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Allocating remaining carbon budgets and mitigation costs[1]

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Abstract

The concept of carbon budgets has become a key and effective tool in terms of communicating the existing environmental challenge and monitoring environmental policy, in the context of the Paris agreement. In this sense, the literature has addressed different mechanisms to distribute them by countries/groups according to reasonable distribution principles, among which fairness and efficiency play an essential role. Given the problem of agreeing on indicators by countries, the paper proposes the use of claims models as a basis for this distribution, which avoid using indicators and only have to agree on elements defining the distribution rules. In this sense and based on a reference of the available global Carbon Budget (Mercator) for 2018-2050, and the CO2 forecasts taken from the intermediate scenario SSP2-45 (Middle of the road) considered by the IPCC (2021), different distribution rules are addressed proposed by the literature (equality, proportional, and α-min) and are evaluated for the available groups of countries. Two relevant exercises are proposed beyond the initial distribution based on

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the previous theoretical rules: first, evaluate the cost of these distributions in terms of the welfare of each group (in particular, in terms of GDP); and two, use the GDP costs themselves to propose new distribution rules that are cost-efficient. The results imply having not only a global cost-efficient distribution proposal but also an annual path. We understand that the work is useful not only in terms of its methodological proposal but also as an alternative guide that structures future distribution policies.

Keywords: allocation methods; claims; carbon budgets; climate change mitigation; equity
JEL classification: D7; H4; H8; Q58; Q54

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1. Introduction

The main challenge of the Paris agreement has been to limit global warming in such a way that the average temperature does not exceed 2 degrees and, with a central reference of 1.5, establishing a medium-term goal in 2030 and a long-term goal in 2050 (UNFCCC, 2020). However, and despite the enormous challenge that humanity faces, emissions have continued to grow until 2019 (Friedlingstein et al., 2020; Lamb et al., 2021), reaching a concentration of 410 parts per million. Given this scenario, emissions should be reduced faster than expected in the future and the window of opportunity would be closing (Höhne et al., 2020).

Carbon Budgets play a prominent role with said climate objectives, from the Fifth Assessment Report of the Intergovernmental Panel on Climate Changes (IPCC, 2013). Specifically, the remaining carbon budgets, which are defined as the amount of emissions that would remain until the climatic objectives are exceeded (temperature rise in relation to pre-industrial levels), have become a key concept for the communication of the global problem and as an axis for global and national policies (Matthews et al., 2020). The associated carbon budgets, of which there are several alternatives (logical given the existing uncertainties), are based on the linear relationship established in the literature between accumulated emissions and temperature increase (Meinshausen et al., 2009). In any case, carbon budgets are subject to significant uncertainties associated with the proper functioning of the geophysical system, socio-economic uncertainties and methodological choices (Jensen and Rasmussen, 2000; Matthews et al., 2020; IPCC, 2021; Goulder et al., 2022)

A natural application of the concept has to do with its territorial distribution. In fact, some countries like the UK and the US have adopted national carbon budgets. The literature has addressed a wide range of methods for distributing these budget carbons and assigning emissions, which vary depending on the indicators or the weight of the dimensions and principles included. For example, Zhou and Wang (2016) review possible methods, ranging from the use of indicators (GDP, population or both), optimisation methods, hybrid or associated with game theory. In relation to the properties required of the methods, the literature speaks of the concepts of responsibility, equality and capacity (Pozo et al., 2020; Matthews et al., 2020). In fact, discussions of equity, for example, have been central to the negotiations from the beginning (UNFCCC, 1992). In any case, obviously the choice of indicators is exposed to the strategic attitude of the parties in terms of the results they obtain and, therefore, the difficulties in reaching agreements. Another acceptable method is "simply" for the countries to agree on some technical properties that the distribution rules must have, accepting the final result that emerges, whatever it may be. This, precisely, is the procedure followed in Giménez-Gómez et al (2016) and in Duro et al. (2020), works in which the use of claim models is proposed to analyze the allocation of emissions . This "neutral" distribution is a reasonable alternative to the use of traditional methods, among which the proportional method has been important, for example (Raupach et al., 2014; Gignac and Matthews, 2015).

On the other hand, the United Nations Framework Convention on Climate Change establishes that measures regarding climate change must reduce the costs associated with their implementation as much as possible. Thus, the IPCC reports (IPCC, 2017) have indicated that macroeconomic costs must be taken into account. In this sense, therefore, it would be convenient to examine CO2 distributions that are cost-efficient and, therefore, that minimise the associated costs.

In this paper, the distribution models based on claims (Giménez-Gómez et al., 2016; Duro et al., 2020) are going to be taken up, which have substantive procedural advantages, but with two novelties that we believe are significant. In the first place, the costs of these distributions are going to be calculated based on the welfare lost (at the same time that the calculations are updated), in this case, approximated by the reduction derived from GDP, and therefore, an approximation to the social cost of the distribution; secondly, given these losses, distributions are re-allocated in such a way as to reduce GDP losses, with which the method would be cost-efficient. These exercises will be implemented for the case of five groups of countries in the period 2018-2050.

At a methodological and data level, the paper, firstly, uses the Mercator estimate for the 2018-2050 period as budget carbon. Second, we need to have future claims for territories. In this case, we use the emission forecasts of the SSP2-45 scenario, Middle of the road (Riahi et al., 2017), which includes moderate mitigation and adaptation measures, and which has considered the latest IPCC report as a basis (IPCC, 2021). In this sense, as auxiliary information for the report, multiple scenarios are considered, whose emissions depend on socio-economic assumptions and mitigation policies. We have considered an intermediate scenario as a reference for our calculations. In any case, and as has been seen, for example, using scenarios with high mitigation efforts may be less realistic given recent experience. Thirdly, and in terms of basic distribution rules, the paper focuses on three types: the constrained egalitarian, the proportional and the α-min solution (Duro et al. (2020)). In this sense, we take a rule very focused on equality, the proportional one (the most popular) and a mixed formula such as the α-min solution, which combines guaranteed minimum allocations and proportionality. Fourth, we need to know the costs of the allocation rules in terms of GDP. For this, the relationship between CO2, GDP, population and trend has been estimated, following the IPAT and Kaya approach (Ehrlich and Holdren, 1971; Dietz et al., 2015), for each of the groups in the period 2000-2017.

The paper is organised as follows. Section 2 reviews the literature on allocation mechanisms. Section 3 synthesises the methodological issues and proposes different solutions to the allocation model taking into account the costs. Section 4 includes the main results applied to five groups of countries for 2018-2050. Section 5 discusses the results and the main implications.

2. Allocating emissions and claims models

The current carbon budgets are not enough to satisfy the emission demands of all countries, provoking the typical economic problem about scarcity. Within this situation, the way to allocate the available resources must be proposed by meeting certain principles, which might be also generally acceptable. Synthesising, two principles stand out in the literature as the basic criteria that any allocation must meet: be efficient and equitable (UNFCC, 2009).

