Fighting carbon leakage through Consumption-Based CO2 emissions policies: empirical analysis based on the World Trade Model with Bilateral Trades

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Abstract

All the environmental policy initiatives towards reduction of CO2 emissions implemented so far are grounded on the so-called Production-Based Accounting (PBA) paradigm: countries are responsible for the emissions occurring within their borders, but not for the emissions caused in foreign countries for producing their imported products. It has therefore become increasingly significant to quantitatively assess whether the policy implementation leads to an overall reduction in emissions, or if the the so-called phenomenon of carbon leakage arises.

In this paper, the alternative approach of Consumption-Based Accounting (CBA) is proposed and formalized, where countries become responsible for the CO2 emissions embedded in their final demand products. Global environmental and economic consequences of carbon emissions reduction policies applied at the European level based on both PBA and CBA paradigms are comparatively assessed based on the World Trade Model with Bilateral Trades (WTMBT). The adopted model is grounded on empirical data provided by the Exiobase v.2 Multi-Regional Input-Output database, and it returns the optimal arrangement of national production and international trades to satisfy a given final demand complying with a set of economic and environmental constraints.

Results of this study suggest that defining CO2 emissions policies based on a Consumption-Based paradigm seems to be the most effective way to reduce the global carbon emissions, avoiding the carbon leakage phenomenon caused by current Production-Based policies. Indeed, an imposed reduction in CO2 emissions embedded in EU final demand through a CBA policy would result in a global CO2 emissions reduction up to almost 1.2 Gton. On the other hand, an imposed reduction in direct EU CO2 emissions according to a PBA approach would result in an overall increase in global carbon emissions up to almost 0.8 Gton.

Keywords: Carbon leakage, production-based policy, consumption-based policy, World Trade Model with Bilateral Trades, GHG Emissions.

1. Introduction

Presence of greenhouse gases (GHG) in the atmosphere has been argued to have a significant impact on the radiative balance of the atmosphere, leading to changes in climatic patterns [1]. Over the last 150 years, concentration of carbon dioxide (CO_2) in atmosphere, which accounts for the largest share of anthropogenic GHG emission, has significantly increased mainly due to combustion of fossil fuels [2]. Even if most of the GHG emissions have been historically produced within developed countries borders, the weight of developing countries in total global emission is becoming increasingly relevant. At the same time, considerable efforts have been made by developed countries to reduce the carbon emission generated within their borders: considering in EU28, while population has grown by 7% from 1990 to 2015, CO_2 emissions have dropped by a factor of 21% [2]. With reference to Figure 1, it is worth to notice the weight of the contributions to global annual CO_2 emission of Annex I countries, which is mostly constituted by industrialized countries, members of the Organization for Economic Cooperation and Development (OECD), and Non-Annex I, mainly composed by developing countries.

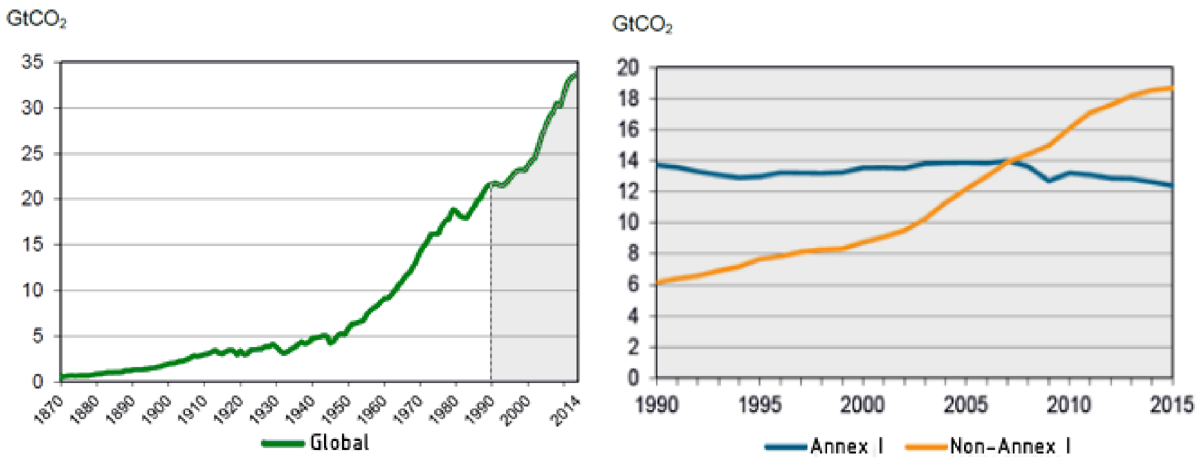

Figure 1. Trend in CO_2 emission from fossil fuel combustion globally produced and by Annex I and Non-Annex I, 1990-2015.

Nowadays, only 15% of global GHG emissions are covered by carbon pricing policies [3]. A large share of these emissions is regulated by developed countries, mostly under the European *Union Emission Trading System* (EU ETS). EU ETS, originally launched in 2005, has been the first large GHG emission trading scheme in the world and the first actuation of Kyoto Protocol international treaty. Recently, it has been argued that, beside direct GHG emission, also the indirect emissions embodied in international trades may have a significant impact in global climate policies effectiveness [4]. Therefore, it has been shown how policies with the purpose of limiting CO2 emission can be inefficient: even if developed countries regulations keep emissions low by limiting or pricing, their economy may react importing more from growing and unregulated regions, which usually rely on a more carbon intensive production system. This phenomenon, known as *carbon leakage*, may occur in two ways: *strong carbon leakage* occurs when an industry in an environmental controlled country shuts down and opens in a nonparticipating region with lax ecological regulation; on the other hand, *weak carbon leakage* occurs when demand for goods is not covered anymore by internal production, which is discourage by environmental regulations, but by imports from economies relying on a less efficient technological structure.

