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The Allocation of Greenhouse Gas Emission in European Union through Applying the Claims Problems Approach

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Abstract: Due to the challenge of global warming, the European Union (EU) signed the Paris Agreement (2015) to diminish total Greenhouse Gas (GHG) emissions. This paper addresses the conflict that EU member states face when they want to follow the target of the Paris Agreement for the period 2021–2030 which is a 55% GHG emission reduction by 2030 (compared with GHG emission in 1990). EU member states have to emit at a level that is lower than their emission needs. To solve this problem, we implement the claims problems approach as a method for distributing insufficient resources among parties with greater demands. We use several well-known division rules to divide the emission budget among EU member states. We define a set of principles that should be satisfied by division rules to select the most optimal allocation method. To diminish the effect of countries' preferences on the allocation we use equity and stability criteria to examine the fairness of the rules. Moreover, we allocate the emission budget in two ways: First, we apply division rules to allocate the total emission budget for 2021–2030 among countries. Second, we allocate the emission budget annually from 2021 to 2030. We propose that Constrained Equal Awards (CEA) is an appropriate division rule to meet the target of 2030.

Keywords: claims problems; bankruptcy problems; Paris Agreement; climate change

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1. Introduction

The EU has a significant impact on the context of global warming. This region is the fourth global GHG emitter [1]. Nonetheless, the EU has always played the role of a leader to navigate activities for diminishing GHG emission [2].

The most prominent role of the EU is its proposal to limit the global temperature increase up to 2 °C above the pre-industrial level in 1996 [3]. This proposal has been the main target of all climate changes protocols and agreements [4]. After this, we can mention the Paris Agreement as a landmark in the EU's leading role to accelerate emission mitigation [5]. To achieve the targets of the Paris Agreement, the EU believes countries' efforts should be clear and quantifiable [6]. Therefore, the EU itself set three objectives: a 20% reduction in GHG emissions by 2020, a 55% reduction by 2030 (compared with the 1990 level), and reaching net zero emissions by 2050. Member states have succeeded in starting a decreasing trend from 1990 onwards. This diminishing path has led to the target of 2020 being overachieved (32% emission reduction in 2020 compared with 1990 [7]).

Nevertheless, countries' emission projections for the period of 2021 to 2030 indicate that this achievement is temporary. The member states' aggregate emission projections show that, in the best condition, their emission reduction is 41% less than 1990 [7]. Thereby, the countries' national efforts are not sufficient in following the EU targets.

Several studies have tried to solve this problem. References [8,9] define different emission budget scenarios aligned with the Paris Agreement and allocate them among countries. The allocation each country receives can work as a criterion to limit their national emissions [10]. The studies allocate the emission budget based on some equity principles. For instance, countries with larger historical emissions and/or a larger Gross

Domestic Product (GDP) per capita should diminish more GHG emissions. Reference [11] considers the equity principle and compromises it with the efficiency principle. The efficiency principle focuses on the economic benefit and minimizing the cost of emission reduction. They define population size, economic development, and historical emissions as the indicators that are utilized for an equitable allocation. Regions with higher population size, GDP, and historical emissions should take more responsibility for GHG emissions reduction. To evaluate the efficiency, they use a model called Super-SBM. Capital, labor, and energy are the inputs of this model and the output is GDP and GHG emissions. The regions with higher efficiency are assigned higher emission allocations. Reference [12] discusses that the eventual allowable emission level that countries can emit is the difference between the target emission budget and countries' historical emissions. They proposed to allocate this allowable budget based on equal per capita or equal per countries' current and future emissions. They also propose to enter the factor of historical emission into the aforementioned allocation methods.

However, the division of emission reduction responsibility is one method to abate the total GHG emission; another way is to sink and capture the cumulative GHG from the atmosphere. References [13–15] focus on this issue rather than studying the emission reduction actions. They divide Carbon Dioxide Removal (CDR) responsibilities fairly among countries. Based on their results, countries with larger GDPs and larger cumulative emissions per person will take a greater portion of CDR.

If we return to the solution of the GHG emission reduction through assigning a target emission budget to countries, reference [16] provides a new approach to do that which is the application of the claims problems approach. Claims problems [17] distribute a limited resource in situations where the total needs of parties in a dispute are more than the available resource. Reference [18] studies the distribution of the GHG emission budget between five main groups of countries by applying the claims problems approach. This method is used in a variety of resource allocation fields. Recently, reference [19] implemented claims problems to distribute the European Structural and Investment Fund to different regions throughout the EU.

