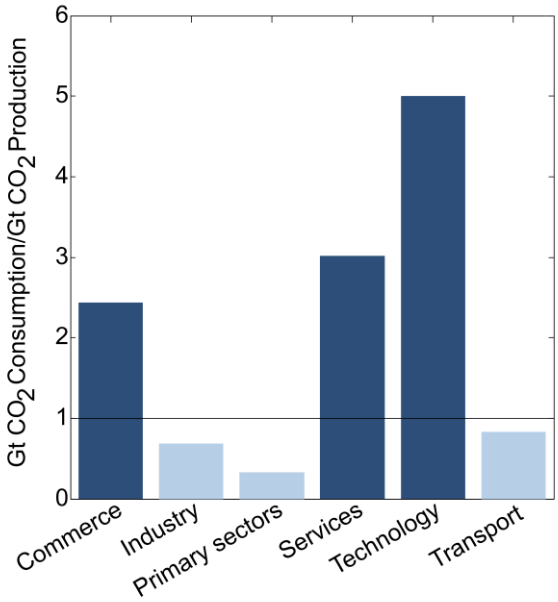

Fig. 6.Comparison between the consumption (dark blue bars) and production-based (light blue bars) accounting approaches in 2009. Each bar represents one sector.

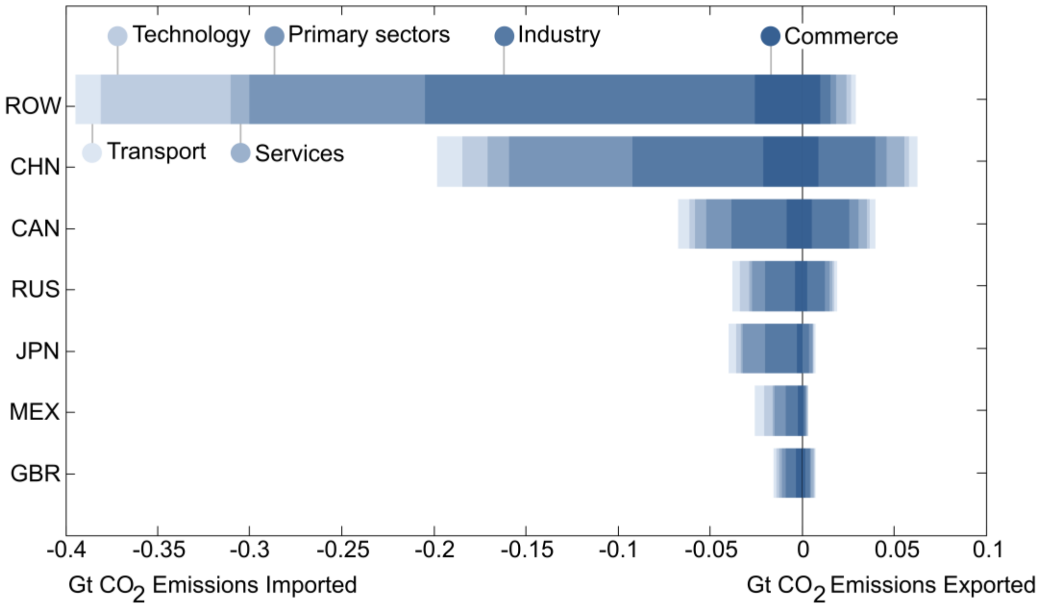

Fig. 7. Countries with higher trade of CO_2 embodied in services/goods exchanged with US in 2009. ROW = Rest of World; CHN = China; CAN = Canada; RUS = Russia; JPN = Japan; MEX = Mexico; GBR = United Kingdom.