As Zhou and Wang (2016) depict, the academic community has proposed different approaches to allocate CO2 emissions, being the use of an indicator the most commonly implemented methodology. It consists on either a single criterion, or an aggregation of criteria (such as, population, GDP, emissions or a mix), that determine the way to distribute the emission permits or the reduction goals among the participating entities (see, for instance, Jensen and Rasmussen, 2000; Miketa and Schrattenholzer, 2006). On the other hand, optimisation methods have also been applied for CO2 emissions allocation, both linear and nonlinear programming models. The main goal of this approach is the efficiency, i.e., find out the optimal emissions paths according to the economic attractiveness (see, Cantore and Padilla, 2010; Heitzig and Kornek, 2018; Traut et al., 2018; Pozo et al., 2020; Goulder et al., 2022, among others). Additionally, a combination of different methodologies have been applied, so called hybrid methods, which can yield clearly different results depending on the solution applied (see, for instance, Akhundjanov et al., 2017; Wang and Zhou, 2017; and, He et al., 2018). It is noteworthy that the agreement about the quantity of CO2 emissions and their distribution requires negotiation among the participating entities.

It is noteworthy that these different approaches gathers an important shortcoming, since the CO2 emission recommended allocations depend on the factors which are taking into account: historical GDP, GDP forecast, GDP per capita, accumulative CO2 emissions, CO2 emissions needs, population, etc. Then, the implementation of game theoretic models appears in a natural way. In this situations, the allocation of CO2 emissions comes from the equilibrium solution to the game (e.g., Ren et al., 2015). Within this context, Giménez-Gómez et al. (2016) and Duro et al. (2020) implement conflicting claims problems (O'Neill, 1982) to analyse the distribution of a maximum emission limit, on the basis of an appealing set of principles that gathers fairness (Höhne et al., 2006), legitimacy and equality (Young, 2011; Kampas, 2015). In doing so, the recommended CO2 allocations do not depend on the considered factors, but on the set of accepted principles that define the range of allowed assignments. Following this vein, Ju et al. (2021) propose and characterise the so-called equal per capita allocation rules, by means of population, emission history and usual emissions criteria; and, Heo and Lee (2022), motivated by the administrator of the Paris agreement, under which the participants hold regular meetings and track their progress, extend Giménez-Gómez et al. (2016) and Duro et al. (2020) results to a dynamic claims problem by analysing CO2 emission allocations over time.[2]

Nonetheless, the optimal distribution rules proposed by all the aforementioned models do not take into account the impacts of mitigation efforts

[2] Note that the approach implemented by Giménez-Gómez et al. (2016) and Duro et al. (2020) is also used in other resource problems. For instance, Rozakis and Kampas (2022) use the minimum rights and nondiscrimination principle to propose a procedure to define a fair and reasonable share of fishing rights for the new members in fisheries governances.

(the reduction of emissions) on welfare associated with the final distribution of CO2 emissions. A factor that becomes even more important nowadays, since the European Union, among other regions, has decidedly committed to reducing CO2 emissions. Specifically, the objective in 2050 is to reach a zero CO2 footprint. Obviously, an emission reduction target and pattern has a direct impact on economic activity, both from the point of view of end users and from the point of view of the business fabric. One way to add both points of view is to analyse the social welfare or the wealth of the country in an aggregate way.

This is the main contribution of the current work. The present paper intends to address various allocation and distribution models, applicable to the analysis of CO2 emission permits or quotas. On the one hand, the current paper, apart from including an update of the distributions based on the new data available on carbon budgets and emissions forecasts, seeks to estimate the economic effects of a redistribution of total CO2 emissions among the different world agents under these claims problems, adding common social welfare functions (Finus and Pintassilgo, 2013). On the other hand, and in addition to its possible analytical interest, using this extension of the claims problem approach not only eliminates most of negotiation discrepancies, but also avoids the necessity to agree on a distribution criteria prior to the process of negotiation. In this way, we prevent the possibility that parties use the negotiation process strategically. The proposed method is neutral and focuses on the principles of distribution, and considers, at the same time, the effort exerted by the different regions by means of its impact on social welfare.

3. Methodology

Once the relation between CO2 emissions and GDP trends has been estimated, we analyze how the proportional and the egalitarian principles can be implemented by means of claims problems, and then, how the proposed allocations impact the growth of each region.

We consider two approaches for the allocation of CO2 emissions and their impact on the GDP of the regions. The first approach consists of a two-step process. First, CO2 emissions are allocated to the regions according to their demands and the global emission restriction and, in a second step, how these allocations impact the GDP of each region is analyzed, taking into account the estimated relationship between CO2 emissions and GDP. The second approach consists of a single step, and the allocation of emissions is carried

Regions	α_i	β_i	γ_i	Adjusted R^2 of the model	P-value of the model
R5REF	-38.5295	1.3529	$8.87 \cdot 10^{-6}$	0.9664	$1.8986 \cdot 10^{-11}$
R5LAM	-1.3683	1.2293	$2.29 \cdot 10^{-7}$	0.9943	$7.9412 \cdot 10^{-17}$
R5MAF	-4.0545	0.9661	$1.19 \cdot 10^{-6}$	0.9929	$3.7215 \cdot 10^{-16}$
R5OECD	-16.1542	0.7446	$4.92 \cdot 10^{-6}$	0.9821	$2.3034 \cdot 10^{-13}$
R5ASIA	-52.8250	0.2698	$1.48 \cdot 10^{-5}$	0.9985	$5.4470 \cdot 10^{-21}$

Table 1: Parameters of the statistical model with quadratic trend for each region.

out taking into account the impact that they will have on the GDP of each of the regions. We call this approach the cost-efficient allocation procedure.

To do that we first need to know how the GDP depends on the CO2 emissions and the trend. In particular, we have statistically shown that

$$\ln(GDP_{it}(CO2_{it})) = \alpha_i + \beta_i \ln(CO2_{it}) + \gamma_i t^2, i \in R, t \in T \qquad (1)$$

where R is the set of regions and T is the period of time to be considered. Table 1 shows the estimated parameters of the model with quadratic trend for each of the regions considered in this paper. Likewise, Table 1 shows some statistical measures of the goodness of fit of the models [3].

3.1. Referral allocation rules and costs

As aforementioned, when a claims problem applies to any situation where a scarce resource should be distributed among different entities. Formally, consider a set of agents $N = \{1, 2, ..., n\}$ and an amount $E \in \mathbb{R}_+$ of an infinite divisible resource, the **endowment** or budget, 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. A **claims problem** (O'Neill, 1982) is a pair (E, c) with $C = \sum_{i=1}^{n} c_i > E$.

To define the endowments, there are enormous uncertainty about data and about precise calculations Nevertheless, for instance, the three levels established by Meinshausen et al. (2009) have been widely used by the literature (Rogelj et al., 2016b; Rogelj et al., 2016a; Giménez-Gómez et al.,

[3]Other statistical models have been adjusted but the results obtained in the analysis are very similar to those presented in this work.

2016; and, Duro et al., 2020). In our case, we have decided to use the last MCC estimate (Mercator Research Institute on Global Commons and Climate Change) given its reasonable and updated numbers nowadays. Thus, and given its last Carbon Clock we would have a carbon budget of $1,170$ Gt for staying below the 2°C threshold (estimated since 2018). This budget will be highly consistent in the bulk of the climate scenarios used in IPCC (2021) and is in line with currently recommended intervals proposed by the literature (see Table 2).[4]

Endowment (E): 1,170 Gt CO_2 (XX%)
Agents (regions): LAM, REF, MAF, OECD, ASIA
Claims (c): MGSSP245, (78,34; 82,26; 165,48; 359,34; 579,44)

Table 2: **Definition of the elements of the CO_2 emissions problem: Endowment, agents and claims**. The first row is the endowments for the intermediate scenario: $1,170Gt$ CO_2. The second row is the agents given by the five considered regions and the third row is the source from where we extract the data to obtain the claims in the considered scenario.