An essential prerequisite for the implementation of environmental emissions policies is the definition of the emissions accounting paradigm, that is, the approach for allocating the responsibility connected with the production of the emissions. The following approaches may be adopted for this purpose:

- *Production Based Accounting* (PBA). Each country is responsible for the emissions produced within its boundaries, disregarding the purpose for which these emissions are produced (i.e. endogenous consumption or exports).
- *Consumption Based Accounting* (CBA). Each country is responsible for the overall emissions caused by the production of goods and services invoked as its own final demand, even if these emissions occur beyond the borders of the country.

The accountability of countries' direct emissions is straightforward: national environmental accounts are regularly updated and made according to widely accepted standards. On the other hand, universal consensus about methodologies to assess emissions embedded into goods and services has not yet reached. For such reasons, all the environmental policies implemented so far are based on a PBA approach, while theoretical definition and practical implementation of policies based on CBA approach is still lagging behind (as well as hybrid PBA-CBA techniques [5]).

The work made by Peters and Hertwich [6] sheds light on the role played by international trade in evaluating the impact of climate policies, assessing that 20-25% of the world CO2 emissions are released for the production of products which are internationally traded. Such an influent portion of GHG is usually embedded in products traded and consumed by economies which have assumed climate reduction commitments. Therefore, if the participation to a climate international commitment is not covering all the world economies, the problem of carbon leakage may arise. A recent article by Afionis et al. [7], provides an extensive discussion about advantages and drawbacks of PBA and CBA techniques, examining opportunities for climate policy innovations. From one side, CBA could strengthen the participation between countries in reducing global emissions, promulgating measures aimed at reducing embodied emissions in developed world consumption, enhancing the development of a wider coalition with a common political vision towards more international actions. However, according to this paradigm, countries should accept to be responsible of emissions on which they have no direct control; at the same time, developing countries would be exposed to influence of economies which import goods and services from them. This scenario implies a not trivial context of cooperation between governments as embodied emission of developing countries exports should be monitored, reported and verified by the international community to provide transparency and to guarantee trustworthiness to the system of responsibility. Jakob, Steckel and Edenhofer [8], in addition to expose the critical issues connected to market imbalances generated by consumption-based policy such as border tax adjustment (BTA), state that both CBA and PBA do not represent an optimal policy for the current geopolitical context, suggesting that a more composite framework of specific policies would be the most efficient solution for emission reduction.

1.1. Brief literature review

This sub-section provides a brief overview of the recent literature focused on modelling carbon emissions reduction policies and on the assessment of their effects on international trades.

A widespread modelling approach in economics relies on Computable General Equilibrium models (CGE). Wang *et al.* [9] study the effect on China's growth of a gradually strengthen energy cap to limit Chinese rapid growth in energy consumption and GHG emissions, finding that energy cap policy will not disadvantage the economic development or harm the consumption in residential sector. The different roles and impacts of upstream and downstream subsidies have been investigated through market equilibrium model by Fischer *et. al* [10], finding that downstream subsidies technology policy may expose global abatement technology price to an undesirable increase while upstream grants reduces it. Other researches analyze the impact of a multi-regional ETS through a CGE model, showing how extending participation, integrating the scheme to a composite set of countries, may represent a more economically effective measure to tackle emission reduction than separate sets of single region ETS [11].

Other modelling approaches slightly different than CGE models belongs to the family of Environmentally-Extended Input-Output models (EE-IO). Static and linear EE-IO models are mostly used to perform different kind of footprinting and LCA analyses. In particular, Ivanova et al. plumb the deep interaction between different world sectors and countries to analyze the environmental impact of household consumption in terms of material, water, land-use and GHG emission, computing households carbon footprint (CF) [12]. Wood et. al introduce a method to evaluate the impact of consumer-oriented policy overall productive system, detecting rebound effects, change in domestic and international production mix and reduction in carbon intensity [13]. Lenzen *et al.* face the problem of carbon footprint double counting demonstrating and discussing a non-arbitrary method of consistently delineating supply chains of goods and services. In this way a mutually exclusive and collectively exhaustive shares of responsibility for all actors in an economy is provided [14]. Zhu et al. propose an alternative paradigm with respect to CBA and PBA, developing an algorithm able to summarize a fair share of responsibility [15].

Duchin et al. proposed two extensions of the traditional EE-IO model, namely the Rectangular Choice of Technology (RCOT) model and the World Trade Model with Bilateral Trades (WTM) [16–18]. These modelling approaches can be defined as Input-Output based optimization models grounded on the comparative advantage principle, respectively adopted to assess the optimal production alternative or the optimal international trades patterns given a set of economic and environmental binding constraints. Many applications of these modelling approaches can be found in recent literature [19–22].

1.2. Objectives of the research

The general objective of this study consists in comparing the effectiveness of Production- and Consumption-based CO2 emissions reduction policies applied in the European context. The two alternative paradigms are implemented at the EU level, testing the economic and environmental effects caused by a gradual reduction in EU carbon emissions budget respectively by allocating responsibility of emissions based on a Production- and a Consumption-based approach.

