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Burden Sharing of Climate Change Mitigation: Global and Regional Challenges under Shared Socio-Economic Pathways

Marian Leimbach[1], Anastasis Giannousakis

Abstract

We analyze the burden sharing of climate stabilization under socio-economic scenario uncertainty and for various burden sharing regimes. For this purpose, we quantify mitigation efforts in terms of emission reductions and mitigation costs for a number of major world regions, considering scenarios with and without climate finance. The influence of socio-economic drivers on the burden sharing is crucial, but has not yet been studied in the context of the most recent scenario framework - the shared socio-economic pathway scenarios (SSPs). Here we show that sustainable development as represented by the SSP1 scenario reduces the challenges of burden sharing and makes it easier to achieve equitable climate policies. In contrast, in a scenario with fossil-fueled development (SSP5), the risk of political infeasibility - measured by the variation of mitigation costs across regions and the amount of implied international transfers - increases with most burden sharing regimes. By a decomposition of mitigation costs, we provide additional insights on how the contribution of cost components (e.g energy investment costs, trade in oil) differs across the SSPs and across regions.

Keywords: climate policy, burden sharing, socio-economic scenarios, mitigation costs, emissions trading

1. Introduction

The current climate policy (Paris Agreement) focuses on national contributions (NDCs) and early entry points of action, but recent studies (e.g. Kriegler et al., 2017; Robiou du Pont et al., 2017; Rogelj et al., 2017; Vrontisi et al., 2018) show that greenhouse gas (GHG) emission reductions in line with NDCs will not be sufficient to achieve a long-term climate stabilization below 2°C. Unilateral emission reductions need to be intensified in ambition and likely be followed by multilateral action. Yet, efforts to implement an ambitious multilateral reduction plan will only be successful if the overall burden sharing meets certain fairness criteria. The principle of Common but Differentiated Responsibilities, as a cornerstone of sustainable development, holds also for climate policies and is thus included in the Paris Agreement (UNFCCC, 2015). The goal-oriented use of instruments that support international climate policy, such as climate finance and emissions trading, could help improve the efficiency, while at the same time increase the fairness of mitigation measures. The burden sharing across countries will likely differ with the level of global mitigation, and its perceived equity depends on the dynamics of climate change and its socio-economic drivers. The newly developed shared socio-economic pathways scenarios (O'Neill et al., 2014) provide a useful tool to consider the uncertainty in the future development of these drivers.

The burden sharing of climate stabilization as well as the feasibility of fair burden sharing regimes have not yet been studied in the context of the SSPs. In this paper, we do so and contribute to the existing literature by comparing the mitigation burden sharing of a 2°C climate stabilization in

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[1] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, P.O. Box 60 12 03, 14412 Potsdam, Germany

different socio-economic futures represented by the scenarios SSP1 ("sustainable development"), SSP2 ("middle-of-the-road") and SSP5 ("fossil-fueled development"). In the absence of climate finance, developing countries would face rather high costs (cf. Tavoni et al., 2015), which conflicts with the principle of Common but Differentiated Responsibilities[2]. We address the underlying fairness dimension by contrasting carbon tax scenarios with cap-and-trade scenarios based on different permit allocation schemes. We quantify the burden sharing of mitigation across a number of major world regions, while using the term burden sharing for both the sharing of financial burdens (mitigation costs and financial transfers) and mitigation efforts (emission reduction levels). Furthermore, we evaluate the burden sharing scenarios with regard to their chances of implementation (i.e. political feasibility) based on their contribution to the equalization of mitigation costs and the requirements of climate finance across regions. In a next step, by decomposing mitigation costs, we identify components that contribute differently to the cost magnitude across regions, and to the cost shares in each region across the SSPs. This decomposition addresses the sensitivity of the mitigation costs to a number of socio-economic and techno-economic parameters and assumptions. Our results provide meaningful information for climate policy-makers on how to design future policy regimes and how to implement and direct financial transfers.

The paper is structured as follows. In section 2, we discuss the existing literature on the burden sharing of climate change mitigation. The analysis in this study is performed by applying the integrated assessment model REMIND, followed by an ex-post analysis of model results. The model and the experimental design are presented in section 3. In presenting results, we start in section 4 with comparing global mitigation levels and costs across different SSPs. In section 5, we discuss the regional allocation of mitigation efforts. We quantify the level of emission reduction each region has to provide according to the globally cost-effective emission reduction strategy, and contrast it to the amount of permits each region is allocated under different burden sharing regimes. Furthermore, we quantify the mitigation costs of the burden sharing regimes and evaluate these regimes along criteria of political feasibility. Equality-based burden sharing schemes perform quite well and are subsequently subject to an in-depth analysis including a decomposition of the implied mitigation costs across different SSP scenarios in section 6. We conclude in section 7.

2. Literature

The literature on international burden sharing of climate change mitigation is rich with fairness playing a major role in most studies (Rose et al., 1998; Berk and den Elzen, 2001; den Elzen et al., 2005; Ekholm et al., 2010; Hof et al., 2010; Leimbach et al., 2010; Lüken et al., 2011; Luderer et al., 2012; Aboumahboub et al., 2014; Höhne et al., 2014; Raupach et al., 2014; Tavoni et al., 2015; Herrala and Goel, 2016; Robiou du Pont et al., 2017). An appropriate setting to investigate burden sharing is provided by cap-and-trade systems. In such systems, countries are entitled to greenhouse gas emissions by an agreed initial allocation of allowances. The burden sharing is a result of this allocation. The higher the share of allocated permits, the lower the relative burden. This mitigation burden can be reduced Pareto-efficiently by the trade of emission permits. Rose et al. (2017) identify

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[2] The principle of Common but Differentiated Responsibilities (as stated in the Framework Convention on Climate Change) requests all parties to act on the basis of equality. While all countries are responsible for protecting the climate system, the level of action should respect national differences of capabilities to avoid unwarranted social costs in particular for developing countries.

mitigation cost savings of 77% when the national reduction pledges in the Paris Agreement are combined with an emission trading system. Extreme emission reduction rates, like e.g. 15% per year for North America under a 2°C scenario and an equity-based allocation of emission quotas – as computed by Raupach et al. (2014) – could be avoided by emissions trading. The problem of distributing emission permits, however, cannot be fully solved by economic criteria, because emissions trading yields Pareto efficiency irrespective of the initial distribution of emission permits (Rose and Stevens, 1993; Manne and Stephan, 2005). This holds under certain conditions in theory and will roughly take effect in this way in reality despite existing market failures. Where-flexibility and the separation of equity and efficiency in emissions reduction follow Coase (1960), who addressed the assignment of property rights as an efficient solution to market externalities. While this leads to equal marginal costs of emission reduction across countries, regional mitigation cost levels vary across countries depending on the applied burden sharing rules.