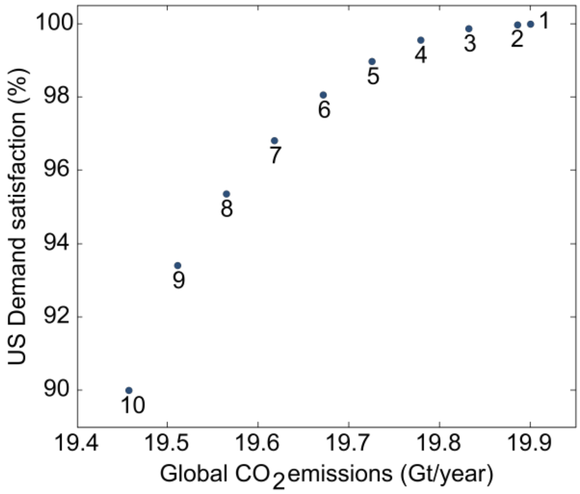

Fig. 8. Pareto optimal frontier for global CO_2 production-based emissions (Gt/year) vs US demand satisfaction (%) in 2009.

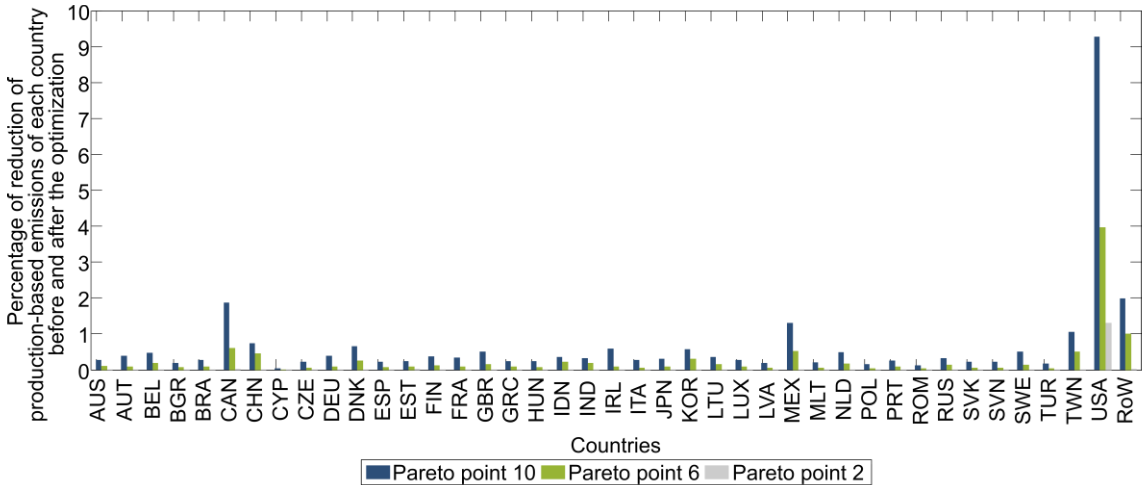

Fig. 9. Total percentage reduction of production-based emissions from maximum to minimum impact. Each bar represents a different Pareto point: the minimum impact solution (blue bar), an intermediate Pareto point (green bar), and the minimum ratio solution (grey bar) (solutions 10, 6 and 2 of Table 4, respectively).

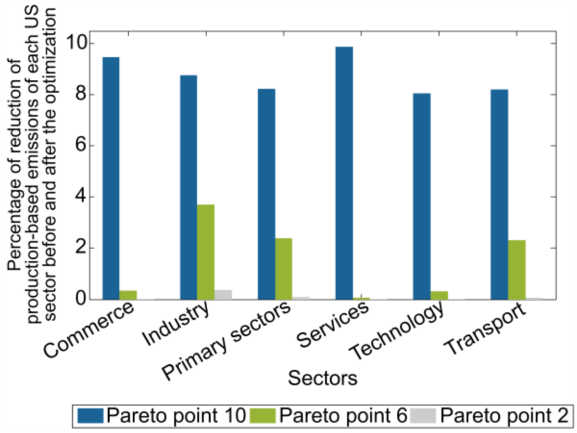

Fig. 10. Total percentage reduction of production-based emissions of US sectors from maximum to minimum impact. Each bar represents one Pareto point: the minimum impact solution (blue bar), an intermediate Pareto point (green bar), and the minimum ratio solution (grey bar) (solutions 10, 6 and 2 of Table 4, respectively).