The analysis is performed according to the *World Trade Model with Bilateral Trades* (WTMBT), assuming the *Exiobase v.2* database as the reference database for macroeconomic empirical data (referred to year 2007). The WTMBT optimizes the global international trade patterns within a given set of constraints and by considering the comparative advantage as the only production and trade mechanism. Therefore, specific country agreements, policy agreements or any social phenomenon that may affect international trades have been neglected. Since the only degree of freedom of the model resides in the shape and arrangement of international trades, the application of alternative carbon emissions policies will generate different production and consumption patterns among countries, resulting in different global consumption of factors of production, resources and CO2 emissions. Any change in trade patterns is assumed to occur overnight (i.e. comparative statics), without considering any structural dynamics of the countries, and by considering constant production technologies. Notably, compared to the current literature on the topic, this study introduces for the first time an empirical comparison of PBA and CBA emissions policies at global level.

The rest of the paper is organized as follows: section 2 introduces and described the adopted modelling approach; section 3 introduces the case study; results are presented and discussed in section 3.3; concluding remarks are finally provided by section 4.

2. Methods and Models

This section introduces the adopted model, conceptualized in the framework of Input-Output analysis, and the way Production- and Consumption-based emission policies are implemented.

2.1. The World Trade Model with Bilateral Trades

The *World Trade Model with Bilateral Trades* [20] (WTMBT in the following) is a macroeconomic linear optimization model based on the *comparative advantage principle*. Considering *m* world regions with *n* industries each, the WTMBT enables to endogenously determine the optimal production yields and trades patterns required to satisfy an exogenously specified final demand yield in each region, minimizing the use of factors of production (labor and capital) by complying with regional factors endowments (e.g. availability of natural resources, land, workforce, etc.). The economic and environmental implications of national and international transport of products are included in the model and weighed depending on transport distances. With respect to General Equilibrium Models (CGE), the WTMBT requires less exogenous data since it considers the national final demand as constant and perfectly rigid with respect to endogenous change in prices of goods and services. Therefore, instead of maximizing social utility, the WTMBT establishes that the highest-cost producers set the products prices, and each region chooses to produce or to import by minimizing the overall costs complying with their own production factors availability. In the WTMBT, production technologies, factors use coefficients and final demand for each country are derived from Multi-Regional Input-Output tables (MRIO). Other exogenous inputs like factor endowments, weights of transported goods and regional distances are derived from other databases (e.g. World Bank, International Energy Agency), depending on the scope of the adopted MRIO and on the type of analysis to be carried out.

Assumptions of WTMBT are simple and grounded on widely recognized economic principles. However, results of the model are affected by sources of uncertainty: process characterization allow each sector to produce only one output, technological coefficients and demand are fixed and sectoral aggregation may lead to detail loss. Furthermore, factor endowments represent crucial parameters, since they practically limit regional production, and are hard to rigorously be determined. Therefore, it cannot be expected that such limitations and hypothesis could intercept even more complex market mechanisms, resulting in a perfect representation of reality.

Table 1. Exogenous and endogenous parameters of the WTMBT.

Category	Symbol	Dimensions	Description
Indices	m		Number of regions
	n		Number of sectors
	k		Number of factors of production
	i, j		Indices for regions $i, j = 1 \dots m$
Exogenous variables	$\mathbf{A}_i$	$(n \times n)$	Matrix of technical coefficients i region i
	$\mathbf{F}_i$	$(k \times n)$	Matrix of factor input in region i
	$\mathbf{D}$	$(m \times m)$	Matrix of interregional distances
	$\mathbf{T}_{ij}$	$(n \times n)$	Matrix of transport supplies from i to j
	$\mathbf{y}_i$	$(n \times n)$	Vector of final demand in region i
	$\boldsymbol{\pi}_i$	$(k \times 1)$	Vector of factor prices in region i
	$\mathbf{f}_i$	$(k \times 1)$	Vector of factor endowments in region i
Endogenous variables	$\mathbf{x}_i$	$(n \times 1)$	Vector of output in region i
	$\mathbf{ex}_{ij}$	$(n \times 1)$	Vector of goods exported from i to j
	$\mathbf{p}_i$	$(n \times 1)$	Vector of goods price index in region i
	$\mathbf{r}_i$	$(k \times 1)$	Vector of factor scarcity rents in region i

Two different mathematical formulation of the WTMBT can be adopted, depending on the adopted endogenous/exogenous parameters summarized in Table 1, but they return the same result, that it, the same optimal arrangement of international trades. In particular:

- *Quantity Model* (also referred as the *Primal Mode*l), expressed by the system of equations (1). It minimizes global factors cost (Z) endogenously returning production and exports by each sector, subjected to three sets of constraints: the first one secures that total domestic supply, which is represent by the sum of output and imports, covers the domestic final uses, expressed in turn by the sum of internal demand, final demand, exports and international transportation of imports. The second constraint defines that all the invoked production factors are less or equal to regional factors endowments. The last constraint establishes that the production in every regional sector cannot be less than zero. Notice that $\mathbf{T}_{ji}(n \times n)$ is the matrix of international transport coefficients and it represents the specific cost of importing products from *j* to *i*: these values depend on each regional technology and on distances between regions (further explained later). Moreover, $\mathbf{y}_i(n \times 1)$ represents the regional final demand, denoting all the quantity of output requested by final users of region *i*, independently from where this good or service is produced.