The literature studies several burden sharing schemes with benefits varying across countries and regions. Recent overviews on burden sharing schemes (also called effort-sharing approaches) are provided by Höhne et al. (2014), Zhou and Wang (2016), by van Ruijven et al. (2012), combined with an analysis for China and India, and by den Elzen et al. (2010), combined with an analysis for several developed countries. As fairness turned out to be a key component of climate policy agreements and the lack thereof a major barrier in current and past negotiations, a number of studies focus on equity-based principles of burden sharing, e.g. Rose and Stevens (1993), Kverndokk (1995), Metz (2000), Vaillancourt and Waaub (2004), Markandya (2011), Mattoo and Subramanian (2012), Klinsky and Winkler (2013), Kverndokk (2018), Leimbach et al. (2018). Lange et al. (2010) find out that even with self-interested agents, equity arguments are used, for example, in order to facilitate negotiations. While the burden sharing schemes mostly rely on the initial allocation of emission permits, Böhringer and Helm (2008) focus on a fair division of the efficiency gains that arise from exchanging permits. Gerlagh (2007), furthermore, address the burden sharing issue not only as an interregional but also as an intergenerational issue.

Previous studies on mitigation burden sharing investigated the influence of different permit allocation rules in scenarios aiming at achieving different climate stabilization targets. The influence of socio-economic drivers on the burden sharing has rarely been studied. Eckholm et al. (2010) have done this based on the SRES scenarios. In few other studies, sensitivity analyses have been carried out by varying growth rates of GDP and population, and by varying elasticity parameters or the availability of technologies (e.g. Yohe and Engel, 2003; Lüken et al., 2011; Aboumahboub et al., 2014). The present study contributes to the literature by investigating the impact of socio-economic drivers and conditions on the burden sharing of climate change mitigation based on a robust approach. In this approach, we take into account the interdependency of socio-economic factors represented by the new SSP scenarios (Riahi et al., 2017). These scenarios provide quantitative projections based on five narratives of alternative socio-economic developments (O'Neill et al., 2014) and a consistent compilation and implementation of economic, demographic, energy related and land-use related model assumptions.

To our knowledge, this study is the first that addresses the burden sharing dimension in the framework of the new SSP scenarios. It moreover puts an aspect into the focus – regional mitigation costs – that so far has not received much attention in the analysis of mitigation scenarios within the SSP context. The SSP overview paper by Riahi et al. (2017) does provide a brief summary of global average mitigation costs, but no indication is given how the costs spread across different countries or world regions. By quantifying regional mitigation costs, this study also goes beyond of what most studies that analyse burden sharing regimes usually do: comparing emission reduction efforts. Even if we admit that the quantification of regional mitigation costs is subject to uncertainties, in relative terms they characterize the cost implications of different burden sharing regimes quite well and allow concluding on their political feasibility.

3. Model and experimental design

We perform the burden sharing analysis by use of the integrated assessment model REMIND, followed by an ex-post analysis. REMIND features verified ability to analyze SSP scenarios (Kriegler et al., 2017). It is a global, multi-regional, energy-economy-climate model (Leimbach et al., 2010). A detailed model description is provided by Luderer et al. (2015) and a summary is given in section A.1 of the Supplementary Material.

The version of REMIND applied here divides the world into eleven model regions: Sub-Saharan Africa (AFR), China, EU-28 (EUR), India, Japan, Latin America (LAM), Middle East and North Africa (MEA), Other Asia (OAS), Russia, USA and Rest of the World (ROW). As a measure of burden sharing, we compute the mitigation cost of each region defined as discounted aggregated consumption losses[3] of a mitigation scenario compared to the respective baseline scenario without climate policy. The computation of mitigation costs is based on a welfare-optimal solution that meets a given climate target cost-effectively. As usual in the cost-effectiveness mode, benefits of avoided climate damages are not additionally taken into account.

The current model implementation allows REMIND to analyze SSP1, SSP2, and SSP5 scenarios. We run for each SSP a baseline scenario that assumes the absence of climate policy, and a set of mitigation scenarios (see Table 1) that all keep the radiative forcing level below 2.6 W/m^2 in 2100. This forcing target implies a high probability for keeping the increase of the global mean temperature below 2°C (compared to the pre-industrial level).

Commonly, SSP-based mitigation scenarios include additional policy assumptions called shared policy assumptions – SPAs (see Kriegler et al., 2014). We follow the SPA benchmark scenarios. They start from a fragmented policy regime with different regional carbon taxes and include a transition phase between 2025 and 2040 towards a climate policy regime with a uniform global carbon tax. We include this scenario type (**TAX**) as a reference policy scenario. Most integrated assessment studies restrict the analysis of mitigation effort sharing on results from this scenario type, thus giving a rather limited perspective on the burden sharing dimension. The burden sharing analysis in this study explores scenarios that assume a global cap-and-trade system succeeding the fragmented policy regime in 2025. Cap-and-trade systems are based on a set of permit allocation rules. Permit trading implies financial transfers on the carbon market that we consider as representative for any form of climate finance that lead to a cost-optimal allocation of emission reductions. In this study, reduction efforts as well as mitigation costs of each policy scenario are measured in comparison with the

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[3] Mitigation costs are measured in percent of baseline consumption discounted by the internal discount rate. Most mitigation cost analyses use an exogenous discount rate (usually 5%). This introduces an imprecision that is avoided by the current approach. Major component of the discount rate is the pure rate of time preference. As in most other comparable models, we use the same rate of time preference for all regions. We apply a value of 3%.

baseline scenario. This is in contrast to other studies on burden sharing regimes that relate reduction efforts to a given emission level in a reference year (e.g. Höhne et al., 2014; Robiou du Pont et al., 2017).

Table 1: Applied scenarios and burden sharing schemes

	Scenario name			Equity principle/ IPCC category	Type of analysis
	SSP1	**SSP2**	**SSP5**		
Baseline					Simulation
Carbon tax (TAX)	SSP1-TAX	SSP2-TAX	SSP5-TAX		Simulation
Contraction & convergence (CC)	SSP1-CC	SSP2-CC	SSP5-CC	Capability & Equality	Simulation
Population share (POP)	SSP1-POP	SSP2-POP	SSP5-POP	Equality	Simulation
Equal effort sharing (EC)	SSP1-EC	SSP2-EC	SSP5-EC	Equality	Ex-Post
Grandfathering (GF)	SSP1-GF	SSP2-GF	SSP5-GF	Sovereignty	Ex-Post
GDP intensity (GI)	SSP1-GI	SSP2-GI	SSP5-GI	Capability-Need	Ex-Post
Historic responsibility (HR)	SSP1-HR	SSP2-HR	SSP5-HR	Responsibility	Ex-Post
Equal per capita (PC)	SSP1-PC	SSP2-PC	SSP5-PC	Equality	Ex-Post

Table 1 provides an overview of the permit allocation schemes. They represent a selection of allocation schemes frequently discussed in the literature (cf. van Ruijven et al., 2012; Höhne et al., 2014; Zhou and Wang, 2106) and linked to the equity principles categorized by IPCC's fifth Assessment Report (IPCC, WG III, p. 318f.).