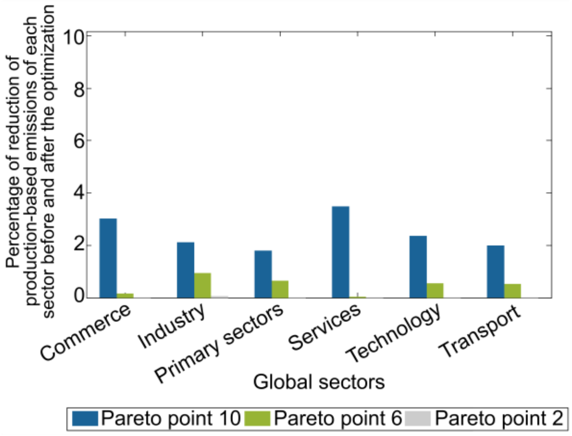

Fig. 11. Total percentage reduction of production-based emissions of global sectors from maximum to minimum impact. Each bar represents one Pareto point: the minimum impact solution (blue bar), an intermediate Pareto point (green bar), and the minimum ratio solution (grey bar) (solutions 10, 6 and 2 of Table 4, respectively).

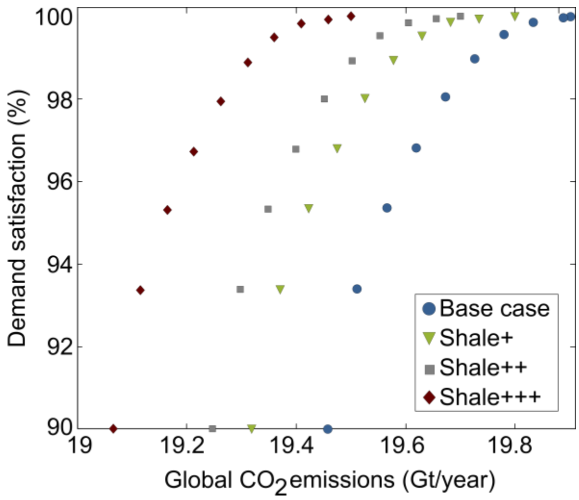

Fig. 12A. Pareto optimal frontier for global production-based CO_2emissions (Gt/year) vs US demand satisfaction (%) in 2009 for the base case, scenario Shale+ (15% of coal replaced by shale gas), scenario Shale++ (25% of coal replaced by shale gas) and scenario Shale+++ (50% of coal replaced by shale gas).

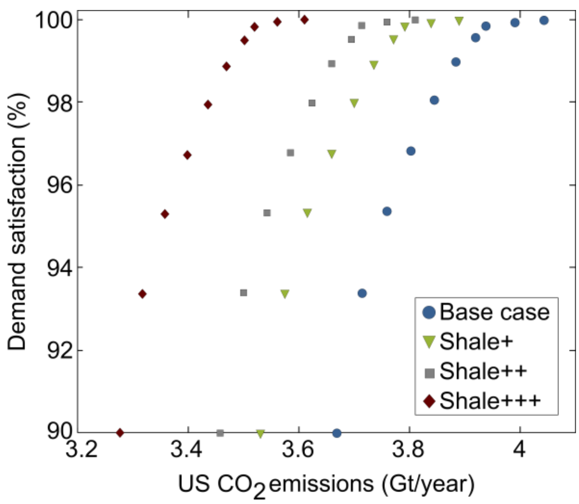

Fig. 12B. Pareto optimal frontier for US production-based CO_2 emissions (Gt/year) vs US demand satisfaction (%) in 2009 for the base case, scenario Shale+ (15% of coal replaced by shale gas), scenario Shale++ (25% of coal replaced by shale gas) and scenario Shale+++ (50% of coal replaced by shale gas).

Tables

Table 1. Illustrative example of an IO table for the case of 1 region and 3 industrial sectors.

		Sales →			
	Sector 1 [$]	**Sector 2 [$]**	**Sector 3 [$]**	**Final demand [$]**	**Total output [$]**
Purchases ↓ Sector 1[$]	x_{11}	x_{12}	x_{13}	y_1	X_1
Sector 2[$]	x_{21}	x_{22}	x_{23}	y_2	X_2
Sector 3[$]	x_{31}	x_{12}	x_{33}	y_3	X_3

Table 2. List of countries that appear in the WIOD database.

European Union		**America**	**Asia and Pacific**
Austria	Latvia	Brazil	Australia
Belgium	Lithuania	Canada	China
Bulgaria	Luxembourg	Mexico	India
Cyprus	Malta	United States	Indonesia
Czech Republic	Netherlands		Japan
Denmark	Poland		Russia
Estonia	Portugal		South Korea
Finland	Romania		Taiwan
France	Slovak Republic		Turkey
Germany	Slovenia		
Greece	Spain		
Hungary	Sweden		

Table 3. List of manufacturing sectors that appear in the WIOD-database.

Commerce		**Services**	
S18	Construction	S22	Hotels and Restaurants
S19	Sale, Maintenance and Repair of Motor Vehicles Retail Sale of Fuel	S29	Real Estate Activities
S20	Wholesale Trade and Commission Trade, Except of Motor Vehicles	S31	Public Admin and Defense; Compulsory Social Security
S21	Retail Trade, Except of Motor Vehicles ; Repair of Household Goods	S32	Education
S28	Financial Intermediation	S33	Health and Social Work
S30	Renting of M&Eq and Other Business Activities	S34	Other Community, Social and Personal Services
Industry		S35	Private Households with Employed Persons
S3	Food, Beverages and Tobacco	**Technology**	
S4	Textiles and Textile Products	S13	Machinery, Nec
S5	Leather, Leather and Footwear	S14	Electrical and Optical Equipment
S7	Pulp, Paper, Paper , Printing and Publishing	S16	Manufacturing, Nec; Recycling
S8	Coke, Refined Petroleum and Nuclear Fuel	S27	Post and Telecommunications
S9	Chemicals and Chemical Products	**Transport**	
S10	Rubber and Plastics	S15	Transport Equipment
S11	Other Non-Metallic Mineral	S23	Inland Transport
S17	Electricity, Gas and Water Supply	S24	Water Transport
Primary sector		S25	Air Transport
S1	Agriculture, Hunting, Forestry and Fishing	S26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
S2	Mining and Quarrying		
S6	Wood and Products of Wood and Cork		
S12	Basic Metals and Fabricated Metal		

Table 4. Optimal solutions found for the CO_2 emissions minimization for 2009. The number of sectors refers to the disaggregated sectors provided in the Appendix.

Pareto Points	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Gobal CO_2 emissions reduction (%)	0.00	0.27	0.54	0.81	1.08	1.35	1.61	1.88	2.15	2.42
US Demand satisfaction (%)	100.0	99.93	99.86	99.56	98.97	98.06	96.83	95.36	93.40	90.01
Ratio	-	0.25	0.25	0.55	0.96	1.45	1.97	2.46	3.06	4.13
Cut sectors	0	14	14	261	449	734	885	885	1075	1435

Table 5. Pollution intensity of electricity technologies in US[25].

Energy Source	**Pollution intensity (kgCO_2/kWh)**
Coal	1.001
Petroleum	0.840
Shale Gas	0.479
Natural Gas	0.469
Geothermal	0.045
Solar	0.042
Nuclear	0.016
Wind	0.012
Hydroelectric	0.004

Table 6. Electricity grid of US for the base case, scenario Shale+, scenario Shale++ and scenario Shale+++. The pollution intensity of sector 17 (CO_2 emissions per monetary unit traded) for every scenario is shown in the last row of the table.

Energy Source	**Base case % of use**[24]	**Shale+ % of use**	**Shale++ % of use**	**Shale+++ % of use**
Coal	44.5	37.8	33.4	22.3
Geothermal	0.4	0.4	0.4	0.4
Hydroelectric	7.0	7.0	70	70
Natural Gas	23.6	23.6	23.6	23.6
Nuclear	20.2	20.2	20.2	20.2
Petroleum	1.3	1.3	1.3	1.3
Shale Gas	0.0	6.7	11.1	22.3
Solar	0.5	0.5	0.5	0.5
Wind	2.0	2.0	20	2.0
$\boldsymbol{e_{s17}^{US}}$ **(kgCO_2/\$)**	5.25	4.93	4.71	4.18