Using Bankruptcy Rules to Allocate CO2 Emission Permits

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Abstract. The global growth of technologies and production affects the climate through emissions of greenhouse gases. The total amount of countries' demands of CO2 emissions permits is higher than what the planet can sustain. This situation can be considered as a bankruptcy problem, where the sum of players' claims exceeds the endowment of the resource. In this paper, we use an approach based on bankruptcy solutions (in particular, on the Weighted Constrained Equal Awards rule) in order to propose a more efficient and fair allocation protocol for sharing CO2 emissions permits among the EU-28 countries.

Keywords: Bankruptcy situations · Weighted Constrained Equal Awards · CO2 emissions · Cooperative games

1 Introduction

Establishing international agreements aimed to reduce greenhouse gas emissions is a current problem [20], due to the fact that greenhouse gases present a big threat to the planet. Negotiation models [18], in particular, have been widely studied with the goal to find an agreement among all countries for reducing their carbon-emission rate. However, no country can influence the climate change system independently of the others, and everyone would benefit from the reduction on global warming, but no one wants to bear the cost of emission reductions. One of the main issues in this research stream is the problem of finding fair and efficient protocols to allocate the permits for carbon dioxide (CO2) emission. In the related literature, the methods used to allocate CO2 emission permits can be classified into four groups [21]: protocols based on global indicators, optimization techniques, game theoretic models and hybrid approaches. The most common allocation protocols are based on indicators, where permits are assigned based

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on one or more global indicators for countries [14] like, for instance, population [9], energy [15], Gross Domestic Product (GDP) [17], or emission intensity [15], etc. Among the optimization methods, some authors have proposed the Data Envelopment Analysis based on linear programming models [5,7]. In the game theoretic literature related to non-cooperative games, a CO2 emission permits allocation is seen as an outcome that is obtained at the equilibrium of a strategic game [2]. In the domain of cooperative games, instead, various allocation rules have been applied, like, for instance, the Shapley value [4]. The hybrid approach is a mixture of different methods, considering, among others, multi-stage regimes or multi-sector convergence approaches [1]. In this paper, we analyse the allocation problem of CO2 emission permits as a conflicting claims problem or *bankruptcy problem* [13], where countries claim a scarce resources or estate (the maximum amount of CO2 emissions) and there is not enough resource to satisfy the aggregate claim [6,8] (see also [10,11,19] for other applications of bankruptcy problems to natural resource sharing). In this paper, the computation of the total amount of CO2 emission is based on the EU emission quantity in 1990. More precisely, we consider a bankruptcy problem where the players are the EU-28 states, claims are the quantity of CO2 emitted in each year from 2010 to 2014, and the resource to be shared corresponds to the 78% of the total production of CO2 in EU in 1990, i.e. the quantity that countries should have produced in 2010 according to the Kyoto Protocol[1]. Our approach is based on a weighted version of the Constrained Equal Awards (CEA) rule [12] for bankruptcy situations, where we consider two parameters to allocate the CO2 emission quantity for each state: the quantity of CO2 emitted by each country in 1990 (claim) and the GDP of each country (weight). To be more specific, we consider a bankruptcy situation where every state claims a quantity of CO2 and it wants to "use" this emission to produce a certain amount of GDP. Nonetheless, a country can not obtain more than $\lambda \times GDP$ of CO2 emission permit, where λ is a fixed coefficient defined to guarantee the budget balance of the allocation, taking into consideration the relation among demands and GDP of all countries. In our application, the GDP is assumed to reflect the total overall economic activity, therefore countries with low $CO2/GDP$ ratio are considered more efficient because of a lower CO2 emission per unit of production of GDP. We compare the results provided by the weighted CEA rule with those of the classical CEA rule, that has been already proposed as an allocation rule for greenhouse gas emission permits [6]. According to the CEA rule, countries with small demands are completely satisfied, while highest demands are only partially satisfied. Instead, using the weighted CEA rule, the allocation changes in favour of countries with more efficient production technologies (low CO2/GDP ratio). Incentives to the transfer of green production technologies from the most efficient countries to the less efficient ones are also studied using a (cooperative) game theoretic approach. The road-map of the paper is as follows. We start in the next section with some preliminary definitions. Then, in Sect. 3, we introduce and compare the allocations of CO2 permits provided by the CEA rule and

[1] https://unfccc.int/process/the-kyoto-protocol.

the weighted CEA one over the EU-28 countries. Section 4 is devoted to a preliminary analysis of an associated cooperative game aimed at finding incentives to transfer technologies from the most efficient countries to the most polluting ones. Section 5 concludes.