The **contraction & convergence (CC)** scheme (Meyer, 2000) allocates global emission permits (determined by the globally optimal emission trajectory) in proportion to the weighted average of each region's share in global emissions in 2005 and an equal per capita share. Weights of the per capita share increase linearly over time. As of 2050, permits are allocated to the regions according to the equal per capita rule only. The **equal effort sharing (EC)** scheme aims to adjust the mitigation costs across regions (see Supplementary Material A.2). According to the **grandfathering (GF)** principle regions are allocated with a share of permits that corresponds to their share on global GHG emissions in 2005, while the **GDP intensity (GI)** principle allocates permits equal to the share of each region on global GDP. **Historical responsibility (HR)** is measured as the contribution of each region to the temperature increase in 2005 and applies data from MATCH (2017). Corresponding data are also used by Höhne et al. (2011). Section A.3 of the Supplementary Material provides the details of how the permit emission share is calculated for this scheme. In the **equal per capita (PC)** scheme each region receives emission permits in proportion to its projected population in each year. The **population share (POP)** scheme is based on a different rule of equal per capita allocation. The share S of region r in global permits is based on the cumulative population share over the 21st century $(t = 1, \ldots, T)$:

$$S_r = \frac{\sum_t P_{r,t}}{\sum_t \sum_r P_{r,t}}$$

Population values $P_{r,t}$ are determined by the SSP population scenarios (KC and Lutz, 2017).

In line with the motivation of this study, we select several burden sharing schemes that are based on equity principles. There is “no absolute standard of equity” (IPCC 2014, p. 317) and no direct way of quantifying the equity of burden sharing regimes. Yet, there is certainly a different degree of fairness associated with each scheme, which can be described in a qualitative way, and which certainly plays an important role in the political discussion.

In this study, we attempt to additionally contribute to the discussion on what the appropriate burden sharing regime might be by deriving quantitative indicators of political feasibility. We select two criteria that both address concerns of international negotiations and are accessible within the applied methodological framework of this study. A first concern relates to the distribution of mitigation costs. A high divergence of mitigation costs across countries is assumed to decrease the acceptance and feasibility of climate protocols. Second, huge amount of transfers (e.g. implied by emission trading regimes) are often seen as barriers for implementing equity-based burden sharing.[4] Consequently, in operationalizing the aspect of political feasibility, we evaluate two indicators:

- volume of carbon trade costs/revenues
- deviation of regional mitigation costs.

We classify the burden sharing schemes according to these two criteria and in addition investigate in how far the respective characteristics of burden sharing regimes vary across different SSP scenarios.

In mitigation scenarios with no climate finance (**TAX**), regions enact carbon pricing in accordance with the above-mentioned shared policy assumptions and a globally uniform carbon tax from 2040 on. There is neither an allocation of emission permits nor any other kind of financial transfer between model regions. To arrive at a cost-effective solution, we compute these scenarios by using exponentially rising global carbon tax paths compatible with the climate target.

The climate finance scenarios assume an explicit burden sharing scheme as part of an international climate agreement. In these scenarios, emission permits are allocated to regions in accordance with the burden sharing scheme as well as with the climate target. Once allocated, emission permits can be traded in our model and generate - as a particular form of climate finance - revenues for permit selling regions. Technically, we compute the cost-effective solution by distributing a global permit budget compatible with the forcing target to regions and making sure that the permit market clears.

While we run some of the scenarios directly with REMIND in order to generate further results that we analyze in section 6, for most of the burden-sharing regimes we derive the desired results based on an ex-post analysis. This part of the assessment makes use of model output from REMIND and builds on a feature that a number of integrated assessment models are associated with - the separation of efficiency and equity (Rose and Stevens, 1993; Manne and Stephan, 2005). This feature results in a pattern of regional technology portfolios and emissions that does not depend on the allocation of emission permits. Moreover, the resulting carbon price is also nearly independent of the

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[4] The evaluation of transfers is mixed (Kverndokk, 2018). Limited and purposeful transfers can certainly facilitate climate agreements as climate finance is part of the UNFCCC. But at the same time, we see resistance regarding some forms of transfers, for example development aid. This resistance is assumed to be increased with the level of transfers. In addition, high transfers on the carbon market bear institutional challenges like the climate rent curse (Kornek et al., 2017).

permit allocation. The revenues on the carbon market represent income that does not change the investment structure but solely increases the consumption level.[5]

The mitigation costs (percentage consumption losses, CL) can hence be represented by two separate parts – the domestic costs DC (mainly costs of energy system transformation) and carbon trade cost CTC (see Luderer et al., 2012):

$$CL \approx DC + CTC \qquad (1)$$

In common tax scenarios the second part vanishes. In cap-and-trade scenarios, the second part is different from zero and can be computed for each region r as a product of the global carbon price (p) and the permit trade volume (PT):

$$CTC_r = p \cdot PT_r \qquad (2)$$

This trade volume can be calculated as the difference between the allocated permits (with S as allocated share) and the actual regional level of emissions E:

$$PT_r = E_r - S_r \cdot \sum_r E_r \qquad (3)$$

The needed input for this ex-post-analysis (i.e. data on global carbon price, global and regional GHG emissions) is derived from REMIND mitigation scenarios SSPx-TAX as introduced before. The remaining unknown variable, the allocated share S, is provided by different burden sharing schemes. Permit allocation and emissions trading are assumed to start in 2025.

4. Global mitigation level and costs across SSPs

The present study analyzes the sharing of mitigation efforts in ambitious climate stabilization scenarios (2.6 W/m^2) based on cost-optimal global emission trajectories. Fig. 1 shows the emission trajectories of baseline and policy scenario runs of each SSP. Mitigation gaps between respective baseline and policy scenarios vary significantly across the SSPs. Differences in resulting mitigation costs can be expected.

Under ambitious climate stabilization scenarios, the SSP1-TAX scenario exhibits costs of around 0.8% of consumption. The costs more than double in SSP2-TAX (1.8%), and triple in SSP5-TAX (2.4%). Due to the separation of efficiency and equity (see section 3), the global mitigation costs are the same for the climate finance scenarios. The cost figures mirror the mitigation challenges that the different socio-economic pathways are linked with (O' Neill et al., 2014). In a world that respects environmental boundaries (SSP1), a less energy and carbon intensive way of production and moderate economic growth result in a relatively small mitigation gap. Comparatively low additional efforts are needed to close this gap. On the other hand, in a world with high economic growth fueled by fossil fuels (SSP5), baseline emissions are huge and the mitigation challenge is large.

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[5] The separation of equity and efficiency as well as the implied consequences, i.e. the independence of carbon price and investment structure from permit allocation, holds under the assumption of perfectly competitive markets, but not necessarily in the presence of market power.

