DOI 10.5281/zenodo.13305562

published on zenodo

Distribution of a Global CO_2 Budget - A Comparison of Resource Sharing Models

Prof. Manfred Sargl
Dr. phil. Daniel Wiegand, M.Sc. M.A.
Günter Wittmann, Graduate Mathematician
Andreas Wolfsteiner, Graduate Economist

save-the-climate@online.ms (mail to)

www.save-the-climate.info

Version: 12/08/2024

Abstract

In view of the connection between the cumulative CO_2 emissions and global warming, as described in the IPCC Reports, the key question arises how a globally remaining budget could be realistically distributed among countries. The discussion of this issue can contribute to NDCs that are Paris-compatible in sum.

Resource sharing models directly address the allocation of such a remaining global budget. This article therefore gives an overview of the properties of resource sharing models that, in principle, use current emissions and population as a distribution key.

We also identified a helpful evaluation criterion for NDCs: the implicit weighting of the population.

Contents

List of Figures

List of Tables

1 Introduction and underlying data

"*Limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO_2 since the preindustrial period, that is, staying within a total carbon budget*" (IPCC, 2018, p. 14).

Even if the fundamental relationship between cumulative CO_2 emissions and the extent of global warming is clear, the concrete global CO_2 budget to which NDCs are oriented must be a scientifically based political decision. If the Parties to the Paris Agreement make transparent a global CO_2 budget behind their NDCs, this could initiate a discourse that leads to converging benchmarks. Once a global budget is given, the key question is how to share it among countries. Discussing the issues of a Paris-compatible global CO_2 budget and its meaningful allocation, can contribute to Paris-compatible NDCs in sum.

In this paper, we have focused on resource sharing models[1] for the issue of sharing a global CO_2 budget, which take into account current emissions and population.[2] We selected these models because we believe they are appropriate for specifying realistic NDCs: Current emissions reflect the present reality and population can map justice. This article wants to present different and common features and increase the transparency of the discussed models.

In Chapter 2 we consider convergence models with a limited convergence period, at the end of which global emissions are allocated to countries according to population only. The Emission Probability Model in Chapter 3 takes into account the emission distribution in a country. In the models in Chapters 2 and 3, a global path is allocated to countries. In contrast, in the approaches under the Extended Smooth Pathway Model (Chapter 4), a global budget is allocated directly to countries and then plausible national emission paths are derived that adhere to this budget.

For a mathematical description of the models with proofs of its properties we refer to the corresponding Supplementary Text 1: (Wittmann & Wolfsteiner, 2023).

Data used

By way of illustration, we show the results of the models for three pure type countries (see Chapter 2.4 and Chapter 5) with the following underlying data:

Global paths

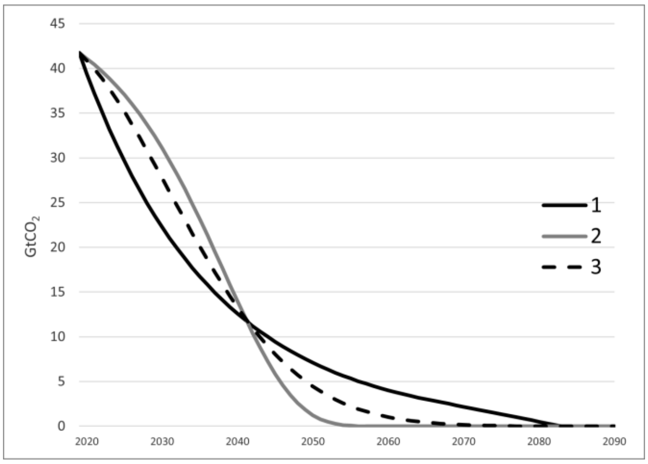

Figure 1: Exemplary global paths that meet a specific budget

All three global paths adhere to the same budget for the period 2020 - 2100. We did not use paths with global net negative emissions because some models cannot map net negative emissions.

In the following we used the global path number 3 in Figure 1 unless otherwise stated.

Three pure type countries

	country			world
	A	B	C	
in the base year 2019	industrial	emerging	developing	
emissions in $GtCO_2$	21.0	19.5	1.2	41.7
population in billions	1.2	4.0	1.7	6.9
per capita emissions in t	17.5	4.9	0.7	6.1

Table 1: Underlying data for the three pure type countries

Our aim is not to explore real countries but pure type countries of which per capita emissions are typical of an industrial, an emerging and a developing country. In our calculations we used a “frozen” population of the base year.

Details including the values of further parameters can be found in the Supplementary Excel Tool 1.

2 Convergence models

All convergence models presented here start with a global path that meets a global budget usually corresponding to a certain degree of global warming. Then the models break down the annual global emissions on country level, transforming the actual emissions in a base year (*BY*) into emissions based on a per capita allocation in a convergence year (*CY*) at the end of a limited convergence period. In the illustration with the three pure type countries, we have chosen 2050 as the convergence year and 2019 as the base year.

The models in Chapters 2.1 and 2.2 gradually replace the allocation key “emissions in a base year” with the allocation key “population” within the convergence period. However, the underlying formulae are different in each model. In Chapter 2.3 we present enhancements of the previous models that enable different rules for some countries and in Chapter 2.4 we compare the models in Chapter 2.

2.1 Contraction & Convergence Model (C&C)

The Global Commons Institute already propounded the following Contraction & Convergence Model in the early 1990s. This model defines the emissions of country *i* in the year *t* $\left(\widehat{E_t^i}\right)$ recursively (Meyer, No date)[3]:

$$\widehat{E_t^i} := \begin{cases} \left((1-\widehat{C}_t) * \frac{\widehat{E_{t-1}^i}}{E_{t-1}} + \widehat{C}_t * \frac{P_t^i}{P_t}\right) * E_t, \text{ for } BY+1 \ \leq t < CY \\ \frac{P_t^i}{P_t} * \ E_t, \text{ for } CY \leq t \end{cases}, \quad (1)$$

where

E_t global emissions in the year *t*,

P_t global population in the year *t* and

P_t^i population of country *i* in the year *t*.