2 Preliminary Notions and Notations

Let $N = \{1, \cdots, n\}$ be a finite set of agents. A bankruptcy situation [13,16] consists of a pair (E, c) where $c \in \mathbb{R}^N_+$ is a vector representing agent's claims and such that $c_i \geq 0$ for all $i \in N$, and $E \in \mathbb{R}$ is the estate to be divided among the agents and such that $0 < E < \sum_{i=1}^{N} c_i$. We denote as B^N the class of all bankruptcy situations with N as the set of agents. An *allocation rule* or *solution* for bankruptcy situations is a map $\phi : B^N \rightarrow \mathbb{R}^N_+$ that associates to every bankruptcy situation in B^N an allocation vector $x \in \mathbb{R}^N_+$ such that $\sum_{i=1}^{N} x_i = E$. So a solution for bankruptcy situations specifies vectors representing the amount of estate that each player should receive. Given a bankruptcy situation (E, c), the Constrained Equal Awards (CEA) rule allocates the estate E to agents according to the following formula:

$$CEA_i(E, c) = \min\{c_i, \lambda\} \tag{1}$$

where the parameter λ is such that $\sum_{i \in N} \min\{c_i, \lambda\} = E$. Given a bankruptcy situation (E, c) and a weight vector $a \in \mathbb{R}^N_+$, we call the triple (E, c, a) a *weighted bankruptcy situation*. We denote by WB^N the class of all weighted bankruptcy situations (E, c, a) with N as the set of agents. A solution for weighted bankruptcy situations is then a map $\psi : WB^N \rightarrow \mathbb{R}^N_+$. The solution called *Weighted* Constrained Equal Awards (WCEA) rule has been studied in [3,12] and it is defined as follows:

$$WCEA_i(E, c, a) = \min\{c_i, \hat{\lambda} a_i\} \tag{2}$$

where the parameter $\hat{\lambda} \in \mathbb{R}$ is such that

$$\sum_{i \in N} \min\{c_i, \hat{\lambda} a_i\} = E \tag{3}$$

A *Transferable Utility* (TU-) *game* with N as the set of players, is a pair (N, v), where $v : 2^N \rightarrow \mathbb{R}$ is the *characteristic function*, representing the *worth* or *profit* $v(S)$ of *coalition* $S \subseteq N$ (with $v(\emptyset) = 0$). Often, we identify a TU-game (N, v) with its characteristic function v. A TU-game (N, v) is *monotonic* if it holds that $v(S) \leq v(T)$ for all S and T such that $S \subseteq T \subseteq N$; it is *superadditive* if it holds that $v(S \cup T) \geq v(S) + v(T)$ for all $S, T \subseteq N$ such that $S \cap T = \emptyset$; it is *convex* or *supermodular* if it holds that $v(S \cup T) + v(S \cap T) \geq v(S) + v(T)$ for all $S, T \subseteq N$. Given a game v, an *imputation* is a vector $x \in \mathbb{R}^N$ such that $\sum_{i \in N} x_i = v(N)$ and $x_i \geq v(\{i\})$ for all $i \in N$. The *core* of a TU-game v is denoted by $C(v)$ and it is defined as the set of imputations defined as follows:

$$C(v) = \{x \in \mathbb{R}^N : \sum_{i \in N} x_i = v(N), \sum_{i \in S} x_i \geq v(S) \quad \forall S \subset N\}.$$

In general, a TU-game may have an empty core, and a TU-game with a non-empty core is said to be *balanced*. It is well known that convex games are balanced, but a balanced game need not be convex.

