UNIVERSITAT ROVIRA i VIRGILI
Departament d'Economia

WORKING PAPERS ECO & ECO-SOS

Distributing the European Union Greenhouse Gas emission 2030

Foroogh Salekpay

Document de treball n. **02 - 2021**

Edita:

Departament d'Economia
Universitat Rovira i Virgili
Facultat d'Economia i Empresa
Av. de la Universitat, 1
43204 Reus
Tel.: +34 977 759 811
Tel.: +34 977 759 812
Email: sde@urv.cat

ECO-SOS
www.eco-sos.urv.cat
Universitat Rovira i Virgili
Departament d'Economia
Av. de la Universitat, 1
43204 Reus
Tel.: +34 977 758 936
Email: eco-sos@urv.cat

Adreçar comentaris al Departament d'Economia / ECO-SOS

ISSN: 2696-5097

Distributing the European Union Greenhouse Gas emission 2030

Foroogh Salekpay

Universitat Rovira i Virgili, Departament d'Economia and ECO-SOS, Av.Universitat 1, 43204 Reus, Spain. (foroogh.salekpay@urv.cat)

Abstract

Due to the challenge of global warming, the European Union (EU) signs the Paris agreement (2015) to diminish the total Greenhouse Gas (GHG) emission. Nonetheless, the European Environmental Agency report (EEA, 2019) shows that EU cannot achieve its 2030 target since in the long-term the GHG emission of member states exceed the target emission budget. We propose to distribute the EU 2030 target emission budget among its member states to keep them in the path leading to this year. In doing so, we apply the claims problems approach which is a method to divide a scarce resource among claimants with larger cumulative claims.

Keywords: Claims problems, Bankruptcy problems, Paris agreement, Climate change

1. Introduction

EU has a significant impact on the context of the global warming. Based on the Eurostat report in 2019, this region is the third global GHG emitter. Nonetheless, EU has always played as a leader to navigate activities for diminishing the GHG emission (Parker and Karlsson, 2017).

The most prominent role of EU is its proposal to limit the global temperature increase up to 2ºc above pre-industrial level in 1996 (Schleussner et al., 2016). This proposal has been the main target of all climate changes protocols and agreements (Rayner and Jordan, 2013). Afterward, we can mention the Paris agreement as a landmark in EU leading role to accelerate the emission mitigation (Höhne et al., 2017). To achieve the targets of the Paris agreement, EU believes countries efforts should be clear and quantifiable (Oberthür and Groen, 2017). Therefore, EU itself set 3 objectives: 20% reduction in GHG by 2020, 40% reduction by 2030 and 80% to 95% reduction by 2050 (compared with 1990 level). Member states succeed to start a decreasing trend of GHG emission from 1990. So that, their emission in 2017 was 21.7% below 1990 (EEA, 2019). Therefore, they overachieve the target of 2020.

Nevertheless, countries emission projections for the period 2021 to 2030 indicate 2020 achievement is temporary. EU set the annual reduction of 81 megatonnes carbon dioxide equivalent (Mt co2e) from 2017 to 2030. Whereas the member states emission projections show that, in the best scenario countries can diminish 63 (Mt co2e) (EEA, 2019). Thereby the national efforts of countries are not sufficient to track the EU consistent targets with the Paris agreement.

Several studies try to solve this problem. du Pont et al. (2017) and Pan et al. (2017) define different emission budget scenarios aligned with the Paris agreement targets. They allocate these emission budgets among countries. The core idea of these studies is considering the emission budget as a finite resource. The allocation each country receives can work as a criterion to limit countries national emissions (Raupach et al., 2014). They allocate the emission budget based on some equity principles. For instance, countries with larger historical emission and/or larger GDP per capita should diminish more GHG emission. But the results of these studies show that there is a gap between the fair emission shares and countries' Nationally Determined Contribution (NDCs). Indeed, this gap is cumulative CO2 emissions that causes deviation from GHG emission mitigation targets.

Fyson et al. (2020) and Pozo et al. (2020) focus on the cumulative emission rather than emission mitigation actions. They divide Carbon Dioxide Removal (CDR) responsibilities fairly among countries. They apply aforementioned equity principles to distribute CDR burden. Based on their results, countries with larger GDP and larger cumulative emission per person will take more portion of CDR.

Duro et al. (2020) study the distribution of GHG emission budget between five main groups of countries by applying claims problems approach. This method is proposed by Giménez-Gómez et al. (2016) as a way to assign the available GHG emission budget among countries. Claims problems (O'Neill, 1982) distributes a limited resource in situations that the total needs of parties in a dispute is more than the available resource. Duro et al. (2020) analyze various division rules and propose Constrained Equal Awards (Maimoindes, 1135,1204) and α-minimal (Giménez-Gómez et al., 2012) as the most efficient division rules.