The formal analysis of claims problems provides a vast number of well-behaved solutions, which propose how to distribute the available resources among the different agents by satisfying the requirements of non-negativity and claim-boundedness. Formally,

A **solution** is a single-valued function $\varphi : \mathcal{B} \to \mathbb{R}^n_+$, such that $\varphi_i(E,c) \geqslant 0$, for all $i \in N$ (**non-negativity**), $\varphi_i(E,c) \leqslant c_i$, for all $i \in N$ (**claim-boundedness**), and $\sum_{i \in N} \varphi_i(E,c) = E$ (**efficiency**).

Among all the proposed solutions by the literature, we focus on the main ways of distributing the endowment: the proportional and the equity methods (Moulin, 2002,Thomson, 2019 and Giménez-Gómez and Peris, 2014). Accordingly, we use: the proportional, the constrained equal awards, and the $\alpha-$minimal solutions. Note that the proportional and the egalitarian solutions are the best-known and most-used solutions. Alternatively, the α-min solution emerges mostly as technically interesting. Indeed, following the Rawlsian Maximin approach (Rawls, 1971; Rawls, 1974) this solution combines the strength of the adoption of a principle of equity, materialized by minimal rights and proportionality. In addition, this solution could be more easily acceptable in practice given that the reductions in the allocations, based on the claims, of a region, are minor and, therefore, so are the

[4]https://www.mcc-berlin.net/en/research/co2-budget.html

possible impacts of this effort on economic parameters.

The **proportional (P)** solution simply recommends distributing the CO_2 emission budget proportionally to the regions' claims. Thus, 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 awards (CEA)** solution (Maimonides, 1135,1204) proposes an equal distribution of the CO_2 emissions, taking each region's claim as an upper threshold. Therefore, CEA does not consider the differences between countries in terms of lost emission rights. 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 $\sum\limits_{i \in N} \min\{c_i, \mu\} = E$.

The **α-minimal (α-min)** solution (Giménez-Gómez and Peris, 2014) recommends, if it is possible, an equal minimum amount (survival amount) given by the lowest region's claim. Then, when the lowest region's claim is fully satisfied for all the regions, the remaining CO_2 emission budget is distributed proportionally among the other claimants according to the revised claims. But, if the amount to divide is not enough to give the lowest region's amount to every region, the rule recommends to divide the CO_2 emission budget equally among all regions. Formally, for each $(E,c) \in \mathcal{B}$ and each $i \in N$, if $c_1 > E/n$ then $\alpha\text{-min}_i(E,c) = E/n$ and if $c_1 < E/n$ then $\alpha\text{-min}_i(E,c) = c_1 + P(E - nc_1, c - c_1)$.

3.2. Cost-efficient allocations

We modify the proportional rule (P), the constrained equal awards rule (CEA), and the α-minimal rule (α-min) in order to simultaneously consider both the demands and the impact on GDP when allocating CO2 emissions between regions. Of course the structure of these new rules depends on the relationship between the GDP and the CO2 emissions, although the methodology to do the modifications would be always the same in any case.

In order to allocate the CO2 budget among the different regions, we can take into account the impact on the GDPs instead of directly allocating the CO2 budget by considering exclusively the CO2 emission claims of the regions. This approach was proposed in Sánchez-Soriano (2016), following the ideas in Lucas-Estañ et al. (2012) and Carpente et al. (2013). To do that we use that the GDP depends on the CO2 emissions and the trend according to Eq. (1).

3.2.1. The proportional approach (PG)

If we assume that the impact of the CO2 budget allocation on the GDPs should be proportional along the time then the following should be held

$$\frac{GDP_{it}(CO2^a_{it})}{GDP_{it}(CO2^c_{it})} = k_t, i \in R, t \in T \tag{2}$$

where $GDP_{it}(CO2^a_{it})$ is the GDP when the CO2 emissions allocated to region i at year t is $CO2^a_{it}$, $GDP_{it}(CO2^c_{it})$ would be the GDP of region i at year t when region i emits its claim $CO2^c_{it}$, and $k_t \in [0, 1]$ is a constant for each $t \in T$.

Note that Eq.(2) is equivalent to

$$\ln(GDP_{it}(CO2^a_{it})) - \ln(GDP_{it}(CO2^c_{it})) = h_t, i \in R, t \in T \tag{3}$$

Therefore, if we take into account Eq.(1), then we have that Eq.(2) is equivalent to

$$\beta_i \ln(CO2^a_{it}) - \beta_i \ln(CO2^c_{it}) = h_t, i \in R, t \in T \tag{4}$$

On the other hand, we know that $CO2^a_{it} = f_{it}CO2^c_{it}$, i.e., the CO2 emissions allocated would be a fraction of the CO2 emissions claimed. As a result Eq.(4) can be written as follows

$$\ln f_{it}^{\beta_i} = \ln f_t, i \in R, t \in T \tag{5}$$

where $h_t = \ln f_t$, $t \in T$.

Moreover, the sum of all CO2 emissions allocated must be equal the corresponding CO2 budget, $CO2^b_t$, so the following condition must be held

$$\sum_{i \in R} f_{it}CO2^c_{it} = CO2^b_t, t \in T. \tag{6}$$

Now, taking into account Eq.(5), Eq.(6) can be written as follows

$$\sum_{i \in R} f_t^{\frac{1}{\beta_i}} CO2^c_{it} = CO2^b_t, t \in T. \tag{7}$$

Therefore, the problem of allocating the CO2 budget among the regions in such a way the impact on the GDPs is proportional reduces to solve Eq.(7).

3.2.2. The egalitarian approach (EG)

If we now assume that the impact of the CO2 budget allocation on the GDPs should be as egalitarian as possible along the time then the following should be held

$$GDP_{it}(CO2^a_{it}) = \min\{GDP_{it}(CO2^c_{it}), k_t\}, i \in R, t \in T \tag{8}$$

where $GDP_{it}(CO2^a_{it})$ is the GDP when the CO2 emissions allocated to region i at year t is $CO2^a_{it}$, $GDP_{it}(CO2^c_{it})$ would be the GDP of region i at year t when region i emits its claim $CO2^c_{it}$, and $k_t \in \mathbb{R}_+$ is a constant for each $t \in T$, so that the total allocated CO2 emissions meets the budget $CO2^b_t$ in the period.

How to do this when we manage the CO2 emissions but not directly the GDP? A possible answer is to resort to mathematical programming. In a first step we solve the following optimization problem:

$$\begin{array}{ll} \max & Y^1_t \\ s.a: & \sum_{i\in R} x^1_{it} \leqslant CO2^b_t \\ & \ln(GDP_{it}(x^1_{it})) = Y^1_t, i \in R \\ & 0 \leqslant x^1_{it} \leqslant CO2^c_{it}, i \in R \\ & Y^1_t \geqslant 0 \end{array} \tag{9}$$

If the CO2 budget is completely distributed, then we have finished and the CO2 allocation is given by the optimal solution to problem (9). Otherwise, the budget and the claims are reduced downwards and a new problem is solved:

$$\begin{array}{ll} \max & Y^2_t \\ s.a: & \sum_{i\in R} x^2_{it} \leqslant CO2^b_t - \sum_{i\in R} x^{1*}_{it} \\ & \ln(GDP_{it}(x^{1*}_{it} + x^2_{it})) = Y^{1*}_t + Y^2_t \delta_{CO2^c_{it} - x^{1*}_{it} > 0}, i \in R \\ & 0 \leqslant x^2_{it} \leqslant CO2^c_{it} - x^{1*}_{it}, i \in R \\ & Y^1_t \geqslant 0 \end{array} \tag{10}$$

where $\left(x^{1*}_{it}\right)_{i\in R}$ and Y^{1*}_t is the optimal solution of problem (9), and $\delta_{CO2^c_{it} - x^{1*}_{it} > 0}$ is 1 if $CO2^c_{it} - x^{1*}_{it} > 0$, and 0 otherwise.