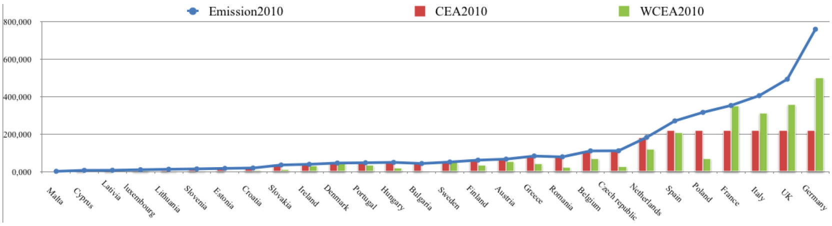
3 Bankruptcy Solutions for Emission Permits Allocation

According to the Kyoto Protocol, in 2010 the EU-28 countries should have reduced their cumulative CO2 by the 22% of the total amount of CO2 produced by the EU in 1990. Unfortunately, based on the CO2 data emissions provided by World Bank Open Data[2], this objective has not been achieved during any of the five years from 2010 to 2014. In this section, we want to analyse *ex-post* how CO2 emission permits would have been allocated among the EU-28 countries using the (W)CEA rule in order to meet the requirement indicated by the Kyoto protocol. To this aim, we model the problem of allocating CO2 permits during a year y, $y = 2010, \dots, 2014$, as a bankruptcy situation (E, c^y), where the agents are the EU-28 countries, the estate E corresponds to the 78% of the cumulative amount of CO2 produced in EU in 1990 (equal to 2434.658 Gt [8]), and claim c_i^y, for each country i, represents the actual amount of CO2 emitted during year y, as indicated in World Bank Open Data.

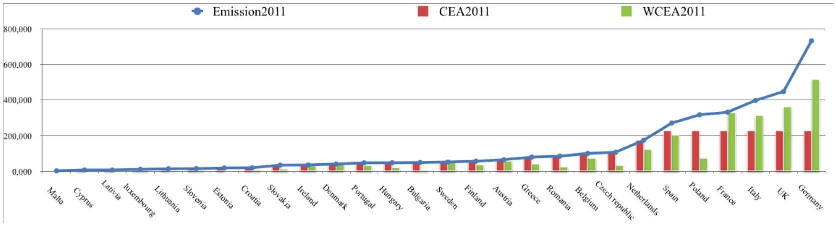
Using the very famous CEA rule, countries with a small claim, receive all their demands (see Fig. 1). Instead, the highest claims are not completely satisfied. If a country's claim decreases due to a new emission reduction policy, it is likely that it receives an amount of emission permits equal to its claim. For instance, until 2012, Spain's claims is higher than 250.000 Gt, so Spain does not receive the full claimed amount of permits. However, when Spain's claim becomes less than 250.000 Gt (see Fig. 2), the allocated amount covers the full claim of emission permits for Spain. On the other hand, countries with high demands like Poland, France, Italy, UK and Germany, receive the same quantity, despite the fact that they have different claims. For example, Germany's claim is double than the one of France and it is three times the claim of Spain (See Fig. 3). In this paper we propose to use an alternative allocation rule, the weighted CEA, which is based on a weighted bankruptcy situation (E, c^y, a^y) for each year y, $y = 2010, \dots, 2014$. As a weight vector, we set a_i^y equal to the GDP (Gros Domestic Product) of country i at year y. Country's GDP is an economic indicator reflecting the total value of "wealth production" within the country. Under this interpretation of a weighted bankruptcy situation, a country i claims the amount of CO2 emission permits c_i to produce the GDP a_i. However, country i will never obtain a share of CO2 emission permits larger than $\hat{\lambda} a_i$, where $\hat{\lambda}$ is the *maximum emission intensity per unit of GDP* calculated according to relation (2).