$$
\begin{aligned}
&Min \quad Z = \sum_i \boldsymbol{\pi}^T{}_i \mathbf{F}_i \mathbf{x}_i \\
&s.t. \quad \begin{cases} \mathbf{x}_i + \sum_{j \neq i} \mathbf{ex}_{ji} \geq \mathbf{A}_i \mathbf{x}_i + \mathbf{y}_i + \sum_{j \neq i} \mathbf{ex}_{ij} + \sum_{j \neq i} \mathbf{T}_{ji} \mathbf{ex}_{ji} & \forall i \\ \mathbf{F}_i \mathbf{x}_i \leq \mathbf{f}_i & \forall i \\ \mathbf{x}_i \geq 0 & \forall i \end{cases}
\end{aligned} \tag{1}
$$

- *Price Model* (also referred as the *Dual Mode*l), expressed by the system of equations (2). It targets to the maximization of of the total values of final demand net of scarcity rents (W), endogenously returning price indices and scarcity rents for each sector, subjected to three sets of constraints: the first and second ones ensure that prices of goods do not exceed costs for endogenous and traded products; the last one ensures the non-negativity of prices indices.

$$
\begin{aligned}
&Max \quad W = \sum_i \mathbf{y}_i^T \mathbf{p}_i - \sum_i \mathbf{f}_i^T \mathbf{r}_i \\
&s.t. \quad \begin{cases} \mathbf{p}_i - \mathbf{A}_i^T \mathbf{p}_i \leq \mathbf{F}_i^T (\boldsymbol{\pi}_i + \mathbf{r}_i) & \forall i \\ \mathbf{p}_i - \mathbf{T}_{ji}^T \mathbf{p}_i \leq \mathbf{p}_j & \forall i \\ \mathbf{p}_i \geq 0 & \forall i \end{cases}
\end{aligned} \tag{2}
$$

A region makes an endogenous choice between potential regional sources for imports by including the related transport costs into account. In the original Dunchin's formulation of the WTMBT [20], transport technologies were modelled by explicitly considering weights of transported products: to overcome the lack of such sectoral detailed data, an alternative approach has assumed here, by assuming that regional specific cost for each transport technology increase proportionally with the travelled transport distance. This has been made by defining the international transport coefficients matrix $\mathbf{T}_{ij}(n \times n)$ (in monetary units) calculated by equation (3): technical coefficients related to transport activities in each region $\mathbf{M}_j(n \times n)$ (in monetary units) are weighted based on the ratio between the average transport distances among countries *i* and *j* (d_{ij}, in km), and the average transport distance covered by the exporting country for its own endogenous transport (CD_j, in km).

$$
\mathbf{T}_{ji} = \frac{d_{ji} \mathbf{M}_j}{CD_j} \tag{3}
$$

Most of the parameters exogenously required by the model (see Table 1) can be obtained from Multi-Regional Monetary Input-Output (MRIO) databases, providing technical coefficients, final demand and factor inputs. Notably, factor input $\mathbf{F}_i$ may collect both the value-added components (with prices π_i different than zero) and the environmental transactions (with prices π_i equal to zero), including CO2 emissions, energy use, land use, and so on. Several MRIO can be adopted for this purpose, and the main ones are: Eora [23], WIOD [24], GTAP [25] and Exiobase [26]. Selection of the appropriate database depends on the purpose and scope of the analysis; a comprehensive comparison among them can be found in the recent literature [27].

Noteworthy, technical coefficients and final demand for each region provided by MRIO databases reflect one specific arrangement of international trades in one given year. However, since arrengement of international trades are provided endogenously by the WTMBT, data provided by the MRIO must be properly processed before being used in the model. In particular, technical coefficients for each region should represent the total inputs required by a region to produce its outputs, independently on where outputs are produced, hence deriving a total direct technical coefficients per unit of each output for the *j*th region: $\sum_i \mathbf{A}_{ij} = \mathbf{A}_j \ \forall j$. The same can be done for final demand matrix, deriving the total amount of product invoked by one region independent by the country which delivers it $\sum_i \mathbf{y}_{ij} = \mathbf{y}_j \ \forall j$. According to this procedure, technical coefficients and final demand matrices are populated only in their diagonal blocks, which characterize the overall input and final demand structures of each region.

2.2. Definition and application of CO2 emissions policies

Once the WTMBT is fully characterized, carbon emissions reduction commitments (named *carbon budgets* in the following) are respectively defined and imposed to one or more regions as additional constraints to the model. In compliance with this new set of constraints, the Primal model returns the new optimal arrangement of international trades that enable to satisfy the final demand of all the regions, while the Dual model returns the related price indices and scarcity rents of products.