The case of GHG mitigation in the EU can evidently be defined as a claims problem. We estimate the total amount of GHG that member states must emit from 2021 to 2030 in the framework of the EU 2030 target and compared it with the member states' aggregate emission projections in this period. We observe that the aggregate projections exceed the desirable emission level and the claims problems approach is applicable. We apply several allocation rules which are well-known in the claims problems literature and study their behavior. The allocation each member state receives by these rules tells how much they should abate their emission in the ten years to reach the target of 55% reduction by 2030 and obliges countries to adjust their emission projections to be more compatible with that target.

Here, the question rises: how countries should adjust the projection? We propose to look at this issue in a more dynamic way by applying the claims problem in each year. Now, countries can adjust their projections step by step according to the annual ceiling which is determined by the claims problems. The annual allocation is conducted as follows: in 2021, we allocate the permitted emission budget for this year to the projections of the year. As the aggregate projection is more than the emission budget, countries' projections cannot be fully satisfied, and part of them will be lost. These losses are added to the projections for 2022 and then we divide the 2022 emission budget based on these revised projections and so on. This method is an opportunity for member states to adjust their annual projections by considering the losses and can accelerate the process of GHG mitigation. If member states define their annual projections without taking into account the losses, they will face large projections when the losses are added. We will see that some division rules extremely penalize these countries by satisfying a slight portion of their projection, which means more loss for countries.

In the claims problems approach, countries are allowed to announce their demands and the claims problems allocates the emission budget on the basis of these demands. In addition, countries' final GHG emissions are limited to the amount that the claims problems assigns to them. Since, in the claims problems, no country can receive more than her claim (i.e., her need to emit), there is no chance for trading the emission allowances. Indeed, the claims problems establishes a strong limitation for rich countries to buy other countries' exceeded emission allowances.

This paper is organized in this order: Section 2 defines the claims problems approach and the division rules we apply to allocate the emission budget. This chapter also mentions the conditions and principles the division rules should satisfy. Section 3 discusses the implementation of division rules. In Section 4, the conclusions are provided.

2. Materials and Methods

Formally, we can define the claims problems as a set of agents $N = \{1, 2, ..., n\}$ and an amount $E \in \mathbb{R}_+$ the **endowment** that has to be allocated among them. Each agent has a **claim**, $c_i \in \mathbb{R}_+$ on it. Let $c \equiv (c_i)_{i \in N}$ be the claims vector.

Then, a **claims problems** [17] is a pair (E, c) with $C = \sum_{i=1}^{n} c_i > E$.

Without loss of generality, we increasingly order the agents according to their claims, $c_1 \leq c_2 \leq \ldots \leq c_n$, and we denote by $\mathcal{B}$ the set of all claims problems.

We define the EU member states as the agents. To define the against' claims, we use countries' national projections of anthropogenic GHG emissions. The projections are the countries' estimations about their future GHG emissions in different sources and GHG removals for the period 2021 to 2030. The projections are prepared in two scenarios: 'with existing measures' (WEM) and 'with additional measures' (WAM).

In WEM scenario, projections reflect the effects of all adopted and implemented measures at the time the projections are prepared. These measures embrace all mitigation actions and instruments which are the yield of governments' official decisions. Measures are supported by assigning adequate financial and human resources and the process of implementation of these measures are guaranteed. In WAM scenario, projections consider all adopted and implemented measures and the measures are at the planning stage at the time the projections are prepared. Although these planned measures are under review when the projections are submitted, they have a realistic chance to be adopted and implemented in the future [20].

The member states are obliged to report their national measures and projections every two years to the Monitoring Mechanism Regulation (MMR). These reports are used to monitor the member states' national mitigation efforts and assess the capability of the current measures to serve the GHG emission mitigation [21]. These measures are mainly implemented in industrial and agricultural sectors, energy supply (i.e., fuel extraction, distribution, and storage), and, energy consumption (i.e., consumption of fuels and electricity by households, services, industry, and agriculture). These measures appear in different forms such as economic incentives to reduce GHG, setting taxes on GHG emissions, building standard regulations, training programs, and research programs [21].

