National Carbon Reduction Commitments: Identifying the Most Consensual Burden Sharing

WORKING PAPER

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Abstract:

How could the burden of GHG emissions reductions be shared among countries? We address this arguably basic question by purely statistical methods that do not rely on any normative judgment about the criteria according to which it should be answered. The sum of current Nationally Determined Contributions to reducing GHG emissions would result in an average temperature rise by 2100 of the order of 3°C to 3.2°C. Implementing policies that enable to achieve the objective of a worldwide average temperature rise below 2°C obviously requires setting a more consistent and efficient set of national emissions targets. While a scientific consensus has been reached about the global carbon budget that we are facing, given the 2°C target of the Paris Agreement, no such consensus prevails on how this budget is to be divided among countries. This paper proposes a Climate Liabilities Assessment Integrated Methodology (CLAIM) which allows for the determination of national GHG budgets compliant with any average temperature target and time horizon. Our methodology does not resort to any scenario- or any simulation-based model. Rather, it computes the allocation of 2°C-compatible national carbon budgets which have a priori the highest probability of emerging from international discussions, whatever being the criteria on which the latter might be based. As such, it provides a framework ensuring the highest probability of reaching a consensus. In particular, it avoids the pitfall of arbitrarily assigning weights according to, for example, to "capacity" or "responsibility" criteria, and simultaneously unifies the different methodologies that have been proposed in the literature aiming at setting national GHG budgets. Sensitivity tests confirm the robustness of our methodology.

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1. INTRODUCTION

Global change continues, despite COP21

Almost exactly one year after the Paris Agreement was opened for signature in April 2016 , the Scripps Institution of Oceanography recorded the first atmospheric CO_2 concentration above the threshold of 410 parts-per-million. Since the late 80s, when 350 ppm were attained, 10 new ppm have been added every 6-7 years, finally hitting the 400 ppm threshold in 2013. This latest increase of 10 ppm happened in only four years, and is a fateful milestone warning that the battle against climate change is far from being won, despite the 195 signatories (and the 150 ratifications) of the 21st Conference of the Parties[1]. In its 2016 Emissions Gap Report, the United Nations Environment Programme (UNEP) called for accelerated pre-2020 efforts, highlighting that current short-term actions were insufficient to achieve the objective of limiting temperature increase below 2°C by 2100. Worse still, the report states that, even if fully implemented, Nationally Determined Contributions would only keep global temperature below 3.0°C (3.2°C if partially implemented), a level far beyond scientific recommendations2. According to UNFCC (2016), aggregate global emission levels should amount to 55.0 (51.4 to 57.3) Gt CO2 eq in 2025 and 56.2 (52.0 to 59.3) Gt CO2 eq in 2030, if NDC are put into practice3. For its part, the World Resources Institute (2015) deduces from a survey of the literature a broader estimated range of 2.7 to 3.7°C of average warming at the end of the century. Such a climate upset would bring about considerable uncertainty. For instance, the extent of economic damages resulting from a 4°C increase is estimated to range from around -5% (Nordhaus, 2008) to as large as -50% of the world GDP (Dietz and Stern, 2015). In any case, this impact is likely to be very unequally distributed, and should largely penalize poor countries4, which would very likely exacerbate geopolitical tensions and widely propagate risk.

Despite the questionable consistency of the NDCs with regards to the 2°C target, the private sector already proposed sectorial transition strategies that claim to be in line with a 2°C scenario. While these initiatives have the virtue of engaging the private sector in the shift, they do not confront the global objective: to make sense, a sectoral budget should in the first place be aligned with a consistent national allocation.

NDCs remain insufficient

NDCs have been designed nationally according to several parameters, including political priorities, local capabilities and international pressures. While all signatories have finally submitted a NDC, these ‘horizontal’ efforts are uneven, sometimes inaccurate, and not constrained by a ‘vertical’ science-based global frame. As a consequence, the global objective may be not achieved, and global warming may still reach an unpredictable degree of aggravation. It is interesting to note that some authors, even before the achievement of the COP21, already pointed out that the trend was unsatisfactory (Stua 2015, Doyle and Wallace 2015).

A simplified relationship between emissions and temperature increase can be estimated from climate models, which allowed the IPPC to infer in its 5th report (2013) a global budget of 1,000

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[1] All the more so as it appears that the willingness of some significant countries to stick to their commitments remains uncertain.

[2] For a story of the « two degrees » recommendation, see Jaeger, C.C. & Jaeger, J. Reg Environ Change (2011) 11(Suppl 1): 15. doi:10.1007/s10113-010-0190-9

[3] Global emissions in 2013 amount to 48.3 Gt CO_2 eq, land-use change and forestry emissions included.

[4] Cf. the “Shock Waves” World bank report (2016).

Gt CO2 eq (starting from 2011 GHG emissions level) to limit the global average temperature rise at less than 2°C above pre-industrial levels, with a likely probability (higher than 0.66). This, obviously, assumes that future generations will confine themselves to the directive. In that matter, we are "in the universe of the gamble about future generations' behaviour" (Lecocq, 2000).

Many authors have tried to derive national budgets from this global carbon constraint. However, this derivation is politically controversial and mobilises ethical considerations (Neumayer 2000, Caney 2009, Raupach et al 2014, Agarwal and Narain 1991).

Gignac and Matthews (2015) noted that in general, allocation methods fall between two extreme cases: the 'grandfathering' perspective, which bases future emissions on current shares of emissions, and the egalitarian perspective, which considers equal rights to emit for everyone. The egalitarian approach implies therefore the necessity for developed countries to abruptly reduce their emissions. Similarly, Raupach et al. (2014) considers two generic metrics: the 'inertia' metrics, which reflects the emissions distribution (grandfathering), and the 'equity' metrics, which reflects the population distribution (egalitarianism). Within egalitarian/'equity' metrics, Neumayer (2000) distinguish an egalitarianism that considers historical emissions from a purely present egalitarianism.

Grandfathering is generally viewed as morally unacceptable, particularly in the developing world. Some authors, such as Agarwal and Narain (1991), consider that the injunction by developed countries to the developing world to "share the blame of heating up the earth" is the expression of "environmental colonialism". We can reasonably postulate that pure grandfathering today is no longer an option. Historical responsibility for climate degradation has been broadly accepted, something that is revealed through the emergence of the "common but differentiated responsibilities" principle, formalized during the 1992 Earth Summit and stressed on the first page of the Paris Agreement. Moreover, as highlighted by Neumayer (2000), historical accountability had already been "buttressed by the polluter-pays-principle which has been embraced by the OECD countries as long ago as 1974". In practice, integrating cumulated GHG emissions does pose certain issues, such as the choice of a starting date, or the time extension historical carbon emitters are authorized to use in order to compensate their debt without destabilizing their economy.

On the other hand, the purely egalitarian perspective, which focuses on the idea of equity, is often viewed as unrealistic, since historical emitters generally benefit from important political power. Because of this political power imbalance, it is arduous for historical low-emitters to make liability recognized. The multiple coalitions that form during the Conferences of the Parties (G77, LMDC, AOSIS…) illustrates in to some extent this power imbalance: the 'G77+China' coalition, for example, mainly consists of historical low-emitters and represents about 80% of the world population. These associations are attempts to rebalance their bargaining power during the negotiations.

The egalitarian perspective can also be considered inefficient, since many historical non-emitters and populous countries (such as African countries) do not have the largest technical and financial means to perform a rapid transition towards a low carbon economy. In an interconnected and globalized world, it could be considered that (i) penalizing big economies with important ramifications could negatively impact the whole world, including non-responsible countries, and that (ii) granting some extra emissions allowances to developed countries could accelerate the development of carbon-neutral technologies and benefit all countries.

In lieu of pure egalitarianism, it can also be considered that humans do not need an equal access to the GHG absorption space: additional criteria can be mobilised (such as climatic conditions, energy intensity, capability, etc.) and lead either to 'adjusted egalitarianism'

(Goeminne and Paredis 2010) or to even more pragmatic approaches such as the contraction and convergence method (Gignac and Matthews 2015) or the method developed by Raupach et al. (2014) based on a blended sharing principle between emissions distribution and population distribution.

In any event, these blended methods do give preference to some reaching a position on the choice between grandfathering and equity, or 'capacity and responsibility' as we will denote them. We define a 'capacity criteria' as an indicator that expresses the country's capacity to mitigate its emissions through a combination of economic development, governance efficiency, technological initiatives as well as willingness/voluntarism. On the other side, a 'responsibility criteria' is an indicator that expresses the responsibility the country bears for past emissions.