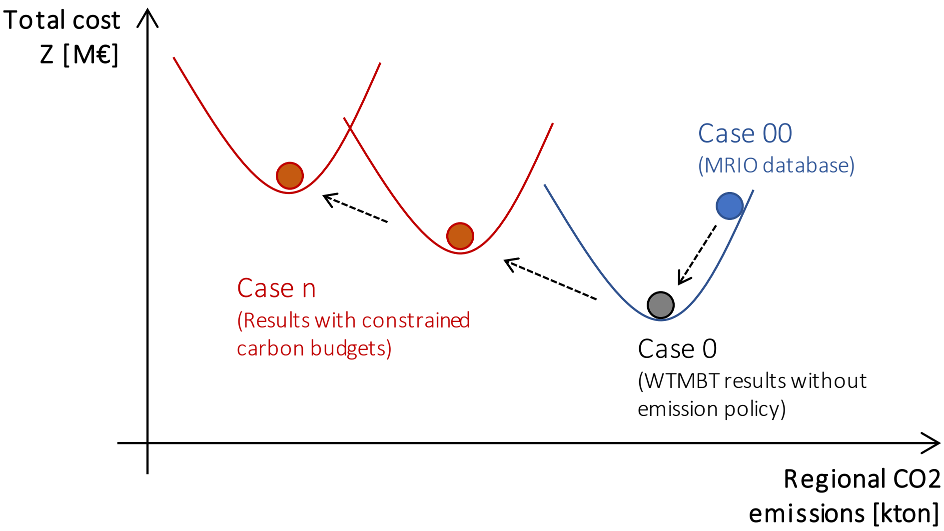

Figure 2. Schematic representation of the modelling process.

Figure 2 provides a general sketched overview of the modelling process, identifying model results based on the overall factor cost (Z) and on the overall regional CO2 emissions. *Case 00* represents the trades, costs and emissions derived from the adopted MRIO database. The arrangement of international trades in the *Case 0* (assumed as the baseline scenario) will be different from the original arrangement of the MRIO model, because production and trades are only governed by the comparative advantage principle, assumed as an approximation of the complex dynamics governing real productive systems. Once carbon budgets are defined and applied through to a PBA or a CBA approach, the WTMBT returns new arrangements of international trades (*Case n*), implying different values of costs and emissions compared to the baseline.

Application of CO2 emissions policy on a given region based on a *Production-Based Accounting (PBA)* paradigm can be performed by imposing to the *i*th region a maximum amount of allowed *direct* CO2 emissions as a new constrained factor endowment $f_{i,CO2}^{PBA}$, defined by equation (4) as a fraction ρ (%) of the baseline CO2 emissions for the same region (i.e. the matrix product of the CO2 emissions coefficients $\mathbf{F}_{i,CO2}(1 \times n)$ and the total production $\mathbf{x}_{i,CO2}^{0}(n \times 1)$).

$$f_{i,CO2}^{PBA} \leq \rho \cdot \left(\mathbf{F}_{i,CO2} \cdot \mathbf{x}_i^0 \right) \tag{4}$$

In the same vein, the implementation of *Consumption-Based Accounting (CBA)* paradigm is performed by imposing to the *i*th region a maximum amount of allowed CO2 emissions *embedded into its own final demand* as a new constrained factor endowment $f_{i,CO2}^{CBA}$, defined by equation (5) as a fraction ρ (%) of the baseline CO2 emissions embedded in the final demand of the same region. The latter term is calculated as the sum of the direct emissions caused by region *i* to produce its own final demand (first term in rhs of (5)) plus the emissions caused by all the other regions to produce exports supplied to the *i*th region (second term in rhs of (5)).

$$f_{i,CO2}^{CBA} \leq \rho \cdot \left[\mathbf{F}_{i,CO2} \left(\mathbf{x}_i^0 - \sum_{j \neq i} \mathbf{ex}_{ij}^0 \right) + \sum_{j \neq i}^{m} \left(\mathbf{F}_{j,CO2} \cdot \mathbf{ex}_{ji}^0 \right) \right] \tag{5}$$

According to the CBA paradigm, every country is responsible for the emissions caused by the production of its own imported products: therefore, the model will try to re-import and re-export products through low emissions country to numerically satisfy constraint (5). To avoid such phenomenon, constraint (6) is formulated by imposing the exports of each country equal at most to its overall production.

$$\sum_{j \neq i} \mathbf{ex}_{ij} \leq \mathbf{x}_i \tag{6}$$

Finally, it is worth to notice that while the interpretation of the results of the Primal model is straightforward (i.e. the amount of products traded among regions), the interpretation of the results of the Dual model is less immediate. Beside the price indices of sectors' outputs, the scarcity rents $\mathbf{r}_i$ endogenously returned by the model can be interpreted as the contribution of the carbon emissions policy in increasing the price of products, that is, the CO2 emissions price endogenously determined by an emissions trading market.

3. Case study: CO2 emissions policies at the EU level

This section describes the adopted MRIO database, provides the main assumptions and simplifications adopted for the analysis, and finally presents and discusses the obtained results.

3.1. Main data and assumptions

The *Exiobase v.2* (http://www.exiobase.eu/) [28] has been selected as the reference Multi-Regional Environmentally Extended Input-Output database database. The database includes data related to 48 countries and 5 rest of the world regions (see Table 2 in Appendix), with a resolution of 163 sectors each, it provides interindustry transactions, 7 final demand categories, 7 value added categories, and a multiplicity of environmental transactions (namely resources consumption and emissions, including CO2 emissions from combustion covered by the analyzed emissions policies). With reference to Table 1, the MRIO database provides technical and input coefficients $\mathbf{A}_i$and $\mathbf{F}_i$, and final demand $\mathbf{y}_i$. To reducing computational efforts due to the WTMBT, Exiobase sectors have been aggregated moving from 163 to 57 sectors (see Table 3 for the detailed list of sectors): logic underlying sectoral aggregation choices has been driven by the attempt of keeping carbon intensive sector fully disaggregated, in order to detect and analyze potential changes in world technology mix. Transport distances matrix $\mathbf{D}$ has been derived as the distances between countries' capitals. Finally, Factor endowments $\mathbf{f}_i$ have been mainly derived from world bank data (https://data.worldbank.org/), including available labor and land (for both agriculture and infrastructures) per country.