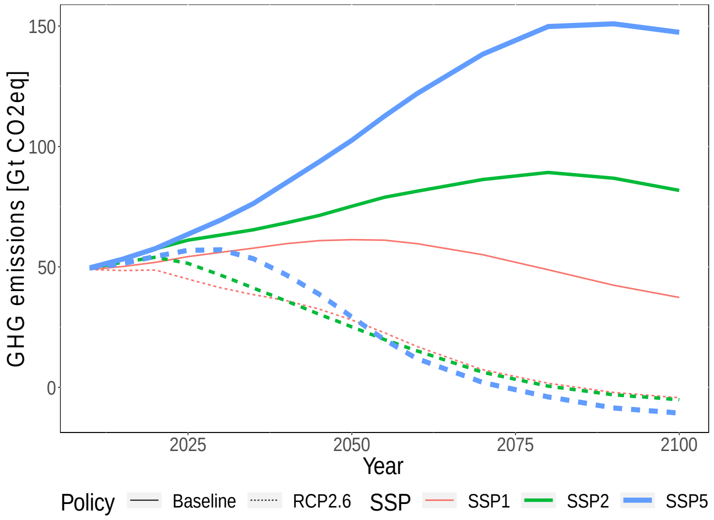

Fig. 1: Emission trajectories of baseline and RCP2.6 policy scenarios

The conclusion of the fifth Assessment Report (AR5) of the IPCC that global costs increase with the ambition of the mitigation goal (IPCC, 2014) applies to the present results if we take the mitigation gap (mitigation challenge) in the evaluation of the mitigation goal into account. That means, with striving for the same climate stabilization goal, the mitigation target is the more ambitious the larger the baseline emissions. This makes the mitigation under the SSP5 scenario more ambitious than under the SSP2 and even more than under the SSP1 scenario.

If we compare the SSP2-TAX results with corresponding figures from IPCC's AR5 (IPCC, 2014), we can summarize that the present analysis yields cost figures that are at the lower end of the respective IPCC range in the years 2030 (1%) and 2050 (2%) and close to the median in 2100 (5%).

5. Regional burden sharing analysis

5.1. Allocation of mitigation efforts

In this subsection, we discuss the allocation of GHG emissions reductions needed to fill the mitigation gap identified in the previous section. The regional distribution of the related costs is discussed in the next subsection. To characterize the reduction efforts, we compare the emission level that each region is qualified for - from the allocation of allowances - with their actual emission level according to the globally cost-effective emission trajectory. From this comparison we can conclude which regions face additional burden. Both variables represent share values measured as percentage amount of cumulated baseline emissions.

Whereas the allocation of allowances depends on the burden sharing regime, the actual emission trajectories do not. We therefore start with analyzing the emission and emission reduction levels computed with the TAX scenarios. Cumulative regional reduction shares increase over time. Emission levels close to or below zero have to be achieved by most regions. As expected, SSP5 shows the highest shares in the long term. In the mid-term, SSP2 demonstrates similar reduction shares (see Fig. 2). The maximum holds for AFR: up to 80% under SSP5 in 2100 compared to 65% in SSP2 and 60% in SSP1. Cumulative reduction shares differ more between regions for the time horizon until 2050 than until 2100. Fig. 2 shows the cumulative emission reduction shares (until 2050) for each region across the three SSP scenarios.[6] Across all SSPs, developing regions (AFR, China, India, LAM) face highest reduction shares. While higher reduction shares do not necessarily mean higher mitigation costs, fair burden sharing schemes may have to take this reduction effort sharing into account.

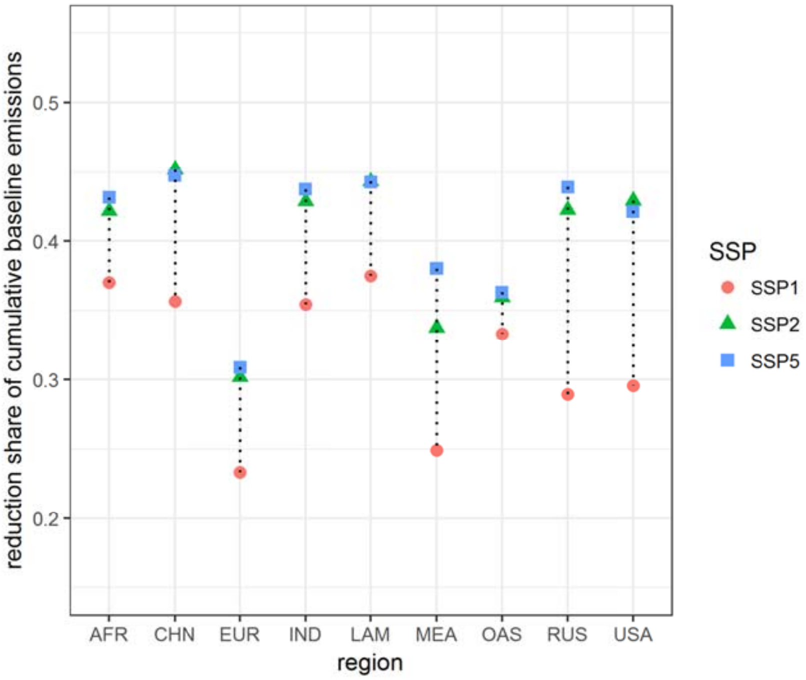

Fig. 2: Regional emission reduction shares cumulated over the time horizon 2015 – 2050

The allocation of emission allowances varies only slightly across the different SSPs (see Fig. 3)[7]. More remarkable is the variation of allocated allowances due to the different burden sharing schemes. For nearly all regions we can identify allocation schemes that provide permits in the range between 30% and 100% of baseline emissions. This range is, on the one hand, more narrow for China, LAM and OAS, and on the other hand, expanded to values of well above 100% for AFR. The latter applies in the case of the equal effort sharing regime also to MEA and Russia. Consequently, for each region allocation schemes exist that provide either permits above or below the actual emission level. This reference level is represented in Fig. 3 by the pink "tax" marker. Whereas the actual emission level is at the upper part of the range of allocated allowances for LAM and for developed regions (USA, EUR), it is more in the lower part for developing regions like AFR, India and OAS. In the former case

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[6] The share levels of SSP2 can be compared to those presented by Tavoni et al. (2015, Fig. 3). In the present study, share levels are in general slightly lower but show a higher spread between regions. In each of the two studies, EUR shows the lowest shares, which implies that the mitigation costs in this region increase faster with emission reductions than in other regions. It, moreover, indicates that the energy system in EUR today is more advanced and will not expand the use of fossil fuels within the near term future as other regions will do in the baseline scenario.

[7] With the same stabilization target, and hence a similar global emission budget, the variation of the allocation of allowances across SSPs only depends on differences in the time profile of global emissions (see Fig. 1). In the short term a higher (lower) absolute amount of permits is allocated under SSP5 (SSP1) than under SSP2. Since the respective baselines show the same differences, the allocation measured as aggregated share of baseline emissions shows low variance across SSPs.

additional expenditures on the carbon market are implied and in the latter case corresponding revenues. A further discussion on the advantages and disadvantages of the different burden sharing regimes for each region will be provided in the context of the implied mitigation costs in the next section. A detailed time profile of respective permit allocations for each burden sharing regime is shown in Fig. S.1 of the Supplementary Material.