Afterward, we need to define the emission budget in line with the target of a 55% reduction by 2030. For this purpose, we assume a constant decreasing trend from the countries' last absolute emission to the desirable emission in 2030. According to the EU database (Eurostat), the latest absolute emission released hitherto belongs to 2020 which is 3124.59 Megatonnes (Mt). The desirable emission in 2030 is 2109.36 Mt which represents a 55% reduction compared with emissions in 1990. Let us show the emission in 2020 by e^{2020} and desirable emission in 2030 by e^{2030} and let us $d = \frac{e^{2020} - e^{2030}}{10}$ where 10 is the period in which the countries are diminishing the emission reduction (i.e., the number of years from 2021 to 2030). To achieve the constant decrease from 2021 and meet the desirable emission in 2030, the emission of EU in each year is the emission of the previous year minus d. Table 1 shows the total of this emission budget for 2021–2030 and the total of projections (in two scenarios) for these years.

Table 1. Total emission budget and projections for 2021–2030, numbers are in megatonnes (Mt).

Emission Budget	Projection (WEM)	Projection (WAM)
25,662.12	33,027.50	30,927.98

As Table 1 depicts the emission budget is not sufficient to satisfy the projections. There is a variety of division rules in the claims problems that each proposes a particular way to divide the emission budget. A division rule is a single-valued function $\varphi : \mathcal{B} \to \mathbb{R}^n_+$, such that $\varphi_i(E, c) \geq 0$. We use division rules which were already implemented in the context of CO_2 emission right by [16,18], these rules include Proportional, Constrained Equal Award, Constrained Equal Losses, Talmud, Adjusted Proportional, and $\alpha - minimal$.

The **Proportional (P)** [22] divides the emission budget proportionally among countries according to their projections. In this rule for each $(E, c) \in \mathcal{B}$ and each $i \in N$, $P_i(E, c) \equiv \lambda c_i$, where $\lambda = E / \sum\limits_{i \in N} c_i$.

The **Constrained Equal Award (CEA)** [22] divides the emission budget equally to all countries' provided that none of them receive more than their projections. The process is as follows: If the average emission budget exceeds the projection of one country, the rule fully satisfies the country's projection, excludes this country from the allocation process, and continues to allocate the remaining emission budget equally to the rest of the countries.

For each $(E, c) \in \mathcal{B}$ and each $i \in N$, $CEA_i(E, c) \equiv \min\{c_i, \mu\}$, where μ is such that $\sum\limits_{i \in N} \min\{c_i, \mu\} = E$. However, this rule neglects the differences between projections of countries.

The **Constrained Equal Losses (CEL)** [22] proposes to divide the loss (difference between aggregate projections and emission budget) equally to all countries given that no country receives a negative amount. The allocation each country receives is the difference between her projection and the loss which is divided by CEL. If this difference is negative for a country, the country's allocation will be zero and she leaves the allocation process. CEL divides the loss equal to the remaining countries.

For each $(E, c) \in \mathcal{B}$ and each $i \in N$, $CEL_i(E, c) \equiv \max\{0, c_i - \mu\}$, where μ is such that $\sum\limits_{i \in N} \max\{0, c_i - \mu\} = E$.

Talmud (T) [23] proposes a combination of CEA and CEL. This rule focuses on the half-sum of aggregate projections. If the emission budget is less than or equal to the half-sum of projections, CEA is applied. Countries receive the average emission budget or half of their projection (if the average emission budget is greater than half of the projection). If the emission budget is greater than the half-sum of projections, the following process is conducted: countries receive half of their projections. The projections and emission budget are revised down by these initial allocations and CEL is applied to these revised amounts. For each $(E, c) \in \mathcal{B}$ and each $i \in N$, $T_i(E, c) \equiv CEA_i(E, c/2)$ if $E \leq c/2$; or $T_i(E, c) \equiv c_i/2 + CEL_i(E - c/2, c/2)$, otherwise.

The **Adjusted Proportional (AP)** [24] has been introduced in two steps. In the first step, AP assigns to each country a minimal right (m_i). This minimal right is the remaining emission budget when the projections of the rest countries have been satisfied, with respect to the condition of $m_i(E, c) = \max\left\{0, E - \sum_{j \neq i} c_j\right\}$. In the second step, the projections are revised down by the minimal rights. Then the remaining emission budget is assigned proportionally among countries based on their revised projections.