$\widehat{C}_t$ denotes the weighting of the population when allocating global emissions to countries. $\widehat{C}_t$ is the same for all countries.

The Global Commons Institute considered two specifications of $\widehat{C}_t$:

- exponential (C&C-exp): $\widehat{C}_t = exp\left(-a\left(1-\frac{t-BY}{CY-BY}\right)\right)$ with the parameter $a > 0$ to be determined. “*The higher the value [a], the more the convergence happens towards the end of the convergence period, and vice-versa. Choosing a = 4 gives an even balance.*” (Meyer, 1998, p. 21)

- linear (C&C-lin): $\widehat{C}_t = \frac{t - BY}{CY - BY}$.

Some more specifications of $\widehat{C}_t$ are presented and discussed in the corresponding Supplementary Text 1 (Wittmann & Wolfsteiner, 2023).

2.2 Regensburg Model (RM)

In the Regensburg Model[4] the emissions of country i in the year t $\left(\overline{E_t^i}\right)$ are given by the following **Regensburg Formula** [cf. (Sargl, et al., 2017) and (Sargl, et al., 2024c)]:

$$\overline{E_t^i} := \begin{cases} (1 - \overline{C}_t) * E_{BY}^i + \overline{C}_t * E_{CY}^i, \text{ for } BY + 1 \leq t < CY \\ \frac{P_t^i}{P_t} * E_t, \text{ for } CY \leq t \end{cases} \quad (2)$$

where $\overline{C}_t = \frac{E_{BY} - E_t}{E_{BY} - E_{CY}}$ and $E_{CY}^i = \frac{E_{CY}}{P_{CY}} * P_{CY}^i$.

An Excel tool can be downloaded with which emission paths for all countries in the world can be calculated using the Regensburg Model (Wolfsteiner & Wittmann, 2024d). Here is a simplified web app: http://RM.climate-calculator.info.

2.3 Different paths for emerging and developing countries

In this chapter we present enhancements of the previous models that enable more favourable rules for some (normally emerging) countries. These modifications involve greater efforts to be made by the other (normally industrial) countries.

2.3.1 Common but Differentiated Convergence Model (CDC)

The Common but Differentiated Convergence Model refines C&C (cf. Höhne, et al., 2006). *"This approach [CDC] eliminates two concerns often voiced in relation to gradually converging per-capita emissions: (i) advanced developing countries have their commitment to reduce emissions delayed […] (ii) CDC does not provide excess emission allowances to the least developing countries"* (Höhne, et al., 2006, p. 181). This is achieved by allocating countries below a continuously decreasing threshold emissions according to their free decision recorded in a business-as-usual scenario. Thus, the C&C model is only used for countries with per capita emissions above this threshold.

2.3.2 Modified Regensburg Model

The RM can also be combined with the idea of CDC, where some countries are exempt from the emission allocation regime as long as their per capita emissions are below the threshold.

It is even possible to exempt some countries from the emission allocation regime throughout the convergence period. This would be a way of allowing, for example, countries which start significantly below the convergence level in the base year to get emissions according to straight paths to the convergence level. This "shortest way to the convergence level" can be seen as a minimum justice level for developing countries.

In this case "global", in the description of Formula (2), must be read as "of the countries under the emission allocation regime".

2.4 Comparison of the convergence models

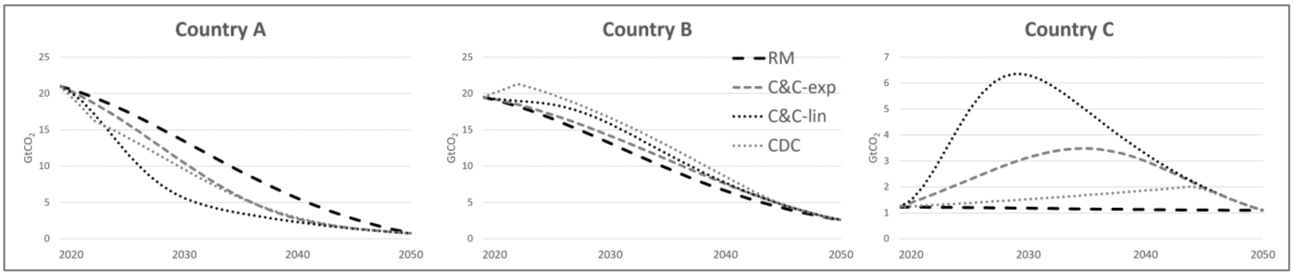

Figure 2: Comparison of the convergence models – emission paths (C&C-exp a = 4)

Figure 2 shows that the RM requiring the least reductions for country A (typical industrial country) corresponds to greater efforts for country B (typical emerging country) and country C (typical developing country).

If the effects of changes in population are suppressed and if global emissions fall during the convergence period, then the RM in contrast to the other models allocates

- countries starting above the convergence level lower emissions from the first year on in the convergence period, irrespective of how far and how long they have already been above the convergence level. Consequently, most emerging countries have to reduce their emissions from the first year on in the convergence period.
- countries starting below the convergence level higher emissions in each year, but, in contrast to other models in Chapter 2, never greater emissions than the convergence level. The RM, therefore, similarly to CDC, does not provide developing countries with excess emission allowances.

For a given global path the weight of population $\widehat{C_t}$ in C&C can be calculated in such a way that the resulting national paths of C&C and the RM are the same if the population is frozen. For a proof we refer to our Supplementary Text 1. This allows making clear that the weighting of population comes into effect in the RM only at the end of the convergence period whereas in C&C-exp the weighting of population increases earlier (cf. Figure 3).