The current paper implements the claims problems approach to analyse how the emission budget can be distributed to navigate member states on the pathway of EU targets. We limit our study to the period of 2021 to 2030 to investigate the different ways we can allocate the total emission budget of these 10 years among member states and achieve the target of 40% reduction in 2030. Furthermore, the main contribution of the current study is proposing the annual emission allocation. The amount countries plan to emit is strongly affected by annual local or global situations (for instance the effects of pandemic obviously change current and future emission of member states). As we use the member states emission projections as the basis of allocation, the annual allocation allows us to reach the updated projections which are revised based on the occasional situations.

The paper is organized in this order: chapter 2 defines the claims problems approach and the division rules we apply to allocate emission budget. This chapter also mentions conditions and principles the division rules should satisfy. Chapters 3 and 4 discuss the implementation of division rules, respectively. Finally, chapter 5 concludes.

2. Claims problems

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** (O'Neill, 1982) 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 EU member states and United Kingdom as the agents. To define the against' claims, we use countries' national projections of anthropogenic GHG emission report to the Monitoring Mechanism Regulation (MMR). These projections were prepared in two scenarios: In 'with existing measures' (WEM) scenario, projections reflect the effects of all adopted and implemented measures at the time the projections were prepared. In 'with additional measures' (WAM) scenario, projections consider all adopted and implemented measures as well as measures were at the planning stage at the time the projections were prepared (EEA, 2019).

To define the emission budget, we consider a down-ward sloping line between two points: last historic emission of countries which belongs to 2017 and EU target for 2030 (40% emission reduction compared with 1990). Table 1 reflects the results.

Year	Emission Budget	Projections(WEM)	Projections(WAM)
Total	37040.50	39475.53	37384.07

Table 1: Total emission budget and projections for 2021- 2030 (Source: European Union Environmental Agency and Eurostat Dataset, 2020)

As Table 1 depicts the emission budget cannot satisfy the projections. Therefore, it is required to find a way for allocating this emission budget among countries. In doing so, we apply different division rules. 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 CO2 emission right conflict (Giménez-Gómez et al., 2016) and (Duro et al., 2020) include Proportional , Constrained Equal Award , Constrained Equal Losses, Talmud, Adjusted Proportional and $\alpha - minimal$.

The **Proportional (P)** 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 $\lambda = E/\sum_{i \in N} c_i$.

The **Constrained Equal Award (CEA)** Maimoindes (1135,1204) divides emission budget equally to all countries provided that non of them receive more than their projections. 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 $\sum_{i \in N} \min\{c_i, \mu\} = E$. However, this rule neglects the differences between projections of countries.

The **Constrained Equal Losses (CEL)** Maimoindes (1135,1204) defines the loss as the aggregate projections that are not satisfied $(L = C - E)$. This rule proposes to divide the loss equally to all countries given that no country receive negative amount.
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 $\sum_{i \in N} \max\{0, c_i - \mu\} = E$.

Talmud Aumann and Maschler (1985) 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. Otherwise, countries receive the half of their projections and the amount is allocated by applying CEL.
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)** Curiel et al. (1987) has been introduced in two steps. In the first step, AP pays to each country a minimal right. This minimal right is the remaining of emission budget when the projections of the rest countries have been satisfied, by respecting 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 minimal amount. 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** Giménez-Gómez et al. (2012) proposes to give each country a minimal amount equal to lowest projection, in the case that the emission budget is enough. Then, it distributes the remaining emission budget proportionally among countries according to their revised projections. But, if the emission budget is not sufficient to give all countries the minimal amount, this rule recommends to divide 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 principles 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 same projection should receive 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 depends on countries projections. The identity of the countries cannot affect the emission allocation each country receives. For each $(E,c) \in \beta$ each $\pi \in \prod^N$ and each $i \in N$, $\varphi_{\pi(i)}(\mathrm{E},(\mathrm{c}_{\pi(i)})_{i\in N}) = \varphi(E,c)$, where $\prod^N$ is the permutations of N.