For each $(E, c) \in \mathcal{B}$ and each $i \in N$, $AP_i(E, c) = m_i(E, c) + P(E - \sum_{i \in N} m_i(E, c), c - m(E, c))$

The **α-minimal (α-min)** [25] proposes to give each country a minimal amount equal to the lowest projection, in the case that the emission budget is enough. After revising down the projections by minimal amounts, the rule distributes the remaining emission budget proportionally among countries according to their revised projections. However, if the emission budget is not sufficient to give all countries the minimal amount, this rule recommends dividing the emission budget equally among countries.

For each $(E, c) \in \mathcal{B}$ and each $i \in N$, if $c_1 > E/n$ then $\alpha - min_i(E, c) = E/n$ and if $c_1 < E/n$ then $\alpha - min_i(E, c) = c_1 + P(E - nc_1, c - c_1)$.

All these rules must satisfy three basic requirements. First, the minimum amount countries receive by applying the rules is 0 (**non-negativity**), $\varphi_i(E, c) \geq 0$, for all $i \in N$. Second, countries cannot receive more than their projections (**claim-boundedness**), $\varphi_i(E, c) \leq c_i$, for all $i \in N$. Third, the whole emission budget should be divided among countries. (**efficiency**) $\sum_{i \in N} \varphi_i(E, c) = E$.

We also introduce some well-known properties in the context of resource distribution. These principles examine the characteristic of each division rule and assist us to select an optimal one.

Equal treatment of equals states that countries with the same projections should receive an equal amount of emission budget. For each $(E, c) \in \beta$ and $i, j \subseteq N$, if $c_i = c_j$ then $\varphi_i(E, c) = \varphi_j(E, c)$.

Anonymity says the allocation of emission budget exclusively depends on countries' projections. Other factors such as the identity of the countries cannot affect the emission allocation. For each $(E, c) \in \beta$ each $\pi \in \prod^N$ and each $i \in N$, $\varphi_{\pi(i)}(E, (c_{\pi(i)})_{i \in N}) = \varphi(E, c)$, where $\prod^N$ is the permutations of N.

Order preservation [23] means the emission allocation assigned to countries with larger projections cannot be smaller than the emission allocation of countries with lower projections. For each $(E, c) \in \beta$ and each $i, j \in N$ such that $c_i \geq c_j$, then $\varphi_i(E, c) \geq \varphi_j(E, c)$. Likewise, countries with larger projections bear an equal or larger amount of loss than countries with lower projections. $c_i - \varphi_i(E, c) \geq c_j - \varphi_j(E, c)$.

Claims monotonicity states if a country increases its projection, the allocation assigned to this country cannot be less than the initial amount. For each $(E, c) \in \beta$, $i \in N$ and each $c'_i > c_i$ we have $\varphi_i(E, c'_i, c_{-i}) \geq \varphi_i(E, c)$.

Composition down [26] is a property for situations in which the emission budget is reduced after allocation due to re-evaluation of the emission budget or setting more strict emission reduction rules. For instance, the EU decides to increase the percentage of emission reduction by 2030 to more than 55%, while the emission budget of 55% reduction has been allocated before this announcement. In this case, we have two choices: First, we cancel the initial emission budget allocation and reallocate the new amount of the emission budget. Second, we consider the initial emission allocation assigned to each country as their claims (rather than considering the projections) and divide the new emission budget by these new claims. for each $(E, c) \in \mathcal{B}$, each $i \in N$, and each $0 \leq E' \leq E$, $\varphi_i(E', c) = \varphi_i(E', \varphi(E, c))$.

Invariance under claims truncation [27] imposes an upper bound to countries' projections. If a country's projection is greater than the emission budget, the exceeding part will be ignored. This property says that countries cannot request more than the available emission budget. For each $(E, c) \in \beta$ and each $i \in N$, $\varphi_i(E, c) = \varphi_i(E, (minc_i, E)_{i \in N})$.

Table 2 shows the division rules and the properties which are satisfied by them. The constrained Equal Awards (CEA) rule satisfies all these basic properties.

Table 2. Properties and division rules. (rows represent division rules and columns show the properties).