Again, if the CO2 budget is completely distributed, then we have finished and the CO2 allocation is given by optimal solution to problem (10) plus the optimal solution of the previous problem. And so on and so forth.

Therefore, in each step the accumulated allocation is considered as a reference point from which to continue assigning CO2 emission permits (see Pulido et al., 2002, 2008).

Note that the procedure described above finishes in at most $|R|$ steps. This means that its computational complexity is not too high.

3.2.3. The egalitarian-proportional approach (EPG)

If we assume that a minimum GDPs should be guaranteed all regions, and the remaining CO2 budget should be allocated in such a way its impact was proportional along the time, then the allocation procedure shouid be done in two steps. In the first step the following problem should be solve in order to guaratee all regions a minimum GDP:

$$\begin{array}{ll} \max & Y_t^1 \\ s.a: & \sum_{i \in R} x_{it}^1 \leqslant CO2_t^b \\ & \ln(GDP_{it}(x_{it}^1)) = Y_t^1, i \in R \\ & 0 \leqslant x_{it}^1 \leqslant CO2_{it}^c, i \in R \\ & Y_t^1 \geqslant 0 \end{array} \tag{11}$$

In the second step, the remaining CO2 budget $CO2_t^b - \sum_{i \in R} x_{it}^{1*}$, where $\left(x_{it}^{1*}\right)_{i \in R}$ is the optimal solution of problem (11), could be allocated proportionally to the remaining claims $CO2_{it}^c - x_{it}^{1*}$ as in Section 3.2.1.

4. Main results

4.1. CO2 emissions and groups

The evolution of CO2 emissions has been especially increasing in the recent period. Thus, since 2000, for example, there have been no absolute reductions, except in the 2009 crisis. For example, and as Lamb et al. (2021), from 2010 to 2019 the average growth would have been 1.2%, with 2019 constituting its maximum value. The concentration of CO2 in the atmosphere, which is what determines temperature increases, would have gone from 277 parts per million in 1750 to 410 in 2019 (Dlugokencky and Tans, 2020), a value that clearly exceeds the planetary boundary (Rockstrom et al., 2009). Based on Figure 1, emissions from fuel combustion (International Energy Agency, 2021) would have gone from 23,200 million tonnes of CO2 in 2000 to 33,500 in 2018. By groups of countries, and being consistent with the subsequent analysis, the evolution is quite heterogeneous (Figure 2). The main emitters are the OECD countries and China, although in both cases with different evolution. Thus, while the OECD stabilizes and moderately reduces its global emissions, China approximately follows a logistic growth pattern, which seems to have slowed down since 2013. Of the rest of the groups considered, the growth of the rest of Asia stands out.

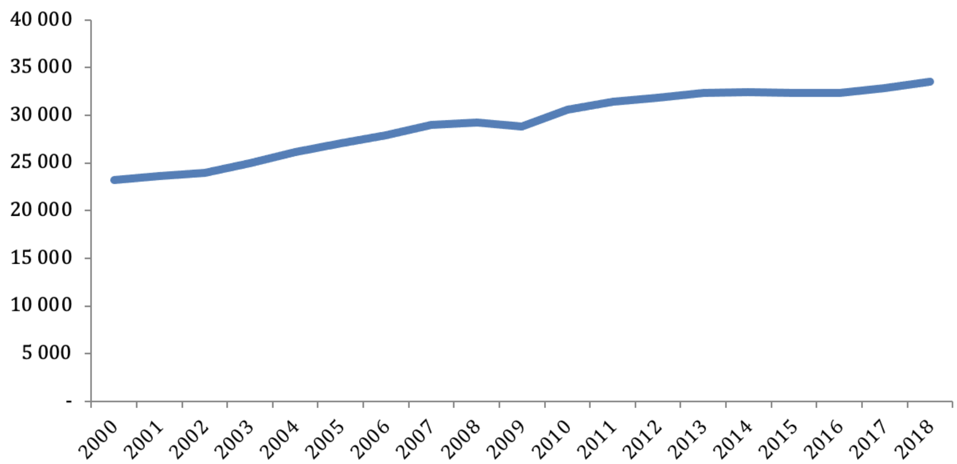

Figure 1: CO2 evolution (in million tonnes) worldwide. Source: own elaboration through IEA data (2021).

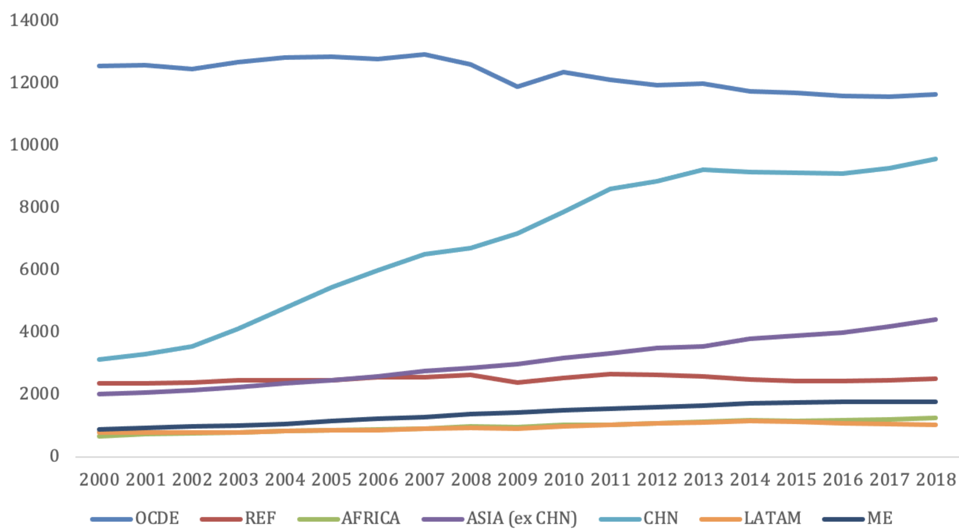

Figure 2: CO2 evolution (in million tonnes) by groups of countries. Source: own elaboration through IEA data (2021).

