# The effectiveness of LCA-based emissions policies against carbon leakage: theory and application

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### Abstract

*Current emissions policies are based on a territorial principle, which lead to the so-called leakage phenomenon: countries are responsible for the emissions occurring within their borders, disregarding the emissions caused in foreign countries for producing their imported products. In this paper, an LCA-based approach is proposed, according to which countries become responsible for carbon emissions embedded in products consumed by their own citizens. Both the territorial- and the LCA-based approach are comparatively assessed based on the World Trade Model with Bilateral Trades (WTMBT), consisting in a linear optimization model grounded on empirical Multi-Regional Input-Output database. Results suggest that carbon emissions policies based on an LCA-based approach may be an effective way to reduce global carbon emissions, avoiding carbon leakages caused by territorial-based carbon emissions policies.*

## 1. Introduction

Nowadays, only 15% of global greenhouse gases (GHG) emissions are covered by carbon pricing policies. A large share of these emissions is regulated by developed countries, mostly under the European Union Emission Trading System (ETS) or through the application of taxes on carbon emissions. Conventional carbon emissions policies limit the emissions directly generated within the country where the policy is applied. However, it has been argued that also the indirect emissions embodied in international trades may have a significant impact in global climate policies effectiveness (Peters et al., 2009). Specifically, it has been shown how such conventional policies can be inefficient, leading to the so-called *carbon leakage* phenomenon: even if developed countries regulations keep emissions low by limiting or pricing, their country may react by increasing imports from growing and unregulated regions, which usually rely on a more carbon intensive production system.

An essential prerequisite for the implementation of carbon emissions policies is the definition of the approach for allocating the responsibility connected with the production of the emissions:

- *Territorial-based paradigm* (also named *Production-based approach*): 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).
- *LCA-based paradigm* (also named *Consumption-based approach*): each country is responsible for the overall emissions caused by the production of goods and services invoked for final consumption, even if these emissions occur beyond the borders of the country.

The accountability of countries' territorial emissions is straightforward, and national environmental accounts are regularly updated according to widely accepted standards. On the other hand, application of LCA to account for carbon emissions embedded in goods and services is subjected to uncertainty issues both from the methodological and the numerical viewpoint. For such reasons, all the environmental policies implemented so far are based on a Territorial-based approach (Gallego and Lenzen, 2005). Compared to this paradigm, the LCA-based one may bring several benefits: it 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.

On the other hand, according to this paradigm, countries should accept to be responsible of emissions on which they have no direct control (Afionis et al., 2017).

The objective of this paper is to comparatively assess the effectiveness of Territorial-based and LCA-based carbon emissions policies applied within the European Union, assessing their global economic and environmental consequences. A model has been developed by the Authors based on the *World Trade Model with Bilateral Trades* (WTMBT) framework, a constrained global optimization model which allows trades at a non-zero cost. Transportation costs, as well as, resources availability have been modelled and calibrated in order to have a suited tool for this research. Notably, compared to the current literature on the topic, this study introduces for the first time an empirical comparison of Territorial-based and LCA-based emissions policies at global level.

## 2. **Modelling carbon emissions policies: a brief literature review**

The assessment of economic and environmental implications of policies in different countries is largely based on *Computable General Equilibrium* models (CGE). Recently, the effect on China's growth of a gradually strengthen energy cap to limit Chinese rapid growth in energy consumption and GHG emissions has been investigated based on CGE, finding that energy cap policy will not disadvantage the economic development or harm the consumption in residential sector (Wang et al., 2018). 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 (Zhang et al., 2017).

Approaches alternative to CGE belong to the family of *Environmentally-Extended Input-Output models* (EE-IO). Static and linear EE-IO models are mostly used to perform environmental footprinting and LCA analyses. In particular, the environmental impact of household consumption in terms of material, water, land-use and GHG emission have been recently investigated, computing households carbon footprint (Ivanova et al., 2016). 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 have been recently introduced (Wood et al., 2017). Finally, an alternative paradigm with respect to Territorial and LCA approach has been proposed, developing an algorithm able to summarize a fair share of responsibility in carbon policies definition (Zhu et al., 2018). One relevant extensions of the traditional EE-IO model has been proposed, namely the WTMBT, consisting in a linear optimization model 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 (Duchin and Levine, 2016).