In the first part of this section, we used the CEA rule to allocate the CO2 emission permits and we had noticed that this method is beneficial for countries with low claims. Differently, the weighted CEA rule favours countries with low emission intensities $\lambda_i = \frac{c_i}{a_i}$. For instance, countries claiming more than

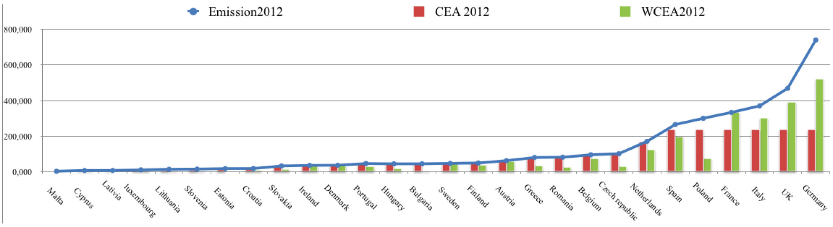
[2] https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?view=map.



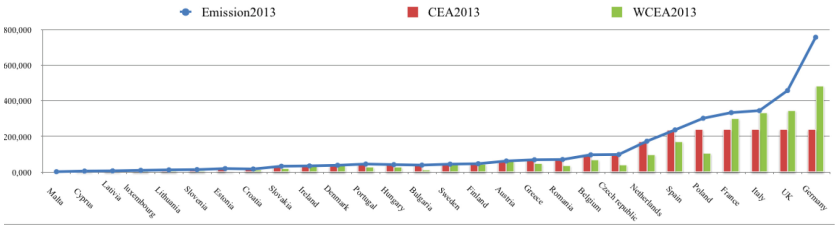
(a) Fig.1.a



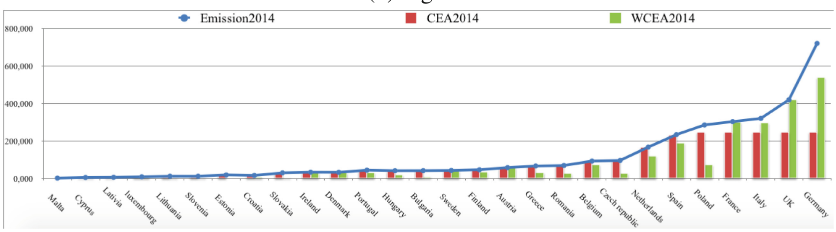
(b) Fig.1.b



(c) Fig.1.c



(d) Fig.1.d



(e) Fig.1.e

Fig. 1. CEA and WCEA allocations CO2 emissions permits for 28-EU

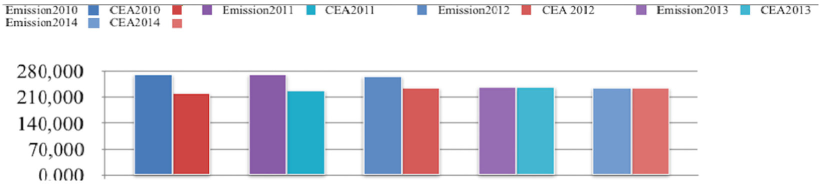


Fig. 2. Spain's allocation of CO2 emissions

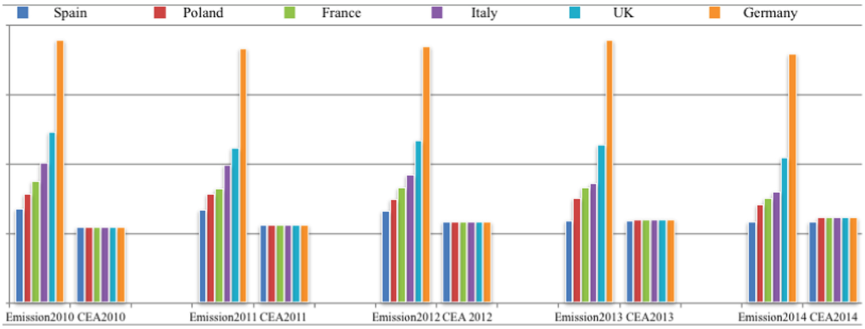


Fig. 3. CO2 allocation for countries with the highest demand.

