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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

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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 will therefore give 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 possible additional helpful assessment criterion for NDCs: the implicit weighting of population.

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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 total.

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. 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 Smooth Pathway Models in Chapter 3 calculates national pathways starting from allocated national budgets. The Emission Probability Model in Chapter 4 determines country specific emission density functions and caps the emissions of individuals.[2]

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 pathways

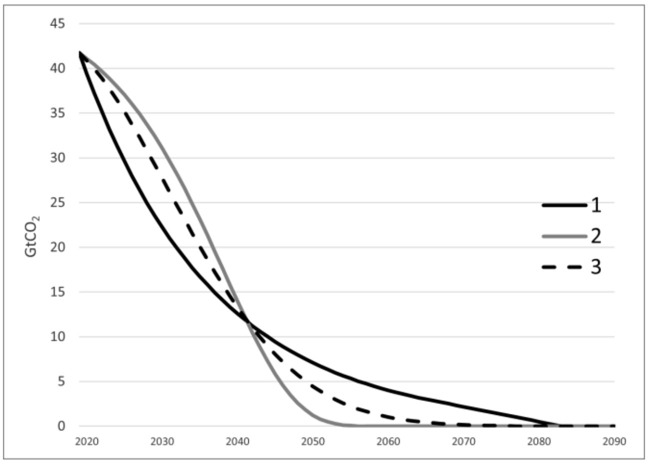

Figure 1: Exemplary global pathways that meet a specific budget[3]

We did not use pathways with global negative emissions because some models cannot map net negative emissions.

In the following we used the global pathway 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 sum the pure type countries approximately reflect the global data. 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 Tool.

For a mathematical description of the models with proofs of its properties we refer to the corresponding Supplementary Text (Wittmann, 2022).

2 Convergence Models

All convergence models presented here start with a global pathway 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)[4]:

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

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.

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 (Wittmann, 2022).

2.2 Regensburg Model (RM)

In the Regensburg Model[5] 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):

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

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 from www.save-the-climate.info with which emission paths for all countries in the world can be calculated using the Regensburg Model (Wolfsteiner & Wittmann, 2022c).

2.3 Different pathways 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 pathways 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

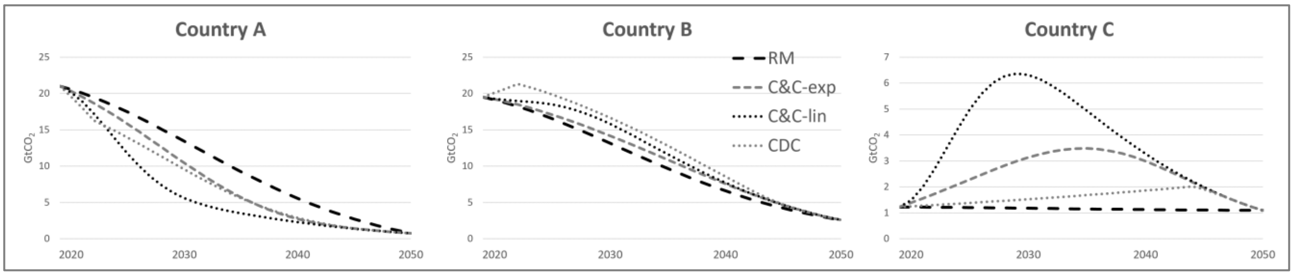

Figure 2: Comparison of the convergence models – emission pathways (C&C-exp a = 4)

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. As a consequence, 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 pathway the weight of population $\widehat{C_t}$ in C&C can be calculated in such a way that the resulting national pathways of C&C and the RM are the same if the population is frozen (see Figure 3). This allows making clear the different weighting of population in the RM and in C&C-exp.

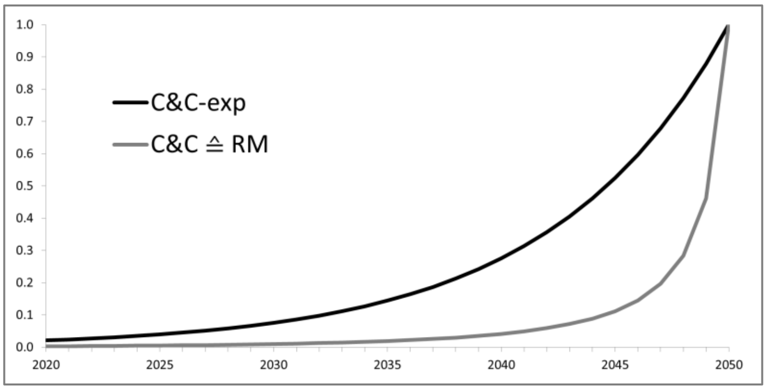

Figure 3: Comparison C&C-exp (a = 4) and RM – population weighting over time

We also examined whether the results of the RM and the C&C model with the "classic exponential" specification of C&C (C&C-exp) are similar (see Figure 4). Choosing the parameter *a* = 8, we obtained similar results for the industrial country A and the emerging country B. However, the results for the developing country C are different.