Order preservation (Auman and Maschler, 1985) means the emission allocation assigned to countries with larger projections can not 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 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 new amount is 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 (Moulin, 2000) makes sense if we have to reduce emission budget due to more strict emission reduction. In this case, we have two choices: First, we cancel the initial emission budget allocation and reallocate the new amount of emission budget. Second, we consider the initial emission allocation assigned to each country as their claims (rather than considering the projections) and we divide the incremental amount of emission budget among countries according to their 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 (Dagan and Volij, 1993) imposes an upper bound to countries projections. If a country projection be greater than the emission budget, the exceeding part will be ignored. For each $(E,c) \in \beta$ and each $i \in N$, $\varphi_i(E,c) = \varphi_i(E,(minc_i,E)_{i\in N})$.

Duality (Auman and Maschler, 1985) indicates that if one rule allocates emission budget between countries in the same way that the other rule assigns looses, these rules are Dual. We can claim that CEA and CEL are dual rules. $f^*(E;c) = c - f(C - E, c)$. Consider the total emission budget is 37040.50 and the total of projections in WEM scenario is 39475.53. Therefore, we have a loss equal 39475.53 - 37040.50= 2435.03. We allocate the loss by applying CEL (see table 11). For instance in Germany, the amount of loss allocation to this country is 2435.03. By subtracting this amount from the projection of Germany we achieve the number that Germany obtains from emission budget allocation by applying CEA (see Table 3).

A rule is **Self- Dual** if assigns emission budget and loss in the same way $f^* = f$. we show that Proportional, Talmud and Adjusted Proportional are Self- Dual rules. For instance, the amount of loss is allocated by proportional rule to Germany is 485.10. By subtracting this number from the projection of Germany we achieve the amount of emission budget Proportional rule allocates to Germany (see Table 3).

Table 2 shows an overview of the division rules and principles they satisfy. We can see that P, CEA and T satisfy most of the principles. If we assume there are no changes in policy maker decisions which can change the emission budget during the period 2021-2030, we can choose T as the most appropriate rule. In this case T satisfy all basic principles.

Principles/Rules	P	CEA	CEL	T	AP	$\alpha - min$
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
Self-duality	Yes	No	No	Yes	Yes	No

Table 2: Principles and division rules. (rows represent division rules and columns correspond to principles)

3. The allocation of GHG emission

As aforementioned, if we follow countries whole GHG emission from 2021 to 2030, we note that they cannot achieve the 40% emission reduction in 2030, despite their down-ward trend (see table 1). For solving this problem, we implement aforementioned division rules to allocate the total emission budget among countries according to their total projections for the period 2021-2030.

Table 3 and 4 show the results for WEM and WAM scenarios. These results are ordered according to countries total projections from lowest. By analysing the division rules based on the amount they allocate to each country we can see that CEA is convenient division rule for countries with lowest projections. Since, CEA assigns emission budget equally to countries without taking in to account the difference between countries projections. Therefore countries with lower projection obtain more percentage of their projection. We can see that all countries except Germany (country with largest projection) are fully compensated by applying CEA. The greatest emission allocation is assigned to Germany by applying CEL. CEL allocates loss without considering countries' projections. Therefore, it cannot be a fair rule for countries with small projection. As the results depicts, CEL allocates 0.00 to countries such as Malta and Cyprus. The measures are allocated by Talmud show the similarity between Talmud and CEL. As far as, in WAM scenario CEL and Talmud allocate equal amount. We can also categorise α-min and AP as appropriate rules for countries with lower claims.

	Claim	P	CEA	CEL	T	AP	α-min
Malta	25.72	24.13	25.72	0.00	12.86	23.38	25.72
Cyprus	81.89	76.84	81.89	0.00	40.95	74.45	78.36
Luxembourg	100.07	93.90	100.07	10.55	50.03	90.97	95.40
Latvia	110.81	103.97	110.81	21.29	55.41	100.74	105.46
Slovenia	170.33	159.82	170.33	80.81	85.17	154.85	161.24
Estonia	174.90	164.11	174.90	85.38	87.45	159.00	165.53
Lithuania	204.15	191.56	204.15	114.63	108.55	185.59	192.94
Croatia	234.44	219.98	234.44	144.92	138.84	213.13	221.33
Slovakia	418.59	392.77	418.59	329.07	322.99	380.54	393.91
Denmark	472.43	443.29	472.43	382.91	376.83	429.49	444.36
Sweden	476.14	446.77	476.14	386.62	380.54	432.86	447.84
Finland	477.85	448.37	477.85	388.33	382.25	434.42	449.44
Portugal	536.44	503.35	536.44	446.92	440.84	487.68	504.35
Bulgaria	625.26	586.69	625.26	535.74	529.66	568.43	587.59
Ireland	635.97	596.74	635.97	546.45	540.37	578.17	597.63
Hungary	639.00	599.58	639.00	549.48	543.40	580.92	600.47
Austria	763.10	716.03	763.10	673.58	667.50	693.74	716.77
Greece	831.96	780.64	831.96	742.44	736.36	756.34	781.30
Czech	1155.03	1083.78	1155.03	1065.51	1059.43	1050.05	1084.08
Belgium	1183.07	1110.09	1183.07	1093.55	1087.47	1075.54	1110.35
Romania	1210.33	1135.67	1210.33	1120.81	1114.73	1100.32	1135.90
Netherlands	1652.86	1550.90	1652.86	1563.34	1557.26	1502.63	1550.63
Spain	3173.99	2978.21	3173.99	3084.47	3078.39	2952.67	2976.18
UK	3868.13	3629.53	3868.13	3778.61	3772.53	3646.81	3626.71
Italy	3979.45	3733.98	3979.45	3889.93	3883.85	3758.13	3731.04
Poland	4065.19	3814.43	4065.19	3975.67	3969.59	3843.87	3811.39
France	4344.25	4076.28	4344.25	4254.73	4248.65	4122.93	4072.92
Germany	7864.16	7379.07	5429.15	7774.64	7768.56	7642.84	7371.67
Gini Index		0.60	0.58	0.64	0.64	0.61	0.60
CV		1.32	1.20	1.40	1.40	1.35	1.32