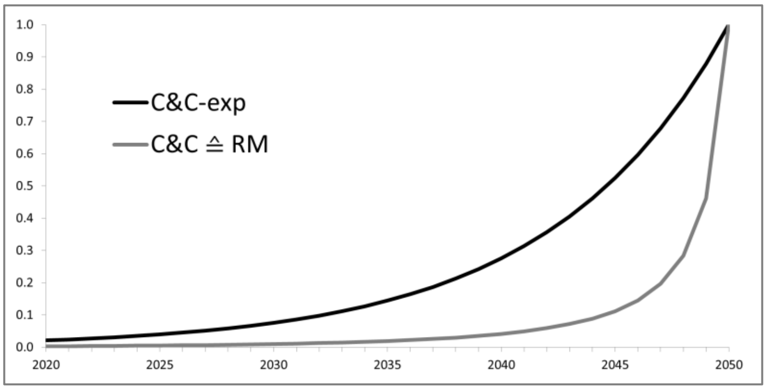

Figure 3: Comparison C&C-exp (a = 4) and RM – population weighting over time

We also examined whether we could obtain similar results as the RM with the “classic exponential” specification of C&C (C&C-exp). We found that choosing the parameter *a* = 8 the results for the industrial country A and the emerging country B are similar. However, the relative deviation of the results of C&C-exp and RM for the developing country C is considerable (see Figure 4).

We also noticed that in the C&C-exp the emissions of country C are falling at the beginning, then rising above the emissions in the base year, only to fall again to the convergence level. This does not make any economic sense.

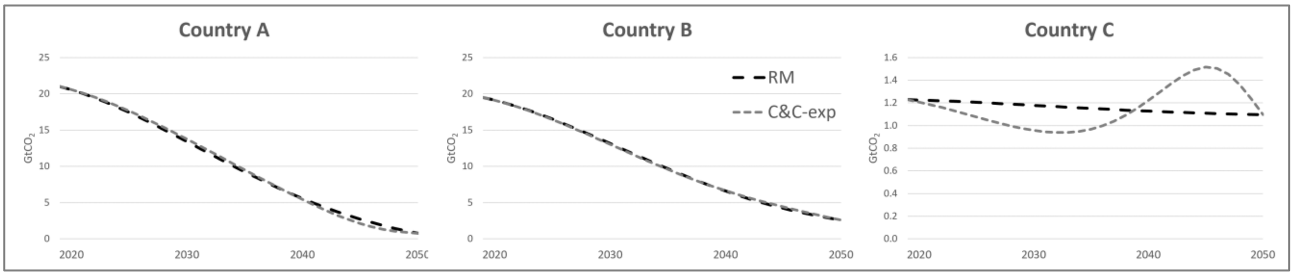

Figure 4: Comparison C&C-exp (a = 8) and RM – emission paths

Finally, we would like to stress that in the RM $\overline{C_t}$ is determined by the underlying global path. In C&C, by contrast, $\widehat{C_t}$, which specifies how fast the per capita distribution comes into effect, can be chosen arbitrarily.

3 Emission Probability Model (EPM)

The Emission Probability Model from Chakravarty, S. et al. not only takes emissions and population into consideration, but also the income distribution of a country (cf. Chakravarty, et al., 2009). EPM assumes that the emission distribution is a scaled income distribution. Then EPM allocates a country the emissions of its inhabitants whose emissions are below a cap and the cap for each inhabitant whose emissions are above the cap. The global cap is chosen each year such that the global emissions are met. Thus EPM, as well as the convergence models in Chapter 2, allocates a preset global path to all countries.

In EPM the emissions of country *i* in the year *t* are given by

$$E_t^i = P_t^i \left(\int_{-\infty}^{CA_t} z \, \tilde{f}^i(z; p^i) \, dz \, + CA_t \int_{CA_t}^{\infty} \tilde{f}^i(z; p^i) \, dz \right), \tag{3}$$

where

CA_t the cap in the year *t* and

$\tilde{f}^i(z; p^i)$ the estimated emission probability density function (PDF) of country *i* with parameters p^i.

4 Extended Smooth Pathway Model (ESPM)

Approaches within the framework of the Extended Smooth Pathway Model (ESPM) derive national budgets directly from a global budget. The distribution keys used for this purpose represent resource sharing models in the strict sense. However, these approaches are only complete with the second step: deriving national emission paths that adhere to the national budget.

Remark: Excel tools can be downloaded from http://downloads.save-the-climate.info that can be used to calculate emission paths for all countries in the world using the ESPM approach [cf. (Wolfsteiner & Wittmann, 2024c) and (Wolfsteiner & Wittmann, 2024b). An overview of the ESPM web apps available is given at https://climate-calculator.info.

4.1 Determination of national budgets

A lot of criteria on how to obtain a budget for each country (gross domestic product (per capita), cumulative emissions per capita, emissions in the past, …) are possible (see also Note 2). But there are two outstanding criteria: population in a base year (equity) and emissions in a base year (inertia). *“These two alternatives act as bounds to a range of blended options, and demonstrate how national quotas [national budgets] can be allotted using any mix of the two alternatives, […]”* (Peters, et al., 2015, p. 3). With this two-dimensional distribution key, the current emissions reflect the current reality, and the population shares address the issue of climate justice. Raupach, M. R. et al. therefore suggest the following formula for allocating a global budget to countries, which we will also use below (cf. Raupach, et al., 2014)):

$$B^i = \left(C * \frac{P^i_{BY}}{P_{BY}} + (1 - C) * \frac{E^i_{BY}}{E_{BY}} \right) * B \tag{4}$$

where

B global budget

B^i budget of country i

C weighting of the population

However, national budgets may also be set differently under the ESPM.

In the following chapter, approaches are shown how plausible national emission paths can be derived from a national budget.

Formula (4) can also be used to determine an indicator for an NDC if a national budget can be derived from it.[5] Using this national budget as well as the emissions and the population in a base year the implicit weighting of population (*IWP*) can be calculated:

$$C = \frac{B^i - B * \frac{E^i_{BY}}{E_{BY}}}{B * (\frac{P^i_{BY}}{P_{BY}} - \frac{E^i_{BY}}{E_{BY}})} = IWP \tag{5}$$

The Supplementary Excel Tool 2 provides a database for emissions and population for all countries in the world (Wolfsteiner & Wittmann, 2024e).

4.2 Determination of national emission paths

4.2.1 Smooth Pathway Formula (SPF)

Raupach, M. R. et al. also showed how to transform the allocated budget of a country into a positive path (i. e. a path which has no net negative emissions), with a smooth transition from the current path and with near-zero emissions at infinity (cf. Raupach, et al., 2014).[6]

According to this Smooth Pathway Formula, the emissions of country *i* in the year *t* (E^i_t) are given by

$$E^i_t = -\dot{E}^i_{BY+1} \frac{e^{-m^i(t-BY)}}{(m^i)^2} \left[\left(r^i m^i + \left(m^i\right)^2 \right)(t - BY) + 2m^i + r^i \right] \tag{6}$$

$$+\dot{E}^i_{BY+1} \frac{e^{-m^i(t-BY-1)}}{(m^i)^2} \left[\left(r^i m^i + \left(m^i\right)^2 \right)(t - BY - 1) + 2m^i + r^i \right],$$

where

$\dot{E}^i_{BY+1}$ emission power, i. e. the derivative of emissions with respect to time or the emissions per unit of time, of country *i* at the end of the base year,

r^i change rate of the emission power of country *i* at the end of the base year and

m^i the mitigation rate (or the decay parameter) of country *i*.

If $r^i > -1/T^i$, the mitigation rate m^i is given by

$$m^i = \frac{1 + \sqrt{1 + r^i T^i}}{T^i},$$

where $T^i = \frac{RB^i}{\dot{E}^i_{BY+1}}$ is the time defined by the budget of country *i* and the emission power of country *i* at the end of the base year.

4.2.2 *Regensburg Model Scenario Types*

We use under the framework of the Extended Smooth Pathway Model (ESPM) the Regensburg Model Scenario Types to derive national paths from a national budget [cf. (Wiegand, et al., 2021), (Sargl, et al., 2021), (Sargl, et al., 2024a) and (Sargl, et al., 2024b)]. These RM Scenario Types differ in the assumption about the property of the annual changes in emissions. The annual changes in emissions can be described via annual change rates (RM 1 – 5; see Figure 5) or annual reduction amounts (RM-6). Table 2 gives an overview of the RM Scenario Types.

scenario type	course of the annual reduction rates		basic function type of the annual reduction rates	course of the annual reduction amounts	course of the emission paths
RM-1-const	linear		$y = const$	concave	convex
RM-3-lin	linear		$y = ax + b$	u-shaped	s-shaped (first concave then convex)
RM-4-quadr	concave		$y = ax^2 + b$		
RM-5-rad	convex		$y = a\sqrt{x} + b$		
RM-6-abs	concave		-	constant	linear

Table 2: Overview of Regensburg Model Scenario Types

With the RM Scenario Types, (global and national) paths can be derived that adhere to a certain budget. The entire range of plausible possibilities is offered. It should be emphasized that annual rates of change are applied in many fields, such as economic growth, inflation, change in employment etc, and are particularly suitable for determining a meaningful trajectory of emission paths. For a comprehensive mathematical description, we refer to the corresponding Supplementary Text 2 (Wolfsteiner & Wittmann, 2023).

Figure 5 shows for country A the resulting emission paths and courses of the annual rates of change [population is weighted at 50% in the weighting formula (4)].

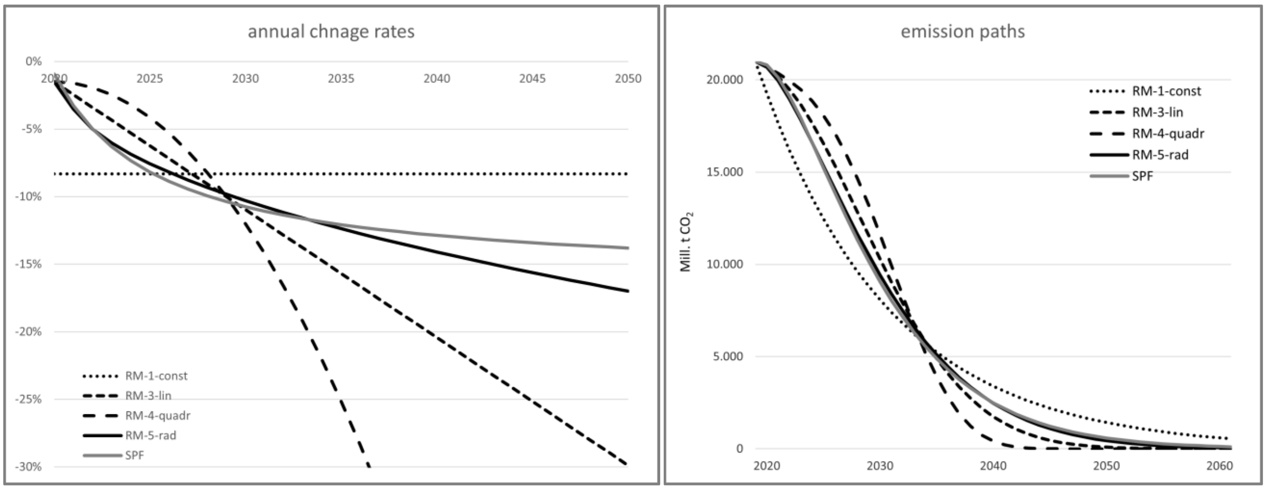

Figure 5: Country A – exemplary courses RM Scenario Types

The properties of RM Scenario Types can also be easily understood with the following web app: http://paths.climate-calculator.info.

The curve of the annual change rates for the SPF correlates with the scenario type RM-5-rad. For clarity, the following chapter does not present the results of the RM Scenario Types separately.

Remark: The global paths in Figure 1 used the following RM Scenario Types:

- Number 1: RM-1-const
- Number 2: RM-4-quad
- Number 3: RM-3-lin

5 Comparison of the models

Figure 6 shows the emission paths 2020 – 2050 of the pure type countries resulting from the presented models for a comparison and Figure 7 depicts their per-capita emissions. For a detailed comparison of the models in Chapter 2 we refer to the results in Chapter 2.4.

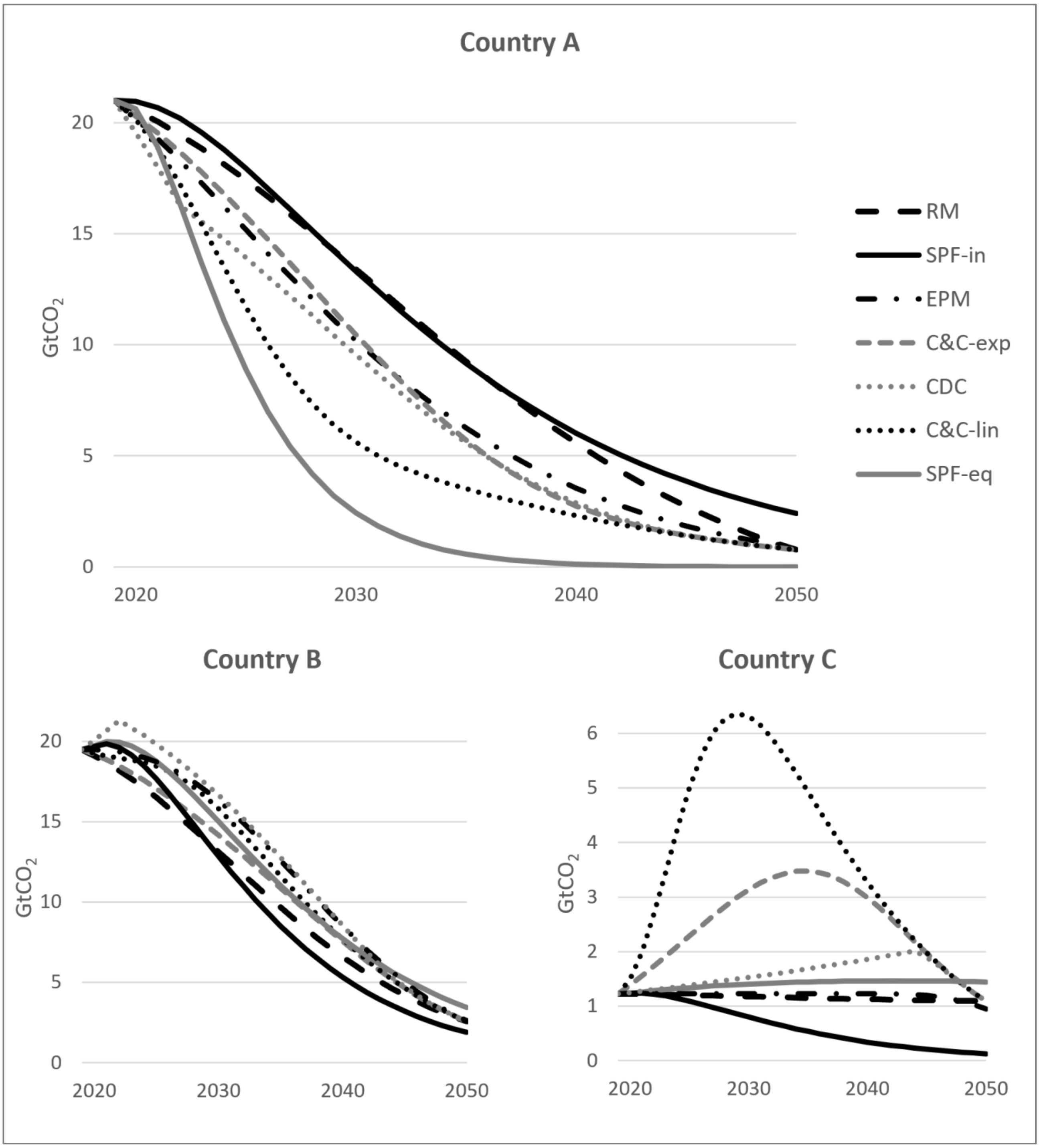

Figure 6: Comparison of resource sharing models – emission paths 2020 - 2050

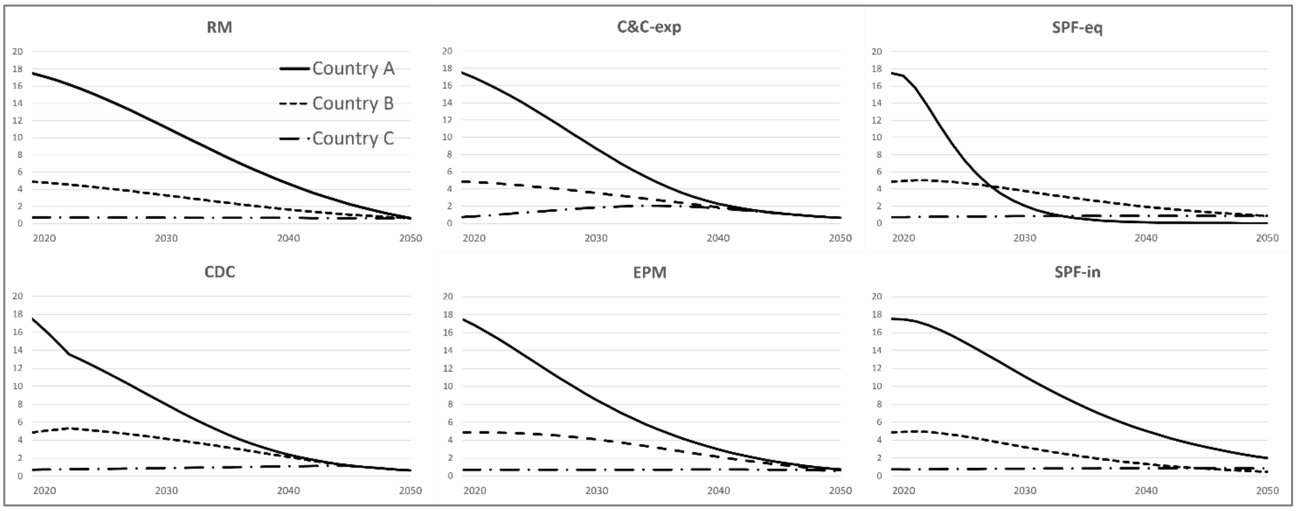

Figure 7: *Comparison of resource sharing models – t per capita emissions 2020 - 2050*

Notes on Figure 6 and on Figure 7:

- SPF-in ("inertia") means that the weighting of the population is set to 0% in formula (4) for calculating the national budgets. SPF-eq ("equity") means that the weighting of the population is set to 100%.
- The SPF correlates with the scenario type RM-5-rad in the ESPM (see Chapter 4.2.2).

5.1 RM most favourable for industrial countries

Figure 6 shows that, if SPF-in, the model that doesn't take population into account at all, is left aside, RM is clearly the most favourable resource sharing model for industrial countries.

5.2 Consideration of population

The idea of the models in Chapter 2 is an annual increase of the influence of the allocation key "population", whereas ESPM approaches can consider

when determining national budgets. EPM does not take into account population as an allocation key but calculates a global cap for per capita emissions.

5.3 Convergence

Convergence models lead to positive identical per capita emissions in a given convergence year (here: 2050). Converging per capita emissions do not necessarily result from the EPM and ESPM.[7] But the SPF leads to zero emissions at infinity. Therefore, from a mathematical point of view, the SPF leads also to per capita emissions that are converging.

5.4 Role of the global path

In contrast to the other resource sharing models, ESPM approaches do not share a global path, but a global budget. National paths can then be calculated, and the global path is obtained by summing up national paths. The global path is therefore an output value of ESPM approaches, whereas in the other models the global path is an input value.

5.5 Dependence of national budgets on the global path

Convergence models have the property that the implicit weighting of the population [see Formula (5)] is the same for all countries and is also independent of the global budget chosen (cf. Wittmann & Wolfsteiner, 2023). This means that the implicit weighting of the population - as a feature of a global path - can be calculated from data of a single country.

In order to illustrate the impact of the choice of the global path, we considered significant different positive global paths (see Figure 1) meeting the same global budget for the period from 2020 - 2100. This led to the results in Table 3, which can be summarized as follows:

- Global paths that foresee high annual reduction rates only in a late phase are more favourable for industrialised countries than global paths that foresee high reductions in an early phase, from the point of view that reducing emissions entails disadvantages for a country (cf. Wittmann & Wolfsteiner, 2023).
- The results illustrate once again that the RM is the most favourable of the approaches considered[8] here for industrialised countries, as this model has the lowest implicit weighting of the population regardless of the global path chosen (see Table 3). Whereby the level of implicit weighting of the population strongly depends on the chosen global path.

Number of the global path in Figure 1	2	3	1
RM	3%	15%	35%
C&C-exp	39%	43%	51%
C&C-lin	68%	69%	73%
EPM	11%	18%	30%

Table 3: Implicit weighting of population resulting from different global paths[9]

5.6 Limitations of convergence models in determining national paths

In Figure 8 the global path number 3 (see Figure 1) was used for the RM emission paths 2020 – 2100 (convergence period: 2020 – 2050). This global path has an implicit weighting of the population (IWP) of 15% (see Table 3). Figure 8 also shows the SPF paths when applying this implicit weighting in Formula (4) as the basis auf the national budgets.

The results for country C show that convergence models are limited in their ability to generate plausible emission paths over the entire budget period, especially if convergence is to occur before the end of the budget period.

Convergence models are therefore more suitable for determining national CO2 budgets with convergence of per capita emissions or the resulting implicit weighting of the population. The results can then be used in the ESPM to derive plausible national emission paths over the entire budget period.

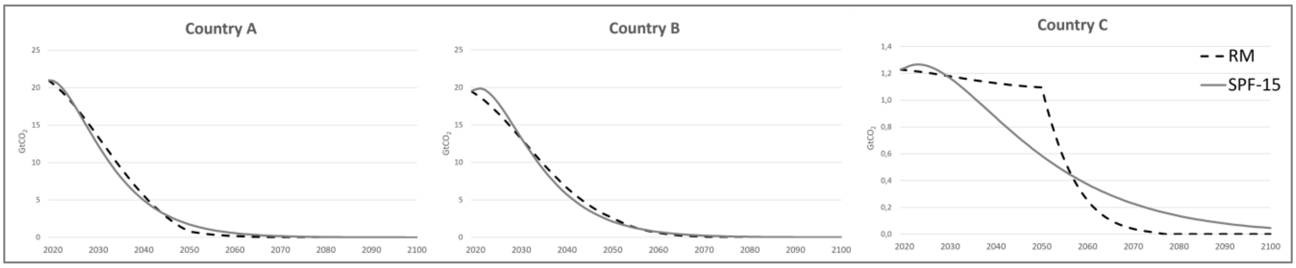

Figure 8: Comparison of emission paths RM and SPF 2020 - 2100

5.7 Further characteristics of the national emission paths of the approaches

The ESPM approaches shown here, CDC and EPM in one way or another take into consideration the national change rate of emissions from the base year. Usually this leads to a soft transition from the emissions in the base year.

If the effects of changes in population are suppressed and if global emissions fall, then the EPM is the only model that also continually reduces the emissions in the developing countries after a base year.

National paths under the EPM will always decline. National paths under the SPF decline after peaking shortly after the base year (see Figure 8).

In contrast, the national path of country C in C&C, shows a change in the gradient within the convergence period (see Figure 6).

6 Conclusions

The direct comparison of resource sharing models using three pure type countries has revealed significant differences between the models.

Leaving aside SPF-in, the model that doesn't take population into account at all, RM is the most favourable resource sharing model for industrial countries. The RM tends to have the highest implicit budgets and the lowest implicit weighting of the population and can therefore be seen as a kind of moral lower limit for the ambitions of industrialised countries if they accept equal per capita rights as a goal. They will otherwise have difficulty explaining their NDCs if they fall below this floor.

If a convergence model or EPM is used to justify or to assess NDCs, the underlying global path must be disclosed, because its results depend on the selected global path.

Convergence models reach their limits when it comes to calculating plausible national emission paths for all countries over the entire budget period. However, convergence models and the EPM can provide information for national budgets and for the weighting of the population in an ESPM approach.

In an overall assessment of the characteristics of the models, ESPM approaches have the advantage that the question of climate justice is addressed explicitly and does not depend on a global path. Furthermore, the SPF and the RM Scenario Types lead to smooth paths until infinity. The RM Scenario Types have the additional advantage that a meaningful course of the annual emission changes can be selected on the basis of a specific holistic climate policy perspective of a country. Emission paths can also be avoided that first imply a build-up of a more fossil-based economy, which would then have to be decarbonised again very quickly.

The global remaining budget to be met is ultimately a political decision based on current scientific knowledge. In particular, if a global budget is to be temporarily exceeded, with the excess amount being compensated for by global net negative emissions, a global budget by the end of this century would make sense. However, it is no longer enough to just keep this budget. Furthermore, it must be ensured that the temporary overshoot is still compatible with the desired limitation of global warming, especially with regard to tipping points in the climate system. This also means that countries are not completely free to choose their path when using an ESPM approach that can also map net negative emissions.

Considering the Paris Ambition Mechanism (Ratcheting Mechanism), the focus should be more on the national budgets seen as a fair and economical reasonable share of a global budget. We have shown that resource sharing models are a useful aid in this. The fact that the Paris Ambition

Mechanism is a bottom-up approach does not mean that one should not ask what an adequate contribution of individual countries to the necessary global effort is. On the contrary, we need a global discourse on this issue in order to arrive NDCs that are Paris-compatible in sum.

Furthermore, it would make sense to calculate the weighting of the allocation keys "current population" and "current emissions" leading to the same national budgets that result from NDCs [see Formula (5)]. This makes clear, which implicit weighting of the allocation key "current population" is considered as legitimate. Thus, this implicit weighting of population could contribute to a more rational discourse of the core question: Who gets, respectively takes, how much of a global budget?

Notes

[1] "*There are two broad approaches to sharing emissions reduction efforts:*

- *sharing the global emissions budget - 'resource-sharing'*
- *sharing the emissions reductions required to meet that budget - 'effort-sharing'* [or 'burden sharing'] […].

In some ways, the two approaches are similar - sharing the remaining budget implicitly sets a mitigation task and vice versa. From a practical perspective, resource-sharing approaches are more straightforward, as they require only an estimate of the global emissions budget and equitable principles. In contrast, effort-sharing also requires an estimate of global emissions in the absence of climate change action; that is, a BAU trajectory. As more countries take more action, this trajectory becomes increasingly abstract and difficult to estimate." (Australian Government Climate Change Athority, 2014)

[2] Four basic allocation approaches can be distinguished: (1) capability, (2) equality, (3) responsibility and (4) grandfathering (cf. du Ponte, et al., 2017, p. 40). Using this classification, the models in Chapter 2 represent a mixture of categories (2) and (4). This is also the case for the ESPM approaches in Chapter 4 when the weighting formula (4) of Raupach et al. is used. However, any approach can be taken there to determine a national budget in the ESPM. The EPM in Chapter 3 additionally tries to include category (1). "The Climate Equity Reference Calculator" is an example of the possible application of a complex mix of criteria (Kemp-Benedict, et al., 2019).

See also corresponding excursus in (Sargl, et al., 2024b) on the question of the allocation of a global budget.

[3] LIMITS, a research project funded by the EU, defines the emissions of country *i* in the year *t* $\left(\widetilde{E_t^i}\right)$ explicitly (cf. Tavoni, et al., 2013):

$$\widetilde{E_t^i} := \begin{cases} \left(\left(1 - \widetilde{C_t}\right) * \frac{E_{BY}^i}{E_{BY}} + \widetilde{C_t} * \frac{P_t^i}{P_t} \right) * E_t, & \text{for } BY + 1 \leq t < CY \\ \frac{P_t^i}{P_t} * E_t, & \text{for } CY \leq t \end{cases}$$

[4] The Regensburg Model includes more than the Regensburg Formula, since global paths can also be determined by using the Regensburg Model Scenario Types [cf. Chapter 4.2.2 and (Wolfsteiner & Wittmann, 2023)].

[5] Here is a tool for deriving an implicit CO_2 budget from Germany's climate protection act: (Wolfsteiner, 2024).

[6] In the corresponding Supplementary Text 1 we show a Generalized Smooth Pathway Formula, which can also map net negative emissions (cf. Wittmann & Wolfsteiner, 2023).

[7] EPM only leads to converging per capita emissions, if global emissions tend to zero. As each country can determine its own emissions path in the ESPM, converging per capita emissions do not result from the model.

[8] If the convergence period is shortened in convergence models, emissions are earlier distributed exclusively according to population. This leads to a higher implicit weighting of the population.

[9] As the implicit weighting of the population is not the same for all countries in the EPM, the weighting was calculated in a way that sum of the relative quadratic deviations of the countries between the budget resulting from the EPM and the budget resulting from the weighting of the population takes on a minimum (see Supplementary Excel Tool 1).

References

Australian Government Climate Change Athority, 2014. *Appendix C Sharing the global emissions budget.* [Online]
Available at: http://resource-sharing.save-the-climate.info/

Chakravarty, S. et al., 2009. Sharing global CO2 emision reductions among one billion high emitters. *PNAS*, 106(29), p. 11884 – 11888.

du Ponte, Y. R. et al., 2017. Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, Jannuary, Volume 7, pp. 38 - 40.

Höhne, N., den Elzen, M. & Weiss, M., 2006. Common bud differentiated convergence (CDC): a new conceptual approacht to long-term climate policy. *Climate Policy*, Volume 6, pp. 181 - 199.

IPCC, 2018. *Special Report 1.5°C. Summary for Policymakers.*. [Online]
Available at: https://www.ipcc.ch/sr15/
[Accessed 15 12 2018].

Kemp-Benedict, E. et al., 2019. *The Climate Equity Reference Calculator.* [Online]
Available at: https://calculator.climateequityreference.org/

Meyer, A., 1998. *The Kyoto Protocol and the Emergence of 'Contraction and Convergence' as a Framework for an International Political Solution to Greenhouse Gas Emissions Abatement.* Heidelberg: Physica-Verlag.

Meyer, A., No date. *Contraction & Convergence.* [Online]
Available at: http://www.gci.org.uk
[Accessed 7 12 2016].

Peters, G. P., Andrew, R. M., Solomon, S. & Friedlingstein, P., 2015. Measuring a fair and ambitious climate agreement using cumulative emissions. *Environmental Research Letters*, 15 October, Volume 10.

Raupach, M. R. et al., 2014. Sharing a quota on cumulative carbon emissions. *Nature Climate Change*, Volume 4, pp. 873 - 879.

Sargl, M., Wiegand, D., Wittmann, G. & Wolfsteiner, A., 2021. Berechnung Paris-kompatibler Emissionsziele für die sechs größten Emittenten mit dem ESPM. *Zeitschrift für Umweltpolitik & Umweltrecht*, Issue 3/2021, pp. 269 - 286.

Sargl, M., Wiegand, D., Wittmann, G. & Wolfsteiner, A., 2024a. *Berechnung Paris-kompatibler Emissionspfade mit dem ESPM am Beispiel Deutschlands und der EU.* [Online]
Available at: https://doi.org/10.5281/zenodo.5678717

Sargl, M., Wiegand, D., Wittmann, G. & Wolfsteiner, A., 2024b. *Calculation of Paris-compatible emission targets for the six largest emitters with the ESPM.* [Online]
Available at: https://doi.org/10.5281/zenodo.4764408

Sargl, M., Wittmann, G. & Wolfsteiner, A., 2024c. *Calculation of Paris-compatible emission targets for the six largest emitters with the Regensburg Model.* [Online]
Available at: https://doi.org/10.5281/zenodo.4764408

Sargl, M., Wolfsteiner, A. & Wittmann, G., 2017. The Regensburg Model: reference values for the (I)NDCs based on converging per capita emissions. *Climate Policy*, 17(5), p. 664 – 677.

Tavoni, M. et al., 2013. The distribution of the major economies' effort in the Durban platform scenarios. *Climate Change Economics*, 4(4), pp. 1340009-1 - 1340009-25.

Wiegand, D. et al., 2021. Berechnung Paris-kompatibler Emissionspfade mit dem ESP-Modell am Beispiel der EU. *Wirtschaftsdienst*, 20 2, pp. 127 - 133.

Wittmann, G. & Wolfsteiner, A., 2023. *Resource Sharing Models − A Mathematical Description.* [Online]
Available at: https://doi.org/10.5281/zenodo.4405448

Wolfsteiner, A., 2024. *Ableitung eines impliziten CO2-Budgets für Deutschland aus dem Klimaschutzgesetz.* [Online]
Available at: https://doi.org/10.5281/zenodo.6535174

Wolfsteiner, A. & Wittmann, G., 2023. *Mathematical Description of the Regensburg Model Scenario Types RM 1 – 6.* [Online]
Available at: https://doi.org/10.5281/zenodo.4540475

Wolfsteiner, A. & Wittmann, G., 2024a. *Distribution of a remaining global CO2 budget - tool for comparing Resource Sharing Models.* [Online]
Available at: https://doi.org/10.5281/zenodo.13221889

Wolfsteiner, A. & Wittmann, G., 2024b. *Tool for the Calculation of Emission Paths with the RM Scenario Types.* [Online]
Available at: https://doi.org/10.5281/zenodo.4568839

Wolfsteiner, A. & Wittmann, G., 2024c. *Tool for the Calculation of Paris-compatible Emission Paths with the ESPM.* [Online]
Available at: https://doi.org/10.5281/zenodo.4580310

Wolfsteiner, A. & Wittmann, G., 2024d. *Tool for the Calculation of Paris-compatible National Emission Paths with the Regensburg Model.* [Online]
Available at: https://doi.org/10.5281/zenodo.5846043

Wolfsteiner, A. & Wittmann, G., 2024e. *Tool: Implicit and explicit weighting of the population in the allocation of a global CO2 budget.* [Online]
Available at: https://doi.org/10.5281/zenodo.5837866

Supplementary material

- Supplementary Text 1: Resource Sharing Models - A Mathematical Description (Wittmann & Wolfsteiner, 2023)
- Supplementary Text 2: Mathematical Description of the Regensburg Model Scenario Types RM 1 – 6 (Wolfsteiner & Wittmann, 2023)
- Supplementary Excel Tool 1: Comparison Resource Sharing Models (Wolfsteiner & Wittmann, 2024a).
- Supplementary Excel Tool 2: Implicit and explicit weighting of the population in the allocation of a global CO_2 budget. The tool contains a database on emissions and population figures for all countries in the world (Wolfsteiner & Wittmann, 2024e).