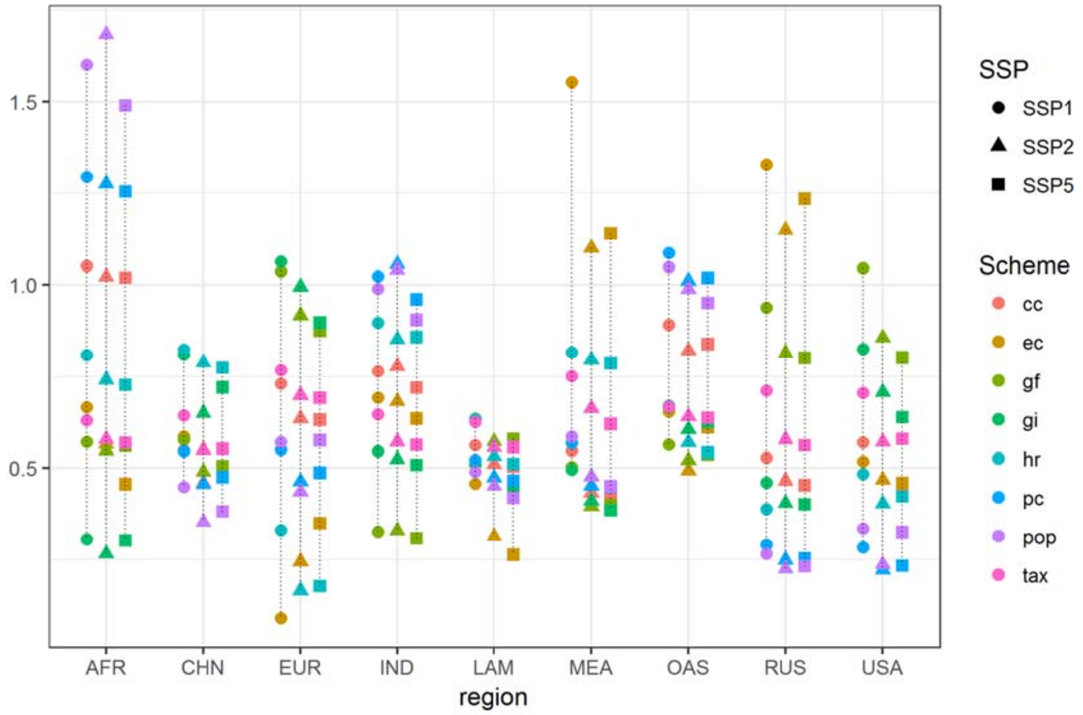

Fig. 3: Allocation of emission allowances per burden sharing scheme measured as aggregated share of baseline emissions between 2015-2050

5.2 Mitigation costs

When analyzing the regional mitigation costs, most integrated assessment studies apply results from tax scenarios only. Adding the SSP dimension, we find that the global ranking of SSPs in terms of mitigation costs also holds on the regional level (see Fig. 4). A notable exception is LAM for which we see lower costs in SSP5 than in SSP2 and SSP1. An explanation is given in section 6 where a decomposition of the mitigation costs is presented. Despite the maintained ranking, we see that the SSP1 and SSP5 scenarios are relatively less costly for the developing countries than the SSP2 scenario. This is linked to the comparatively favorable demographic development (i.e. less population growth) and a higher degree of technological progress and diffusion in SSP1 and SSP5. While there are large differences in mitigation costs across countries and regions, each region’s deviation from the global average, however, does not vary much across the different SSPs.

In the policy reference scenario (TAX), we see highest mitigation costs for MEA and Russia, than AFR and India. OAS, China, and USA face mitigation costs around the global average, or in the case of China and USA partly even below the average. Finally, we observe lowest costs for LAM and EUR. Apart from LAM, this ranking is the same as identified by Tavoni et al. (2015, Fig. 5) based on a multi-model comparison study of a policy scenario similar to the present SSP2-TAX scenario. Moreover, the level of mitigation costs of the SSP2-TAX scenario is also comparable with the results from the study by Aboumahboub et al. (2014, Fig. 1), except for China and Russia, for which we find lower mitigation costs.

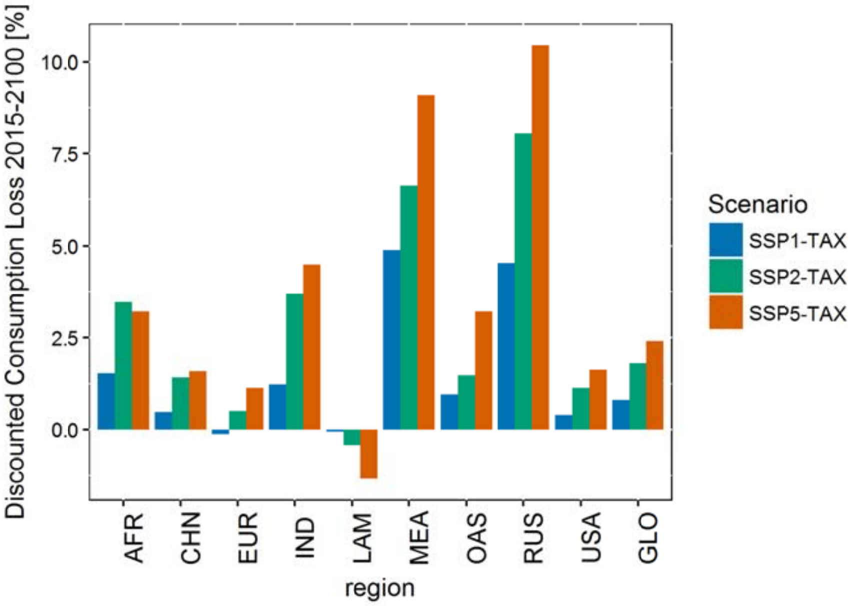

Fig. 4: Regional mitigation costs across the SSPs in ambitious climate stabilization scenarios (2.6 W/m^2) without climate finance

The policy reference scenarios assume after an initial period of fragmented mitigation action a globally uniform carbon tax. While this ensures global efficiency, it disproportionately burdens less affluent countries. With introducing burden sharing schemes that include climate finance based on an initial allocation of emission allowances, the distribution of mitigation costs (see Fig. 5) changes significantly. Non-equality based burden sharing regimes (e.g. GF, GI) increase the mitigation costs of developing regions like AFR and India substantially. For Russia and MEA all burden sharing regimes other than the equal effort sharing (EC) yield mitigation costs well above the global average. The range of variation is rather small for the most developed regions EUR and USA, which is mainly due to the fact that even comparably high expenditures on the carbon market represent a low share of consumption and GDP, respectively. Also for China and LAM, the variation is comparably low. Most extreme is the distribution of mitigation costs under the HR burden sharing scheme. As the global mitigation costs are always the same across the burden-sharing schemes for a given climate target and a given SSP scenario, variation in the permit allocation always implies that some regions profit while others lose. The position of each region shows little variation across the SSPs. The implications of the PC and POP burden sharing schemes in the case of India constitute a notable exception. While in SSP1 and SSP2 these burden sharing regimes result in comparable low mitigation costs, they are well above the global average in SSP5. Due to higher economic growth in India in SSP5, that in the short-term is partly fueled by fossil resources, the domestic demand on emission permits increases and results in additional consumption losses that cannot be compensated by permit sales. Table 2 summarizes qualitatively the relative burden of each region under the different burden sharing schemes.