200.000 GT of CO2 emissions receive less than their claim using the CEA rule, but adopting the WCEA rule, they are better off. This is, for instance, the case of Germany, that in 2010 claims 758860 GT of CO2, and using the CEA rule obtains 220420 GT of CO2 emission permits, i.e. less than half of the claim. Instead, using the weighted CEA, Germany obtains 500647 GT of CO2 emission permits, i.e. about two-thirds of the claim. Differently, Poland has a high claim but also a large emission intensity λ_i. So, using the CEA rule, Poland receives a larger quantity of CO2 emission permits than using the weighted CEA rule (See Fig. 4). In the next section, we show how the sharing policy generated by the weighted CEA rule may boost the technological transfer from efficient countries (with a low emission intensity) to most polluting ones (with a high emission intensity) that can be compensated by profit transfers among cooperating countries.

4 Surplus and Technology Transfer

Based on the allocation provided by the WCEA solution, countries with a high ratio $\frac{c_i}{a_i}$ receive less than their claims, even if their claims are small, whereas countries with a low $\frac{c_i}{a_i}$ likely receive their full demands. As observed in the previous section, a low ratio $\frac{c_i}{a_i}$ reflects a good ability to emit low quantities of CO2 for unit of GDP. We argue that this ability is the consequence of a more efficient use of resources and a higher level of green technologies. In this section, we study the problem of implementing economic incentives to transfer technology

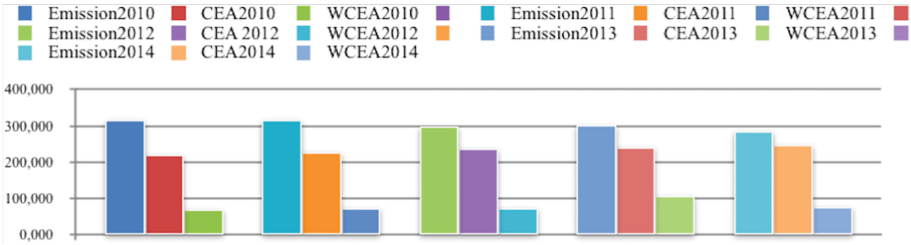


Fig. 4. Poland's allocation CO2 emissions permits

from the most efficient countries to the less efficient ones. To this purpose, we introduce a TU-game where the profit of each coalition of players (again, the EU-28 countries) is computed as the total profit obtained within the coalition using the highest technological level available for players in the coalition.

Definition 1. *Let* (E, c, a) *a weighted bankruptcy situation and let* $WCEA(E, c, a) = (x_1, x_2, \ldots, x_n)$. *For each* $i \in N$, *let* $\lambda_i = \frac{c_i}{a_i}$ *and let* $\lambda(S) = \min_{i \in S: x_i - c_i = 0} \lambda_i$ *for all* $S \subseteq N$ *(with the convention that* $\lambda(S) = 0$ *if* $x_i - c_i \neq 0$ *for all* $i \in S$*). The corresponding Technology-Transfer (TT-) game is defined as the TU-game* $(N, \tilde{v})$ *such that for all* $S \subseteq N$

$$\tilde{v}(S) = \begin{cases} \sum_{i \in S: c_i - x_i > 0} \left(\frac{x_i}{\lambda(S)} - \frac{x_i}{\lambda_i} \right) & \text{if } \lambda(S) \neq 0, \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

So the worth $\tilde{v}(S)$ of a coalition S represents the profit that a coalition $S \subseteq N$ can guarantee from adopting the best technology in use among the players in S, which corresponds to the best emission rate $\lambda(S) = \min_{i \in S: x_i - c_i = 0} \lambda_i$ among players in S who have received the claimed amount of emission permits. Precisely, the quantity of CO2 emission permits x_i allocated by the WCEA rule to each country $i \in S$ whose claim is not completely satisfied (i.e., $c_i - x_i > 0$) is used to produce a profit at the rate $\lambda(S)$, i.e. $\frac{x_i}{\lambda(S)} - \frac{x_i}{\lambda_i}$, and these profits are summed up over the countries in S. In other words, the "transfer" of technology within a coalition is only allowed from countries $i \in N$ with $\lambda_i \leq \hat{\lambda}$ to countries $j \in N$ with $\lambda_i > \hat{\lambda}$, where $\hat{\lambda}$ is the limit of emission intensity imposed by relation (2). Notice that $\frac{x_i}{\lambda(S)} - \frac{x_i}{\lambda_i} \geq 0$ for all $S \subseteq N$ such that $\lambda(S) \neq 0$ and every $i \in S$.