Properties/Rules	P	CEA	CEL	T	AP	α-min
Equal treatment of equals	Yes	Yes	Yes	Yes	Yes	Yes
Anonymity	Yes	Yes	Yes	Yes	Yes	Yes
Order preservation	Yes	Yes	Yes	Yes	Yes	Yes
Claims monotonicity	Yes	Yes	Yes	Yes	Yes	Yes
Composition down	Yes	Yes	Yes	No	No	Yes
Invariance under claims truncation	No	Yes	No	Yes	No	No

3. Results and Discussion

3.1. The Allocation of total GHG Emission

As we saw, the countries' total GHG emission from 2021 to 2030 is more than the estimated emission budget to achieve the target of 55% emission reduction in 2030 (see

Table 1). To solve this problem, we implement the aforementioned division rules to allocate the total emission budget among countries according to their total projections for the period of 2021–2030.

Tables 3 and 4 show the results for WEM and WAM scenarios. In these tables, countries are ordered according to their projections from smaller to larger.

Table 3. The total GHG emission allocation 2021–2030 (WEM), numbers are in megatonnes (Mt).

Country	Projection	P	CEA	CEL	T	AP	α-min
Malta	30.11	23.40	30.11	0.00	15.05	23.28	30.11
Cyprus	79.16	61.51	79.16	0.00	39.58	61.21	67.95
Sweden	108.77	84.51	108.77	0.00	54.38	84.11	90.79
Luxembourg	115.98	90.12	115.98	0.00	57.99	89.69	96.35
Slovenia	120.76	93.83	120.76	0.00	60.38	93.38	100.03
Estonia	121.97	94.77	121.97	0.00	60.98	94.32	100.97
Lithuania	138.88	107.91	138.88	0.00	69.44	107.39	114.01
Latvia	140.36	109.06	140.36	0.00	70.18	108.54	115.15
Croatia	207.86	161.51	207.86	0.00	103.93	160.74	167.22
Finland	278.29	216.23	278.29	0.00	139.15	215.20	221.55
Slovakia	405.30	314.92	405.30	50.99	202.65	313.41	319.52
Denmark	428.22	332.72	428.22	73.91	214.11	331.14	337.20
Bulgaria	499.75	388.30	499.75	145.44	249.88	386.45	392.37
Portugal	499.77	388.32	499.77	145.46	249.88	386.47	392.39
Hungary	602.23	467.93	602.23	247.92	301.12	465.70	471.42
Ireland	685.67	532.76	685.67	331.36	342.83	530.22	535.79
Austria	734.51	570.71	734.51	380.20	367.25	567.99	573.46
Romania	798.82	620.68	798.82	444.51	399.41	617.72	623.07
Greece	801.66	622.88	801.66	447.35	400.83	619.91	625.26
Czech	1173.08	911.47	1173.08	818.77	677.29	907.13	911.76
Belgium	1260.61	979.48	1260.61	906.30	764.82	974.81	979.27
Netherlands	1764.67	1371.14	1764.67	1410.36	1268.88	1364.60	1368.09
Spain	2964.72	2303.57	2933.14	2610.41	2468.93	2292.58	2293.76
Italy	3641.23	2829.21	2933.14	3286.92	3145.44	2815.72	2815.60
France	3732.83	2900.38	2933.14	3378.52	3237.04	2886.55	2886.26
Poland	3787.25	2942.67	2933.14	3432.94	3291.46	2928.64	2928.24
Germany	7905.04	6142.16	2933.14	7550.73	7409.25	6235.22	6104.55

The CEA rule divides the emission budget equally among the member states. By analyzing the results depicted in the Table 3 the first 21 countries receive the exact amount of their projections. It means the allocations that CEA proposes to them exceed their projections. Therefore, these countries are permitted to emit at the level they estimated (according to the requirement of claim-boundedness, countries cannot emit more than their projections, and therefore, if one rule assigns them an emission allocation more than their projections, that assignment is truncated to the countries' projections). In WAM, the first 22 countries are assigned equal to their projections (Table 4). Hence, we can claim that CEA is an appropriate rule for countries with smaller projections. Since CEA assigns the emission budget equally to countries without taking into account the magnitude of countries' projections. Thereby, countries with lower projections obtain more percentage of their projection.