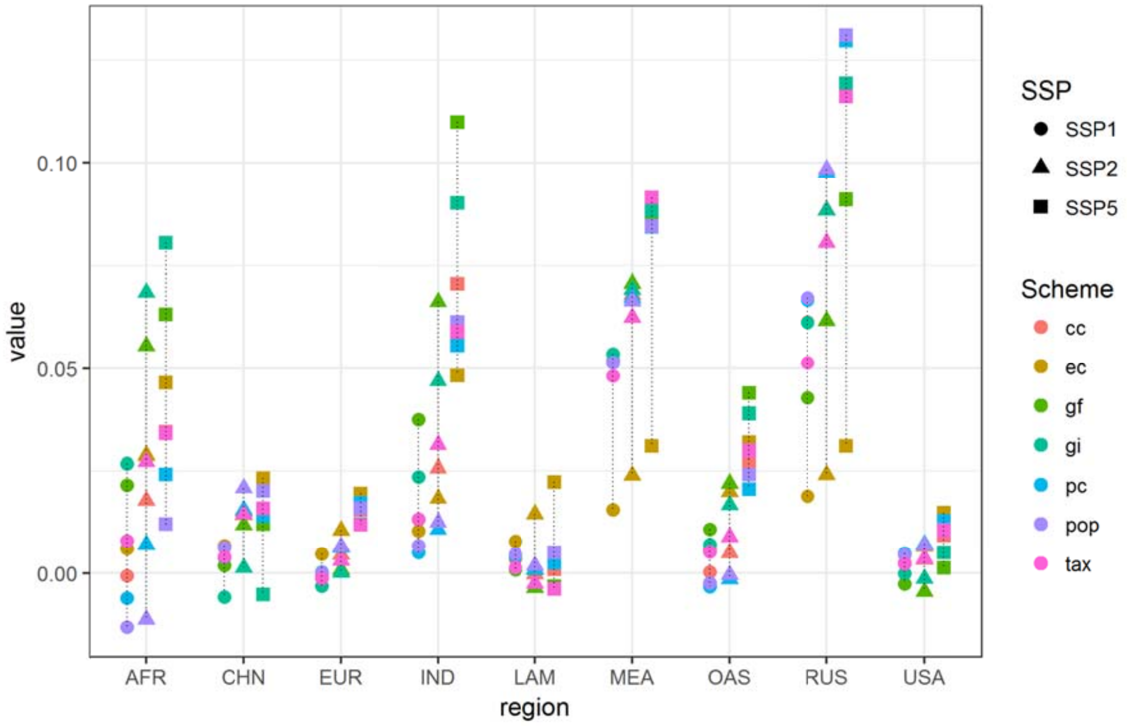

Fig. 5: Regional mitigation costs across the SSPs and burden sharing regimes (we omit the HR scheme due to its extreme values for single regions)

Table 2: Regional mitigation costs compared to global average (+ above average; o around average; - below average)

	AFR	CHN	EUR	IND	LAM	MEA	OAS	RUS	USA
CC	o	o	o/-	o/+	o/-	++	o	++	o/-
EC	o/+	o	o	o/+	o	o/+	o	o/+	o/-
GF	+	o/-	o/-	++	-	++	o/+	+	-
GI	++	-	-	+	o/-	++	o	++	-
HR	---	-	+	---	+	o/-	o	+++	o/+
PC	o/-	o	o/-	o	o/-	++	o/-	++	o/-
POP	-	o	o/-	o	o/-	++	o/-	++	o/-

5.3 Political feasibility of burden sharing schemes

In the following, we aim for a further classification of the burden sharing schemes. We assess their political feasibility measured by the implied amount of net transfers and the variation of regional mitigation costs.

The Supplementary Material (SM) illustrates and quantifies the cumulated permit trade value for each region, burden sharing scheme and SSP, until 2100 (Fig. S.2 and Table S.1). The transfer values show a wide range across the burden sharing schemes for regions like AFR, EUR and India, while they are narrower for Russia, LAM and MEA if the EC regime is neglected. This can mainly be explained by the variation in the allocation of permits (see Fig. 3) – high variation for AFR, EUR and India, low variation for LAM. For MEA and Russia we observe large revenues from the permit market with the EC regime, but small trade volumes with all other regimes, due to the relative small scale of these economies. Fig. 6a summarizes the total amount of transfers on the carbon market. It is highest for the HR regime, comparatively high for the EC regime and lowest for the CC regime. Across all burden sharing regimes, we see highest transfers for SSP5 and lowest for SSP1, which implies that net transfers increase with the variation across regional mitigation costs. The spread, however, is not always equal. While the GF and GI regimes have a comparable amount of transfers as the PC and PI regimes under SSP1 and SSP2, it is substantially higher under SSP5. This is in particular due to the large increase of permit imports of AFR and India (and exports of China) under the GF and GI regime in SSP5 (see Fig. S.2).

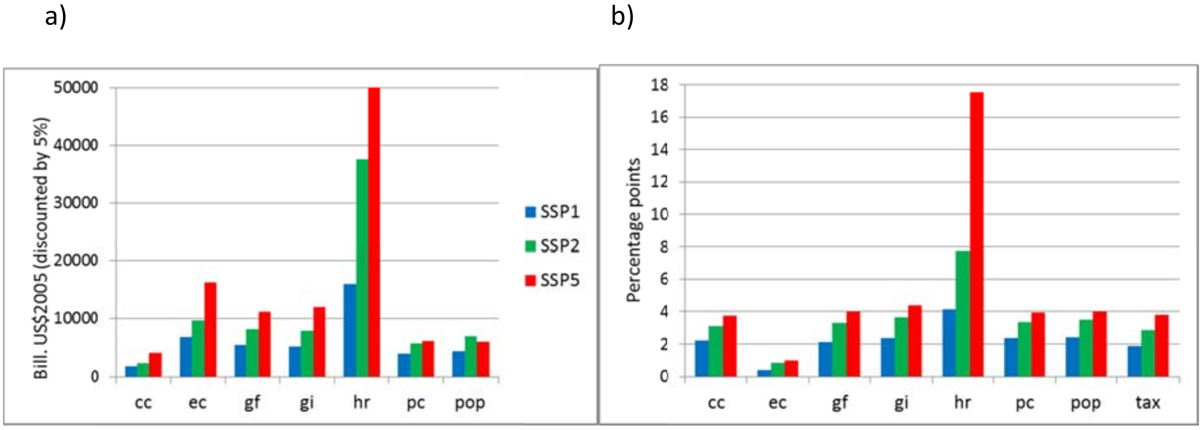

Fig.6: Criteria of political infeasibility (panel a: global transfers on the carbon market until 2100; panel b: standard deviation of regional mitigation costs)

With regard to the comparison of implied mitigation costs, we computed the standard deviation of mitigation costs – summarized in Fig. 6b. The contribution of permit trade to the mitigation costs in each region is presented in Table S.2 (SM). By construction the EC regime demonstrates the lowest deviation of regional mitigation costs. Again, highest levels are related to the HR regime. All other regimes demonstrate a similar standard deviation between 2 and 4 percentage points. These latter levels are comparable with the deviation of regional mitigation costs in the TAX scenarios. The ranking of mitigation cost levels across SSPs also holds for the standard deviation, with highest figures for SSP5. While the increase of costs differences between SSP2 and SSP5 is in particular high for the HR regime, the PC and POP regimes see just a small difference between SSP2 and SSP5. In all burden sharing regimes apart from the EC and HR schemes, a substantial contribution to the standard deviation level is caused by high mitigation costs for MEA and Russia.