Although political positioning is inevitable (and, to some extent, necessary), this subjectivity in the choice of criteria represents a risk of rejection by the most penalized actors. There is a need for a more consensual budget allocation method, that would gather the maximum of actors, without compromising the Paris objective. CLAIM's ambition is to assign, thanks to a statistical exploration, a budget that respects in the best possible way a country's interest between 'capacity' and 'responsibility' criteria. It ensures adapted (and therefore acceptable) national budgets, while conforming to the global limit.

In the next sections, we will give a sequential description of the method, with a list of the criteria mobilised, a mapped presentation of the results, a robustness analysis and finally a discussion about limitations and potential improvements.

2. METHOD

1. – Overview

The methodology aims at estimating national budgets over the 2030-2100 period that fit a 2°C (or any other temperature increase) target. This timeframe is consistent with both NDC targets (2030), the horizon considered in both the IPCC reports (2100), the Paris agreement and international organizations such as the Deep Decarbonization Pathways Project[5]. This long-time perspective does not consider the ongoing transition period (2015-2029) but does focus on the post NDC timeframe.

The core aspect of our methodology is based on the fact that, whatever the set of criteria to which the international negotiations would converge, there is presumably no single weighting upon which all countries could agree. Previous negotiations mainly broke at this stage, especially in Copenhagen 2009. We therefore offer an alternative solution that does not require to explicitly determine any weighting. In statistical terms, it is an unparameterized approach applicable to any set of criteria. Numerical computation will be presented in detail in paragraph 2.2.

The methodology takes place in 4 steps:

- Determine a set of criteria considered as relevant for future emissions allowance. It could either be "responsibility criteria" corresponding to past emissions or "capacity criteria" corresponding to the country's capacity to mitigate its emissions. As we shall see, for the sake of acceptability, we only require that the set of criteria be

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[5] http://deepdecarbonization.org/about/

consistent in the sense that they can be written in terms of a Kaya equation (Kaya 1998).

- Identify ways to penalise (favour) responsibility criteria (capacity criteria) to compute emissions breakdown for each criterion selected in the previous step, and every country, considering UN-population forecasts (the so-called 'penalty function').
- Simulate all the combinations of criteria and weights compatible with steps 1 and 2 and compute the corresponding per capita carbon budget compatible with the 2°C target.
- Determine the mode (most frequent value) of the distribution of national carbon budgets that are 2°C-compliant, that is, the GHG allowance that fits the largest number of simulations performed in Step 3. The resulting distribution corresponds to the amount of GHG emissions that, within the range of 2°C-compliant emissions, has the highest probability of reaching a consensus ---equivalently, which exhibits the lowest dependence on the choice of criteria and weights.

2. – Detailed description

Kaya's equation[6] (or identity) generally reads as follows:

$$\frac{GHG\ Emissions}{Population} = \frac{GDP}{Population} * \frac{Energy}{GDP} * \frac{GHG\ Emissions}{Energy}$$

Equation 1

Its strength is to ensure the consistency of the set of criteria under scrutiny. Suppose, indeed, that we were to consider the truncated family of criteria (CO2-e emissions +GDP per capita + energy intensity of GDP). Obviously, the basic link between these three parameters would be missing, namely the CO2-e intensity of energy dissipation. This, however, can be readily seen from the Kaya tautology.

In the sequel we apply our methodology using 15 criteria directly derived from the Kaya identity above, comprising of (i) criteria expressing a trend, and (ii) criteria indicating a current state (see table 1). The formers are called 'relative variables' and the latter 'absolute variables'.

Each of the Kaya-derived criteria (except historical emissions) can be expressed either as a 'relative' variable or as an 'absolute' variable, according to whether one wants to consider the past evolution or not. To some extent, favouring 'relative' variables would amount to favouring the 'responsibility' criterion over the 'capacity' criterion (and vice versa). Here, in order to avoid the pitfall of arbitrary choice, both types of variables are included. Gathering all these variables provides us with a 15-tuple of criteria.

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[6] Developed by Yoichi Kaya, professor at Keio Tokyo University and President of Japan Society of Energy and Resources, in « *Environment, Energy, and Economy: strategies for sustainability* », 1997. The work of the Intergovernmental Panel on Climate Change (IPCC) makes explicit reference to this tautology (see http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=50)

Notice that our methodology does not depend upon the specific choice of *this* 15-tuple of variables. The Human Development Index[7], the Ecological footprint[8], public or private debt-to-GDP ratio, the Gini coefficient over income or wealth or any other criterion could be adopted instead of these variables. Theoretically, our sole requirement is consistency which, as said, can be checked *via* a Kaya-like equation that is exhaustive with regards to its arguments. Present developments are, however, limited to the standard Kaya identity as described above, given its international recognition.

For relative variables, we fixed the base year as 2000. Indeed, the Kyoto protocol (1997) is the first official agreement to combat climate change and limit GHG emissions. Considering time to approval, ratification and first political decisions, 2000 can be considered as the first year for an actual implementation.

Table 1 – List of variables integrated in the computation

Variables
GDP/capita in constant $ (Last Available Data: LAD)
GDP/capita evolution since 2000
Energy intensity of GDP at US$ constant (without biomass) (LAD)
Energy intensity of GDP at US$ constant (without biomass) evolution since 2000
CO2 intensity of energy dissipation (kg per kg of oil-equivalent-energy use) (LAD)
CO2 intensity (kg per kg of oil equivalent energy use) evolution since 2000
GHG including LULUCF per capita (LAD)
GHG including LULUCF per capita evolution since 2000
CO2 emissions from energy sector (LAD)
CO2 emissions from energy sector evolution since 2000
GHG emissions excluding CO2 from energy sector (LAD)
GHG emissions excluding CO2 from energy sector evolution since 2000
Primary energy consumption per capita (LAD)
Primary energy consumption per capita evolution since 2000
Total CO2 emissions since 1950

The next question and main sticking point for negotiation is: how do we fairly aggregate all these criteria to propose an acceptable reduction of national GHG emissions?

To reach this target, we use a 3 step approach:

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[7] http://hdr.undp.org/en/content/human-development-index-hdi

[8] https://www.footprintnetwork.org

a) According to each criterion, we calculate relative emissions/capita between countries for future years;

b) Based on population forecasts and a yearly 2° compliant emissions target, we adjust emissions to fit world emissions;

c) Simulations and identification of the "most likely" (most acceptable) emissions/capita per country.

a) Relative emissions/capita distributions based on each criterion

In a first step, raw data must be adapted for the calculation. For each variable, data may be transformed using a decreasing function, which we call the "penalty function".

To increase the robustness of the method, 3 different decreasing functions are proposed:

- affine = medium penalisation: f(x) = (max – x) / (max – min)
- logarithmic = Low penalisation: f(x) =log(1/x)
- inverse = high penalisation: f(x) = 1/x

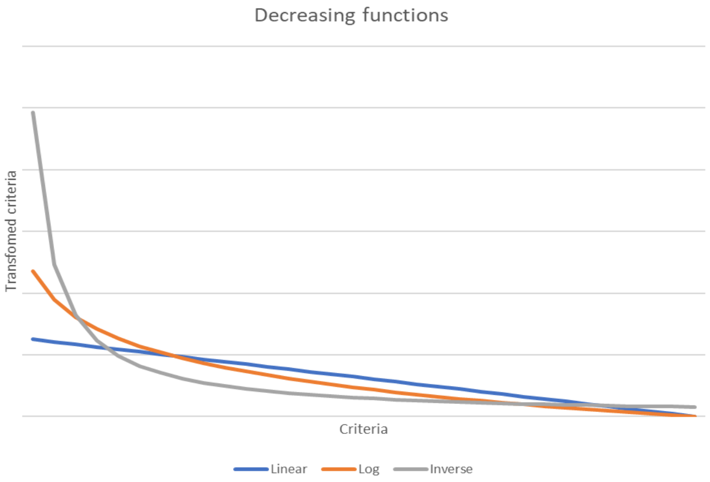


Figure 1 – Penalty functions

Each of these curves supports a certain vision on how past emissions should be considered in future emissions allowances. Any choice could be challenged and, consequently, all are simultaneously considered in our methodology. Results that are presented in section 3 have been computed using a mix of all of these functions, which increases the method's robustness.