The CEL divides the loss (i.e., aggregate projections minus current emission budget) equally among the member states. The CEL determines how much each country should decrease its emission. Each country's permitted emission is obtained by subtracting the allocated loss from the country's projections. In some cases (e.g., Malta or Cyprus), this subtraction is negative. According to the basic requirement of non-negativity, the allocation of countries cannot be negative. Thereby, these countries are assigned zero emission permission. Indeed, CEL sacrifices countries with smaller projections, and the reason lies in the equal division of loss without considering the size of the projections. T shows that this rule supports the countries with larger claims. Since the mission budget is greater than the half-sum of projections, CEL is applied. P, AP, and α-min show moderate behaviors with respect to extremely small or large projections, since they consider the size of the projections while they allocate the emission budget.

Table 4. The total GHG emission allocation 2021–2030 (WAM), numbers are in megatonnes (Mt).

Country	Projection	P	CEA	CEL	T	AP	α-min
Malta	30.11	24.98	30.11	0.00	15.05	24.51	30.11
Cyprus	75.29	62.47	75.29	0.00	37.65	61.28	67.39
Luxembourg	90.77	75.32	90.77	0.00	45.38	73.87	80.16
Sweden	108.77	90.25	108.77	0.00	54.38	88.52	95.02
Lithuania	119.70	99.32	119.70	0.00	59.85	97.42	104.03
Estonia	120.66	100.12	120.66	0.00	60.33	98.20	104.83
Slovenia	132.02	109.54	132.02	0.00	66.01	107.44	114.20
Latvia	132.76	110.16	132.76	0.00	66.38	108.05	114.81
Croatia	198.58	164.77	198.58	0.00	99.29	161.61	169.12
Finland	264.21	219.22	264.21	27.70	132.10	215.03	223.28
Slovakia	360.87	299.43	360.87	124.36	180.44	293.70	303.03
Denmark	428.22	355.31	428.22	191.71	214.11	348.51	358.61
Portugal	448.84	372.42	448.84	212.33	224.42	365.29	375.62
Bulgaria	483.58	401.24	483.58	247.07	241.79	393.56	404.29
Hungary	558.34	463.28	558.34	321.83	279.17	454.41	465.97
Ireland	627.44	520.61	627.44	390.93	336.65	510.64	522.99
Greece	672.19	557.74	672.19	435.68	381.40	547.06	559.92
Austria	699.54	580.43	699.54	463.03	408.75	569.32	582.48
Romania	757.57	628.58	757.57	521.06	466.78	616.55	630.37
Czech	1057.91	877.79	1057.91	821.40	767.12	860.98	878.19
Belgium	1151.02	955.04	1151.02	914.51	860.23	936.76	955.02
Netherlands	1769.12	1467.91	1769.12	1532.61	1478.33	1439.80	1465.04
Spain	2486.89	2063.47	2486.89	2250.38	2196.10	2023.96	2057.30
Italy	3159.62	2621.66	3159.62	2923.11	2868.83	2571.47	2612.40
Poland	3356.11	2784.69	3242.70	3119.60	3065.32	2731.38	2774.53
France	3732.83	3097.27	3242.70	3496.32	3442.04	3037.98	3085.38
Germany	7905.04	6559.11	3242.70	7668.53	7614.25	6924.81	6528.04

The main question is which of these rules should be selected to allocate the emission budget and meet the target of 2030. Countries tend to maximize the emission allocation they receive by accepting the rules, giving them more allocation and denying the rules which seem not fair to them. Therefore, just by considering the amount each rule assigns to countries, we cannot propose a specific division rule which can be accepted by all countries.

To offer an efficient division rule, we need criteria to make rule selection independent from countries' tendencies. In doing so, we analyze division rules from equity and stability points of view. For this purpose, we consider two criteria: the Gini index and the Coefficient of Variation.

Gini index (Gi): [28] Gini index is a statistic dispersion indicator that evaluates the degree of inequality in a resource allocation. Its value is in the interval of 0 and 1, 0 indicates perfect equality and 1 represents extreme inequality. Given an n-dimensional endowment, the Gini index is defined as follow:

$$Gi = \frac{1}{2n^2\mu}\sum_i\sum_{j<i}|r_i - r_{j<i}|.$$

where vector r is the assignment of the endowment to the individuals $i = \{1, \ldots, n\}$ and $\mu = \frac{1}{N}\sum_i r_i$.