In any case, a relevant question that emerges in this regard is what are the drivers of this evolution. In particular, a widely used approach in the environmental literature consists of the IPAT approach (Ehrlich and Holdren, 1971; Dietz et al., 2015), which focuses on the role of affluence (GDP, or GDP per capita), population and technology. In fact, this approach also coincides with the well-known Kaya Identity, where the technological factor is proxied by energy intensities (Energy consumption over GDP) and carbon intensities (carbon emissions over energy consumption); International Energy Agency, 2021). In this sense, and at a descriptive level, a logarithmic decomposition of the evolution of CO2 in these four factors has been carried out as a previous context analysis: population, GDP per capita, energy intensity and carbonisation rate. The IEA performs this same decomposition (International Energy Agency, 2021), which can also be found in multiple academic articles (Duro and Padilla, 2006; Lamb et al., 2021). Figure 3 and 4 by groups, evaluate the role of the factors (which enter in a multiplicative way to determine the level of absolute CO2) for the period 2000-2018 and the sub-period since 2009 (just since the crisis) at a global level. If we take the global period, it is observed that the growth of emissions (which in logarithmic difference would have been 37%) is explained fundamentally by economic growth and, secondly, by population, with energy intensities acting as a partial compensator. In fact, the connection between CO2 and GDP is strongly established in the literature. (Stern, 2011, Lindenberger and Kümmel, 2011). If we go down to the various groups observed, growth always has a role, but its prevalence varies. In the Asian case, where emissions grow substantially (especially in China, by 111%), the role of GDP is crucial in explaining the increase in emissions. The population plays a relevant role in Africa and the Middle East. And, energy intensities have slowed down the rise of CO2 in a relevant way in the OECD, REF or Asia.

4.2. Allocating emissions and their costs

First of all, the Carbon Budget comes from the IPCC (2021 as of 2020 and has taken a reference of 1170 Gt since 2018 and not to exceed 2 degrees Celsius. Even though there are uncertainties about these calculations, it would seem the best reference so far. For the claims scenarios, the CO2 forecasts have been taken by groups of countries (the only ones available) contained in the SSP2-45 scenario of the MESSAGE-GLOBIOM model associated with the Shared Socioeconomic Pathways scenarios (Riahi et al., 2007; Fricko et al., 2017). This scenario is an intermediate scenario that is part of a moderate narrative where there are mitigation efforts but also projects past trends into the future, particularly in terms of energy and carbon intensities. These forecasts and their annual interpolation allows us to have an indication of the claims. Below Table 3 reproduces the results of the budget allocations by group for the three rules considered: the more equalizer, the proportional and the intermediate alternative.

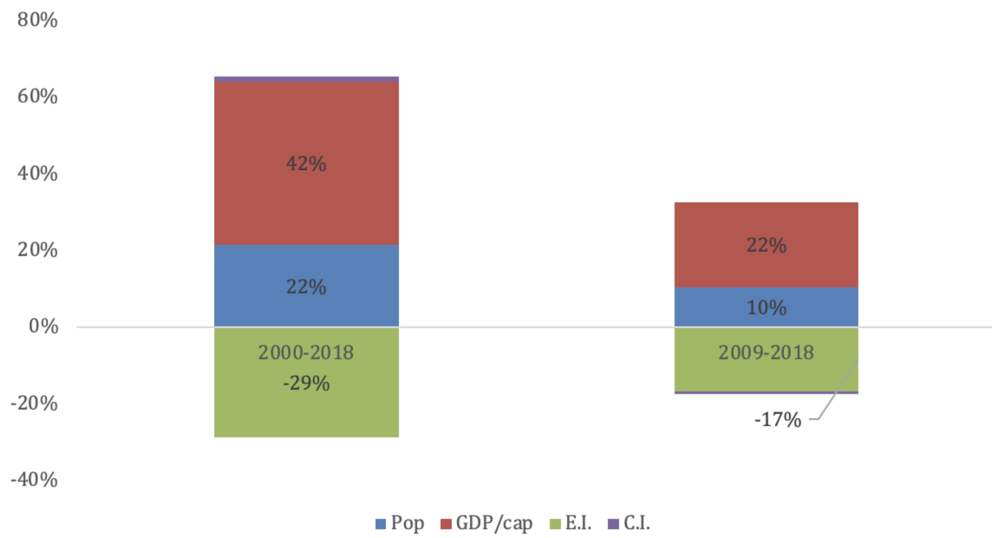

Figure 3: Kaya decomposition evolution CO2 emissions 2000-2018, worldwide values. Source: own elaboration through IEA data.

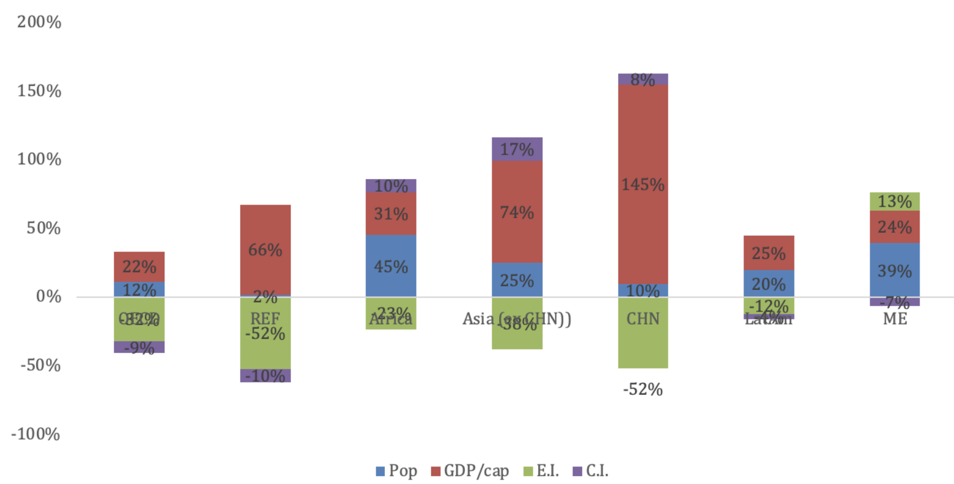

Figure 4: Kaya decomposition evolution CO2 emissions 2000-2018, groups' values. Source: own elaboration through IEA data.

In the first place, and as can it be seen, the egalitarian rule grants all the claims to the three groups that emit the least, that is, Latin America, Reforming and Middle-East and Africa, and submits the highest costs to the main emitters, that is, the OECD and China, which is globally reasonable.

MGSSP245 $E = 1,170$	Claim	Proportional	CEA	α-Min
R5REF	78.34	71.1	78.34	78.34
R5LAM	81.25	73.18	81.25	80.07
R5MAF	165.49	147.98	165.49	150.78
R5OECD	359.35	326.34	354.12	322,35
R5ASIA	579.45	525.54	464.94	512.58
Gini Index	0.75	0.41	0.38	0.39

Table 3: **Allocation solutions for the MGSSP245 scenario.** This table depicts three different allocation proposals depending on the CO_2 endowment (1,170 Gt). The regions, their claims and the proposed solutions are shown in the columns. The first five rows of each case indicate the emission allocations that each region receives according to the different solutions considered. Furthermore, the last row of each case shows the values of the Gini Index applied for all the possible solutions.

The most thorny issue has to do with the degree of adjustment of the OECD and Asia. In particular, the adjustment rests mainly on Asia and, therefore, China, which, in addition to the economic costs for this group that it would entail, may be unacceptable in historical terms (of accumulated liability) and per capita. Obviously the proportional distributes the burdens but it is the most unequal distribution, according to the Gini Index. In any case, obviously for Asia it would be a more acceptable distribution than the equal one. The intermediate option, which combines equality and proportionality, seems especially interesting not only at a methodological level but also in its final objection. As it is shown in Figure 5 where we have the allocations over claims for the α-min rule, it ensures for LAM and REF almost the total of the claims and distributes the adjustment in the rest (see Figures 5).