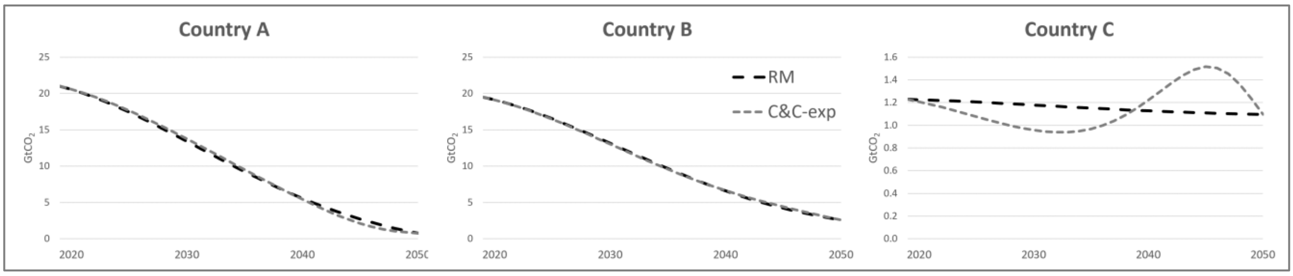

Figure 4: Comparison C&C-exp (a = 8) and RM – emission pathways

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

3 Smooth Pathway Models (SPM)

Smooth Pathway Models derive national budgets directly from a global budget. These approaches represent resource sharing models in the narrower sense. However, these approaches are only complete when in a second step national emission paths are derived from the national budgets.

3.1 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 in the following (cf. Raupach, et al., 2014)):

$$B^i = \left(\check{C}_{RB} * \frac{P_{BY}^i}{P_{BY}} + \left(1 - \check{C}_B\right) * \frac{E_{BY}^i}{E_{BY}}\right) * B \tag{3}$$

where

B global budget

B^i budget of country i

$\check{C}_B$ weighting of population

However, national budgets can also be determined differently under the SPM approach.

In the following, approaches are shown to derive plausible national emission pathways from a national budget.

3.2 Determination of national pathways

3.2.1 Smooth Pathway Formula (SPF)

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

In this Smooth Pathway Formula, the emissions of country *i* in the year *t* (E_t^i) are given by

$$E_t^i = -\dot{E}_{BY+1}^i \frac{e^{-m^i(t-BY)}}{(m^i)^2}\left[\left(r^i m^i + \left(m^i\right)^2\right)(t-BY) + 2m^i + r^i\right]$$
$$+\dot{E}_{BY+1}^i \frac{e^{-m^i(t-BY-1)}}{(m^i)^2}\left[\left(r^i m^i + \left(m^i\right)^2\right)(t-BY-1) + 2m^i + r^i\right], \quad (4)$$

where

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

3.2.2 Extended Smooth Pathway Model (ESPM)

The Extended Smooth Pathway Model[1] uses several types of scenarios to derive national paths from a national budget. These Regensburg Model Scenario Types (cf. Wolfsteiner & Wittmann, 2022a) differ in the assumption about the property of the annual changes in emissions. The annual changes in emissions can be described via annual reduction rates (RR_t; RM 1 – 5; see Figure 5) or annual reduction amounts (RA_t; RM-6). Table 2 gives an overview of the RM Scenario Types.

With the RM Scenario Types, plausible (global and national) paths can be derived that adhere to a certain budget. For a comprehensive mathematical description, we refer to the corresponding Supplementary Text (Wolfsteiner & Wittmann, 2022a).

[1] See publications with exemplary reference values calculated with the ESPM for Germany and the EU (Sargl, et al., 2022a) and for the six largest emitters (Sargl, et al., 2022b).

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 pathways
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

For country A, a population weighting of 50% results in a national budget of 232 Gt CO_2 from 2020 on using the above Weighting Formula (3), which is the basis for Figure 5. The course of the reduction rates for SPF corresponds to scenario type RM-5-rad.