For criteria based on a reference (relative variables), neither logarithmic nor inverse penalty functions are directly compatible with negative values. In this paper, we restrict the penalty function to affine transformation for relative variables. Alternative penalty functions will be considered in subsequent research.

Notations:

$X_{i,c}$ = value of the criterion $i \in [1\text{-}15]$ for the country $c \in [1\text{-}196]$

F_k = penalty function, $k \in [1\text{-}3]$

$REC_{i,k,c}$ = relative emissions/capita for country $c \in [1\text{-}196]$, for a penalty function $k \in [1\text{-}3]$ applied to the criterion $i \in [1\text{-}15]$ compared to country 1

$P_{c,y}$ = Estimated population of country $c \in [1\text{-}196]$ for any period y in [2030-2100].

$GHG_{t,y}$ = Total amount of GHG compliant with a t °C scenario in the y period

$CNB_{c,t,y,i,k}$ = Carbon National Budget of country c in the period y compliant with a t °C scenario based on criterion i and decreasing function k

S_s = simulation s is defined by a set of weights $\{w_{1,s},\ldots\ldots,w_{15,s}\}$, with

$CNBS_{c,t,y,s,k}$ = Carbon National Budget of country c in the period y compliant with a t °C scenario based on simulation s and penalty function k.

During the first step, relative emissions/capita is estimated for every country by the formula:

$$RECi,k,c = Fk\ (Xi,c)\ /\ Fk\ (Xi,1)$$

Consequently, RECi,k,1 = 1 for all criteria and all penalty functions.

At the end of this first step, we have a relative distribution of the emissions/capita per criterion and per penalty function. Country 1 is normalised to 1 and all other countries are adjusted to it. For instance, for criteria 1and penalty function 1, Country 2 emissions per capita is set to 0,5. It means that its allowance is two times lower than that of Country 1.

Table 2 – Country weights matrix

Country	Relative emissions per capita (criteria 1, function 1)	Relative emissions per capita (criteria 1, function 2)	Relative emissions per capita (criteria i, function k)	Relative emissions per capita (criteria 15, function 3)
Country 1	1	1	1	1
Country 2	0,5	0,8	…	1,4
…	…	…	…	…
Country 40				
…	…	…	…	…
Country 196	1,8	1,4	…	1,1

The choice of Country 1 has no impact on the results. Indeed, relative emissions per capita will be aggregated thanks to population forecasts and compared to a worldwide allowed emission. A proportional adjustment will be then performed that makes the choice of Country 1 ineffective.

b) Based on population forecasts and a 2°C compliant emissions amount, emissions are uniformly adjusted to fit the target

For the 2nd step, we use UN population forecasts and a world emission amount for any targeted temperature *t* (1.5°C, 2°C…) to determine Carbon National Budget.

At the end of the second step, several Carbon National Budgets based on different allocation criteria are obtained. However, how to gather all of them is the remaining question. Indeed, depending on individual choices and country specific situations, one could choose a specific set of weights or another. It appears, and the current failures of negotiations confirms this, that a universal setting that would fit all countries' expectations is unlikely to exist. The way we suggest addressing this issue is based on a simulation-based approach so as not to freeze a repartition between criteria.

c) Simulations and identification of the "most likely" (most acceptable) emissions budget per country

The core aspect of the methodology is an "agnostic" way of computing emissions per capita that is not based on an explicit set of predetermined weightings. For that purpose, we use a simulation process (around 2 million set of weightings, see appendix) and for each of them, we calculate the associated Carbon National Budget.

Then, for a given couple (Temperature, Period), we have a distribution of possibilities for every country and we define the mode of the distribution as a potentially consensual emissions allocation. Explicit weights become unnecessary, and implicit weights can vary from one country to the other. Implicit weights are consequently considered as the best ones for each country.

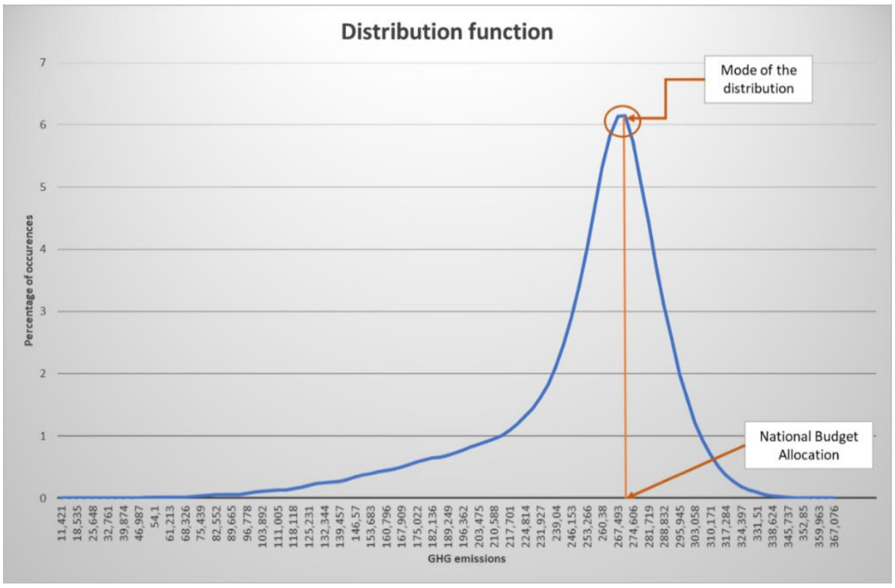


Figure 2 – Illustration of the simulation results for a country

All that remains is to proportionally adjust national emissions, in order to fit the global target, as the sum of these national emissions does not necessarily equal the global budget.

d) Data used

All data come from international and reputable sources:

© WRI, CAIT. 2014. Climate Analysis Indicators Tool: WRI's Climate Data Explorer. Washington, DC: World Resources Institute. Available at: http://cait2.wri.org ; Total Greenhouse Gas including LULUCF emissions and CO2 emissions from energy sector, total CO2 emissions since 1950 (historical emissions).

© FAO, 2017, CO2 emissions from LUCF via CAIT

United Nations, Department of Economic and Social Affairs, Population Division (2016). World Population Prospects: The 2016 Revision: Current and forecasted populations

Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee, United States, via World Bank [2017]: CO2 intensity (kg per kg of oil equivalent energy use)

World Bank national accounts data, and OECD National Accounts data files: GDP per capita (constant 2010 US$),

Enerdata (www.enerdata.net): GDP energy intensity and total primary consumption (Beyond Ratings adjustments).

3. RESULTS

1. – Overview

In this paragraph, we present the GHG emissions allowances (national budget and per capita) in 2030 that are compliant with a 2°C target in 2100. The first outcome of the methodology is a worldwide convergence of GHG emissions per capita around 4,7 tCO2-e (Figure 3 and descriptive statistics in Table 3).

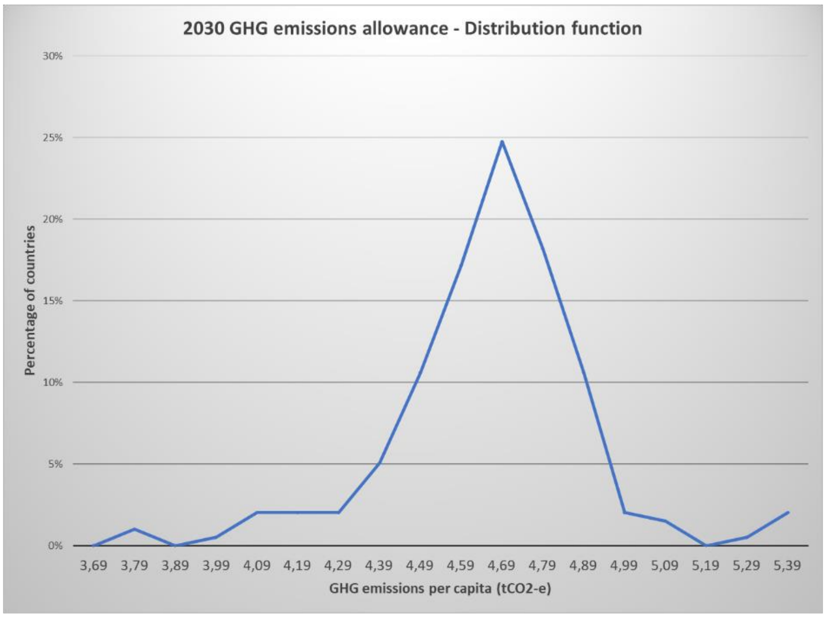


Figure 3 – Results distribution curve for 2030

Table 3 – Results descriptive statistics

Descriptive statistics	Value (tCO2-e/capita)
Average	4,65
Median	4,62
Quarter 1	4,50
Quarter 3	4,74
Maximum	11,91 (South Sudan)
Second	6,09 (Burundi)
Minimum	3,70 (Isle of Man)

South Sudan is a specific case because only 2(/15) criteria are available for this country. It is a quite rare situation where most of criteria are missing. This point and its criticality is discussed in the robustness section.