Now, by applying the analysis yearly using our quadratic model, Table 4 depicts the decreasing effects of the allocations on GDP. On the one hand, note that the proportional solution, since allocates the emissions in terms on the claim, affects more negatively to smaller claimants (LAM, REF and MAF). On the other hand, the CEA solution induces a larger reduction of GDP to larger claimants, i.e., OECD and Asia. Finally, the α-Min allocates a general guarantee to all the regions, so its impact on GDP is smoother, favoring regions with smaller claims. Note that, in this case, the GDP and CO2 ratio influences and, in particular, the ability of the groups to decouple and improve energy efficiency and emission intensity. That is why the costs per unit of CO2 removed are higher in groups such as LAM, REF and MAF. In this sense, the costs, if the GDP-CO2 ratio does not improve, are important. The proportional allocation originates a great cost in terms of absolute GDP reduction, smaller for the most emitters, which contradicts

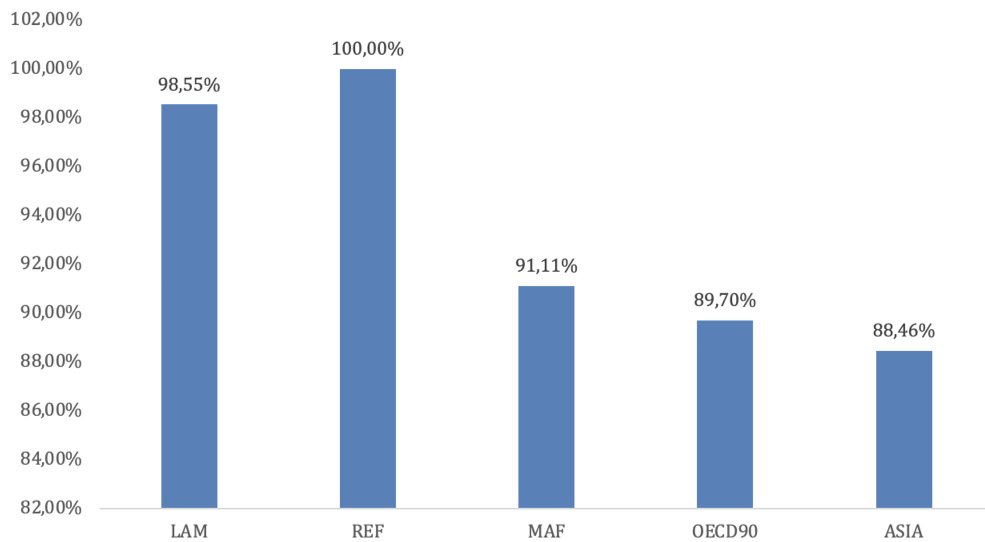

Figure 5: Allocation over claims, α-min rule.

the principle of equality enshrined by the UN in its different reports. The equality scenario, on the other hand, induces a large reduction in GDP that could be lessened if Asia decouples CO2 and GDP from intensities and renewables. The intermediate option adjusts above all the GDP of the OECD, and of the MAF, which does not seem highly recommended.

MGSSP245 $E = 1,170$	Claim	GDP claim	ΔGDP Proportional	ΔGDP CEA	ΔGDP α-Min
R5LAM	81.26	320,294.87	-16%	0%	0%
R5REF	78.34	203,450.86	-12%	0%	-2%
R5MAF	165.49	292,354.86	-11%	0%	-9%
R5OECD	359.35	229,0564.77	-8%	-1%	-9%
R5ASIA	579.45	198,0554.24	-4%	-9%	-5%

Table 4: **Effects of the allocation solutions for the MGSSP245 scenario.** This table depicts the effects on GDP of the three allocation rules proposed. The regions, their claims, the GDP depending on the emissions claimed and the effects on GDP induced by the proposed solutions are shown in the columns. The rows indicate emission allocations that each region receives according to the different solutions considered.

4.3. Allocating in cost-efficiency manner: Scenario with quadratic trend

In this section we are going to review the optimal allocations that arise when taking into account their impacts on the welfare of groups of countries, following the methodology explained in 3.2. In this sense, the scenario of maximum CO2 emissions between 2018 and 2050 of 1.170Gt is distributed in a decreasing way in the period and the scenario of demands for CO2 emissions MGSSP245 distributed throughout the period have been considered. Three possible scenarios are considered regarding the relationship between GDP and CO2 emissions: business-as-usual, with linear trends and with quadratic trends. The allocation of CO2 emissions between regions is done for each of the years separately, therefore, we have as many allocations as years under study.

Table 5 shows the results in the quadratic trend version. Figure 6 shows the resulting results by rules (proportional, equity and mix) on the initial claims. Note, for example, that the three rules give significant allocations to groups with lower emissions. In particular, and unsurprisingly, the equity rule (CEA, EG) gives LAM, REF, and MAF everything they would ask for. In any case, note that EPG (the α-min) also gives almost all the claims to these groups. In particular, the advantage of this rule, which combines a criterion of minimums guaranteed with proportionality, is that it would imply less relative costs than the equality rule on the two largest emitting groups (particularly, the OECD). Thus, the OECD group could achieve 94% of its claims with the previous rule, for 84% that of Asia, the main sacrificed. The popular proportional rule gives similar sacrifices to the OECD and Asia to the mixed EPG rule but, in this case, it is less egalitarian, since it does not cover the claims of the least emitting groups, with its logical effects on welfare (GDP).[5]

Figure 7 reproduces the results in terms of inequality of the different distributions, using the coefficient of variation as a reference measure of inequality. Note that, except for the allocations of the egalitarian rule (E), EPG would be the one that would give less inequalities between the groups, to which it would add its greater relative acceptability with respect to the equality rule by the emitting groups.

In any case, the aforementioned results are aggregated for the period. The methodology used, in fact, aggregates the results through annual al-

[5] In any case, these costs in terms of GDP are global costs throughout the entire period. With the data of the annual patterns, the losses would be concentrated in the groups in a different way as of 2028.

2018-2050

Regions	Claim	$GDP(CO2^c)$	P	$GDP(CO2^P)$	PG	$GDP(CO2^{PG})$
R5LAM	81.25	320294.87	73.18	281029.02	78.13	304899.12
R5REF	78.34	203450.85	71.10	171614.97	75.79	191894.92
R5MAF	165.49	292354.86	147.98	261513.51	156.92	277274.33
R5OECD	359.35	2290564.77	326.34	2104401.06	338.68	2174584.16
R5ASIA	579.45	1980554.24	525.54	1903421.34	494.61	1853267.79
Regions			E	$GDP(CO2^E)$	EG	$GDP(CO2^{EG})$
R5LAM			81.25	320294.87	81.25	320294.87
R5REF			78.34	203450.85	78.34	203450.85
R5MAF			165.49	292354.86	165.49	292354.86
R5OECD			354.12	2258001.61	327.99	2135949.37
R5ASIA			464.94	1802568.02	491.07	1818289.46
Regions			EP	$GDP(CO2^{EP})$	EPG	$GDP(CO2^{EPG})$
R5LAM			80.07	314443.81	80.53	316756.56
R5REF			78.34	203450.85	78.34	203450.85
R5MAF			150.78	266419.52	163.39	288688.07
R5OECD			322.35	2081324.27	337.02	2164801.22
R5ASIA			512.58	1883239.15	484.86	1835143.45

Table 5: Aggregate allocations of CO2 emissions in the period 2018-2050 in the scenario with quadratic trend by applying the proportional rule (P), the egalitarian rule (E) and the egalitarian-proportional rule (EP) taking only into account the claims; and the same rules but taking into account both the claims and the impact on the GDPs (PG, EG, EPG) in a year-by-year scheme.

	ΔGDP (PG)	ΔGDP(EG)	ΔGDP(EPG)
R5LAM	-4.81%	0.00%	-1.10%
R5REF	-5.68%	0.00%	0.00%
R5MAF	-5.16%	0.00%	-1.25%
R5OECD	-5.06%	-6.75%	-5.49%
R5ASIA	-6.43%	-8.19%	-7.34%

Table 6: **Aggregate growth decreases by rules in the cost-efficiency allocations.**

locations, thus providing detailed dynamic results. In this sense, the adjustments, based on our scenarios, would be concentrated as of 2028, with a similar pattern of decrease in allocations and impact on GDP for LAM,

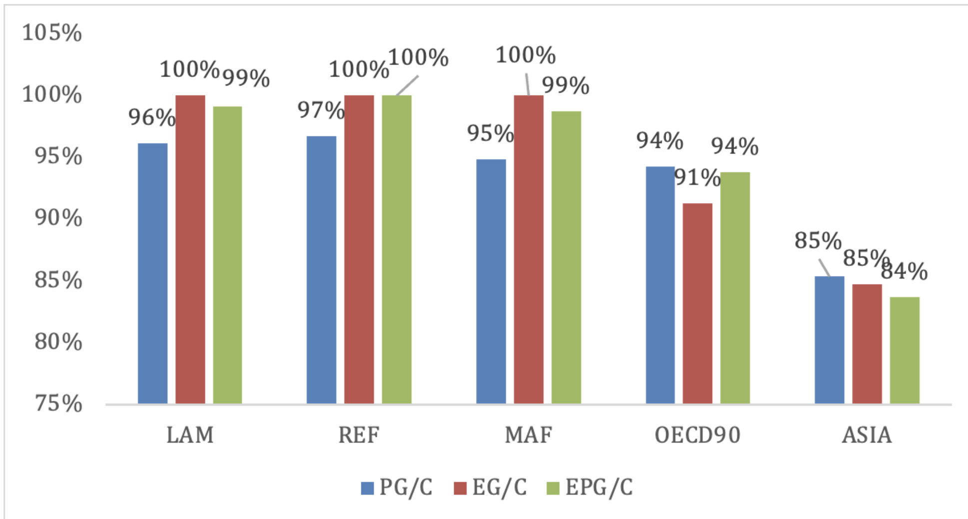

Figure 6: Allocating in a cost-efficient mechanism. Relative results over claims by rules.

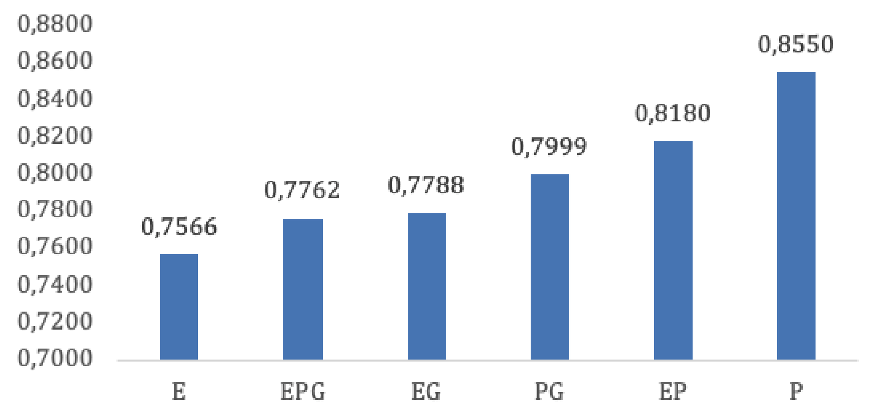

Figure 7: Inequality values for allocation cost-efficient and rules.

REF and MAF (decreasing with a different slope depending on the rule), as depicted by Table 6.

Finally, Figures 8 , 9, 10, 11 and 12 show the impact on the abatement of emissions of the different groups over time when the rules introduced in this work are applied and their corresponding effect on the annual GDP in the period 2018-2050 using the quadratic trend scenario. As can be seen in Figures 8-12, the different groups would have to start making efforts to reduce emissions and face their impact on their GDP as of 2028. The paths

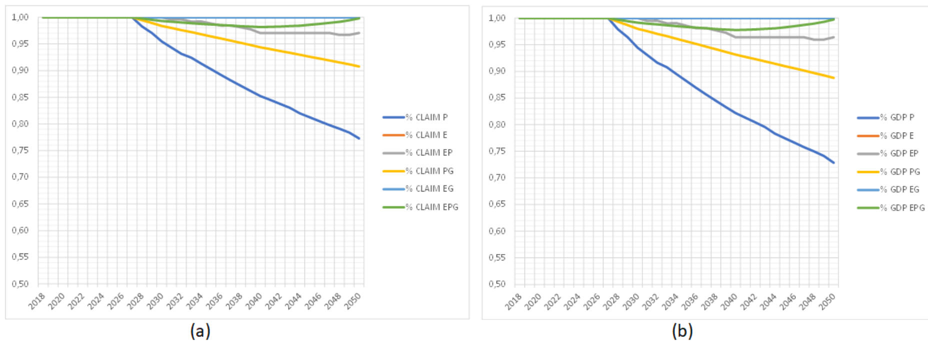

Figure 8: Allocations to LAM under the quadratic trend scenario year-by-year. (a) Percentage of CO2 emissions allocated with respect to the emissions claims for each of the six introduced rules. (b) Percentage of GDP obtained with respect to the GDP with the emissions claims for each of the six introduced rules.

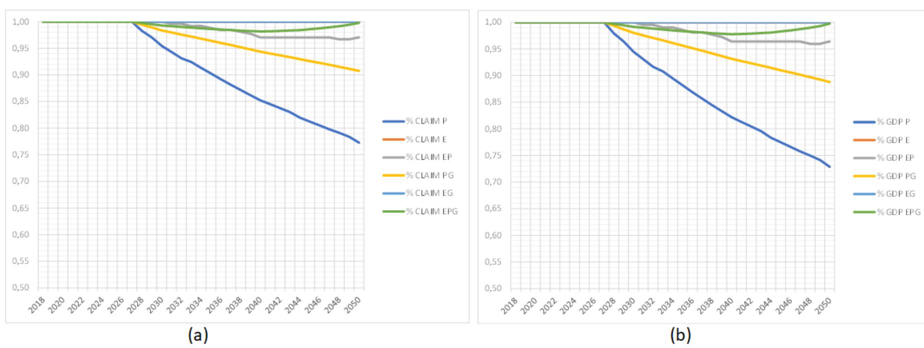

Figure 9: Allocations to REF under the quadratic trend scenario year-by-year. (a) Percentage of CO2 emissions allocated with respect to the emissions claims for each of the six introduced rules. (b) Percentage of GDP obtained with respect to the GDP with the emissions claims for each of the six introduced rules.

of emission reductions and their effect on GDP for each of the six rules considered are similar in the case of LAM and REF. The paths of emission reductions and their effect on GDP for each of the six rules considered for the MAF, OECD90 and ASIA regions are quite different from each other. Although, being the paths for the MAF region somewhat similar to those of the LAM and REF regions. In general, the allocations that simultaneously take into account emissions and their impact on GDP, i.e the cost-efficient approach, are the most favorable for the LAM, REF and MAF regions, while those that do not take them into account are the most favorable for the OECD90 and ASIA regions. Thus, allocating in a cost-efficiency manner