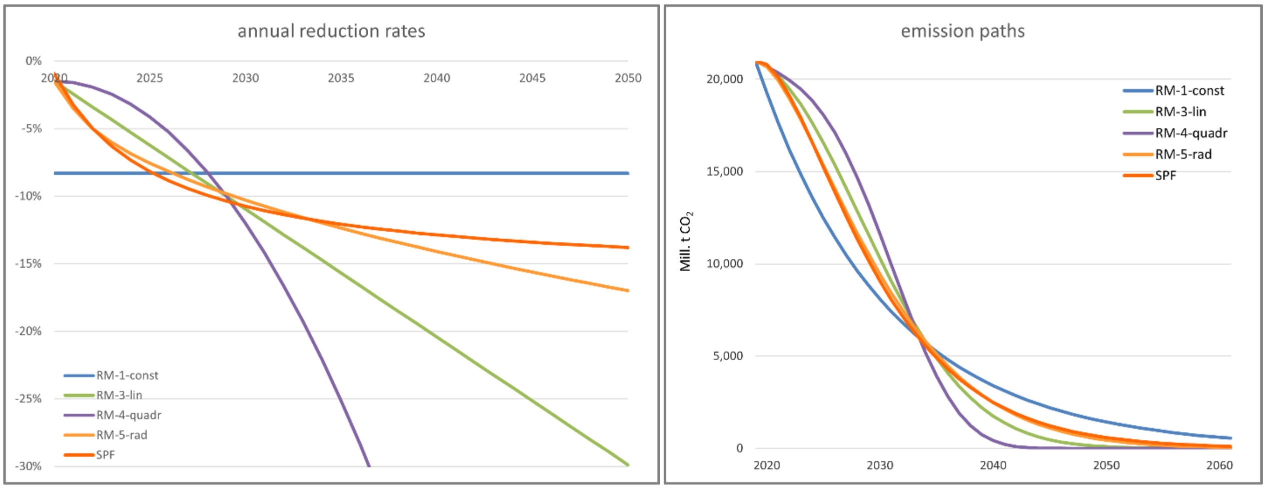

Figure 5: Country A – exemplary courses RM Scenario Types (weighting population: 50%)

Excel tools can be downloaded from www.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, 2021) and (Wolfsteiner & Wittmann, 2022b). An overview of the ESPM web applications available is given at https://climate-calculator.info.

4 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 pathway to all countries.

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

$$E_t^i = P_t^i \left(\int_{-\infty}^{CA_t} z\, \tilde{f}^i(z; p^i)\, dz \; + CA_t \int_{CA_t}^{\infty} \tilde{f}^i(z; p^i)\, dz \right), \tag{5}$$

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.

5 Comparison of the Models

The Figure 6 show the emission pathways and the Figure 7 the per-capita emissions of the pure type countries resulting from the presented models for a comparison:

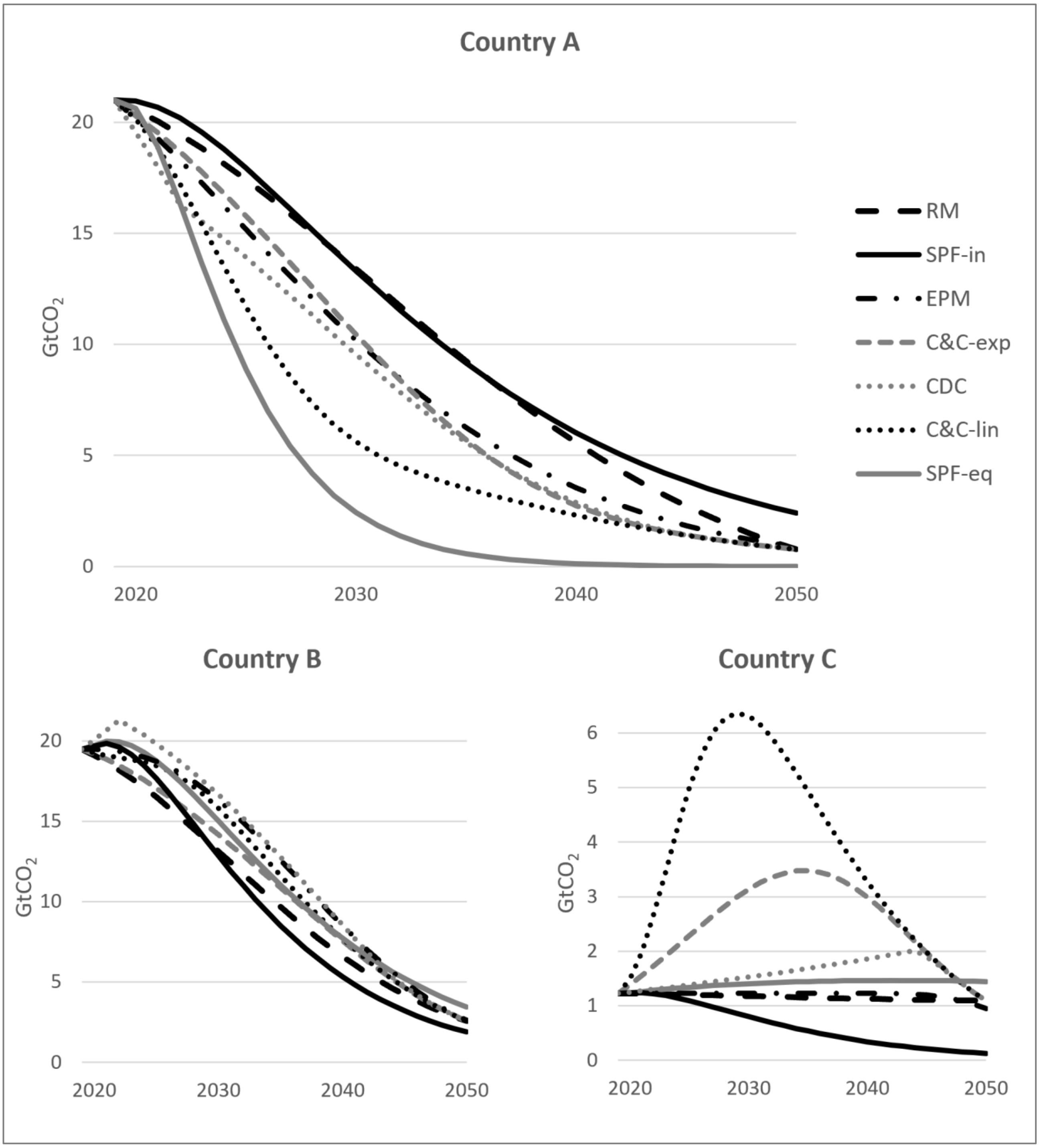

Figure 6: Comparison of Resource Sharing Models – emission pathways

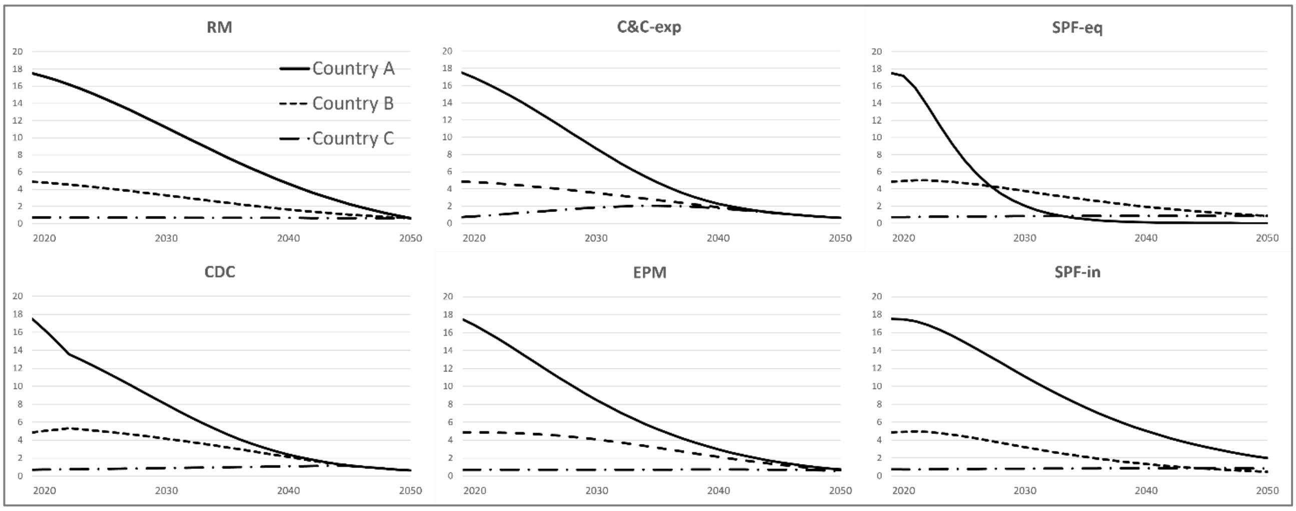

Figure 7: *Comparison of Resource Sharing Models – t per capita emissions*

The SPF corresponds with the scenario type RM-5 in the ESPM. SPF-in means weighting the population with 0% and SPF-eq with 100%.