European Union (EU27) has selected for the application of the carbon emissions policies, assuming 2007 as the reference year for defining the baseline case (Case 0). While the selection of the time frame is mainly due to the MRIO data availability, the choice of the EU as the country scope for the application of the carbon emissions policies is motivated by the need to better understand the reasons behind to the undesirable effect of carbon leakage occurred with the EU Emissions Trading System (EU ETS), and which countermeasures could be taken to mitigate this effect.

3.2. Scenarios definition

With reference to Figure 2, starting from MRIO data (Case 00), the baseline scenario (Case 0) has been determined by running the WTMBT without any emissions policy implemented, and it will be subsequently adopted as the reference case for comparing effects of PBA and CBA emissions policies (Case n).

With respect to Case 00, global factors use in Case 0 (i.e. global value added) is overestimated by +5.2%. The shares of macro-regions factor use do not change significantly: Canada (+14.8%) and Middle East (-2.5%) respectively results as the most over- and under-estimated regions. Overall, EU27 results in a +9.3% overestimation of factors use. From an environmental point of view, global CO2 emission from fossil fuel combustion results in line with 2007 IEA data (approximately 29 Gton). Overall, observed differences between Case 0 and Case 00 have been considered acceptable.

From a practical viewpoint, the only differences between PBA and CBA resides in the definition of the carbon budget constraints, respectively determined through relations (4) and (5). Both the scenarios are performed by imposing a progressive reduction of the EU27 carbon budget of 1%, 5%, 10%, 20%, 30% and 40%, hence simulating the imposition of policy commitments. Notably, such carbon budgets are applied to the whole EU27 region: this choice is in line with the current EU ETS, which established a CO2 emissions allowances market at the European level, stimulating a cooperative behavior between its countries.

Finally, due to the crucial role played by exogenously determined national factors endomwents, a sensitivity analysis has been carried out by testing different sets of them in order to assess the robustness of the obtained results.

3.3. Results and discussion

Starting from output of the Case 0, assumed as the baseline, results PBA and CBA policies implementation have been derived. Among the multiplicity of results returned by the WTMBT, this sub-section focuses on two parameters:

- *Direct CO2 combustion emissions* (Figure 3). Optimal arrangement of production and trades among regions resulting from PBA and CBA policies influence the direct carbon emissions of each region, that ultimately results in a net change in global CO2 emissions. If an increase in overall CO2 emissions occurs, it reveals that the carbon leakage effect is predominant compared to the effect of the implemented policy.
- *Factors use* (Figure 4). The application of CO2 emissions policies forces each region to change its endogenous production yield and trade partners to comply with the new carbon budget constraint. This is likely to cause an overall increase in Gross Domestic Product (revenues side) compared to the baseline, since more factors of production will be invoked compared to the baseline. Since final demand for all the regions is fixed, this result can be interpreted as the overall cost required to implement the policy.

With reference to Figure 3 and Figure 4, the following comments can be made:

- For carbon budget reductions greater than 5%, the application of CBA policy results increasingly more expansive than PBA. This is motivated by the fact that while a decrease in PBA carbon budget allows EU countries to rely on less expensive and higher carbon intensive imports, the same is not allowed for a same reduction in CBA carbon budget, which forces EU countries to rely on more expansive technologies with lower carbon intensities.
- For carbon budgets reduction within 5%, both PBA and CBA provide a comparable environmental effectiveness and costs. However, while the application of CBA stimulates the cooperation between EU countries and the adoption of their own cleaner technologies, with PBA EU countries find more convenient to import products from abroad, hence causing carbon leakages.
- With PBA, the carbon leakage effect becomes increasingly important with the increase in carbon budgets reductions: after 20%, the direct emissions in foreign countries (rest of Europe, Russia and Canada in particular) becomes increasingly relevant, becoming greater than avoided CO2 emissions in EU. Notably, even if the direct EU emissions get lower, the overall cost of the policy and the overall emissions increase, thus resulting in an overall inefficient and undesirable plot.
- An opposite result is obtained through the implementation of CBA with high values of carbon budget reductions, that ultimately results in a reduction of CO2 emissions both at global level and in EU region.
- With a carbon budget reduction ranging from 1% up to 20%, the implementation of CBA results in global CO2 emissions reduction accompanied by cost increase for EU and a corresponding cost decrease in other regions: EU regions are thus relying on more expansive endogenous technologies by reducing imports from foreign carbon intensive industries (from USA in particular). However, after 20% of carbon budget reduction, reduction in cost for the EU region reveals that a portion of the EU final demand is satisfied by imports from a balanced mix of foreign industries.

- These results are useful to reveal the potential of international trades in reducing overall carbon emissions given a set of constant technological alternatives to produce the same products. A reduction in CO2 emissions embedded in EU final demand through a CBA policy would result in a global CO2 emissions reduction up to almost 1.2 Gton. On the other hand, an imposed reduction in direct EU CO2 emissions according to a PBA approach would result in an overall increase in global carbon emissions up to almost 0.8 Gton.