Coefficient of Variation (CV): For analyzing the stability of the allocation results, the countries' historical emissions should be considered. Countries decide about the fairness of a rule by comparing their historical emission with the emission allocation a particular rule assigns them. Countries would accept a division rule when they are ensured about the fairness of that rule [29]. If the amount they receive by a rule is far from their historical emissions, countries would refuse that rule. For this purpose, we apply the Coefficient of Variation Index to evaluate the weights of countries [30]. CV calculates the dispersion of allocation around the mean. Formally, we can define it as:

$$CV = \frac{\delta}{\bar{PI}}$$

where δ is the standard deviation and $\bar{PI}$ is the mean of Power Index. The range of CV is a value between 0 and $\sqrt{N-1}$ for a finite sample of N [31] that $\sqrt{N-1}$ shows the complete instability.

Tables 5 and 6 show the values of the Gini index and Coefficient of Variation for the different division rules. As we can see, CEA, P and, α-min are more equitable and stable division rules, they have a lower Gini index and Coefficient of Variation compared with other division rules.

Table 5. Gini Index (Gi) and Coefficient of Variation (CV) for the total GHG emission allocation (WEM scenario).

Criterion	P	CEA	CEL	T	AP	α_{min}
Gi	0.63	0.55	0.75	0.70	0.63	0.63
CV	1.45	1.10	1.82	1.74	1.47	1.44

Table 6. Gini Index (Gi) and Coefficient of Variation (CV) for the total GHG emission allocation (WAM scenario).

Criterion	P	CEA	CEL	T	AP	α_{min}
Gi	0.64	0.57	0.74	0.71	0.64	0.63
CV	1.50	1.17	1.79	1.76	1.55	1.50

3.2. The Annual Allocation of GHG Emission

By comparing the annual emission budget and annual projections, we can clearly observe that projections are surplus to the emission budget in both WEM and WAM scenarios (table 7).

Table 7. The annual emission budget and projections for 2021–2030, numbers are in megatonnes (Mt).

Year	Emission Budget	Projection (WEM)	Projection (WAM)
2021	3,023,064.45	3,393,431.76	3,326,137.63
2022	2,921,541.73	3,408,314.62	3,305,192.39
2023	2,820,019.00	3,408,667.03	3,269,079.93
2024	2,718,496.27	3,377,677.61	3,200,327.53
2025	2616,973.55	3,356,436.31	3,143,477.10
2026	2,515,450.82	3,310,391.92	3,077,607.66
2027	2,413,928.10	3,268,123.97	3,012,592.09
2028	2,312,405.37	3,217,965.41	2,938,835.50
2029	2,210,882.64	3,173,982.99	2,872,139.24
2030	2,109,359.92	3,112,504.27	2,782,595.63

In the annual allocation, we limit our study to the WEM scenario which shows fewer efforts to diminish the GHG emission. As we mentioned, from 2022, we revise the claims of each country by adding the loss of the previous year to the projection of the current year. More precisely, we allocate the annual emission of the year 2021 to the countries based on their projections for this year, by implementing the aforementioned division rules. As the emission budget is not sufficient to cover most of the countries' projections, a part of the countries' projections in 2021 remains unsatisfied. We add this unsatisfied part to the projection of countries in 2022. Then, we allocate the 2022 emission budget to these revised projections and so on. Table 8 represents the sum of the annual allocation which are dedicated by division rules from 2021 to 2030.

We narrow our interpretation to the behavior of two extreme rules, CEA and CEL. The former serves countries with lower projections and the latter supports countries with higher projections. In 2021, all countries except Germany (with the largest projection) are fully honored, by applying CEA. The allocation of Germany is around 480 Mt, which decreases to 372 Mt in 2022. The reason is a significant growth in Germany's 2022 projection due to adding the loss of 2021 to that. From 2022 onward, countries such as France, Poland, and Italy are also punished by CEA. While, despite the growth in projections of countries such as Malta, CEA increases their allocation. This confirms our previous results which show that CEA supports countries with smaller projections. In 2021, CEL imposes an equal amount of loss (15.02 Mt) to all countries which cause zero allocation to some countries with smaller claims such as Malta and Cyprus. From 2021 onward, the number of countries that receive zero allocation by applying CEL increases. On one hand, the annual emission is decreasing with a constant slope and on the other hand, most of the countries increase their projections. Therefore, the loss which is the difference between the aggregate projections and the emission budget increases.