However, this convergence hides some specific patterns that mainly depends on the income group (as defined by the World Bank). As shown in Figures 4 and 5, the lower the income, the higher the emissions allowance. Even if upper middle-income and high-income groups are similar, their GHG emissions allowances are below lower middle- and low-income groups. In the high-income group, a significant gap exists between OECD and non-OECD countries in favour of the former. It also appears that dispersion is higher for non-OECD countries, which is consistent with the heterogeneity of this set of countries.

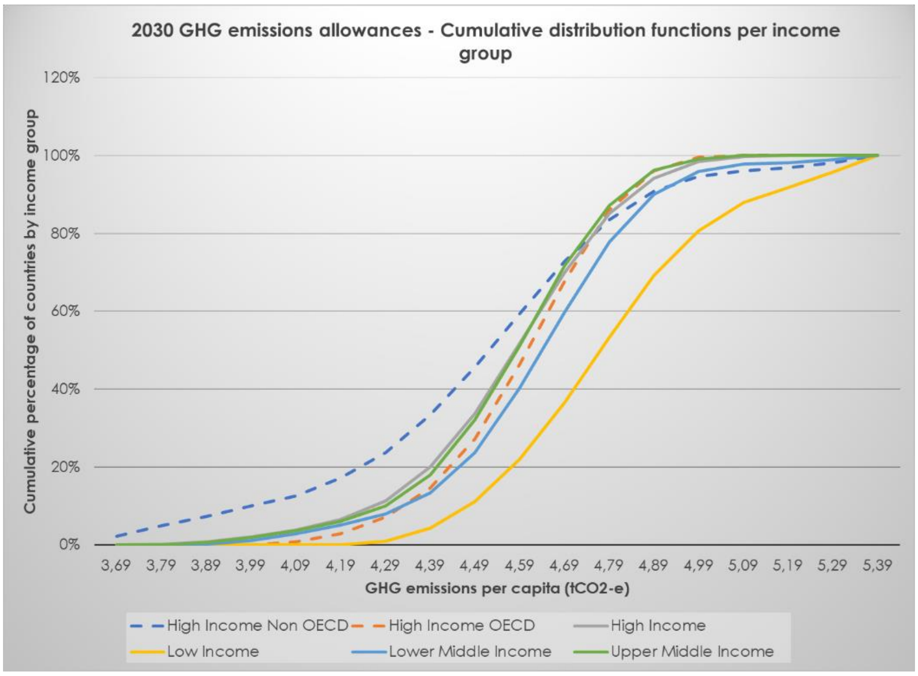


Figure 4 – Cumulative distribution functions per income group

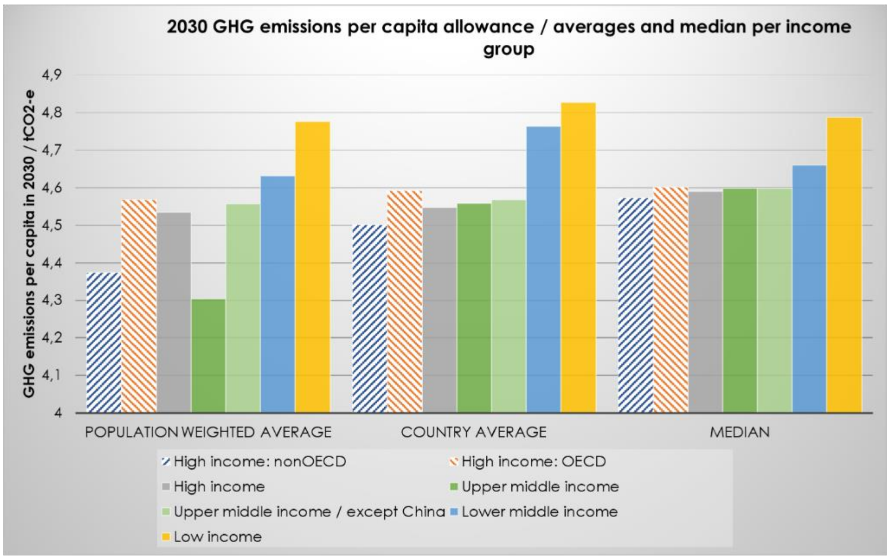
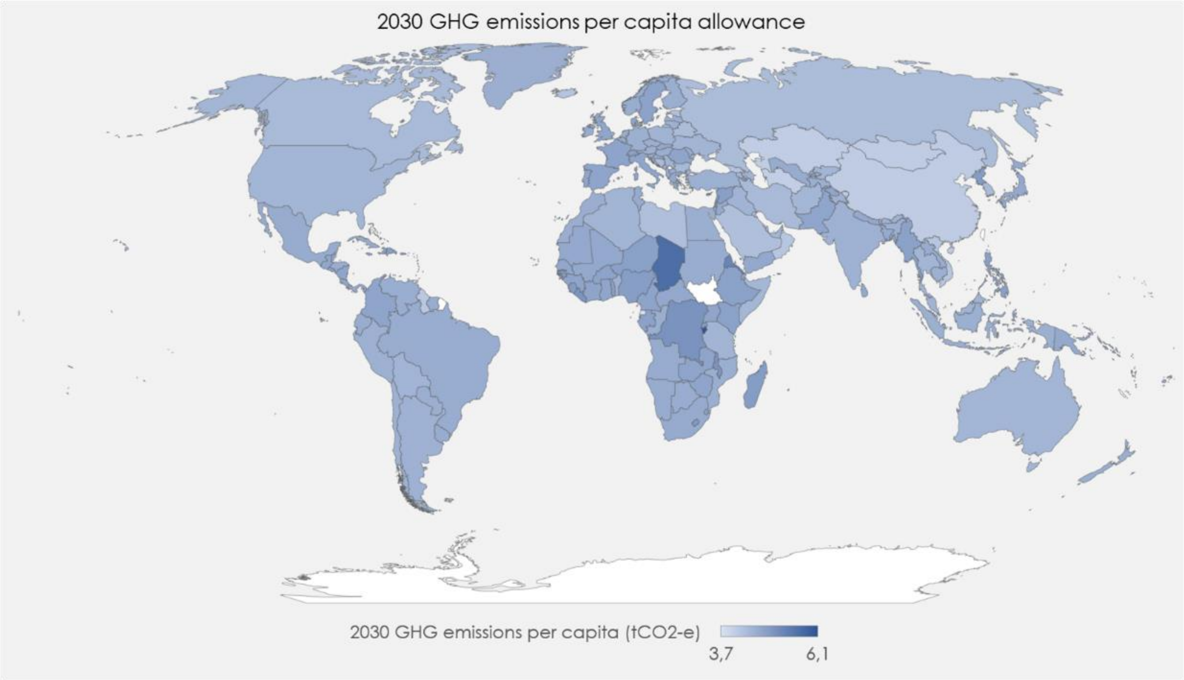


Figure 5 – Average and median allowances (per capita) per income group

When it comes to GHG intensity per capita, the map hereafter [Map 1] shows that Africa, India and South-America have higher emissions allowance per capita than China and developed countries (US, Europe, Russia and Australia). This mainly reflects their low historical emissions. Due to missing data, some countries cannot be assessed. They are represented as blank in the map.



Map 1: 2°C-compatible GHG emissions per capita in 2030[9]

From a national point of view (budget per country), the podium is composed of the United States, China, and India as the top emitter. This mainly reflects its demographical evolution and the fact that India is historically a low emitter.