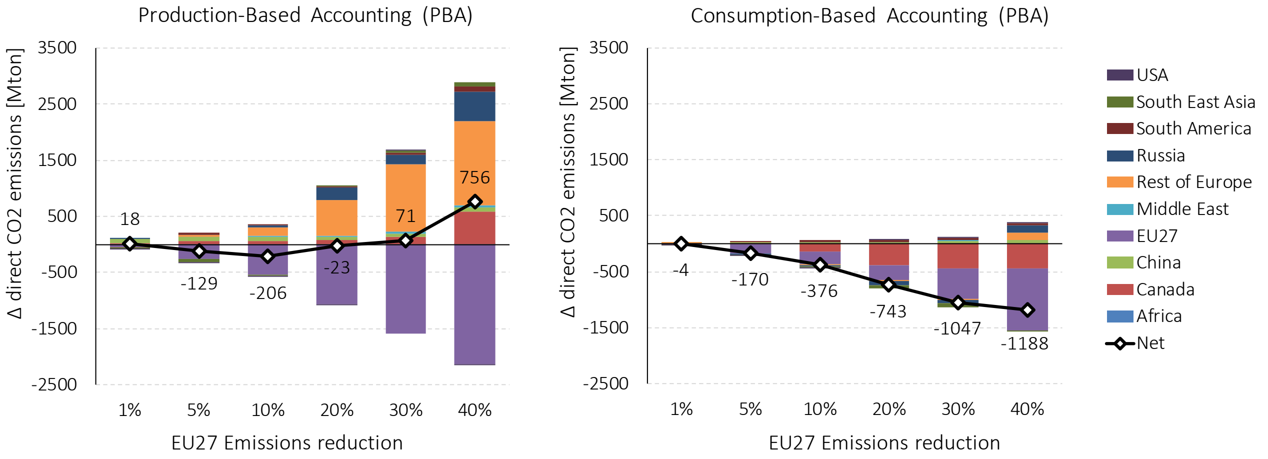

Figure 3. EU27 carbon budget reduction (%) vs regional and global change in CO2 emissions (Mton). Left side: results of PBA; Right side: results of CBA.

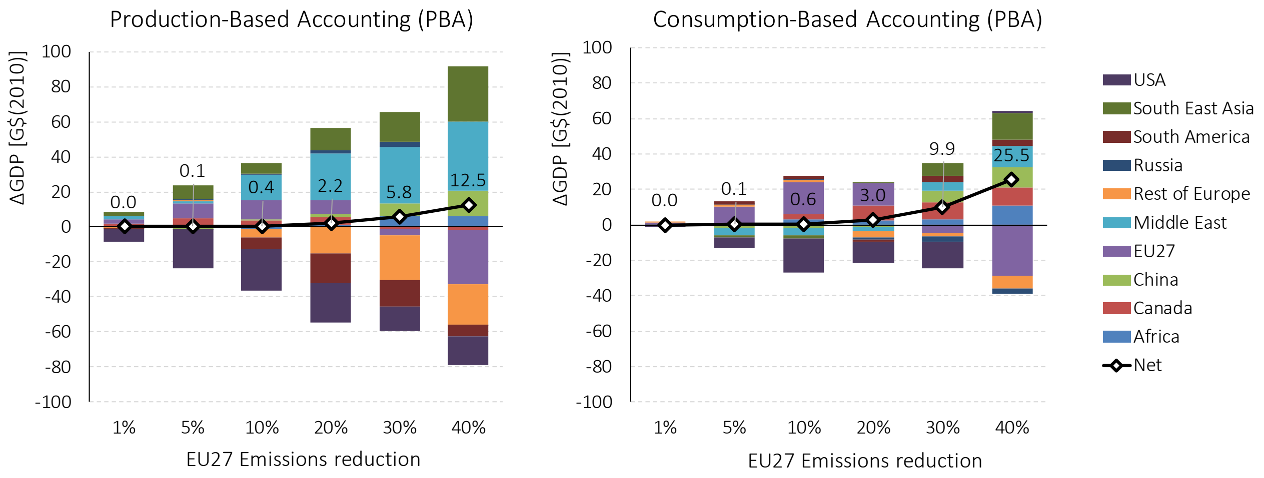

Figure 4. EU27 carbon budget reduction (%) vs global change in factor use (revenues side GDP, in G$2010). Left side: results of PBA; Right side: results of CBA.

Results of the sensitivity analysis on factors endowments of all the national economies are reported in Figure 5, where a reduction in the available amount of national workforce, land and primary energy have been tested. As suggested by the figure, CO2 emissions and factor use are strongly sensitive to change in factor endowments, and this sensibility increases with the increase in carbon budgets reductions. Economic cost of CBA policy still appears to be higher compared to PBA. The robustness of the model results is demonstrated by the sensibility of CO2 emissions, that keep the same trends for PBA and CBA: overall, policies based on PBA always result affected by carbon leakage, while CBA policies provides always a net emissions reduction.