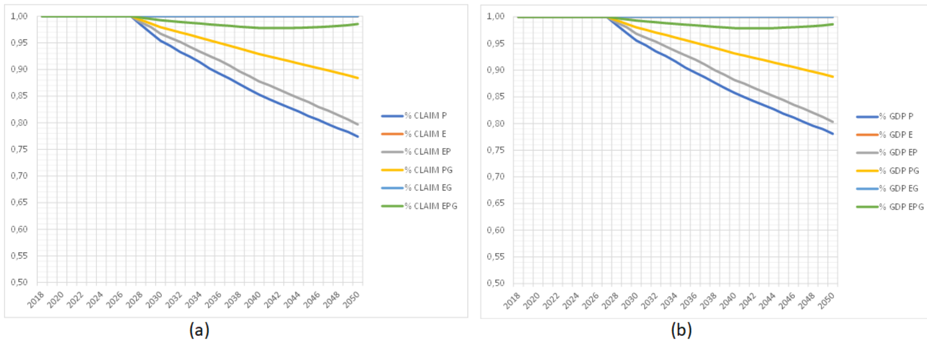

Figure 10: Allocations to MAF under the quadratic trend scenario year-by-year. (a) Percentage of CO2 emissions allocated with respect to the emissions claims for each of the six introduced rules. (b) Percentage of GDP obtained with respect to the GDP with the emissions claims for each of the six introduced rules.

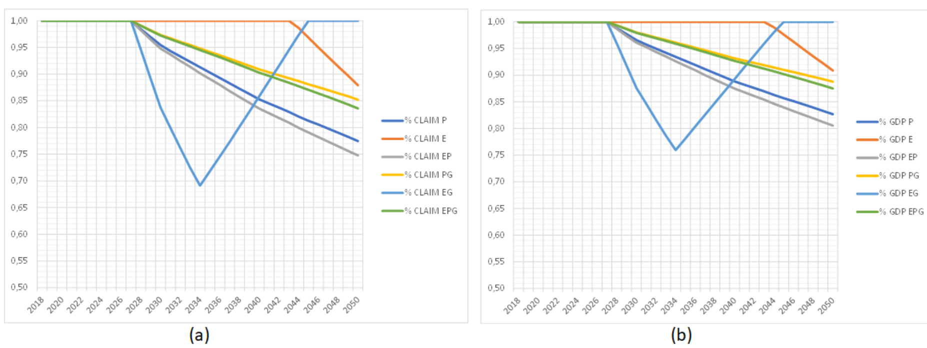

Figure 11: Allocations to OECD90 under the quadratic trend scenario year-by-year. (a) Percentage of CO2 emissions allocated with respect to the emissions claims for each of the six introduced rules. (b) Percentage of GDP obtained with respect to the GDP with the emissions claims for each of the six introduced rules.

keeps along the time the CO2 emissions and the GDP of the regions LAM, REF y MAF above the 90% regarding the situation without limitations while OECD90 and ASIA are more affected. In this sense, we believe that the cost-efficient approach responds quite adequately to the UN recommendations that efforts be shared fairly, taking into account the situation of the different regions.

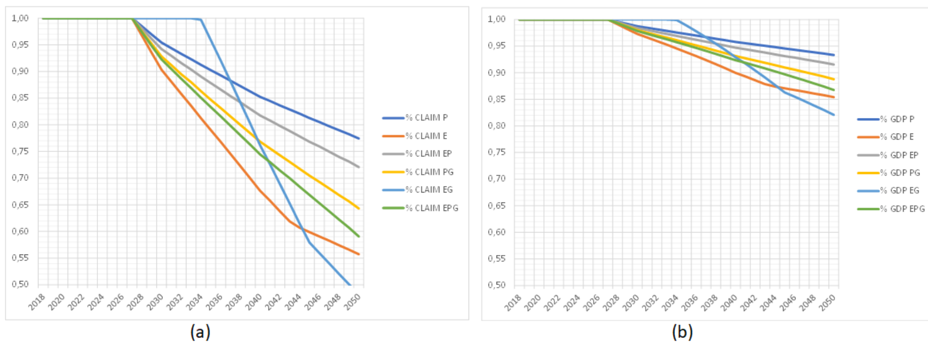

Figure 12: Allocations to ASIA under the quadratic trend scenario year-by-year. (a) Percentage of CO2 emissions allocated with respect to the emissions claims for each of the six introduced rules. (b) Percentage of GDP obtained with respect to the GDP with the emissions claims for each of the six introduced rules.

5. Conclusions and Further Research

Achieving climate change goals requires substantial efforts by countries to consistently adapt their behavior. In this context, there is a problem of sharing the associated sacrifices, given the CO2-well-being relationship. In this sense, an operational concept that has gained popularity as a reference indicator at the sustainability policy level of is that of carbon budgets, which approximate the maximum level of emissions consistent with the climate objectives of temperature reduction in a given period. Although there is a practical problem of determining them, we have varied reasonable estimates that indicate an order of magnitude for them worldwide. In this sense, we have taken as a reference the 1,170 Gt between 2018 and 2050, if we do not want to see an increase of more than 2 degrees Celsius over the average pre-industrial temperature.

It would now be a question of distributing this global budget in a reasonable and operational way. There are distribution methods for this purpose, from the simplest based on indicators to the most complex based on optimization. In this regard, the usefulness of claim models, little used in this field, has recently been considered. These models are based on using theoretical distribution rules that succeed in fulfilling a list of technical properties. If we decide to use this approach, we will need an estimate of the claims by country, or group, in the allocation period. In our case, the latest available estimates from the MESSAGE-GLOBIOM model associated with the SSP scenarios have been used, which only allow data for 5 groups of countries. This is an intermediate model that does not foresee substantive advances very different from the current ones in terms of energy efficiency and the incidence of renewables in the energy mix. Therefore, the particular calculations must be taken in a context where the world continues without making very striking progress (as it has been up to now). In particular, results will be provided for 3 theoretical distribution rules: the popular proportional, the CEA (egalitarian) and a hybrid between CEA and proportional (α-min).

In any case, the main methodological added value of the paper is not the above, but rather: one, estimating the costs associated with each distribution rule based on the lost GDP (for which CO2-GDP ratios are estimated); and second, to use precisely these costs to rethink the previous distribution so that it is cost-efficient, a crucial criterion in the analysis of sustainability policies.

The results and the analysis indicate, in summary, the benefits of the rules that combine equality with proportionality, as is the case of the α-min, and that can increase the probability of global acceptance. In particular, this rule would reduce the sacrifices in terms of GDP for the least emitting groups and would have a higher, although not excessive, annual cost for the OECD and Asia. In this sense, we understand that the use of analytical frameworks such as those proposed are transparent and neutral and can reduce the strategic behavior of the parties.

The work, obviously, can be extended from various paths. For example, the emissions scenarios may be different, assuming greater improvements in efficiency and the weights of renewable energies, which, in turn, increase the decoupling between CO2 and GDP and, consequently, mitigation costs. On the other hand, it would be especially convenient, in order to provide greater applicability to the proposed analysis, to be able to have more detailed homogeneous predictions on emissions territoriality, and not only at the level of groups of countries.

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