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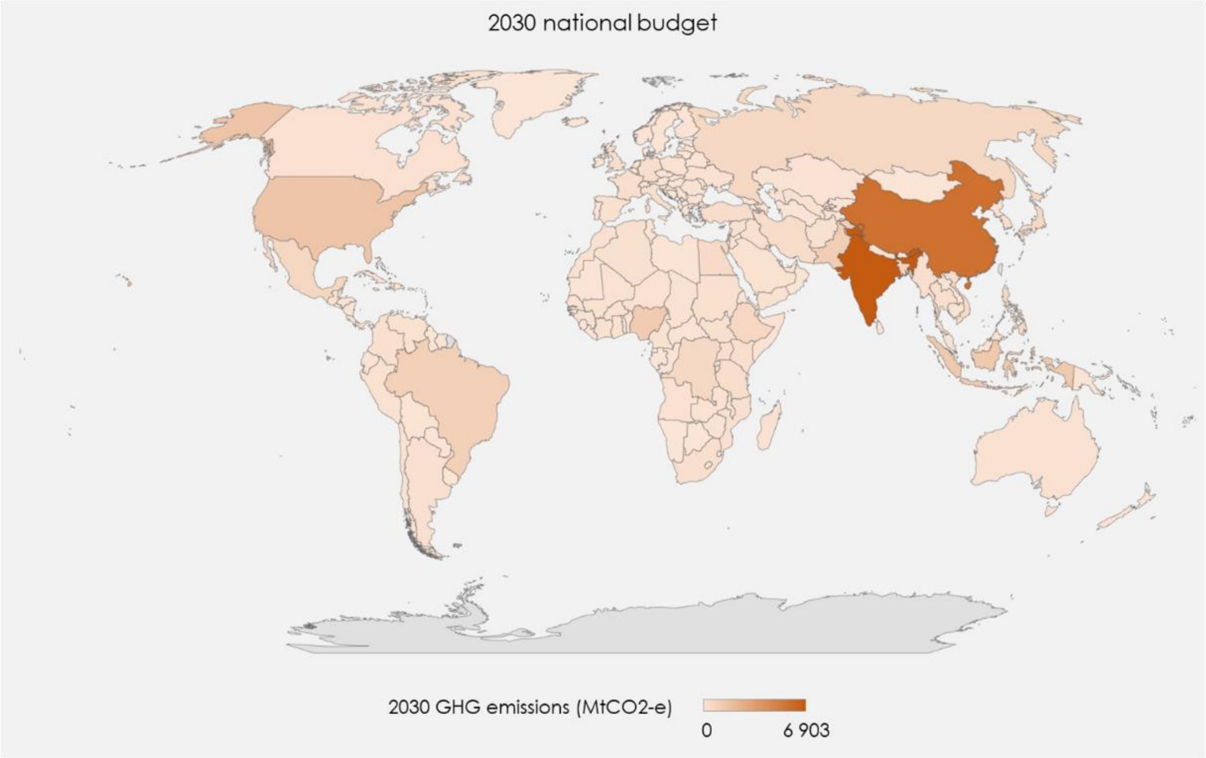
[9] South Sudan excluded (see above)



Map 2: 2°C compatible national carbon budget in 2030

2. – Top 10 emitting countries

The top 10 emitting countries in 2030 are cross-continental: Asia (India, China, Indonesia, Pakistan and Bangladesh), Africa (Nigeria and Ethiopia) and Americas (United States of America, Mexico and Brazil) are represented. Reconsidering some terms of the Kaya identity, it appears that national budgets variations follow different patterns (Figures 6 and 7). Emissions growth might result from a population increase (Nigeria, Ethiopia, Pakistan, India, Mexico, Indonesia) and/or a rise in GHG emissions per capita (Ethiopia, Bangladesh, Pakistan). On the other hand, other countries face limited population increases and high GHG emissions per capita reductions (China, United States of America and Brazil), leading leads to a drastic required effort.

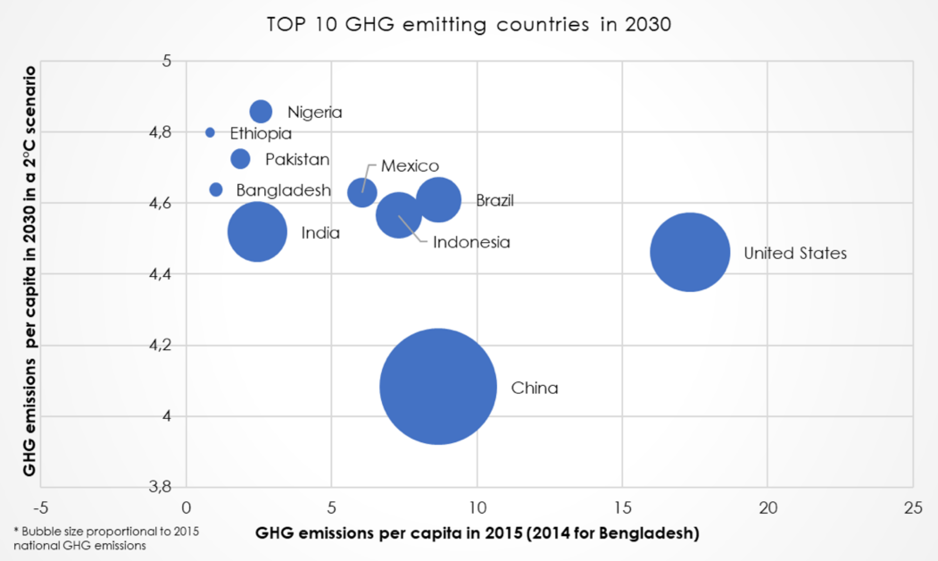


Figure 6 – Present and future emissions per capita for the top 10 countries

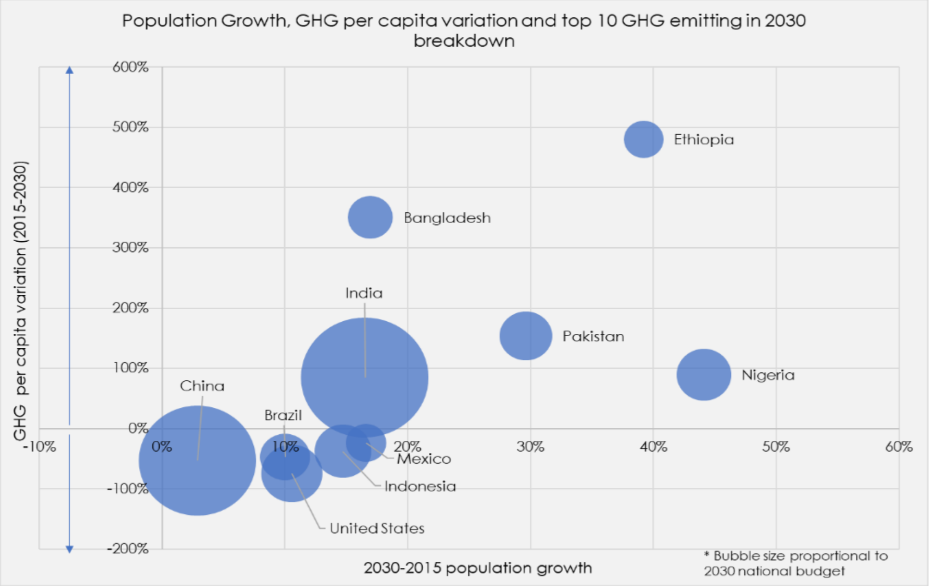
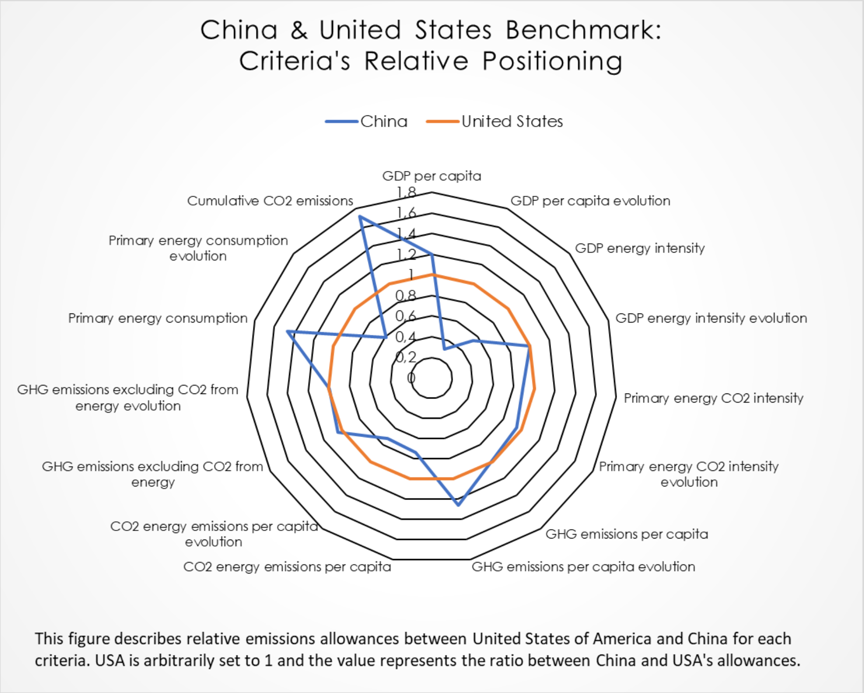