Table 3: Total GHG emission allocation 2021- 2030 (WEM)

	Claim	P	CEA	CEL	T	AP	α-min
Malta	25.72	25.48	25.72	13.45	13.45	24.61	25.72
Cyprus	80.93	80.19	80.93	68.66	68.66	77.43	80.41
Luxembourg	100.07	99.15	100.07	87.80	87.80	95.74	99.37
Latvia	109.33	108.33	109.33	97.06	97.06	104.60	108.55
Estonia	164.73	163.22	164.73	152.46	152.46	157.60	163.43
Slovenia	170.33	168.76	170.33	158.06	158.06	162.96	168.98
Lithuania	197.51	195.69	197.51	185.24	185.24	188.96	195.90
Croatia	215.75	213.77	215.75	203.48	203.48	206.41	213.97
Slovakia	377.02	373.56	377.02	364.75	364.75	362.15	373.73
Finland	446.61	442.51	446.61	434.34	434.34	431.74	442.67
Denmark	472.43	468.09	472.43	460.16	460.16	457.56	468.24
Sweden	476.14	471.76	476.14	463.87	463.87	461.27	471.92
Portugal	484.28	479.83	484.28	472.01	472.01	469.41	479.98
Ireland	583.81	578.45	583.81	571.54	571.54	568.94	578.58
Hungary	588.74	583.33	588.74	576.47	576.47	573.87	583.46
Bulgaria	625.26	619.51	625.26	612.99	612.99	610.39	619.64
Austria	763.10	756.09	763.10	750.83	750.83	748.23	756.19
Greece	804.18	796.79	804.18	791.91	791.91	789.31	796.89
Belgium	1060.99	1051.24	1060.99	1048.72	1048.72	1046.12	1051.29
Czech	1150.50	1139.93	1150.50	1138.23	1138.23	1135.63	1139.96
Romania	1184.64	1173.75	1184.64	1172.37	1172.37	1169.77	1173.78
Netherlands	1652.86	1637.67	1652.86	1640.59	1640.59	1637.99	1637.61
Spain	2667.22	2642.71	2667.22	2654.95	2654.95	2652.35	2642.47
Italy	3583.82	3550.89	3583.82	3571.55	3571.55	3568.95	3550.48
France	3614.95	3581.73	3614.95	3602.68	3602.68	3600.08	3581.32
UK	3853.77	3818.36	3853.77	3841.50	3841.50	3838.90	3817.90
Poland	4065.19	4027.83	4065.19	4052.92	4052.92	4050.32	4027.34
Germany	7864.16	7791.89	7520.62	7851.89	7851.89	7849.29	7790.71
Gini Index		0.60	0.60	0.61	0.61	0.61	0.60
CV		1.34	1.32	1.35	1.35	1.35	1.34

Table 4: Total GHG emission allocation 2021- 2030 (WAM)

Countries tend to maximise their emission budget by accepting the rules give more emission allocation and deny the rules which seems not fair for 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 tendency. In doing so, we analyze division rules from equity and stability point of views. For this purpose we consider two criteria: Gini index and Coefficient of Variance (CV).