Table 8. The aggregate annual GHG emission allocation 2021–2030 (WEM), numbers are in megatonnes (Mt).

Country	Projection	P	CEA	CEL	T	AP	α-min
Malta	30.11	22.85	30.11	0.00	26.95	22.86	30.11
Cyprus	79.16	60.99	79.16	0.00	71.31	61.03	67.95
Sweden	108.77	87.48	108.77	0.00	99.73	87.51	94.32
Luxembourg	115.98	88.97	115.98	0.00	104.26	89.02	95.70
Slovenia	120.76	92.10	120.76	0.00	108.46	92.15	98.76
Estonia	121.97	93.68	121.97	0.00	109.77	93.73	100.37
Lithuania	138.88	108.63	138.88	0.23	125.91	108.69	115.25
Latvia	140.36	104.62	140.36	0.00	124.72	104.69	111.15
Croatia	207.86	159.70	207.86	5.32	187.03	159.79	165.87
Finland	278.29	217.62	278.29	26.23	252.29	217.73	223.42
Slovakia	405.30	311.47	405.30	74.48	364.66	311.63	316.40
Denmark	428.22	336.49	428.22	101.32	389.14	336.65	341.40
Bulgaria	499.75	390.00	499.75	149.90	452.86	390.20	394.43
Portugal	499.77	403.29	499.77	168.57	459.74	403.47	407.92
Hungary	602.23	466.18	602.23	239.45	543.40	466.42	469.96
Ireland	685.67	529.00	685.67	322.90	617.76	529.28	532.23
Austria	734.51	567.38	734.51	371.73	662.40	567.68	570.31
Romania	798.82	620.65	798.82	436.03	722.28	620.98	623.25
Greece	801.66	621.47	801.66	438.88	724.09	621.79	624.03
Czech	1173.08	921.42	1173.08	810.30	1065.12	921.87	921.99
Belgium	1260.61	963.89	1260.61	897.83	1131.79	964.42	963.44
Netherlands	1764.67	1374.69	1764.67	1401.89	1598.57	1375.38	1371.37
Spain	2964.72	2289.44	2739.55	2601.94	2473.20	2290.63	2278.63
Italy	3641.23	2822.37	2939.66	3278.45	2792.57	2823.82	2807.41
France	3732.83	2886.75	2961.27	3370.04	2829.77	2888.24	2871.20
Poland	3787.25	2902.18	2956.14	3424.48	2816.08	2903.73	2885.97
Germany	7905.04	6218.81	3069.07	7542.26	4808.34	6208.75	6179.30

Table 9 indicates the average measures of Gini index and Coefficient of Variation in this method. The result shows: CEA $<$ P, AP, α-min $<$ T $<$ CEL

It is noteworthy to mention that in the annual allocation, the rules satisfy all basic requirements and properties except order preservation. As we can see in Table 8, the projection of Lithuania is less than Latvia, while the allocation she receives is greater than Latvia (except CEA).

Table 9. Gini Index (Gi) and Coefficient of Variation (CV) of the annual GHG emission allocation).

Criterion	P	CEA	CEL	T	AP	α-min
Gi	0.63	0.55	0.75	0.58	0.63	0.63
CV	1.46	1.10	1.83	1.27	1.46	1.45

4. Conclusions

In this study, all the proposed division rules are evaluated from different aspects. First, their capability to satisfy a set of basic properties. We saw that the Constrained Equal Awards (CEA) is the rule which satisfies all the properties (Table 2). The second aspect is fairness in allocation. To evaluate the degree of fairness of each rule, we used two indicators, Gini index and the Coefficient of Variation. The results also confirm that CEA shows fair behavior. Another reason that makes CEA the final solution of this study is the rule's protective behavior to countries with smaller projections. This rule imposes the reduction pressure on the countries with larger projections. The countries with higher projections are mainly industrialized and well-developed countries (e.g., Germany). These countries are the main target of greenhouse gas (GHG) emission reduction. Since, on one hand, they are the larger GHG emitters, and on the other hand, they have the technological and financial ability to reduce GHG emissions. CEA is the rule that reduces these countries' emission allocation in the favor of less developed countries.

As the final remark, we would like to propose an extension for the current study which is the evaluation of the division rules by analyzing their impact on countries' Gross Domestic Product (GDP) and Human Development Index (HDI).

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