Figure 7 – Emissions and population change for the top 10 countries

One may be surprised by the respective positions of China and the United States of America. Indeed, GHG emissions per capita in 2030 is higher for the USA than China (Figure 6). Besides the fact that China is the world's manufacturer (i.e. emitter for other countries), a detailed analysis of the 15 criteria offers an additional perspective: Figure 8 shows that GDP per capita evolution and GDP energy intensity tend to lower the level of allowed emissions for China, which cannot be compensated by the cumulative CO2 emissions and primary energy consumption. Regarding the USA, its high position in terms of allowances is mainly due to its demographic position (3rd largest population). From a GHG emissions per capita perspective, USA obtains a low rank (163/198).



This figure describes relative emissions allowances between United States of America and China for each criteria. USA is arbitrarily set to 1 and the value represents the ratio between China and USA's allowances.

Figure 8 – China scores in relation to the United States

In light of the fact that COP23 that is hosted by Fiji, and since Pacific Islands are particularly threatened by the effects of climate change (especially sea level rise), we present hereafter a focus on these islands. As shown in the following figure, CLAIM confirms that most of these islands would receive an above average emission allowance:

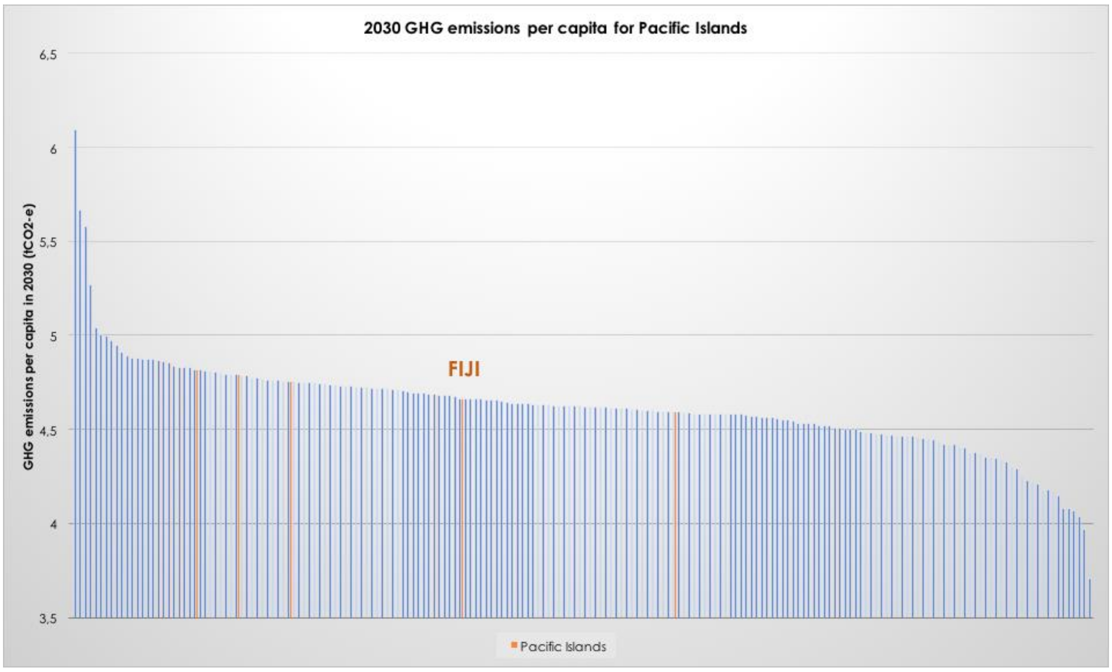


Figure 9 – Pacific islands performance

3. – Robustness

This section seeks to assess the robustness of the method by testing the results' sensitivity to criteria and penalty functions. We will first compare results when one indicator is removed. In a second stage, the effect of the penalty function on the output will be evaluated.

- Criteria sensitivity:

Obviously, emissions allowances vary dramatically from one criterion to another. Therefore, to ensure that criteria choice has a limited impact on final emissions, we perform the entire process 15 times excluding 1 different indicator at each iteration. As a result, 15 national budgets per country are provided. Figure 10 presents the minimum and maximum allowances for all countries:

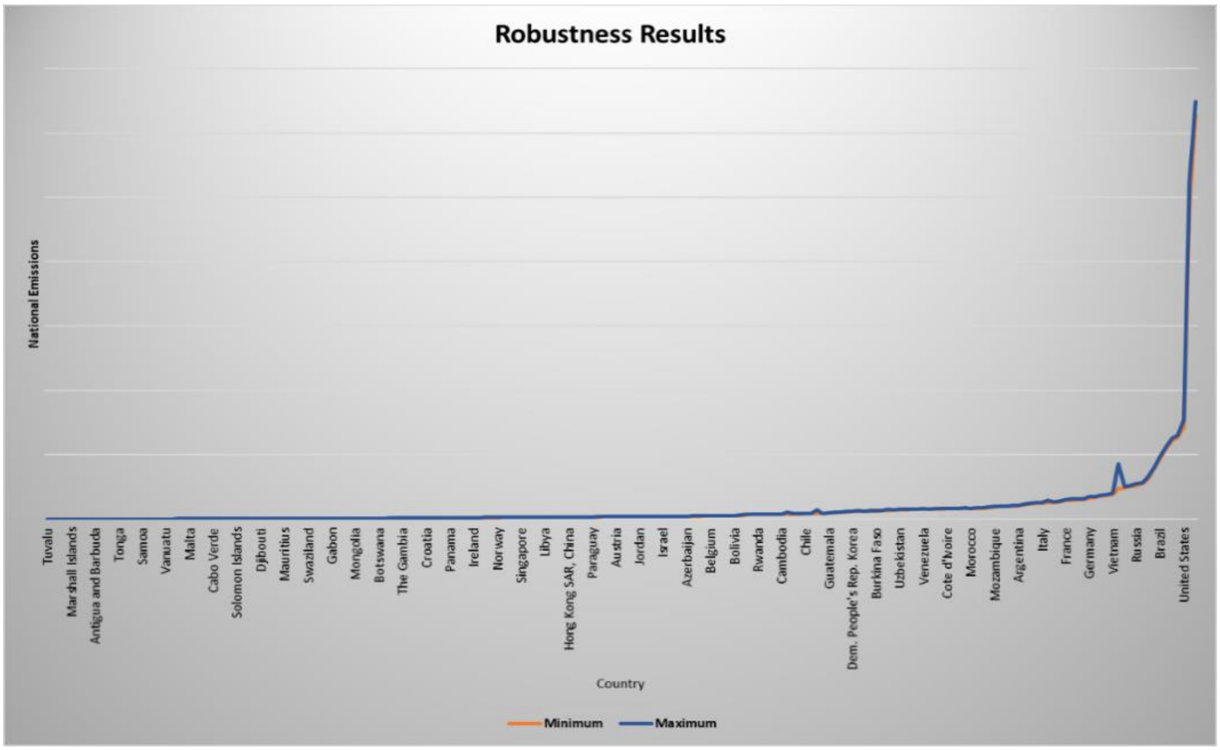


Figure 10 – Robustness evidence

As Figure 10 demonstrates, the choice of variable does not greatly affect the results.. The only country that shows some sensitivity is Ethiopia. This is due to the fact that one criterion (GDP) is particularly low for this country, which leads to an extremely high value and creates a low minimum. It explains the gap in the graph.

- Penalty functions sensitivity

As previously mentioned, we use 3 different penalty functions (high, neutral and low discrimination) to compute emissions allowances, and it is legitimate to wonder if such a complexity is necessary. Hereunder, results for each pair of penalty functions, computed separately, are compared. It appears that differences are relatively significant between penalty functions (see Table 4).