Proposition 1. *TT-games are monotonic and superadditive.*

Proof. We omit the straightforward proof that TT-games are monotonic. Consider a TT-game $(N, \tilde{v})$ corresponding to the allocation generated by the weighted CEA rule $WCEA(E, c, a) = (x_1, x_2, \ldots, x_n)$. Consider any coalitions $S, T \subseteq N$ with $S \cap T = \emptyset$. If $\tilde{v}(S) = 0$ or $\tilde{v}(T) = 0$ (or both), by monotonicity of $\tilde{v}$, it directly follows that $\tilde{v}(S) + \tilde{v}(T) \leq \tilde{v}(S \cup T)$. Otherwise, if $\tilde{v}(S) > 0$ and $\tilde{v}(T) > 0$, we have that

$$\tilde{v}(S) + \tilde{v}(T) \leq \sum_{i \in S \cup T : c_i - x_i > 0} \left(\frac{x_i}{\min\{\lambda(S), \lambda(T)\}} - \frac{x_i}{\lambda_i} \right) = \tilde{v}(S \cup T),$$

where the equality follows from the fact that $\min\{\lambda(S), \lambda(T)\} = \lambda(S \cup T)$. So, we have proved that $\tilde{v}(S)$ is superadditive.

The following example show that TT-games are not convex in general.

Example 1. Let $(N, \tilde{v})$ be the TT-game corresponding to the weighted bankruptcy situation (E, c, a) with $E = 14$ and the other parameters as shown in Table 1. It is easy to check by relations (2) and (3) that $\lambda^* = \frac{1}{2}$, yielding the weighted CEA allocation shown in the last column of Table 1. Let $S = \{2, 3, 5\}$ and $T = \{3, 4\}$. Then: $\tilde{v}(S) = \left(\frac{3}{\frac{1}{3}} - \frac{3}{2}\right) + \left(\frac{\frac{5}{2}}{\frac{1}{3}} - \frac{\frac{5}{2}}{5}\right) = 14$, $\tilde{v}(T) = \frac{\frac{5}{2}}{\frac{2}{5}} - \frac{\frac{5}{2}}{5} = \frac{23}{4}$, $\tilde{v}(S \cap T) = \tilde{v}(\{3\}) = 0$, $\tilde{v}(S \cup T) = \tilde{v}(\{2, 3, 4, 5\}) = \tilde{v}(\{2, 3, 5\}) = 14.5$. Then, $\tilde{v}(S) + \tilde{v}(T) > \tilde{v}(S \cup T) + \tilde{v}(S \cap T)$. So, $\tilde{v}$ is not convex.

Table 1. A weighted bankruptcy situation and the corresponding WCEA allocation.

$i \in N$	c_i (CO2)	a_i (GDP)	λ_i	x_i (WCEA)
1	9	3	3	$\frac{3}{2}$
2	12	6	2	3
3	5	5	1	$\frac{5}{2}$
4	4	10	$\frac{2}{5}$	4
5	3	9	$\frac{1}{3}$	3

The previous example shows that we cannot immediately guarantee the balancedness of TT- games using the convexity argument (and, similarly, we cannot use this argument to guarantee that the Shapley value lies the core of TT-games). Nevertheless, in the following we introduce a rule providing an allocation always in the core of a TT-game.

Definition 2. *Let $(N, \tilde{v})$ be the TT-game corresponding to (E, c, a).*

Let $i^* \in \arg\min_{i \in N : x_i - c_i = 0} \lambda_i$. Define the allocation $z \in \mathbb{R}^N$ such that for each $i \in N$

$$z_i = \begin{cases} \frac{x_i}{\lambda(N \setminus \{i^*\})} - \frac{x_i}{\lambda_i} \text{ if } c_i - x_i > 0, \\ 0 \text{ if } c_i - x_i = 0 \text{ and } i \neq i^*, \\ \tilde{v}(N) - \sum_{i \in N \setminus \{i^*\}} z_i \text{ if } i \neq i^*. \end{cases} \tag{5}$$

Proposition 2. *TT-games are balanced.*

Proof. Consider a TT-game $(N, \tilde{v})$ corresponding to the allocation generated by the weighted CEA rule $WCEA(E, c, a) = (x_1, x_2, \ldots, x_n)$. Allocation z is clearly efficient, as $\sum_{i \in N} z_i = \tilde{v}(N)$. Let $P = \{i \in N : c_i - x_i > 0\}$, and let $I = N \setminus P$. If $P \neq \emptyset$, from the fact that $\lambda(N \setminus \{i^*\}) \leq \lambda_i$, we have that $z_i \geq 0$ for each $i \in P$. Moreover, by the fact $\lambda(N \setminus \{i^*\}) \geq \lambda(N) = \lambda_{i^*}$, we also have that

$$\tilde{v}(N) = \sum_{i \in P} \frac{x_i}{\lambda_{i^*}} - \frac{x_i}{\lambda_i} \geq \sum_{i \in P} \left(\frac{x_i}{\lambda(N \setminus \{i^*\})} - \frac{x_i}{\lambda_i} \right),$$

and then it immediately follows that $z_{i^*} = \tilde{v}(N) - \left(\frac{x_i}{\lambda(N \setminus \{i^*\})} - \frac{x_i}{\lambda_i} \right) \geq 0$. Then, for each $S \subseteq N$ such that $S \cap P = \emptyset$ or $S \cap I = \emptyset$, we have that $\sum_{i \in S} z_i \geq 0 = \tilde{v}(S)$.

Now, let $S \subseteq N$ be such that $S \cap P \neq \emptyset$ and $S \cap I \neq \emptyset$. If $i^* \notin S$, we have that

$$\tilde{v}(S) = \sum_{i \in S \cap P} \frac{x_i}{\lambda(S)} - \frac{x_i}{\lambda_i} \leq \sum_{i \in S \cap P} \frac{x_i}{\lambda(N \setminus \{i^*\})} - \frac{x_i}{\lambda_i} = \sum_{i \in S} z_i, \qquad (6)$$

where the first equality follows directly from relation (4), and the inequality follows from the fact that $\lambda(S) \geq \lambda(N \setminus \{i^*\})$. Otherwise, if $i^* \in S$, we have that

$$\tilde{v}(S) = \sum_{i \in S \cap P} \frac{x_i}{\lambda(S)} - \frac{x_i}{\lambda_i} \leq \sum_{i \in S \cap P} \frac{x_i}{\lambda(N \setminus \{i^*\})} - \frac{x_i}{\lambda_i} + z_{i^*} = \sum_{i \in S} z_i, \qquad (7)$$

where the inequality follows from the previous arguments and the fact that we have shown earlier that $z_{i^*} \geq 0$. So, we have proved that $z \in C(\tilde{v})$.

5 Conclusions

In this paper, we have studied how to allocate CO2 emissions permits among the EU-28 using bankruptcy rules and we have shown that the WCEA rule keeps into account not only countries' claims but also countries' productions. In order to study incentives to the transfer of efficient technologies from countries with a low emission intensity to those with a high one, we have proposed a preliminary approach based on cooperative games and we have shown that, thanks to the properties of the allocation provided by the weighted CEA rule, the core of these games is non-empty. For space reasons, we have omitted a more exhaustive analysis of the WCEA solution in comparison with other allocation methods for CO2 permits proposed in the literature. We finally observe that the GDP index is often considered as a good measure to compare the environmental performance of countries with similar social and economic conditions. However, for scenarios dealing with heterogeneous states, the use of a more comprehensive estimation of the environmental performance of countries policies is recommended.

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