## 3. **Formulating carbon emissions policies based on LCA**

### 3.1 The World Trade Model with Bilateral Trades (WTMBT)

The WTMBT is a 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 availability of factors of production represent crucial parameters, hard to be determined in a rigorous and accurate way.

Starting from the existing WTMBT framework formulated by Duchin (Duchin and Levine, 2016), the model have been fully characterized by means of empirical macroeconomic data retrieved in the Multi-Regional Input-Output (MRIO) database EXIOBASE (Tukker et al., 2014). Moreover, further data required to calibrate the model have been assumed and the model for international trades modes has been improved since the WTMBT original formulation. Notably, the economic and environmental implications of national and international transport of products are, in this way, included in the model and weighed depending on transport distances. The full list of indices, endogenous and exogenous parameters useful to characterize the WTMBT are listed in Table 1.

*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 $i, j = 1, \dots, mi, j = 1, \dots, m$ |
| Exogenous variables | $\mathbf{A}_i$ | $(n \times n)(n \times n)$ | Matrix of technical coefficients inregion $ii$ |
| | $\mathbf{F}_i$ | $(k \times n)(k \times n)$ | Matrix of factor input in region $i\ i$ |
| | $\mathbf{D}$ | $(m \times m)$ $(m \times m)$ | Matrix of interregional distances |
| | $\mathbf{T}_{ij}$ | $(n \times n)(n \times n)$ | Matrix of transport supplies from $ii$ to $jj$ |
| | $\mathbf{y}_i$ | $(n \times 1)(n \times 1)$ | Vector of final demand in region $ii$ |
| | $\mathbf{f}_i$ | $(k \times 1)(k \times 1)$ | Vector of factor endowments in region $ii$ |
| Endogenous variables | $\mathbf{x}_i$ | $(n \times 1)(n \times 1)$ | Vector of output in region $i\ i$ |
| | $\mathbf{ex}_{ij}$ | $(n \times 1)(n \times 1)$ | Vector of goods exported from $ii$ to $jj$ |

The WTMBT is resumed in the linear optimization problem (1), which works by minimizing the global factors cost (*Z*) endogenously returning production and exports by each sector, subjected to three sets of constraints:

A. The total domestic supply (the sum of output and imports) covers the domestic final uses (internal demand, final demand, exports and international transportation of imports);
B. All the invoked production factors must be less than or equal to the available regional factor endowments;
C. The production in every regional sector cannot be less than zero.

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

Notice that $\mathbf{y}_i\,(n \times 1)\mathbf{y}_i\,(n \times 1)$ 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. Moreover, $\mathbf{T}_{ji}\,(n \times n)\mathbf{T}_{ji}\,(n \times n)$ 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.

The WTMBT is part of the family of optimization models based on Input-Output empirical data; despite its ability to provide a comprehensive picture of global supply chains, the model suffers of two main disadvantages, resumed as follows (Strømman et al., 2009):

- Extreme solutions: an optimization model, grounded on the only principle of comparative advantage, may provide an extreme solution in which global demand of a certain sector is unrealistically entirely covered by a single region. However, if factor endowments are characterized precisely enough, this situation rarely occurs.

- Unperfected real-world characterization: base-year flows are not exactly replicable by the model, since real life make-or-buy decisions do not always gravitate towards most cost-effective producers solely on the principle of comparative advantage. Nonetheless, those dynamics could be partly addressed by a specific characterization of transport matrices.

### 3.2. **Definition and application of carbon emissions policies**

Figure 1 provides a general sketched overview of the modelling process, identifying model results based on the overall factor cost (Z) and on the overall regional $CO_2$ 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 Territorial-based or an LCA-based approach, the WTMBT returns new arrangements of international trades (Case n), implying different values of costs and emissions compared to the baseline.

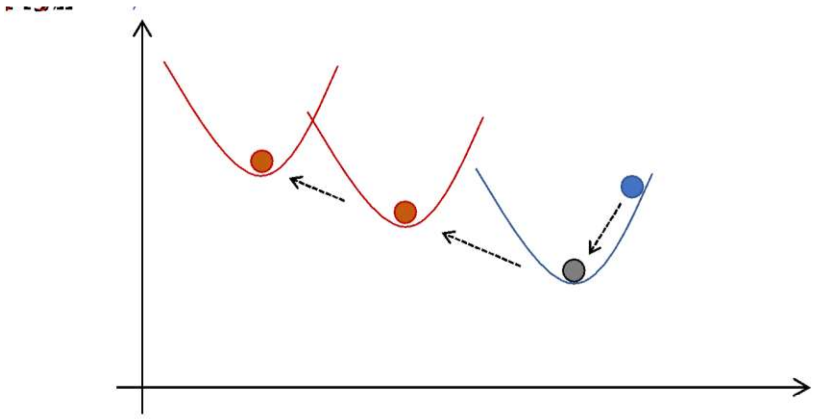

*Figure 1: Schematic outline of the modelling approach*

**Territorial-based paradigm**. It can be performed by imposing to the *i*th region a maximum amount of allowed *direct* $CO_2$ emissions as a new constrained factor endowment $f_{i,CO_2}^{Territorial}$ $f_{i,CO_2}^{Territorial}$, defined by equation (2) as a fraction $\rho\rho$ (%) of the baseline $CO_2$ emissions for the same region (i.e. the vector product of the $CO_2$ emissions coefficients $\mathbf{F}_{i,CO_2}(1 \times n)$ $\mathbf{F}_{i,CO_2}(1 \times n)$ and the total production $\mathbf{x}_i^0(n \times 1)\mathbf{x}_i^0(n \times 1)$).

$$f_{i,CO_2}^{Territorial} = \rho \cdot \left( \mathbf{F}_{i,CO_2} \cdot \mathbf{x}_i^0 \right) \qquad (2)$$

**LCA-based paradigm**. On the other hand, the implementation of LCA-based paradigm is formulated by imposing to the *i*th region a maximum amount of allowed $CO_2$ emissions *embedded* into its own final demand as a new constrained factor endowment $f_{i,CO_2}^{LCA} f_{i,CO_2}^{LCA}$, defined by equation (3) as a fraction $\rho\rho$ (%) of the baseline $CO_2$ 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 (3)) plus the emissions caused by all the other regions to produce exports supplied to the ith region (second term in rhs of (3)).

$$f_{i,CO_2}^{LCA} = \rho \cdot \left[ \mathbf{F}_{i,CO_2} \left( \mathbf{x}_i^0 - \sum_{j \neq i} \mathbf{ex}_{ij}^0 \right) + \sum_{j \neq i}^{m} \left( \mathbf{F}_{j,CO_2} \cdot \mathbf{ex}_{ji}^0 \right) \right] \qquad (3)$$

LCA-based paradigm radically differs with respect to the Territorial-based one, since every country becomes responsible for the carbon emissions directly and indirectly required to deliver products for final demand, hence including all the supply chain emissions, even those generated in foreign countries.

## 4. Application of carbon emissions policies in Europe

The WTMBT has been developed and calibrated by the Authors based on the *Exiobase v.2 MRIO database* (http://www.exiobase.eu/), which provides macroeconomic and environmental empirical data for 48 countries and 5 Rest of the World closure regions, each represented by 167 industries for the baseline year 2007. Other exogenous inputs like factor endowments, weights of transported goods and regional distances must be derived from other public sources (e.g. IEA, World Bank, …).

The Territorial- and LCA-based carbon emissions policies defined in paragraph 3.2 have been applied to the *European Union* (EU27), by imposing a progressive reduction of the EU27 carbon budget from 1% up to 40%. From the modelling perspective, this is equivalent to the application of a carbon tax respectively on $CO_2$ emissions directly caused by domestic industries and on the $CO_2$embedded into products produced and imported by the domestic economy; notably, the policies are applied to the whole EU27 region: this choice is in line with the current EU ETS, which established a $CO_2$ emissions allowances market at the European level, stimulating a cooperative behavior between its countries.

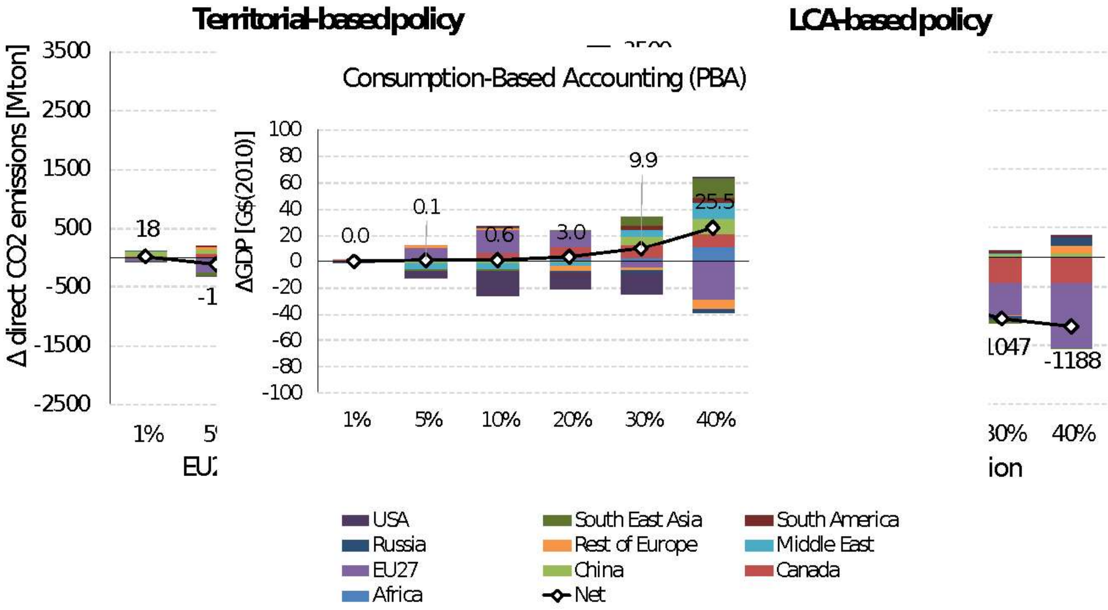


*Figure 2: Schematic outline of the standard Input-Output model*

Among the multiplicity of results returned by the WTMBT, Figure 2 reports the changes in direct $CO_2$ emissions in the global economy: indeed, the implementation of a policy constraint on emissions is expected to change the optimal arrangement of production and trades among world regions, influencing in turn the overall direct carbon emissions of each region, that ultimately results in a net change in global $CO_2$ emissions. An increase in global $CO_2$ emissions then reveals that the carbon leakage effect is predominant compared to the beneficial effect of the implemented policy. With reference to Figure 2, the following comments can be made:

- For carbon budgets reduction within 5%, both Territorial- and LCA-based paradigms provide a comparable environmental effectiveness. However, while the application of LCA policy stimulates the cooperation between EU countries and the adoption of their own cleaner technologies, with the Territorial one EU countries find more convenient to import products from abroad, hence causing carbon leakages.
- With a Territorial-based policy, 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 $CO_2$ emissions in EU.
- An opposite result is obtained through the implementation of LCA-based policy with high values of carbon budget reductions, that ultimately results in a reduction of $CO_2$ emissions both at global level and in EU region.
- 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 $CO_2$ emissions embedded in EU final demand through a LCA-based policy would result in a global $CO_2$ emissions reduction up to almost 1.2 Gton. On the other hand, an imposed reduction in direct EU $CO_2$ emissions according to a Territorial-based approach would result in an overall increase in global carbon emissions up to almost 0.8 Gton.

# 5. **Conclusions**

This paper provides a formalization and a first comparative application of two opposite paradigms for allocating responsibility for $CO_2$ emissions. In particular, a global empirical application of a carbon emissions policy based on a LCA-based paradigm is performed for the first time, and the obtained results are compared with the traditional Territorial-based approach based on the same modelling framework, data sources and set of assumptions.

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 carbon emissions policies based on a LCA paradigm seems to be the most effective way to reduce the global carbon emissions, avoiding the carbon leakage phenomenon caused by current Territorial-based policies.

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, a more sophisticated sensitivity analysis should be conducted based on a Monte Carlo numerical approach. Moreover, 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.
- Provide an in-depth analysis of results by inspecting how changes in production and trades patterns affect the operativity of national industries.
- Finally, practical and legislative barriers that may arise in the implementation of an environmental policy based on the LCA-based paradigm should be addressed, understanding how it could be implemented within the World Trade Organization regulation framework.

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