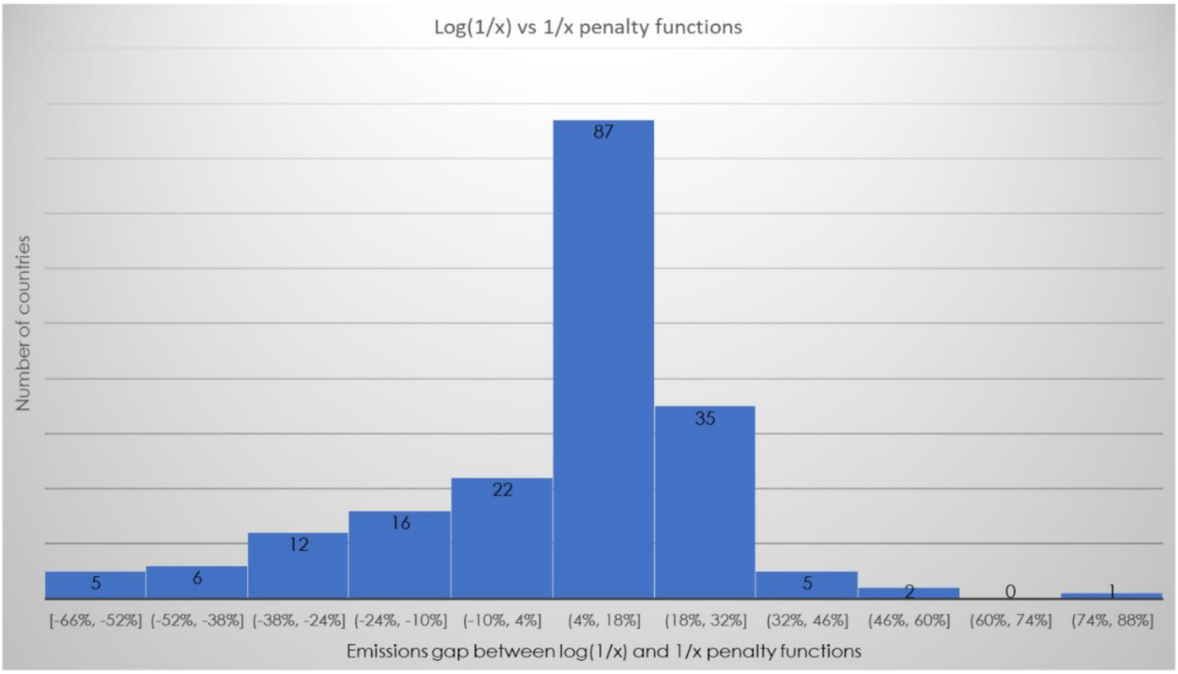


Figure 11: log(1/x) vs 1/x; emission gaps histogram

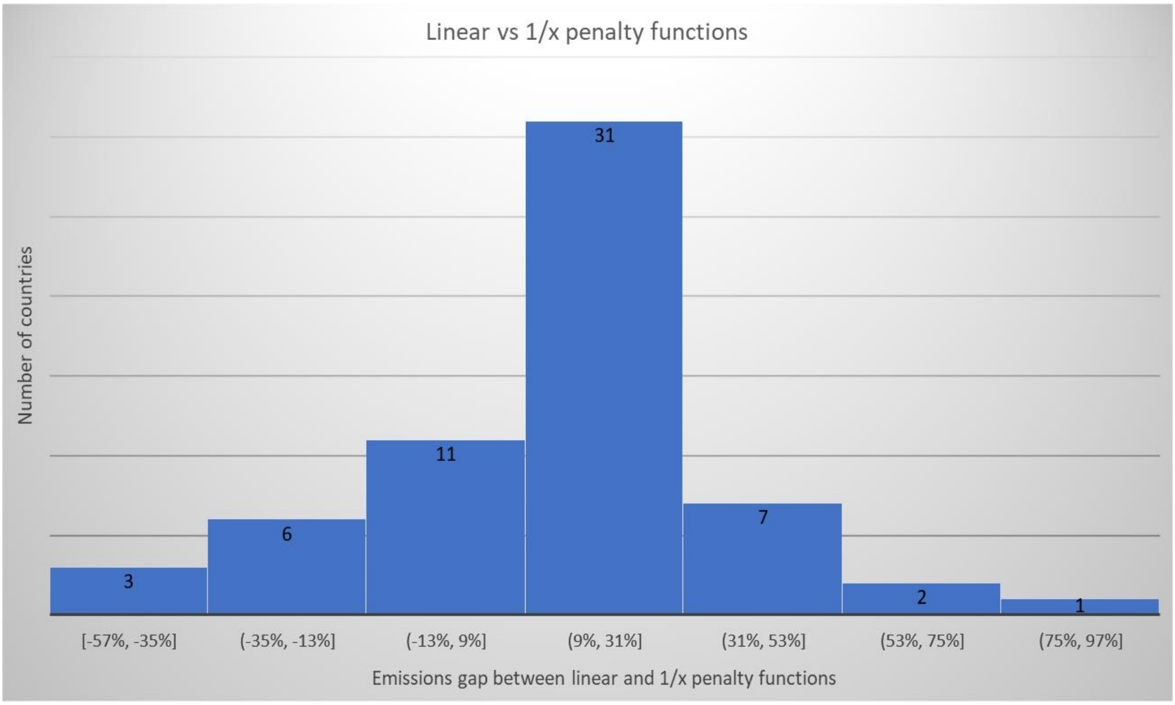


Figure 12: Linear vs 1/x; emission gaps histogram

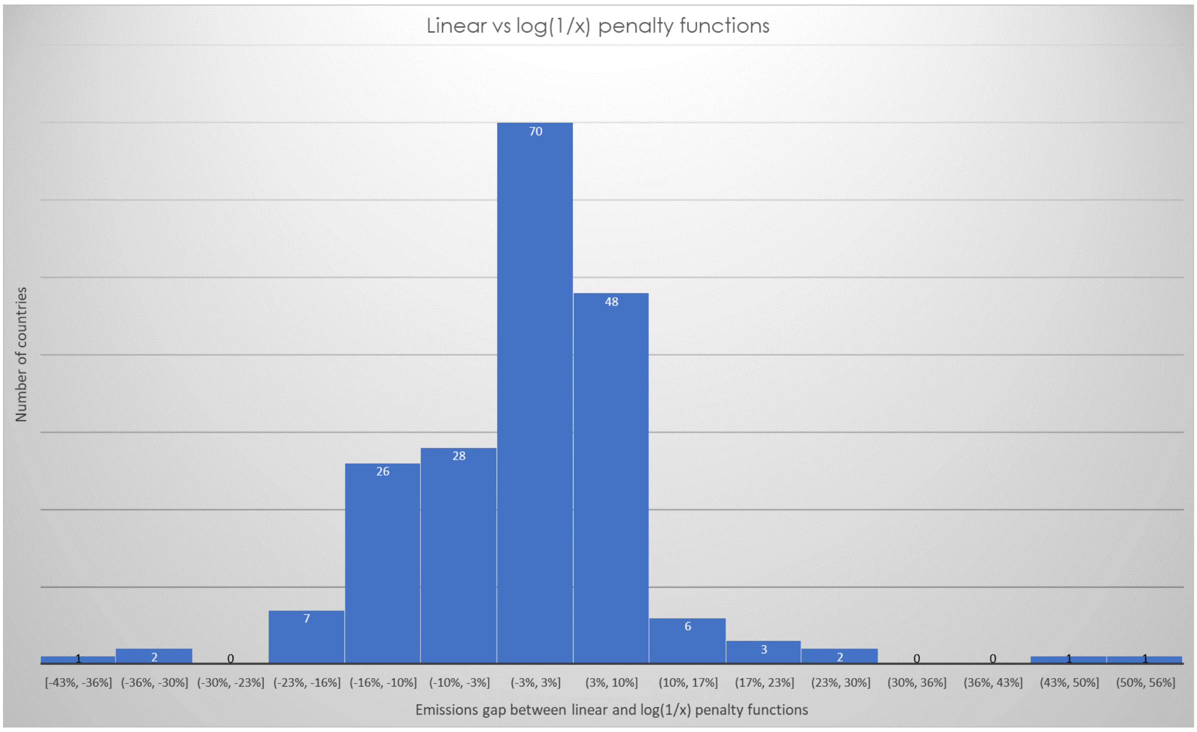


Figure 13: Linear vs log(1/x); emission gaps histogram

Table 4 – Summary of the penalty function robustness test

	Min	Max	Median	Bottom quartile	Upper quartile	Inter-quartile
Log(1/x) vs 1/x	-66%	+78%	12%	-3%	17%	20pts
Linear vs 1/x	-72%	+76%	14%	-9%	22%	31pts
Linear vs log(1/x)	-21%	+54%	1%	-7%	5%	12 pts

Based on the inter-quartile metrics, the closest penalty functions are Linear and log(1/x), which are considered as low and neutral functions. Oppositely, 1/x function (high penalty) offers a very different vision. For instance, the USA allowance is 10% lower using 1/x penalty function instead of linear penalty function. In the same comparison, Uganda has a 25% higher emissions allowance. Consequently, a mix of these three penalty functions has been used for the calculation, for more robust results.