If we interpret high values in the two analyzed criteria (implied transfers and deviation in regional mitigation costs) as barriers of political feasibility, we come to the following conclusion. The regime based on historical responsibility is hardly feasible in the form implemented here, as it turns around the reduction burdens in an extreme way. Developed countries have to pay for the major part of global emission reduction despite of decreasing emission and population shares. Overall, the grandfathering and GDP intensity regimes - due to its higher amount of transfers - appear less feasible as the equality-based burden sharing regimes, from which the contraction & convergence scheme has some additional merits due to a slightly lower implied transfer volume compared to the equal per capita and cumulated population share regime. The equal effort sharing regime has a clear advantage with respect to one criterion but also a clear disadvantage with respect to the other. Compared to the burden sharing scenarios with climate finance, the non-finance TAX scenarios (previous section) have a comparative advantage with respect to the two criteria assessed: no transfers at all and an average deviation of mitigation costs. Overall, the risk of political infeasibility increases clearly from SSP1 to SSP2 and to SSP5. A sustainable development as represented by the SSP1 scenario clearly reduces the challenges of burden sharing and makes it easier to achieve equitable climate policies.

At this point, we want to stress that we only analyzed pure allocation schemes – mixed types are possible and can potentially combine advantages. In addition, other evaluation criteria may shift the overall picture. In particular, the domestic dimension of distributional effects of climate policies is important, but not in the scope of this study.

6. Equality-based burden sharing

Equality-based burden sharing regimes perform relatively well under the criteria considered in the previous section. In particular, they do not imply above average financial transfers as generally expected. We subject two of these schemes to an in-depth analysis: the per capita convergence (CC) and the population share (POP) burden sharing schemes. This analysis provides findings that partly apply to other burden sharing regimes as well and hence complements the analysis of section 5.

Surprisingly, for most regions mitigation cost differences are much higher between the two equality-based policy scenarios than between the corresponding TAX and CC scenarios (see Fig. 5). While mitigation costs for some of the most affected regions, namely AFR and India, are high in the case of a global carbon tax and CC scenarios, they are low or even negative in the POP scenarios. In the POP scenarios, higher costs can be observed in particular in regions that feature according to the demographic projections less population growth or even a decline in population: China, EUR, and Russia. For the USA, under the POP scenario there is hardly an increase of mitigation costs in SSP5 compared to the other SSPs. Because of higher population growth in SSP5, a larger amount of allocated emission permits benefits the USA.

Overall, there are large burdens on MEA and Russia. From a fairness perspective, this can be justified by the large benefits from fossil resource extraction in the past, which have only been possible due to ignorance of the external effects of fossil fuel consumption. Moreover, the large policy cost for MEA and Russia are heavily driven by a baseline that assumes a prolongation of the favor of non-internalizing external effects into the far future. Despite these arguments, a resistance of countries with large burden can be expected in climate policy negotiations. In order to reflect on this, we run an additional scenario ("POP-07") where the consumption losses compared to baseline in each year are limited to a maximum of 7%. We chose this value in order to identify sensitivities of the interregional trade-offs. Beyond that, there is no other rationale behind this particular number.

The POP-07 scenario changes the burden sharing under SSP2 and in particular under SSP5 significantly (see Fig. 7). While the mitigation costs of Russia more than halve in both SSP2 and SSP5, those of MEA nearly halve in SSP5 and decrease by around 25% in SSP2. Mitigation costs increase in SSP2 and SSP5 by up to 0.3 and 0.5 percentage points, respectively, in other regions (China, India, EUR, USA, OAS, LAM). In general, in all POP and CC scenarios, changes in the burden sharing (compared to the TAX scenario) result from indirect climate finance (i.e. endowment of emission permits). The POP-07 scenarios with a cost constraint imply an additional transfer. While the model computes this as a deficit in the intertemporal budget constraint (see the Supplementary Material A.5 for more details), in the real world this can be any type of transfer, debt relief and redistribution of carbon market revenues.

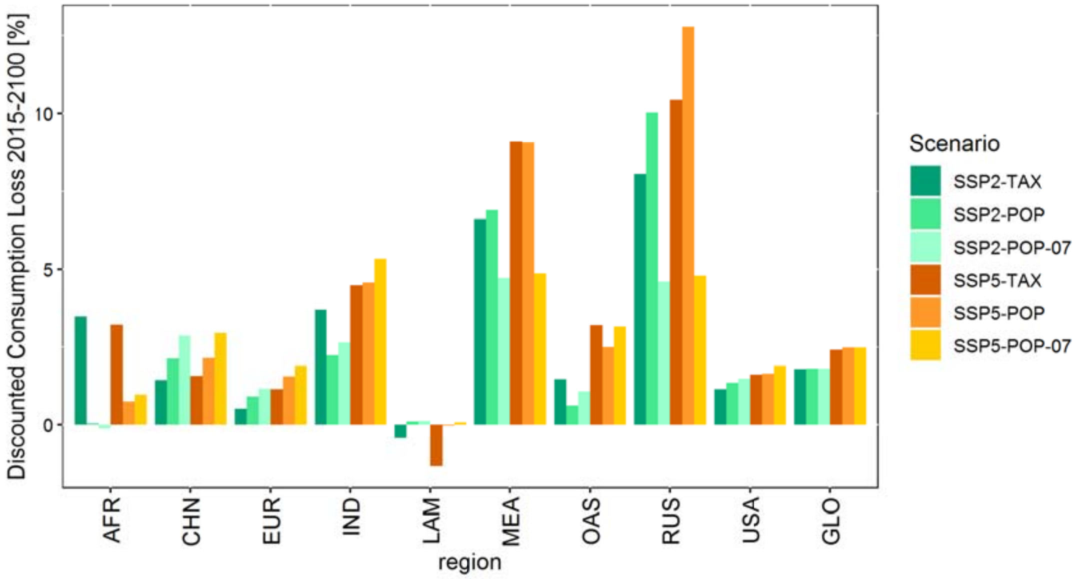

Fig. 7: Mitigation costs per region for the SSP2 and SSP5 in ambitious climate stabilization scenarios (2.6 W/m^2), including the 7% cost cap scenarios

In the case of SSP2-POP-07, these additional transfers are largely compensated by transfers at the carbon market in the opposite direction. Hence, the total volume of net transfers only increases by few percentage points. In contrast, the SSP5-POP-07 scenario exhibits an increase of transfers by one third compared to the respective SSP5-POP scenario. On the other hand, there is a significant decrease in terms of the deviation of regional mitigation costs. The standard deviation for both, the SSP2-POP-07 and SSP5-POP-07 scenario, is around 1.7% and thus more than halves compared to the respective POP scenarios (cf. Fig. 6b). In case of SSP2, this result may be interpreted as an increase in political feasibility of the underlying burden sharing regime.