Figure 6 shows that, if SPF-in is not taken into account, RM is clearly the most favourable resource sharing model for industrial countries. For a detailed comparison of the models in Chapter 2 we refer to the results in Chapter 2.4.

The following key figures of the models can be reproduced with the help of the Supplementary Tool.

Approximation of C&C, RM and EPM with SPF

In the model with three pure type countries and the underlying global pathway (number 3 in Figure 1) we approximated the pathways of C&C-exp (a = 4), RM and EPM with SPF, minimising the sum of the squared relative deviations in each year. By this means we obtained a weighting of the population (see Formula (3)) of 50% for C&C-exp (a = 4), 16% for RM (see Figure 8) and 24% for EPM.

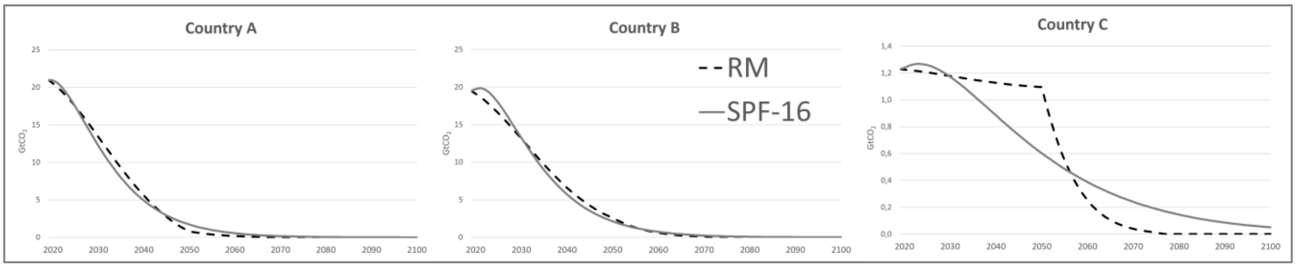

Figure 8: Comparison SPF (weighting population: 16%) and RM – emission pathways

Consideration of population

The idea of the models in Chapter 2 is an annual increase of the influence of the allocation key “population”, whereas SPMs can only consider population once when determining national budgets.

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

Convergence

Convergence models lead to positive identical per capita emissions in a given convergence year. The SPF leads to zero emissions at infinity. Therefore, from a mathematical point of view, SPF leads to per capita emissions that are converging. EPM only leads to converging per capita emissions when global emissions are tending to zero.

Role of the global pathway

In contrast to the other resource sharing models, SPMs does not share a global pathway, but a global budget. National pathways can then be calculated and the global pathway is obtained by summing up national pathways. The global pathway is therefore an output value of SPMs, whereas in the other models the global pathway is an input value. Due to the SPF, the resulting global pathway at the beginning has relatively fast declining emissions. This should be taken into account when comparing national reference values of the different models.

Dependence of national budgets on the global pathway

In the convergence models and the EPM the national budgets also depend on the choice of the global pathway. Here the principle holds that global pathways that stipulate high reductions only at a late stage are more favourable - from the perspective that the reduction of emissions carries disadvantages for a country - for industrial countries than global pathways that stipulate high reductions at an early stage. This property holds all the more for the RM, since its weighting of population also depends on the global pathway.

In order to illustrate the impact of the choice of the global pathway, we considered significant different positive global pathways (see Figure 1) meeting the same global budget for the period from 2020 - 2100. We then calculated with the different global pathways the national budgets that result from the RM, C&C-exp, C&C-lin and EPM. We also calculated the national budgets directly with a weighting of the allocation keys "population" and "emissions in a base year" using Formula (3). We then minimised over the weighting of population the sum over each country of the squared relative deviations of the two national budgets (best approximation of the national budgets of the RM, C&C and EPM with a direct blended allocation of population and emissions in a base year). This led to the results in Table 3.

If the population is frozen and if there are no global negative emissions in the period under consideration the results of the convergence models (RM, C&C-exp and C&C-lin) do not depend on whether a „pure type country model“ or the “real world” is used. The weighting of population is hence a characterising key figure of the convergence model that depends only on the global pathway (cf. Wittmann, 2022).