Gini index Gini (1921) is a statistic dispersion indicator which evaluates the degree of inequality in a resource allocation. Its value is in the interval of 0 and 1 that 0 indicates the perfect equality and 1 represents the extreme inequality. We can define it as:

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

Coefficient of variation (CV) For analyzing the stability of results we consider the historic emission information of each country. The key point of accepting the result of division rule is that countries should be ensured about the fairness of results Lee (2009). If the allocation result be far from the historic emission experience of countries, they deny the result. For this purpose, we apply Coefficient of Variation Index to evaluate the weights of countries Wang et al. (2019). CV calculates the dispersion of allocation around the mean. Formally, we can define it as:

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

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 Abdi (2010) that $\sqrt{N-1}$ shows the complete instability.

Table 5 shows the values of Gini index and CV of different division rules for total allocation of GHG emission budget. As we can see CEA, P and α-min are more equitable and stable division rules as they have lower Gini index and CV compared with other division rules. Moreover, we saw that CEA and P are the division rules which can satisfy most of the minimal principles.

	P	CEA	CEL	T	AP	α-min
Gini Index	0.60	0.58	0.64	0.64	0.61	0.60
CV	1.32	1.20	1.40	1.40	1.35	1.32

Table 5: Gini Index and CV of total GHG emission allocation

4. Annual allocation

We propose to limit the scope of investigation from the whole period to each year. We aim to study the effects of probable differences this dynamic way can produce. To do that, we propose to allocate the annual emission budget to countries according to their annual projections.

4.1. Non-revised annual projections

As aforementioned, countries are obliged to report their annual national projections to MMR each two years. We use these annual projections as the countries annual claims. To calculate the annual endowment, we divide the total emission budget of 2021-2030 by 10. Table 6 depicts these measures in two scenarios.

Comparing the measures in the table shows that countries' projections exceed the emission budget in WEM scenario from 2021 to 2030. Therefore, we apply division rules to allocate the emission budget annually among countries. Table 7 indicates the sum of the annual allocation each rule assigns to countries during the 10 years. Results represent some significant differences in emission budget allocation compared with the total emission allocation (see tables 3 and 7). In annual allocation, by applying CEA countries with highest projections receive more emission allocation. In contrary, by applying CEL countries with lowest projections obtain more percentage of the emission budget. For instance, the emission allocation to Malta and Cyprus increase from 0.00 to a positive number. In annual allocation countries with larger projections (from Slovakia to Germany) loss a total fixed amount (4.18 Mt) by applying T. By applying AP, countries with lower projections receive more allocation.

Year	Emission Budget	Projections(WEM)	Projections(WAM)
2021	4025.08	4079.40	3994.27
2022	3953.74	4048.29	3935.03
2023	3882.40	4021.60	3880.42
2024	3811.06	3991.30	3820.67
2025	3739.72	3961.30	3762.22
2026	3668.38	3930.68	3702.12
2027	3597.04	3905.69	3652.52
2028	3525.70	3876.78	3599.81
2029	3454.36	3846.24	3545.73
2030	3383.02	3814.25	3491.27

Table 6: Annual emission budget and projections for 2021- 2030 (Source: European Environmental Agency and Eurostat Database, 2020)

	Claim	P	CEA	CEL	T	AP	α-min
Malta	25.72	24.09	25.72	0.54	12.82	23.45	25.71
Cyprus	81.89	76.76	81.89	15.48	43.53	74.72	78.31
Luxembourg	100.07	93.84	100.07	25.15	54.66	91.30	95.36
Latvia	110.81	104.01	110.81	33.45	62.15	101.20	105.58
Slovenia	170.33	159.85	170.33	79.45	102.77	155.54	161.30
Estonia	174.90	164.48	174.90	85.48	108.49	159.95	165.95
Lithuania	204.15	191.44	204.15	112.76	127.25	186.30	192.85
Croatia	234.44	219.79	234.44	143.04	150.99	213.89	221.16
Slovakia	418.59	392.59	418.59	327.21	318.82	382.04	393.74
Denmark	472.43	442.12	472.43	381.04	372.65	430.44	443.17
Sweden	476.14	446.77	476.14	384.76	376.37	434.71	447.89
Finland	477.85	448.76	477.85	386.46	378.07	436.54	449.88
Portugal	536.44	505.02	536.44	445.05	436.66	491.29	506.05
Bulgaria	625.26	587.36	625.26	533.86	525.47	572.06	588.29
Ireland	635.97	596.06	635.97	544.58	536.19	580.46	596.95
Hungary	639.00	599.29	639.00	547.60	539.21	583.61	600.18
Austria	763.10	715.96	763.10	671.70	663.31	697.75	716.71
Greece	831.96	780.89	831.96	740.57	732.18	761.33	781.56
Czech	1155.03	1084.40	1155.03	1063.64	1055.25	1059.78	1084.72
Belgium	1183.07	1108.39	1183.07	1091.68	1083.29	1082.84	1108.62
Romania	1210.33	1133.99	1210.33	1118.93	1110.54	1108.13	1134.20
Netherlands	1652.86	1551.00	1652.86	1561.47	1553.09	1520.66	1550.72
Spain	3173.99	2977.83	3173.99	3082.59	3074.20	2960.35	2975.74
UK	3868.13	3629.31	3868.13	3776.74	3768.35	3634.71	3626.41
Italy	3979.45	3734.51	3973.31	3888.06	3879.67	3744.31	3731.48
Poland	4065.19	3810.78	4016.93	3973.82	3965.43	3826.17	3807.61
France	4344.25	4077.33	4270.50	4252.85	4244.46	4104.39	4073.93
Germany	7864.16	7383.96	5557.30	7772.76	7764.38	7622.50	7376.52