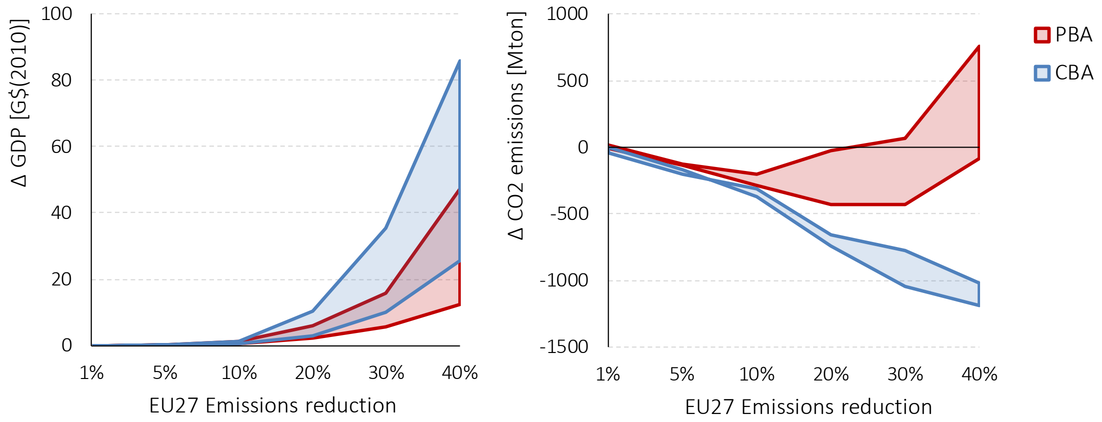

Figure 5. Results of the sensitivity analysis on global factor endowments. Left side: change in global revenues side GDP (G$2010); Right side: change in global CO2 emissions (Mton).

4. Conclusion

This paper provides a formalization and a first comparative application of two opposite paradigms for allocating responsibility for CO2 emissions. In particular, the research provides for the first time a global empirical application of a CO2 emissions policy based on a Consumption-Based Approach (CBA), and compares the obtained results with the widely adopted Production-Based Approach (PBA). The study adopted the World Trade Model with Bilateral Trades (WTMBT) applied to background macroeconomic data supplied by the Exiobase v.2 global Multi-Regional Input-Output database.

Results of this study are useful to understand the potential of international trades in reducing overall carbon emissions given a set of constant technological alternatives available to produce the same products. The obtained results suggest that defining CO2 emissions policies based on a Consumption-Based paradigm seems to be the most effective way to reduce the global carbon emissions, avoiding the carbon leakage phenomenon caused by current Production-Based policies. Indeed, an imposed reduction in CO2 emissions embedded in EU final demand through a CBA policy would result in a global CO2 emissions reduction up to almost 1.2 Gton. On the other hand, an imposed reduction in direct EU CO2 emissions according to a PBA approach would result in an overall increase in global carbon emissions up to almost 0.8 Gton.

In order to improve the quality and reliability of the obtained results, the following aspects deserve to be developed in further studies:

- Given the crucial role of factor endowments in determining optimal production and trade patterns, a more sophisticated sensitivity analysis should be conducted based on a Monte Carlo numerical approach. Moreover, more and more detailed factors endowments should be included as new model constraints (e.g. availability of renewable energy sources, water, others...).

- Transport could be better modelled by providing the exact reference distances among countries depending on the transport technology. Moreover, all the unrealistic transport solutions should be numerically constrained by the model.
- Provided an in-depth analysis of results by inspecting how changes in production and trades patterns affect the operativity of national industries, looking for systematic narratives to better understand how different industrial infrastructures may react to different environmental policies.
- Finally, beside the improvements related to the modelling approach, one very crucial aspect that deserve for a thorough discussion is concerned with the practical and legislative barriers that may arise in the implementation of an environmental policy based on the CBA paradigm.

Appendix

Table 2. Country list of Exiobase MRIO v.2 (http://www.exiobase.eu/).

Country #	Country Code	Country Name	Country Group	Country Group Name
1	AT	Austria	EU	European Union
2	BE	Belgium	EU	European Union
3	BG	Bulgaria	EU	European Union
4	CY	Cyprus	EU	European Union
5	CZ	Czech Republic	EU	European Union
6	DE	Germany	EU	European Union
7	DK	Denmark	EU	European Union
8	EE	Estonia	EU	European Union
9	ES	Spain	EU	European Union
10	FI	Finland	EU	European Union
11	FR	France	EU	European Union
12	GR	Greece	EU	European Union
13	HU	Hungary	EU	European Union
14	IE	Ireland	EU	European Union
15	IT	Italy	EU	European Union
16	LT	Lithuania	EU	European Union
17	LU	Luxembourg	EU	European Union
18	LV	Latvia	EU	European Union
19	MT	Malta	EU	European Union
20	NL	Netherlands	EU	European Union
21	PL	Poland	EU	European Union
22	PT	Portugal	EU	European Union
23	RO	Romania	EU	European Union
24	SE	Sweden	EU	European Union
25	SI	Slovenia	EU	European Union
26	SK	Slovak Republic	EU	European Union
27	GB	United Kingdom	EU	European Union
28	US	United States	AM	North America
29	JP	Japan	AS	Asia
30	CN	China	AS	Asia
31	CA	Canada	AM	North America
32	KR	South Korea	AS	Asia
33	BR	Brazil	MA	South America
34	IN	India	AS	Asia
35	MX	Mexico	MA	South America
36	RU	Russian Federation	RU	Russia
37	AU	Australia	AU	Australia
38	CH	Switzerland	CH	Switzerland
39	TR	Turkey	TR	Turkey
40	TW	Taiwan	AS	Asia
41	NO	Norway	NO	Norway
42	ID	Indonesia	AS	Asia
43	ZA	South Africa	AF	Africa
44	WA	RoW Asia and Pacific	WW	Rest of World
45	WL	RoW America	WW	Rest of World
46	WE	RoW Europe	WW	Rest of World
47	WF	RoW Africa	WW	Rest of World
48	WM	RoW Middle East	WW	Rest of World

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