Number of the global pathway in Figure 1	2	3	1
RM – pure type country model and real world	3%	15%	35%
C&C-exp – pure type country model and real world	39%	43%	51%
C&C-lin – pure type country model and real world	68%	69%	73%
EPM – pure type country model	11%	18%	30%

Table 3: Weighting of population resulting from different global pathways

This finding leads to the idea that such a key figure should also exist for NDCs. It should be possible to deduct a national emission pathway and then the national budget. Using this national budget as well as the emissions and the population in a base year the implicit weighting of population can be calculated (cf. Formula (3)):

$$\mathrm{C} = \frac{B^i - B * \frac{E^i_{BY}}{E_{BY}}}{B * (\frac{P^i_{BY}}{P_{BY}} - \frac{E^i_{BY}}{E_{BY}})} \qquad (6)$$

A corresponding tool can be found under Supplementary Material, with a database for emissions and population for all countries in the world (Wolfsteiner & Wittmann, 2022d).

Further properties of the models under consideration

- In SPF with a low weighting of the population, developing countries have to reduce their emissions relatively quickly, but emissions remain at a higher level longer than in the RM (see Figure 8).
- 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.
- SPMs, CDC and EPM in one way or another take into consideration the change rate of emissions from the base year. Usually this leads to a soft transition from the emissions in the base year.
- SPF always leads to positive national pathways. Hence, the resulting global pathway is also always positive. SPF can therefore map neither global nor national net negative emissions in a year. In contrast, net negative emissions can be mapped with the ESPM.
- National pathways under the EPM will always decline. National pathways under the SPF will fall after they have reached a maximum. In contrast national pathways, particularly of

developing countries in C&C, show a change of direction within the convergence period. The pathways of developing countries in the RM usually show a clear kink at the end of the convergence year if the global pathway declines rapidly after the convergence period (see Figure 8). If the global path has already reached a low level after the end of the convergence period, the kink does not occur.

6 Conclusion

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

If SPF-in is not taken into account, RM is the most favourable resource sharing model for industrial countries. Therefore, national emission pathways calculated with the RM describe a floor of ambition for industrial countries if they accept taking into account equal per capita rights as an aim. They will otherwise have difficulty explaining their NDCs if they fall below this floor.

In an overall assessment of the characteristics of the models, SPMs have the advantage that the question of climate justice is addressed explicitly and does not depend on a global pathway. Furthermore, SPMs lead to smooth pathways until infinity. The ESPM has 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.

The global remaining budget to be meet 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 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. In addition, it must be ensured that the temporary overshoot is still compatible with the desired limitation of global warming. This also means that when using an SPM that can also map net negative emissions, countries are not completely free in choosing their path.

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

The question of the convergence of the per capita emissions as a property of a model becomes less important the sooner global emissions must be zero or even negative. A higher weighting of the population in models that determine national budgets via a weighted distribution formula also tends to produce results that do not make sense when it comes to determining territorial emission paths. For countries with low per capita emissions today, a high weighting of the population would mean that a more fossil-heavy economy would first be built up, which would have to be decarbonised again shortly afterwards. The later global emissions begin to decline, the sooner emissions neutrality must be reached. This is due to the budget property of CO_2.

Considering the Paris Ambition 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 resource sharing models give useful help when it comes to determining these budgets.

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 (6)). 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, No date)

[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 SPMs in Chapter 3 when the weighting formula of Raupach et al. is used. However, any approach can be taken there to determine a national budget in the SPM approach. The EPM in Chapter 4 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).

[3] The paths adhere to a global budget 2018 - 2100 of around 770 Gt CO_2. Insofar as actual figures are referred to in this paper, they are based on the 2018 data.

[4] 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):

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

[5] The Regensburg Model includes more than the Regensburg Formula, since global paths can also be determined using the Regensburg Model Scenario Types (Wolfsteiner & Wittmann, 2022a).

[6] In the corresponding Supplementary Text we show a Generalized Smooth Pathway Formula, which can also map net negative emissions (cf. Wittmann, 2022).

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Supplementary Material

Supplementary Material can be downloaded at: www.save-the-climate.info.

Supplementary Text: Resource Sharing Models - A Mathematical Description (Wittmann, 2022)

Supplementary Text: Mathematical Description of the Regensburg Model Scenario Types RM 1 – 6 (Wolfsteiner & Wittmann, 2022a)

Supplementary Excel Tool: Comparison Resource Sharing Models

Supplementary Excel Tool: 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, 2022d).