Table 7: Annual GHG emission allocation 2021-2030 (WEM)

We analyse the equity and stability of division rules in annual allocation. Table 8 shows the average amount of Gini and CV for 10 years. The result shows: $CEA<P, \alpha-min<AP<CEL, T$

	P	CEA	CEL	T	AP	α-min
Gini Index	0.60	0.58	0.64	0.63	0.61	0.60
CV	1.32	1.21	1.40	1.40	1.35	1.32

Table 8: Gini Index and CV of annual GHG emission allocation

4.2. Revised annual projections

We also consider the part of countries projections which are not satisfied by emission budget to offer another probable way of annual emission allocation. We propose to add the unsatisfied amount of projection in year $n-1$ to the annual projection of year n and divide the emission budget of year n according to this cumulative projections. For instance, in the case of Malta we allocate the annual emission budget of 2021 by applying the Proportional rule in WEM scenario. The allocation is 2.45 (see table 7) and 0.03 remains unsatisfied. We add 0.03 to the projection of Malta in 2022 (2.51+0.03=2.54). We allocate the annual emission budget of 2022 to this new measure. Table 9 indicates the sum of this type of allocation for each division rule for the period of 2021 to 2030. This table depicts some differences in allocation compared with the total emission allocation. For instance, CEA reduces emission allocation of countries with largest projections where as AP gives more emission allocation to these countries. This method of annual allocation also affects the outcome of T. T allocates more emission allocation to countries with lower projections and countries with larger projections significantly receive smaller amounts. In addition, by comparing the result of two methods of annual allocation we can see that T allocates more emission allocation to countries with lower projections and less emission allocation to countries with larger projections when we use cumulative projection method. Table 10 indicates the average measures of Gini and CV in this method. The result shows: $CEA{<}P, AP, \alpha - min{<}T{<}CEL$

	Claim	P	CEA	CEL	T	AP	α-min
Malta	25.72	24.04	25.72	0.54	23.05	24.03	25.72
Cyprus	81.89	76.66	81.89	15.48	73.69	76.66	78.27
Luxembourg	100.07	93.67	100.07	25.15	90.07	93.67	95.25
Latvia	110.81	104.14	110.81	33.46	100.38	104.14	105.73
Slovenia	170.33	159.94	170.33	79.45	154.07	159.94	161.45
Estonia	174.90	165.28	174.90	85.46	159.76	165.27	166.80
Lithuania	204.15	191.19	204.15	112.76	183.76	191.19	192.65
Croatia	234.44	219.47	234.43	143.05	210.99	219.47	220.89
Slovakia	418.59	392.24	418.59	327.20	377.52	392.24	393.44
Denmark	472.43	439.96	472.43	381.04	421.70	439.96	441.05
Sweden	476.14	446.72	476.14	384.75	430.66	446.71	447.85
Finland	477.85	449.43	477.85	386.46	433.87	449.43	450.59
Portugal	536.44	508.61	536.44	445.05	493.39	508.61	509.76
Bulgaria	625.26	587.96	625.25	533.87	569.24	587.96	588.94
Ireland	635.97	595.05	635.97	544.58	571.92	595.05	595.97
Hungary	639.00	599.04	638.99	547.61	577.00	599.04	599.97
Austria	763.10	715.90	763.09	671.71	690.87	715.89	716.68
Greece	831.96	780.98	831.96	740.57	755.13	780.98	781.70
Czech	1155.03	1084.89	1155.03	1063.64	1052.24	1084.89	1085.23
Belgium	1183.07	1105.12	1183.07	1091.68	1066.67	1105.11	1105.30
Romania	1210.33	1130.43	1210.32	1118.94	1091.96	1130.42	1130.58
Netherlands	1652.86	1551.85	1652.87	1561.47	1508.71	1551.85	1551.57
Spain	3173.99	2976.14	3173.98	3082.60	2957.88	2976.13	2973.96
UK	3868.13	3628.26	3868.13	3776.74	3655.28	3628.26	3625.25
Italy	3979.45	3734.84	3973.31	3888.06	3764.27	3734.83	3731.72
Poland	4065.19	3804.68	4016.93	3973.80	3844.14	3804.67	3801.27
France	4344.25	4078.34	4270.50	4252.86	4130.32	4078.32	4074.80
Germany	7864.16	7395.67	5557.30	7772.77	7651.81	7395.74	7388.09

Table 9: Cumulative GHG emission allocation 2021-2030 (WEM)

	P	CEA	CEL	T	AP	α-min
Gini Index	0.60	0.58	0.64	0.61	0.60	0.60
CV	1.32	1.21	1.40	1.35	1.32	1.32

Table 10: Gini Index and CV of cumulative annual GHG emission allocation

5. Conclusion

The paper addresses the conflict EU faces to achieve its 2030 GHG mitigation targets compatible with the Paris agreement. EU determines the GHG emission budget equal 37040.50 (Mt co2e) for 2021-2030. But this amount is lower than aggregate emission needs of members states in this period.

To solve this problem, we implement the claims problems approach as a method for distributing insufficient resource among parties with greater demands. We introduce several well-known division rules related to the claims problems literature to divide the emission budget of the period 2021-2030 among EU member states and United Kingdom. We define a set of minimal principles should be satisfied by division rules to select the most optimal allocation method. To diminish the effect of countries preferences on the fair allocation we use equity and stability criteria to examine rules fairness.

We allocate the emission budget in two ways: First, we apply division rules to allocate the total emission budget of 2021-2030 among countries. Second, to consider all unpredictable elements in the emission allocation, we propose to allocate the annual emission budget of each year from 2021 to 2030 among countries.

References

Abdi, H., 2010. Coefficient of variation. Encyclopedia of research design 1, 169–171.

Auman, R., Maschler, M., 1985. Game theoretic analysis of a bankruptcy problem from the talmud. Journal of Economic Theory 36, 195–213.

Aumann, R.J., Maschler, M., 1985. Game theoretic analysis of a bankruptcy problem from the Talmud. Journal of Economic Theory 36, 195–213. doi:10.1016/0022-0531(85)90102-4.

Curiel, I.J., Maschler, M., Tijs, S.H., 1987. Bankruptcy games. Zeitschrift für Operations Research 31, A143–A159.

Dagan, N., Volij, O., 1993. The bankruptcy problem: a cooperative bargaining approach. Mathematical Social Sciences 26, 287–297.

Duro, J.A., Giménez-Gómez, J.M., Vilella, C., 2020. The allocation of co2 emissions as a claims problem. Energy Economics , 104652.

EEA, 2019. Trends and projections in Europe 2013. 10. URL: eea.europa.eu.

Fyson, C.L., Baur, S., Gidden, M., Schleussner, C.F., 2020. Fair-share carbon dioxide removal increases major emitter responsibility. Nature Climate Change 10, 836–841.

Giménez-Gómez, J.M., Peris, J.E., et al., 2012. A proportional approach to bankruptcy problems with a guaranteed minimum .

Giménez-Gómez, J.M., Teixidó-Figueras, J., Vilella, C., 2016. The global carbon budget: a conflicting claims problem. Climatic change 136, 693–703.

Gini, C., 1921. Measurement of inequality of incomes. The economic journal 31, 124–126.

Höhne, N., Kuramochi, T., Warnecke, C., Röser, F., Fekete, H., Hagemann, M., Day, T., Tewari, R., Kurdziel, M., Sterl, S., et al., 2017. The paris agreement: resolving the inconsistency between global goals and national contributions. Climate Policy 17, 16–32.

Lee, S., 2009. Fairness, stability and optimality of adaptive multiagent systems: Interaction through resource sharing. IEEE transactions on automation science and engineering 7, 427–439.

Maimoindes, M., 1135,1204. Book of Judgements, (translated by Rabbi Elihahu Touger, 2000). Moznaim Publishing Corporation, New York; Jerusalem.

Moulin, H., 2000. Priority rules and other asymmetric rationing methods. Econometrica 68, 643–684.

Oberthür, S., Groen, L., 2017. The european union and the paris agreement: leader, mediator, or bystander? Wiley Interdisciplinary Reviews: Climate Change 8, e445.

O'Neill, B., 1982. A problem of rights arbitration from the Talmud. Mathematical Social Sciences 2, 345–371.

Pan, X., den Elzen, M., Höhne, N., Teng, F., Wang, L., 2017. Exploring fair and ambitious mitigation contributions under the paris agreement goals. Environmental Science & Policy 74, 49–56.

Parker, C.F., Karlsson, C., 2017. The european union as a global climate leader: confronting aspiration with evidence. International Environmental Agreements: Politics, Law and Economics 17, 445–461.

du Pont, Y.R., Jeffery, M.L., Gütschow, J., Rogelj, J., Christoff, P., Meinshausen, M., 2017. Equitable mitigation to achieve the paris agreement goals. Nature Climate Change 7, 38–43.

Pozo, C., Galán-Martín, Á., Reiner, D.M., Mac Dowell, N., Guillén-Gosálbez, G., 2020. Equity in allocating carbon dioxide removal quotas. Nature Climate Change , 1–7.

Raupach, M.R., Davis, S.J., Peters, G.P., Andrew, R.M., Canadell, J.G., Ciais, P., Friedlingstein, P., Jotzo, F., Van Vuuren, D.P., Le Quéré, C., 2014. Sharing a quota on cumulative carbon emissions. Nature Climate Change 4, 873–879. doi:10.1038/nclimate2384.

Rayner, T., Jordan, A., 2013. The european union: the polycentric climate policy leader? Wiley Interdisciplinary Reviews: Climate Change 4, 75–90.

Schleussner, C.F., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E.M., Knutti, R., Levermann, A., Frieler, K., Hare, W., 2016. Science and policy characteristics of the paris agreement temperature goal. Nature Climate Change 6, 827–835.

Wang, Q., Li, S., Li, R., 2019. Evaluating water resource sustainability in beijing, china: Combining psr model and matter-element extension method. Journal of Cleaner Production 206, 171–179.

	Claim	P	CEA	CEL	T	AP	α-min
Malta	25.72	1.59	25.72	0.00	12.86	2.34	25.72
Cyprus	81.89	5.05	81.89	0.00	40.95	7.44	28.21
Luxembourg	100.07	6.17	89.52	0.00	50.03	9.10	29.01
Latvia	110.81	6.84	89.52	0.00	55.41	10.07	29.49
Slovenia	170.33	10.51	89.52	0.00	85.17	15.48	32.12
Estonia	174.90	10.79	89.52	0.00	87.45	15.90	32.32
Lithuania	204.15	12.59	89.52	0.00	95.60	18.56	33.62
Croatia	234.44	14.46	89.52	0.00	95.60	21.31	34.96
Slovakia	418.59	25.82	89.52	0.00	95.60	38.05	43.10
Denmark	472.43	29.14	89.52	0.00	95.60	42.94	45.49
Sweden	476.14	29.37	89.52	0.00	95.60	43.28	45.65
Finland	477.85	29.48	89.52	0.00	95.60	43.43	45.73
Portugal	536.44	33.09	89.52	0.00	95.60	48.76	48.32
Bulgaria	625.26	38.57	89.52	0.00	95.60	56.83	52.25
Ireland	635.97	39.23	89.52	0.00	95.60	57.80	52.72
Hungary	639.00	39.42	89.52	0.00	95.60	58.08	52.86
Austria	763.10	47.07	89.52	0.00	95.60	69.36	58.35
Greece	831.96	51.32	89.52	0.00	95.60	75.62	61.39
Czech	1155.03	71.25	89.52	0.00	95.60	104.98	75.69
Belgium	1183.07	72.98	89.52	0.00	95.60	107.53	76.93
Romania	1210.33	74.66	89.52	0.00	95.60	110.01	78.14
Netherlands	1652.86	101.96	89.52	0.00	95.60	150.23	97.72
Spain	3173.99	195.79	89.52	0.00	95.60	221.32	165.03
UK	3868.13	238.60	89.52	0.00	95.60	221.32	195.74
Italy	3979.45	245.47	89.52	0.00	95.60	221.32	200.67
Poland	4065.19	250.76	89.52	0.00	95.60	221.32	204.46
France	4344.25	267.97	89.52	0.00	95.60	221.32	216.81
Germany	7864.16	485.10	89.52	2435.03	95.60	221.32	372.56
Gini Index		0.60	0.03	0.96	0.09	0.48	0.43
CV		1.32	0.14	5.29	0.24	0.91	0.95

Table 11: Allocation of loss (WEM)