To conclude, this method allows us to propose national breakdown for any target of temperature, thanks to the temperature-GHG emissions mapping. No predetermined criteria weightings are needed, and the method is robust to the choice of indicators. The high sensitivity to penalty functions encourages the use of a mix of penalty functions. At a later stage, other types of functions should be considered.

- Limitations

Due to a lack of data, all criteria are not necessarily available for all countries and scenarios are adjusted accordingly. If a criterion is missing, all scenarios with a non-0 weight associated to this criterion are excluded for this particular country.

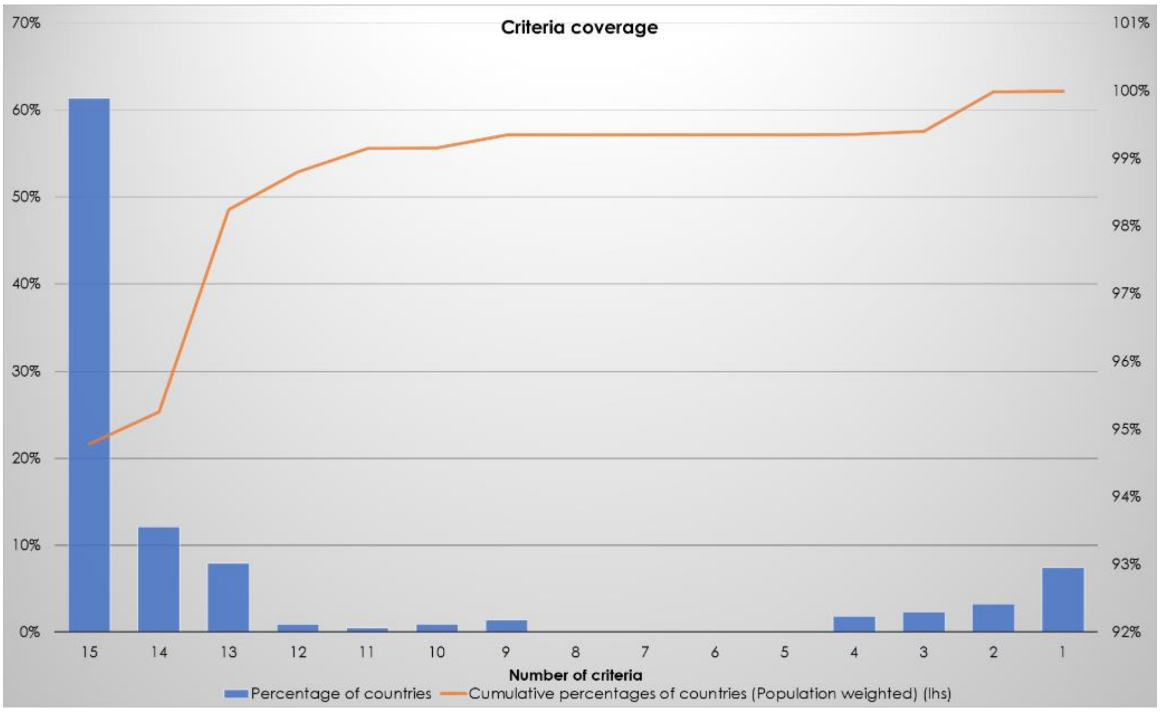


Figure 14 – Countries criteria coverage

More than 80% of countries has 13 effective criteria or more that represents 98% of worldwide population. As proved in previous section, global robustness of the method makes results acceptable.

4. DISCUSSION

Our method allows for the determination of national GHG emissions budgets for any global emissions target and time horizon by integrating any set of consistent criteria and weighting. The purpose is (i) to adopt the Kaya equation as an elementary consistency requirement for the choice of criteria, and (ii) to use a simple statistical procedure to identify a distribution of carbon budgets that would exhibit the highest level of acceptability by the largest range of parties involved in international negotiations. This increases the potential for enlarging the community of decision-makers (whose interests may not necessarily be aligned) directly taking part in or indirectly influencing international negotiations. The statistical approach avoids the pitfall of arbitrarily assigning weights to the variables. Only the population scenarios and the choice of the reference period for the calculation of relative variables (energy intensity, per capita income, carbon intensity of energy) may introduce a structural bias in the results of estimating national GHG emissions budgets.

A key point of the method lies in the fact that it does not require any exogenous economic or energy scenario as either a reference or an alternative. This is all the more beneficial to the acceptability of the proposed method as these scenarios suffer from two weaknesses. First, none of them provides a complete geographical coverage, thereby ignoring a significant number of countries. The mismatch between the geographical structure of an exogenous scenario as a key input and the actual international community involved necessarily undermines the degree of political acceptability of modelling results. Second, any scenario reflects arbitrary choices to a certain extent, from modelling methodology to range of values associated to selected variables. This applies to all scenarios built and made available in the public domain by non-governmental organizations as well as inter-governmental organizations such as the International Energy Agency. Although our method requires the input of long-term population projections, these projections are based on United Nations data, which is fully accessible. This allows for the opportunity to test alternative cases and produce related results in complete transparency. It therefore offers the potential to study with accuracy the effects of demographic issues and uncertainties on future allowable GHG emissions budgets.

The proposed method therefore increases the potential for political acceptability and provides an analytical framework for the definition and assessment of emissions targets and trajectories by government bodies. It thus presents four fields of application: (i) ex-ante assistance of States in the formulation of their commitments and pledges; (ii) the ex-post evaluation of these same commitments and pledges; (iii) providing a signal to investors and lenders; (iv) contributing to the definition of an innovative country risk analysis framework, integrating transition risks associated with the evolution of productive systems towards a low-carbon economy and the risk of liability born from insufficient mitigation measures.

There are three areas for improvement to increase robustness and acceptability in this first version of CLAIM.

The first area of improvement relates to the features of energy consumption series on which the Kaya equation is applied. Results presented above are based on raw energy consumption data, not corrected for any structural nor cyclical factors. However, in addition to income per capita, which is the first driver of energy consumption, population density and concentration structurally shape energy use. As empirical evidence suggests, the needs for mobility and the associated energy consumed for transportation are an inverse function of both density and concentration. Furthermore, population density and concentration shape the extent to which gas and power grid energy industries develop, thereby having a ripple effect on the range of options for energy substitutes and, ultimately, on the structure of final energy consumption. In addition to structural factors, energy consumption is cyclically determined by meteorological conditions, especially in countries at temperate latitudes. To the best of our knowledge, there is no comprehensive set of international energy consumption data corrected from either structural or cyclical factors or both. Applying the method on corrected energy consumption data (accounting for structural and cyclical factors) would further improve the robustness and acceptability of our results by increasing the degree of fairness with which all parties are treated.

The second area for improvement lies in revisiting the form of the Kaya equation. The current form is based on energy consumed and greenhouse gases emitted inside the national boundaries of each country. This largely disadvantages export-oriented countries which generate emissions during the production of goods, while the importers of these goods preserve their carbon balance. Replacing production by consumption and then letting our statistical method speak on both approaches simultaneously, would ensure a higher degree of equity in the treatment of parties. We leave this extension for further research.

Finally, the third area of improvement covers the number and types of penalty functions from which emissions budgets are derived for each allocation criterion. Linear, logarithmic and inverse functions have been tested. Other functions, such as power and polynomial, could be explored in order to test further the robustness of the method.

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6. APPENDIX

We generate all combination of weights that fit hereunder rules:

- Each of the fifteen criteria has a weight in [0; 0,1; 0,2; 0,3; 0,4…0,9; 1]
- Sum of weights = 1

⇨ It leads to 1 961 256 scenarios

Example: