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. Standard environmental regulations focus on reducing the impact in the place of origin regardless of the final destination of the goods produced, which might lead to an unfair allocation of responsibilities. 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 identify sectors that should be regulated first to reach a given environmental target while maximizing the demand satisfaction. Our findings show that the application of process systems engineering tools at a macroeconomic level can provide valuable insight for public policy makers during the development of more effective environmental regulations.

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1. Introduction

In today's globalized market, countries must face the challenge of reducing their greenhouse gas (GHG) emissions while remaining economically competitive. Policies like the Kyoto Protocol have focused on reducing the direct emissions of nations in an attempt to mitigate global warming on time. It is well known, however, that countries can mask their environmental impact by displacing the manufacturing tasks to regions with softer environmental regulations [1–6]. To avoid this, environmental policies should distinguish between production-based and consumption-based impact. The production-based impact is caused by the facilities operating within the limits of a country. Some of these facilities might produce goods that are exported overseas, so the responsibility of their impact should be assigned to the final consumer rather than to the producer. Conversely, consumption-based impact refers to the impact caused by all the facilities (located anywhere in the world) that produce the goods demanded by a region. By defining environmental policies based on consumption, final customers are penalized 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.

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 behind consumption-based calculations, however, was developed in economics long time ago through the use of input-output models (IO) [7]. These models study economic flows between sectors of the same or different nations, and allow for the prediction that changes in the demand of a region have on an entire economy. The original IO approach focused on a single economic region, but was later enlarged in scope in order to deal with several regions simultaneously by covering international transactions between sectors of different nations[8].

Furthermore, it is possible to integrate environmental aspects into IO models, thereby giving rise to environmentally extended input-output models (EEIO)[9]. These models are constructed from standard IO tables by incorporating an additional column that displays the impact associated with the monetary flows between economic sectors. Recent efforts have been undertaken to gather the necessary data to build environmentally extended multi-regional input-output tables (EEMRIO) at a global scale [10,11]. EEMRIO models attribute pollution or resources depletion to the final demand of a product or service following a consistent holistic approach[12], which makes them very useful for policy making.

EEIO models have been integrated recently with multi-objective optimization as a manner to automate the search for alternatives with improved performance at a global macroeconomic level. Some authors applied this approach to 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 primarily on optimizing single economies (without considering international economic transactions). This narrow scope neglects the impact that changes in the economy of one region may have on other overseas economies.

This work introduces a systematic strategy that combines multi-objective optimization and multi-regional input-output models within a unified framework that enables the identification of key economic activities that are contributing marginally to the economy but significantly to the total impact. The main novelty of our approach is that it makes use of a multi-regional model that enables the assessment of the effects that the environmental strategies adopted in 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 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 and a discussion of the optimization results produced by the model, which are generated also for the case of replacing coal by shale gas. Finally, section 5 summarizes the conclusions of our work.

2. 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 the economic sectors (located in different nations as well as within the same country) that produce the goods and services demanded by the global population. The impact associated with each economic transaction is expressed in the form of pollution intensity vectors that represent the impact caused per unit of money traded. The goal of the analysis is to find the sectors to be regulated in order to simultaneously minimize the CO_2 emissions at a global macroeconomic scale and the changes that need to be performed in the economy in order to achieve 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 can use it in different ways. The most straightforward one is to define taxes on the most polluting sectors so as to reduce their demand and therefore the corresponding environmental impact. A decrease in the demand will result in turn in a reduction of the economic flows, and therefore of the gross domestic product of the country. Hence, a more appealing alternative to decrease the impact (without modifying the economy to a large extent) is to foster research on cleaner technologies that will improve the environmental efficiency of the target sectors. This positive environmental effect will eventually propagate to other industrial sectors via trade, thereby enhancing the level of sustainability of the global economy.

3. Mathematical formulation

Figure 1 summarizes the overall approach. In this example, 2 countries and 3 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 the others as well as to the final consumer, while columns denote purchases from one sector to the others. 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.

The input-output tables allow us to quantify the impact from production based and from consumption based perspective, Figure 2 illustrates the differences between those two approaches. In this example we consider 4 countries. From a production based approach, A and D are slightly polluting countries, B is highly polluting and C is totally clean. On the contrary, from the consumption based approach, A and C become the most polluting countries, while country B changes from the most polluting to a totally clean country.

Taking this IO table as starting point, an optimization model is formulated next and then efficiently solved via optimization methods. 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 very first place to achieve a given environmental target while causing minimum disturbances in the economy (i.e., while maximizing the satisfaction of the current demand).

The approach presented here relies on a bi-objective linear programming model that contains the basic equations of an environmentally extended multi-regional input-output (EEMRIO) table. This section starts by describing IO models, a topic that is typically missing in the standard chemical engineering literature, before presenting the complete mathematical formulation.

3.1. 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:

$$X(i) = \sum_{j} a(i,j)X(j) + y(i) \qquad \forall i \tag{1}$$

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(i,j) 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).

$$a(i,j) = \frac{\bar{x}(i,j)}{\bar{X}(j)} \qquad \forall i,j \qquad (2)$$

where, $\bar{x}(i,j)$ 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$) of sector *j*. The coefficients *a(i,j)* represent the amount (in US$) 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(i,j)* can be considered constant for a certain period, assuming that the technological conditions of the total production of an economy remain unchanged. IO tables are typically used for predicting changes in the sectors of an economy according to changes in the demand of a single (or several) sectors. This analysis is carried out by fixing the demand to the predicted value and then solving the resulting system of linear equations. This calculation provides the economic flows (corresponding to sectorial transactions) required to satisfy the new demand.

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

3.2. 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:

$$Imp(i) = X(i)e(i) \qquad \forall i \tag{3}$$

$$TImp = \sum_i Imp(i) = \sum_i X(i)e(i) \tag{4}$$

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). Finally, *TImp* is the total environmental impact generated by all of the sectors of the economy.

3.3. 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:

$$X(i,r) = \sum_j \sum_{r'} X(j,r')a(i,j,r,r') + y(i,r) \qquad \forall i,r \tag{5}$$

The following notation is used here:

X(i,r), X(j,r') are variables denoting the total output in currency units (e.g. US$) of sector *i/j* in region *r/r'*.

a(i,j,r,r') 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, similarly to the previous case, for a given demand and technical coefficients, 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):

$$a(i,j,r,r') = \frac{\bar{x}(i,j,r,r')}{\bar{X}(j,r')} \qquad \forall i,j,r,r' \tag{6}$$

In Eq. 6, $\bar{x}(i,j,r,r')$ 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, the current values of the economic flows are used to calculate the values of the technical coefficients, and these technical coefficients are then employed in the calculation of the economic flows that would be required to satisfy another given demand. Hence, the reader should not confuse the current economic flows (i.e., parameters $\bar{x}(i,j,r,r')$ and $\bar{X}(j,r')$) corresponding to the current demand with those calculated for a different demand (i.e., variables $x(i,j,r,r')$ and $X(j,r')$). The technical coefficients *a(i,j,r,r')* 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.

3.4. 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 the unknown variable, while its demand is a fixed parameter. The system of linear equations is typically solved for different demand values ($y(i,r)$), which provides valuable insight into the effect that demand changes have on 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. On the one hand, we would like to minimize the environmental impact. Since it is assumed that the technologies (and therefore the corresponding pollution intensities) are given, the only option to accomplish this goal is to reduce the economic flows ($x(i,r)$), that is, the economic activity of each sector. This action will reduce in turn the demand satisfaction level attained by the economy. Hence, the goal of the optimization is twofold: to minimize the environmental impact and to minimize the extent to which the economy needs to be modified in order to reduce the impact to the level sought. The latter objective is here modeled through the maximization of the demand satisfaction (i.e., maximization of demand flows, $y(i,r)$). In our case, the environmental impact is quantified via the total CO_2 emissions (note however that any other impact indicator could be used instead). Finally, our approach leads to the following bi-criterion optimization problem:

$$\min\left\{-\sum_{i}\sum_{r} y(i,r),\ \ TImp\right\} \tag{9}$$

$$\begin{aligned} s.t.\quad & X(i,r) = \sum_{j}\sum_{r'} X(j,r)a(i,j,r,r') + y(i,r) && \forall i,r \\ & TImp = \sum_{i}\sum_{r} Imp(i,r) = \sum_{i}\sum_{r} X(i,r)e(i,r) && \\ & \underline{y_0(i,r)} \leq y(i,r) \leq \overline{y_0(i,r)} && \forall i,r \\ & X(i,r),\ \ y(i,r),\ \ TImp,\ \ Imp(i,r) \in \mathbb{R}^{+} && \end{aligned}$$

where $Imp(i,r)$ denotes the environmental impact (i.e., the 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 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 are released. This approach avoids solutions in which the emissions of a country are minimized by displacing the manufacturing tasks to other regions.

In this formulation, the demand is represented by a continuous variable 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. With this modeling approach, the model is flexible enough to leave part of the demand unsatisfied, which reflects the situation that would arise when regulating the demand of the sector. The LP identifies in a systematic manner those sectors whose demand needs to be modified in first place so as to achieve a given environmental target while maximizing the demand satisfaction. This information provides valuable insight for public policy makers on how to improve the environmental performance of the global economy. Specifically, the solution calculated by the optimization algorithm can be implemented in practice by: (i) imposing taxes on these key sectors; (ii) improving the environmental efficiency of their technologies; (iii) combining both strategies simultaneously.

3.5. 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. These Pareto points show the property that it is impossible to improve them simultaneously in all of the objectives without necessarily worsening at least one of the others. There are several methods available for solving multi-objective optimization problems. Without loss of generality, 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].

4. Results

The approach presented was applied to the US economy in order to minimize the CO_2 emissions at a global scale by regulating its 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. Section 4.4 analyzes the effect that replacing coal by shale gas, an emerging trend in the US economy, will have on the outcome of the optimization.

4.1. 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, which was chosen on the basis of initial data-availability exploration, ensures a maximum level of detail without the need for additional information that is typically lacking in the system of 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).

4.2. 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 CO_2 emissions according to the sector of origin. Every bar in the figure represents the total emissions of each economic sector, which was quantified following a production-based approach; that is, the figure shows the emissions released within the limits of US (and regardless of the final destination of the goods produced). The production-based CO_2 emissions of sector i of country r (denoted by $Imp^P(i,r)$) are calculated from the sales of the sector and the associated pollution intensity, as follows:

$$Imp^P(i,r) = X^P(i,r)e(i,r) \qquad \forall i, r = US \qquad (10)$$

where $X^P(i,r)$ represents the sales of sector i of region r, and $e(i,r)$ is the pollution intensity (environmental coefficient for sector i of region r expressed in Gt CO_2 per US$).

Note that the CO_2 emissions are originated from economic transactions that 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, 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 disaggregated analysis (see Fig. A.1. in the appendix) 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 emissions, while the production of utilities (sector *electricity, gas and water supply*) represents 48% of the total emissions.

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 that send goods that cover the demand of the US sector) or indirectly (sectors whose output is used as intermediate input by other sectors that ultimately cover the demand of the US sector). The consumption-based CO_2 emissions (denoted by $Imp^C(i,r)$) are therefore obtained as follows:

$$Imp^C(i,r) = \sum_{r} \sum_{i'} X^C(i',r) e\,(i',r) \qquad \forall i, r = US \qquad (11)$$

where X^C denotes the economic transactions 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 might be associated with sectors different from *i* that produce goods used as intermediate products to ultimately cover the demand of *i*. The value of X^C is obtained by solving the following system of linear equations with |I|·|R| equations and unknowns:

$$X^C(i,r) = \sum_{j} \sum_{r'} X^C(j,r') a(i,j,r,r') + y(i,r) \qquad \forall i, r = US \qquad (12)$$

where demand $y(i,r)$ corresponds to the demand of sector *i* in region *r* (i.e., US). Note that this equation considers all the economic transactions required to satisfy the demand of every sector of the US economy regardless of the place where they take place.

The total US consumption-based emissions are 4.8 Gt (versus 4.2 Gt of production-based emissions), while the total imported emissions are 1.1 Gt (versus 0.3 Gt of CO_2 emissions exported). Hence, almost 90% of the total CO_2 emissions (4.2 out of 4.8 Gt) attributed to the US economy are generated by internal activities, while the remaining 10% are imported from abroad via trade. This 10% mismatch between production-based and consumption-based emissions shows 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 (regardless of the region and sector where they occur). 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). Note that these 2.5 Gt of CO_2 are associated with the facilities of this sector that aim to fulfill either the intermediate demand of other sectors or the final demand of the sector itself.

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 released 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 are ultimately associated with other sectors that purchase goods/services from it and use them as intermediate products. Hence, the sector industry is indeed the largest ultimate source of impact, but in practice its outputs are used by other sectors that should share the corresponding responsibility.

Within the sector industry (see Figure A.2 in the appendix), 22% of the direct consumption-based emissions are associated with the subsector electricity, gas and water supply. Chemical engineering sectors represent 9% of the production-based emissions, and 7% of the 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 industry sector according to the ultimate destination of the goods. As observed, the main sectors that have transactions with the sector industry are the same sector itself (54%), followed by services (23%) and business (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 close to the line have a lower mismatch between production-based and consumption-based emissions (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 mismatch can be significantly larger on a sectorial basis. More precisely, consumption-based emissions are significantly higher than production-based emissions in the sectors business (ratio of 143%), services (202%) and technology (401%), while they are lower in 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 sector *coke, refined petroleum and nuclear fuel* is a net producer sector (its consumption-based emissions are 34% lower than its production-based emissions); while sectors *chemicals and chemical products and rubber and plastics* are net consumer sectors (consumption-based emissions are 4% and 52% higher than 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 exchange 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 accounted for in “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].

4.3. 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 (note however that the objective that is maximized is the summation of the demand flows rather than the percentage of demand satisfied). This percentage is obtained as follows:

$$DSat = 100 \sum_{i} \frac{y(i,r)}{y_0(i,r)} \qquad r = US \qquad (13)$$

where demand $y(i,r)$ corresponds to the optimized demand of sector i in region r (i.e., US) and $y_0(i,r)$ is the current demand of sector i in region r (i.e., US). In the calculations, we assume that the optimized demand must fall within 90% to 100% of the actual demand.

The resulting LP model features 5,742 variables and 4,308 constraints. It was implemented in the General Algebraic Modeling Software (GAMS v 24.4.1) and solved with CPLEX v12.6.1.0. The CPU time varied between 15.77 and 44.35 CPU seconds depending on the instance being solved.

Figure 8 shows the 10 Pareto points obtained using the epsilon constraint method. The Pareto frontier, as expected from the LP nature of the 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: Those with a demand hitting its lower bound, those with a demand hitting its upper bound, and only one sector with a demand lying between the 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 and the corresponding optimal reduction in CO_2 emissions for every point of the Pareto frontier:

$$Ratio = \frac{\text{demand unsatisfaction (\%)}}{\text{CO}_2\text{ emissions reduction (\%)}} \tag{14}$$

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 and 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 (4.1), 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, 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 Supplementary material for the disaggregated results). As observed, as we move from the maximum impact solution to the minimum impact one (Pareto point 2), the first sector that is cut is industry (0.36%), which shows a low ratio demand satisfaction/CO_2 emissions (see Eq.14). An increasing number of sectors are then gradually cut until the minimum impact solution is reached in which the emissions reductions in all sectors are above 8%. A more disaggregated analysis shows that the first sector affected by the optimization is electricity, gas and water supply (2.6%). In addition, 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 business sector (3.0%) (see Figure A.7. of the Supplementary material for the disaggregated results).

4.4. Impact of Shale Gas

The interest in shale gas as an available source of natural gas has grown rapidly in the US, where it has become one of the major sources of energy. This trend in the US is 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)[23].

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, this section analyzes 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 proceeded as follows. The pollution intensity parameter of the US sector *Electricity, gas and water supply* (subsector S17 belonging to the sector industry, as shown in Table A.1. of disaggregated sectors provided as supplementary material) 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:

$$energy(s17, US) = \frac{e(s17, US)}{\sum_n PI(n) \cdot w(n)} \qquad (15)$$

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* in the electricity grid of US (that 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 US, expressed in $kgCO_2/\$$.

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 then obtained as follows:

$$e'(s17, US) = energy(s17, US) \sum_{n} PI(n) \cdot w'(n) \qquad (16)$$

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

Figure 12A shows the 10 Pareto points (CO_2 emissions worldwide 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, maximizing the demand satisfaction for different targets on the emissions. Figure 12B is equivalent to Figure 12A, but it 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 emissions vs demand satisfaction", despite the fact that they were generated in the subspace "Global emissions vs 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 the Pareto points (the Pareto frontier shifts to the left).

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 the shale gas is included in the electricity grid, the CO_2 emissions reductions are significantly larger.

5. 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 impact at a minimum change in demand satisfaction. The tool introduced 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, evidencing that part of its impact is currently being masked by displacing the manufacturing tasks to other countries. This happens as well on a sectorial basis, where 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 supplementary material). Most of these emissions, however, are ultimately associated with sectors that differ from the one that releases them (i.e., the emissions are originated in one sector, but are required to cover the demand of a different sector). 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 algorithm identified the 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 business, with a reduction of 3.5% and 3.0%, 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 intense commercial activity.

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

Our analysis provides valuable insight for decision makers during the development of more effective environmental regulations. This approach can be easily extended to deal with other economic regions and environmental impacts, and opens new avenues for the application of process systems engineering tools in macroeconomic problems.

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(i,j)	Amount (in US$) of output of sector *i* necessary to produce one dollar of output of sector *j*
a(i,j,r,r')	Amount (in US$) of output of sector *i* of region *r* necessary to produce one dollar of output of sector *j* of region *r'*
e(i)	Environmental pollution intensity for sector *i* (i.e., impact per monetary unit traded)
e(i,r)	Environmental pollution intensity for sector *i* of sector *r* (i.e., impact per monetary unit traded)
energy(s17,US)	Amount of energy required per unit of money traded
$Imp^C(i,r)$	Consumption-based CO_2 emissions
$Imp^P(i,r)$	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
$X^C(i,r)$	Economic transactions required to fulfill the demand of sector *i* of region *r*
$X^P(i,r)$	Sales of sector *i* of region *r*
x(i,j)	Output of sector *i* acting like an input for sector *j*
$\bar{x}(i,j)$	Current output of sector *i* acting like an input for sector *j*
x(i,j,r,r')	Output of sector *i* of region *r* acting like an input for sector *j* of region *r'*
$\bar{x}(i,j,r,r')$	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) associated with 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 the sector *i*
y(i,r)	Final demand (end user) of the sector *i* of region *r*
$y_0(i,r)$	Current final demand (end user) of the sector *i* of region *r*

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Figures

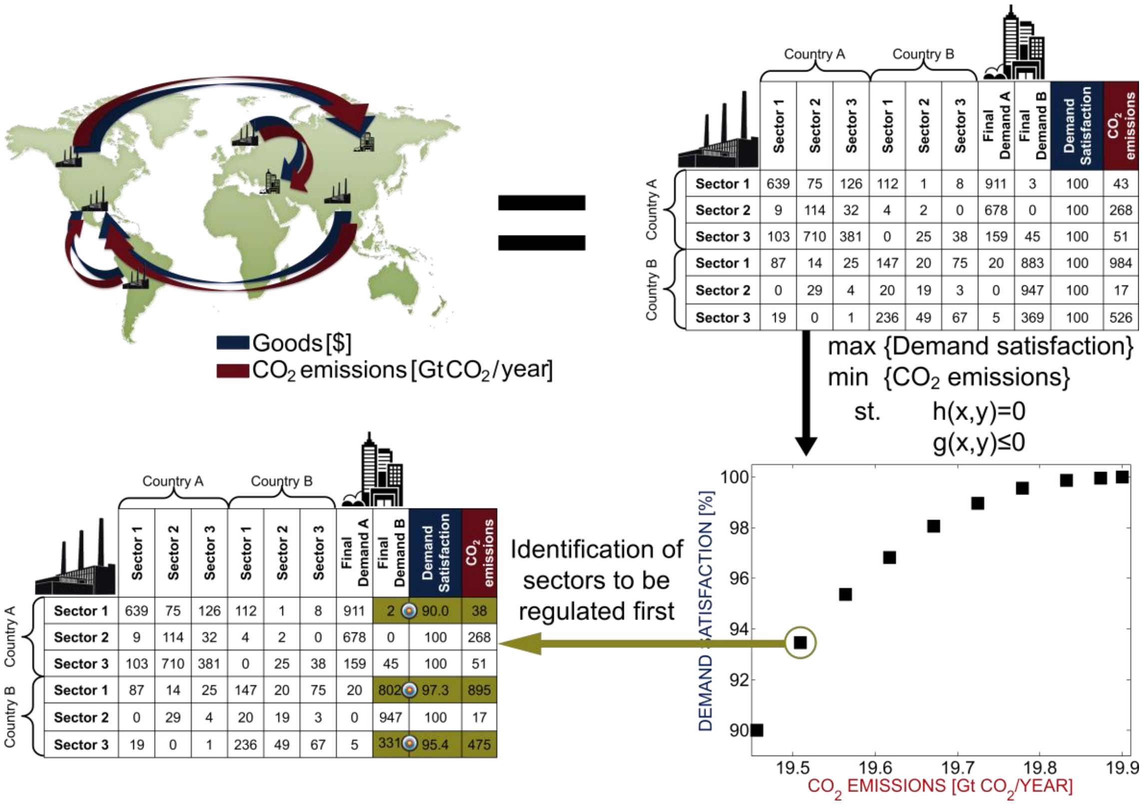

Fig. 1. Outline of the approach. Environmental impacts are embodied in the flows of goods. Input-output tables describe the economic transactions taking place between sectors of an economy. The solution of a multi-objective model based on input-output tables identifies the sectors that need to be regulated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

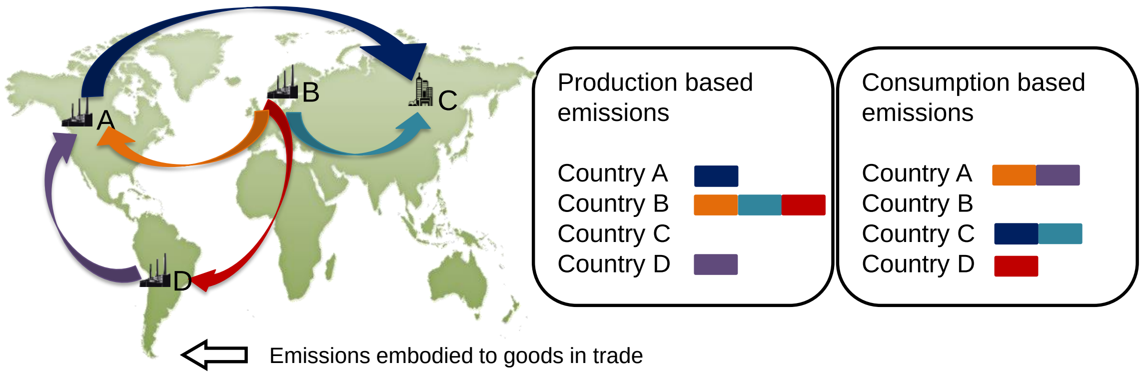

Fig. 2. Illustrative example of the differences in the quantification of impacts between the production based and the consumption based perspective. The arrows represent the emissions embodied to goods in trade between countries.

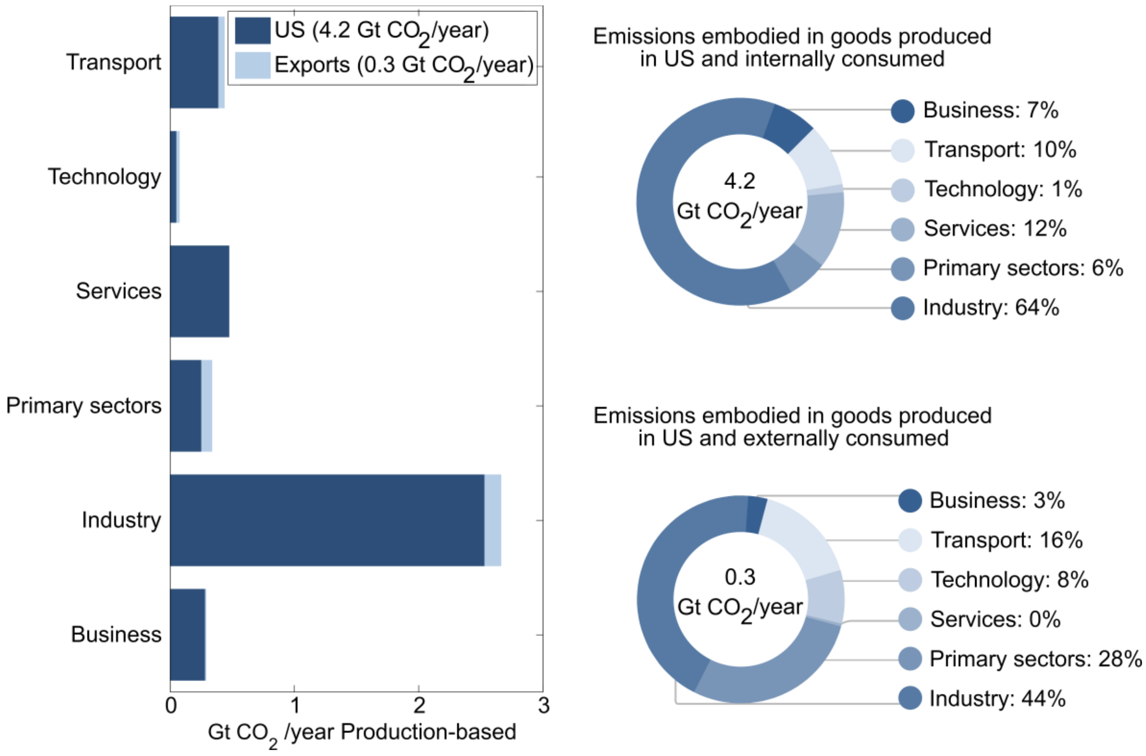

Fig.3. Dark blue bars represent the breakdown of total production-based CO_2 emissions generated within the limits of US (total emissions equal 4.2 Gt CO_2/year). Light blue bars are the breakdown of CO_2 emissions exported via trade (total exported emissions equal 0.3 Gt CO_2/year).

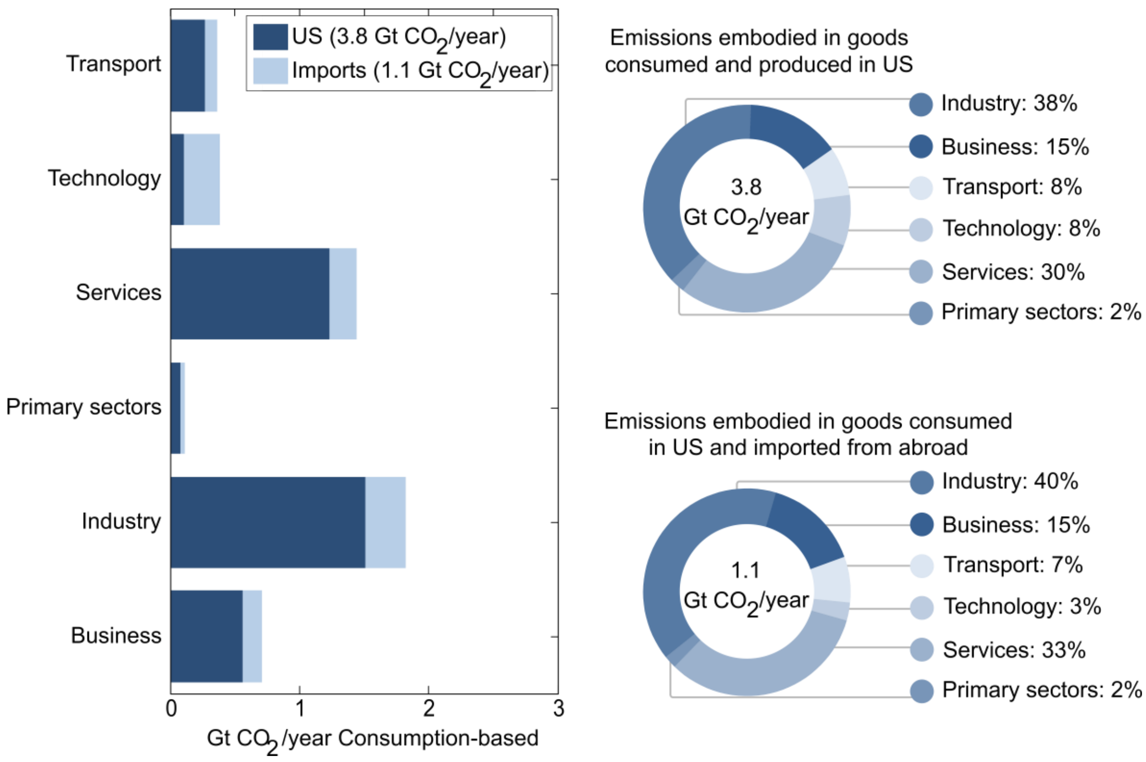

Fig. 4. Dark blue bars represent the breakdown of total consumption-based CO_2 emissions generated to satisfy the demand of each US sector (total emissions equal 3.8 Gt CO_2/year). Light blue bars are the sectorial breakdown of CO_2 emissions imported via trade (total imported emissions equal 1.1 Gt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

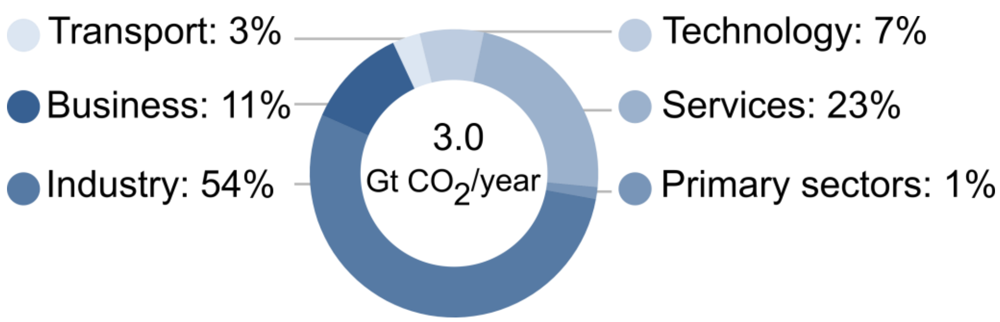

Fig. 5. Breakdown of the emissions of the sector industry in 2009 according to the final destination of the goods/services provided. Each portion represents the percentage of production-based CO_2 emissions generated by the sector industry that are attributed to the intermediate demand of each US sector.

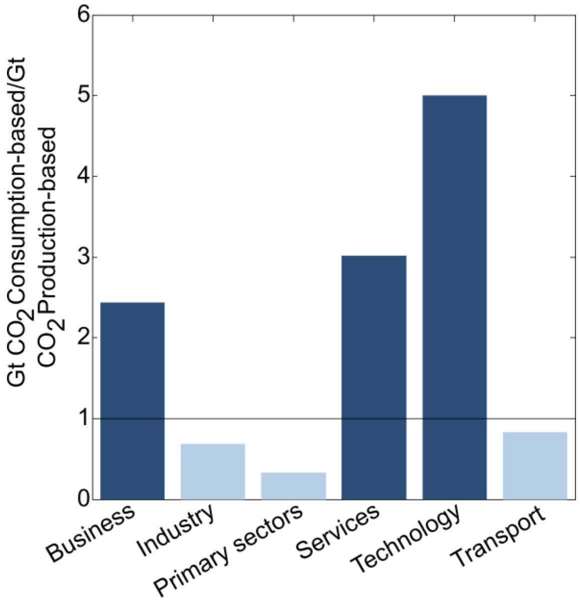

Fig. 6.Comparison between the consumption (dark blue bars) and production-based (light blue bars) accounting approaches in 2009. Each bar represents one industrial sector.

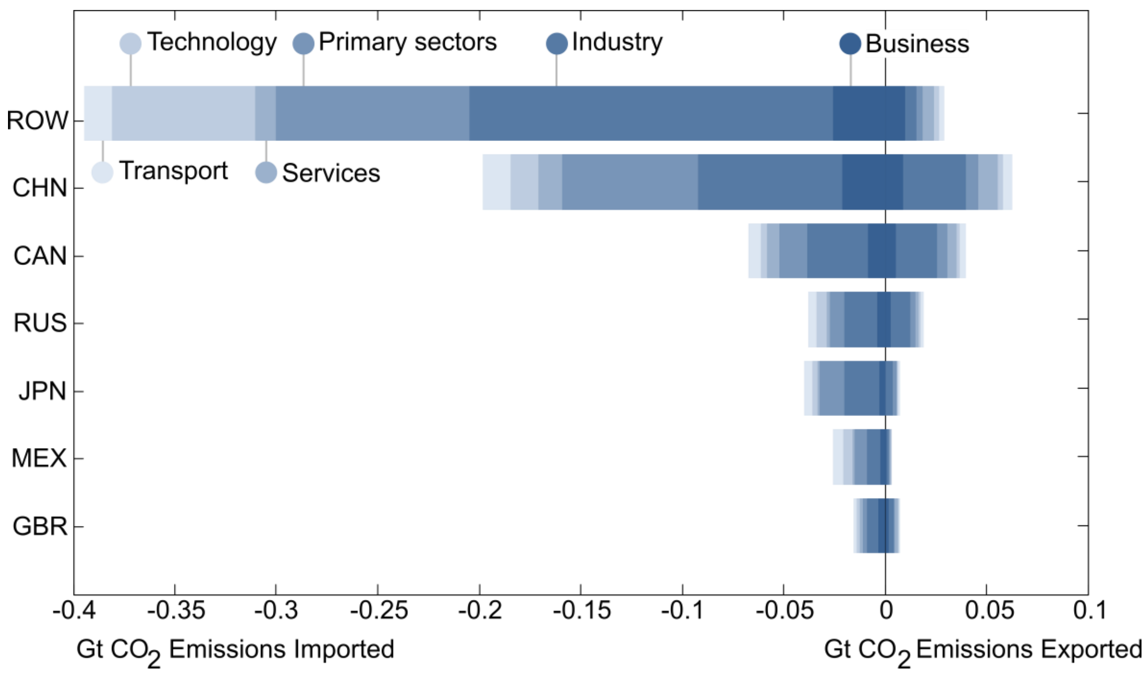

Fig. 7. Countries with higher trade of CO_2 embodied in services/goods exchanged with US in 2009. ROW = Rest of World; CHN = China; CAN = Canada; RUS = Russia; JPN = Japan; MEX = Mexico; GBR = United Kingdom.

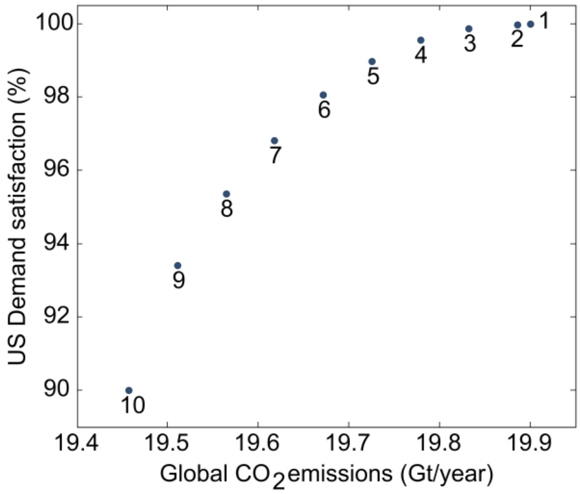

Fig. 8. Pareto optimal frontier for global CO_2 production-based emissions (Gt/year) vs US demand satisfaction (%) in 2009.

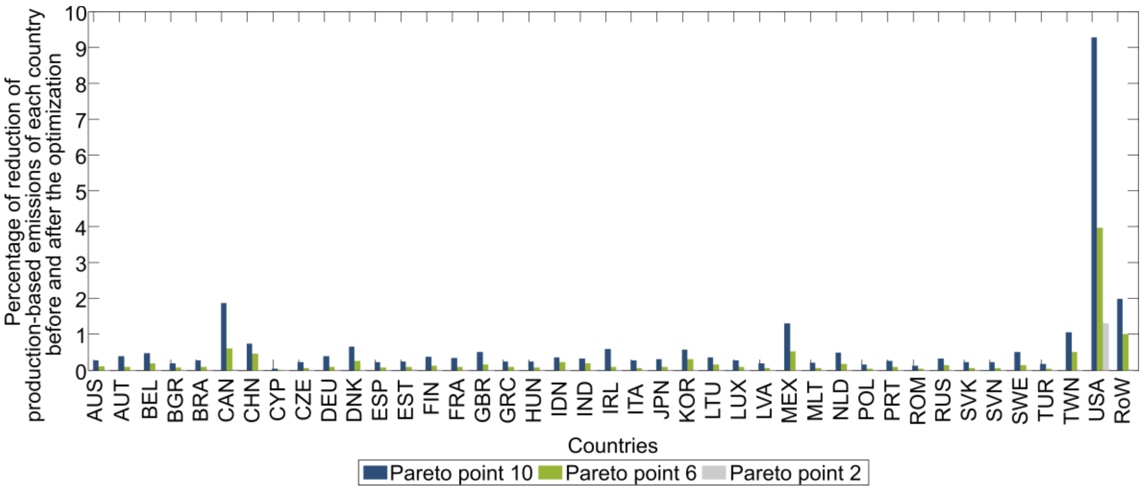

Fig. 9. Total percentage reduction of production-based emissions before and after the optimization. Each bar represents a different Pareto point: the minimum impact solution (blue bar), an intermediate Pareto point (green bar) and the minimum ratio solution (grey bar) (solutions 10, 6 and 2 of Table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

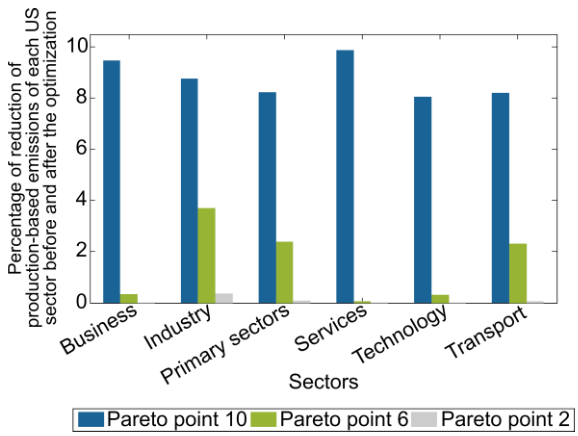

Fig. 10. Total percentage reduction of production-based emissions of US sectors before and after the optimization. Each bar represents one Pareto point: the minimum impact solution (blue bar), an intermediate Pareto point (green bar), and the minimum ratio solution (grey bar) (solutions 10, 6 and 2 of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

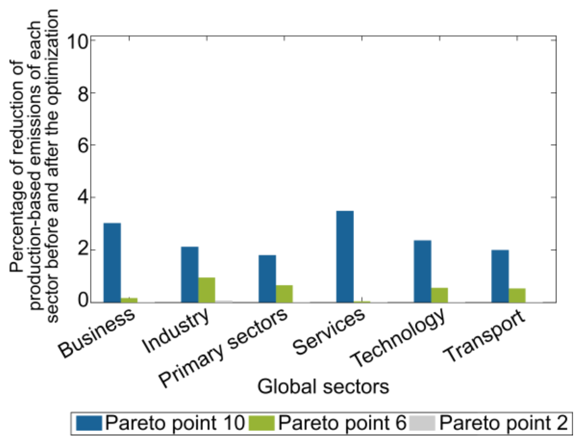

Fig. 11. Total percentage reduction of production-based emissions of global sectors before and after the optimization. Each bar represents one Pareto point: the minimum impact solution (blue bar), an intermediate Pareto point (green bar), and the minimum ratio solution (grey bar) (solutions 10, 6 and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

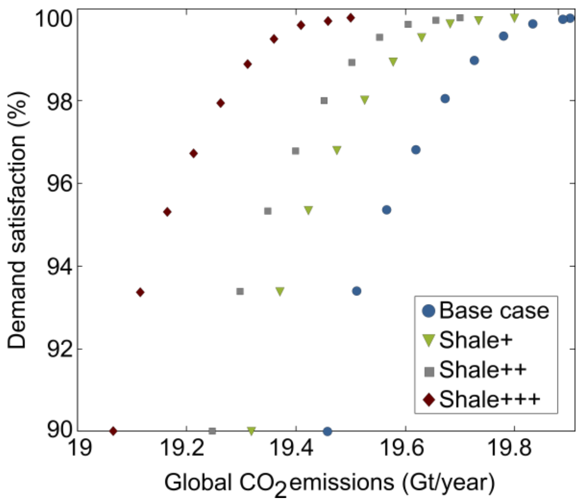

Fig. 12A. Pareto optimal frontier for global CO_2 production-based emissions (Gt/year) vs US demand satisfaction (%) in 2009 for the base case, scenario Shale+ (15% of coal replaced by shale gas), scenario Shale++ (25% of coal replaced by shale gas) and scenario Shale+++ (50% of coal replaced by shale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

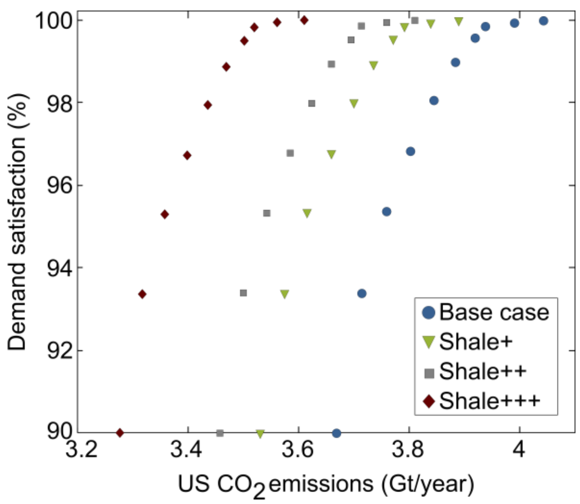

Fig. 12B. Pareto optimal frontier for production-based CO_2 emissions in US (Gt/year) vs US demand satisfaction (%) in 2009 for the base case, scenario Shale+ (15% of coal replaced by shale gas), scenario Shale++ (25% of coal replaced by shale gas) and scenario Shale+++ (50% of coal replaced by shale 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 [$]**
Purchases ↓	**Sector 1[$]**	$x_{(1,1)}$	$x_{(1,2)}$	$x_{(1,3)}$	$y_{(1)}$	$X_{(1)}$
	Sector 2[$]	$x_{(2,1)}$	$x_{(2,2)}$	$x_{(2,3)}$	$y_{(2)}$	$X_{(2)}$
	Sector 3[$]	$x_{(3,1)}$	$x_{(1,2)}$	$x_{(3,3)}$	$y_{(3)}$	$X_{(3)}$

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.

Business	**Services**
Financial Intermediation	Hotels and Restaurants
Renting of M&Eq and Other Business Activities	Education
Construction	Health and Social Work
Retail Trade, Except of Motor Vehicles ; Repair of Household Goods	Other Community, Social and Personal Services
Sale, Maintenance and Repair of Motor Vehicles Retail Sale of Fuel	Public Admin and Defense; Compulsory Social Security
Wholesale Trade and Commission Trade, Except of Motor Vehicles	Private Households with Employed Persons
Industry	Real Estate Activities
Coke, Refined Petroleum and Nuclear Fuel	**Technology**
Chemicals and Chemical Products	Electrical and Optical Equipment
Rubber and Plastics	Post and Telecommunications
Other Non-Metallic Mineral	Machinery, Nec
Electricity, Gas and Water Supply	Manufacturing, Nec; Recycling
Food, Beverages and Tobacco	**Transport**
Textiles and Textile Products	Transport Equipment
Leather, Leather and Footwear	Inland Transport
Pulp, Paper, Paper , Printing and Publishing	Water Transport
Primary sector	Air Transport
Agriculture, Hunting, Forestry and Fishing	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
Mining and Quarrying	
Wood and Products of Wood and Cork	
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 Supplementary Material.

Pareto Points	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Gobal CO_2 emissions reduction (%)	0.0	0.3	0.5	0.8	1.1	1.4	1.6	1.9	2.2	2.4
US Demand satisfaction (%)	100	99.9	99.9	99.6	99.0	98.1	96.8	95.4	93.4	90.0
Ratio	-	0.3	0.3	0.6	1.0	1.5	2.0	2.5	3.1	4.1
Cut sectors	0	14	14	261	449	734	885	885	1075	1435

Table 5. Pollution intensity of electricity technologies in US[24].

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**[23]	**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

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

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Supplementary Material

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Table A.1. List of manufacturing sectors that appear in WIOD-database

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

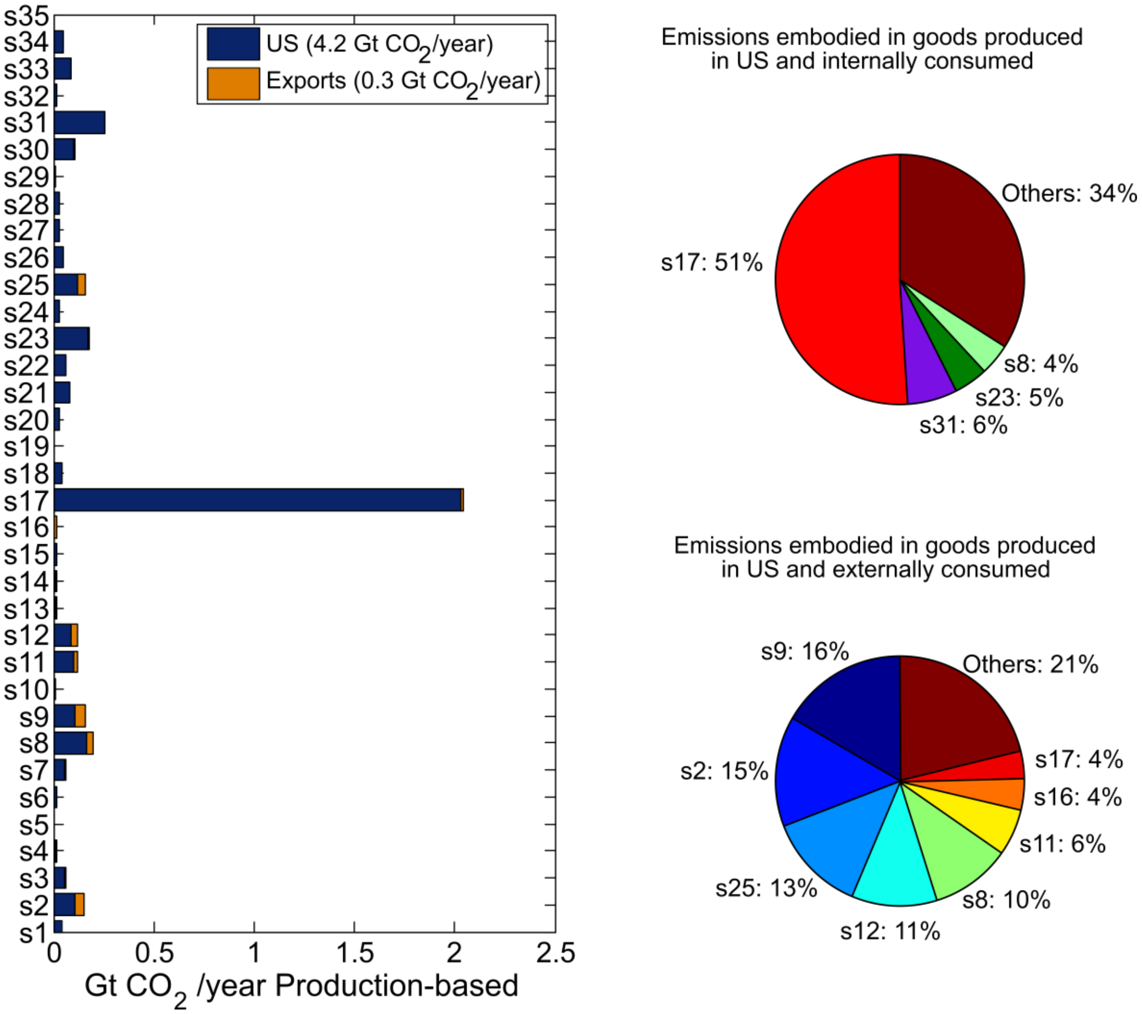

Fig.A.1 Blue bars represent the breakdown of total production-based CO_2 emissions generated within the limits of US (total emissions equal 4.2 Gt CO_2/year). Orange bars are the breakdown of CO_2 emissions exported via trade (total exported emissions equal 0.3 Gt CO_2/year)

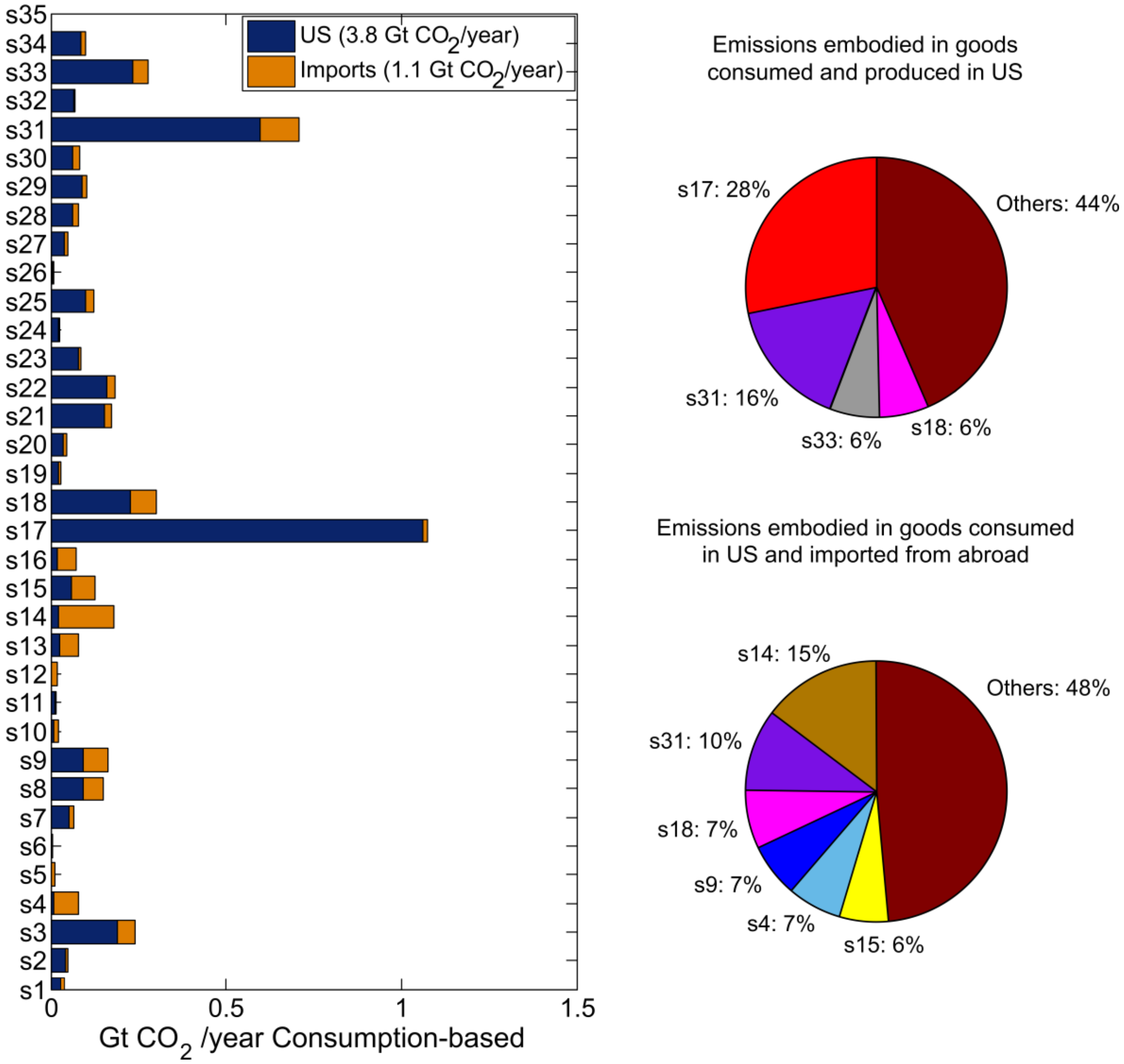

Fig. A.2 Blue bars represent the breakdown of total consumption-based CO_2 emissions generated to satisfy the demand of each US sector (total emissions equal 3.8 Gt CO_2/year). Orange bars are the sectorial breakdown of CO_2 emissions imported via trade (total imported emissions equal 1.1 Gt CO_2/year.

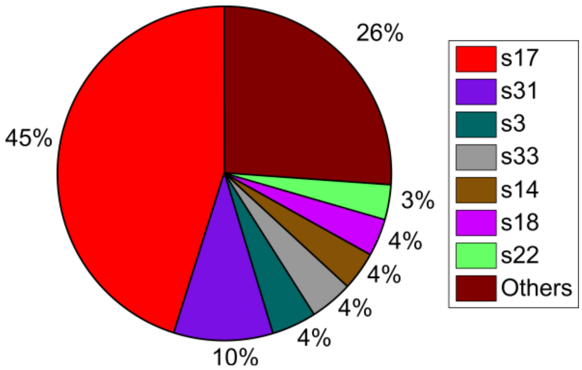

Fig. A.3. Breakdown of the emissions of Electricity, Gas and Water Supply in 2009 according to the final demand of the sectors. Each portion represents the percentage of production-based CO_2 emissions generated by the US sector *Electricity, Gas and Water Supply* (S17) that are attributed to the intermediate demand of each US sector

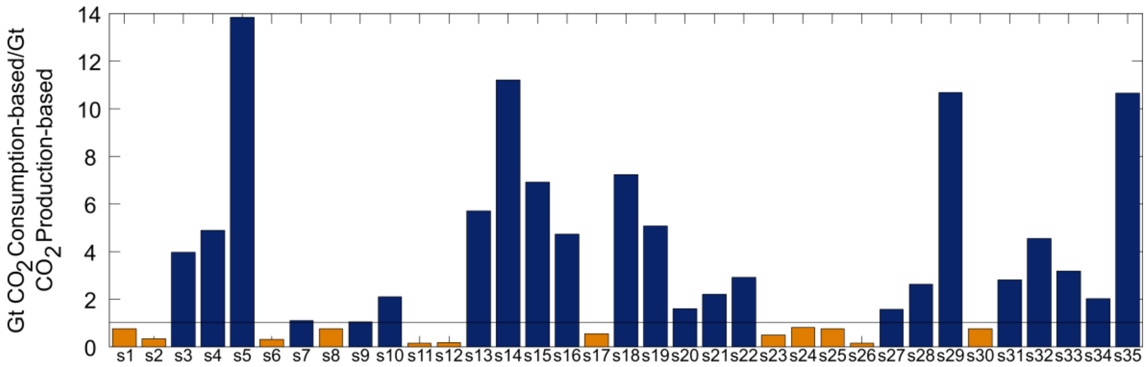

Fig. A.4. Comparison between the consumption (blue bars) and production-based (orange bars) accounting approaches in 2009. Each bar represents one industrial sector.

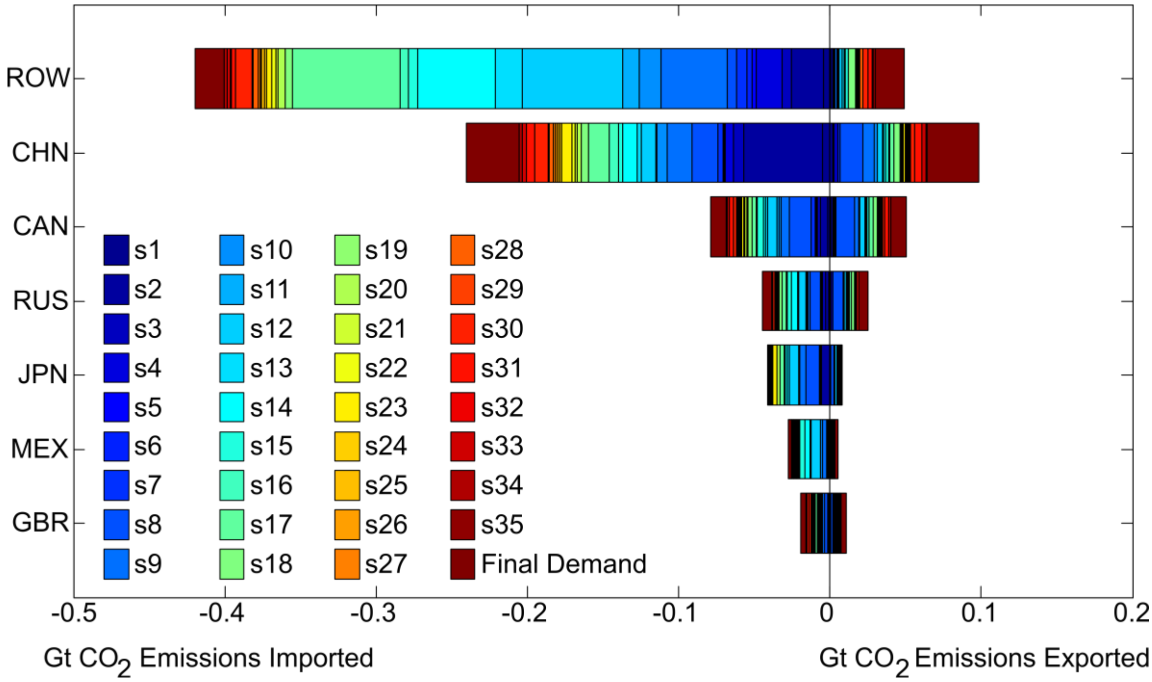

Fig. A.5. Countries with higher trade of CO_2 with US in 2009. ROW = Rest of World; CHN = China; CAN = Canada; RUS = Russia; JPN = Japan; MEX = Mexico; GBR = United Kingdom

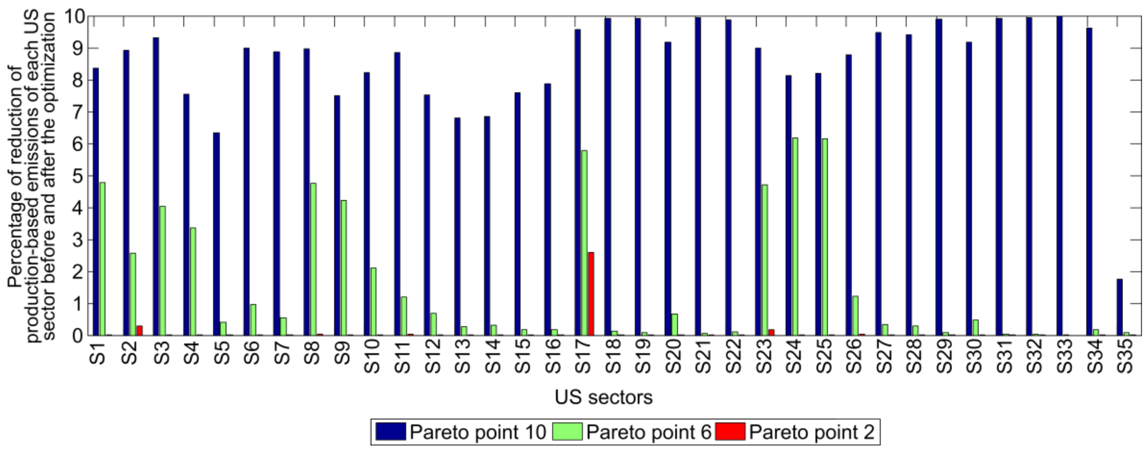

Fig. A.6 Total percentage reduction of production-based emissions of US sectors before and after the optimization. Each bar represents one Pareto point: the minimum impact solution (blue bar), an intermediate Pareto point (green bar) and the minimum ratio solution (red bar) (solutions 10, 6 and 2 of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

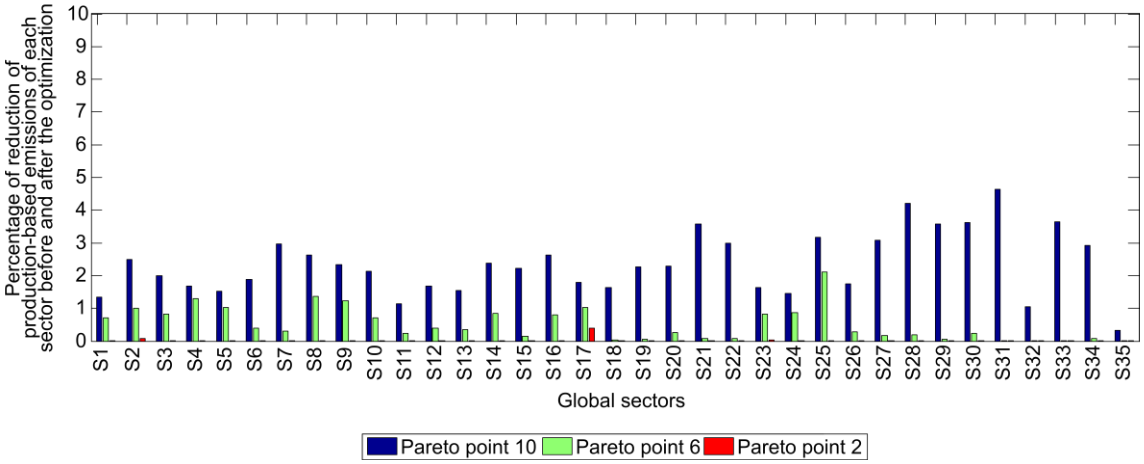

Fig. A.7 Total percentage reduction of production-based emissions of global sectors before and after the optimization. Each bar represents one Pareto point: the minimum impact solution (blue bar), an intermediate Pareto point (green bar) and the minimum ratio solution (red bar) (solutions 10, 6 and 2 of Table 4, respectively).