In order to get additional insight into the differential impacts of SSPs on the regional mitigation costs, we perform a decomposition analysis. Details on this analysis are provided in the Supplementary Material (A.6). We identify components that contribute differently to the cost magnitude across regions, and to the cost shares in regions across the SSPs. The slightly lower economic growth rates (Dellink et al., 2017) and the contained population growth (cf. KC and Lutz, 2017) in SSP1 result in a somewhat lower contribution of GDP losses to the mitigation costs in SSP1, whereas energy system investments demonstrate a higher share in SSP1. First, this indicates that additional investments in carbon-free technologies are requested independently of the economic growth rate. Secondly, risk aversion on external environmental effects associated with large-scale biomass technologies (e.g.

loss of biodiversity, reduction of food security) results in SSP1 in a preference to other forms of carbon–free energy technologies, like solar and wind, which have a higher fixed cost share than biomass technologies. Usage of biomass technologies in combination with carbon storage is in particular needed in SSP5 due to high fossil fuel use in the early years and is supported by less risk aversion to this technology compared to SSP1. In SSP5, biomass is used intensively as a liquid fuel and hence causes a price drop on the oil market that changes the contribution of oil and biomass trade to the mitigation costs substantially. The biomass trade effect is most pronounced for LAM. LAM is the major exporter of biomass and profits from a higher global demand for biomass and a price increase in SSP5. Consequently, LAM faces even lower mitigation costs in SSP5 than in SSP1 (cf. Fig. 7).

The contribution of permit trade to the mitigation costs was already discussed in section 5. The simulation of the CC and POP scenarios provide additional insights on the intertemporal dynamics of trade flows and transfer volumes (see Supplementary Material A.7 for details). Across all SSPs we have a similar pattern: highest trade level (in $GtCO_2eq$) in the beginning, a decreasing trade level until 2060 and a slight increase and stabilization at moderate levels towards the end of the century (Fig. S.5). High trade volumes in early years (2025 and 2030) are associated with large transfers measured as share on GDP. In SSP5-POP and SSP2-POP, we see maximum values of around 20% of GDP for AFR; for India the initial revenues are between 4% and 5% of GDP. These revenues on the carbon market are accompanied by payments that amount in 2030 to around 4% of GDP for Russia, around 2% of GDP for China and MEA, and around 1% of GDP for LAM and USA. Later in the century, transfers are still high, due to a high carbon price, but flow in the opposite direction. Permit trading in the scenarios analyzed implies huge financial transfers, which however is put into perspective when compared to alternative burden sharing schemes as investigated in section 5. Improved institutions are required for administering financial transfers with care to avoid adverse effects, such as a “climate finance curse” (Jakob et al., 2015, Kornek et al., 2017).

7. Conclusions

This study quantifies the mitigation burden sharing of climate stabilization in different futures represented by the newly developed socio-economic pathways scenarios SSP1, SSP2, and SSP5. In accordance with what Riahi et al. (2017) already found, we identify highest mitigation costs in SSP5 and lowest in SSP1 at the global level. We show that this ranking also holds on the regional level. However, depending on the chosen burden sharing scheme mitigation costs can vary significantly across regions. Overall, the risk of political infeasibility of global burden-sharing regimes increases clearly from SSP1 to SSP2 and to SSP5, since the amount of net transfers increases as the variation across regional mitigation costs also does. This shows that a sustainable development pathway as represented by the SSP1 scenario reduces the challenges of burden sharing and makes it easier to achieve equitable climate policies.

By comparing different burden sharing schemes with respect to criteria of political feasibility, we find that the equal effort sharing scheme, while clearly distinguished by the balance of regional mitigation costs, has a disadvantage in the implied amount of net transfers. In contrast, the absence of any transfer implies a lower political challenge for non-climate finance scenarios like global tax scenarios. Yet, global tax scenarios disproportionately burden developing countries, which, in addition, will be affected by climate change impacts more heavily. Equality-based burden sharing schemes perform quite well with respect to the criteria of political feasibility. They likely have an additional advantage regarding the fairness dimension that has not been quantified. By combination with a cost constraint we demonstrate how the variation of regional mitigation costs in equality-based burden sharing schemes could be decreased further. Under SSP2, this causes just a marginal increase of transfers and hence provides an alternative burden sharing regime with a reasonable degree of political feasibility.

While this paper cannot provide final suggestions of how future climate policy regimes have to be designed, it nevertheless identifies burden sharing implications of different socio-economic pathways that policy-makers should take into account. The burden sharing perspective as well as the contributing components change with the SSPs and hence depend on how the world evolves. Further research will have to further deepen the understanding on this interrelation as well as add the perspective of the SSP3 and SSP4 pathways in this context.

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Supplementary Material

A.1 The integrated assessment model REMIND

REMIND is a global, multi-regional, energy-economy-climate model used in long-term analyses of climate change mitigation (e.g. Leimbach et al., 2010, Bauer et al., 2012, Bertram et al., 2015). A detailed model description is provided by Luderer et al. (2015).

The macro-economic core of REMIND is a Ramsey-type optimal growth model in which intertemporal global welfare is maximized. The model computes a unique Pareto-optimal solution that corresponds to the market equilibrium in the absence of non-internalized externalities. The world is divided into eleven model regions: Sub-Saharan Africa (AFR), China, EU-28 (EUR), India, Japan, Latin America (LAM), Middle East and North Africa (MEA), Other Asia (OAS), Russia, USA and Rest of the World (ROW). Model regions trade final goods, primary energy carriers, and in the case of climate policy, emissions permits. Macro-economic production factors are capital, labor, and final energy.

Economic activity results in demand for different types of final energy (electricity, solids, liquids, gases, etc.), determined by a production function with constant elasticity of substitution, and differentiated by stationary and transport uses. The energy system accounts for regional exhaustible primary energy resources through extraction cost curves. Bioenergy comes from different feedstocks: traditional biomass and first generation biomass, both assumed to phase out in the near future, as well as ligno-cellulosic residues and purpose-grown second-generation biomass. The regional biomass potential is represented by regional supply curves (Klein et al., 2014), which are derived from the land use model MAgPIE (Lotze-Campen et al., 2008). Costs of biomass production hence include opportunity costs of alternative land uses, e.g. using land for food production. Non-biomass renewable energy potentials are reflected in detail on the regional level. More than 50 technologies are available for the conversion of primary energy into secondary energy carriers as well as for the distribution of secondary energy carriers into final energy. Techno-economic parameters (investment costs, operation and maintenance costs, fuel costs, conversion efficiency etc.) characterize each conversion technology.

The model accounts for carbon dioxide emissions from fossil fuel combustion and land use as well as emissions of other greenhouse gases (GHGs). The climate model MAGICC6 (Meinshausen et al., 2011), which emulates more complex general circulation models, is used to translate emissions into changes of atmospheric GHG concentrations, radiative forcing, and global mean temperature.

A.2 Equal effort sharing

In the burden sharing regime with equal effort sharing, regions face the same, i.e. global average, consumption losses per GDP (or consumption, alternatively) at each point in time:

$$\frac{CL_r}{GP_r} = \frac{CL_{glob}}{GP_{glob}} = CL^0 \quad \forall\, r = 1, .. n$$

Applying eq. (1) as strict equation we get

$$DC_r + CTC_r = GP_r * CL^0$$

Applying eqs. (2) and (3) it holds

$$p\left(S_r \sum_{r=1}^{n} E_r - E_r\right) = DC_r - GP_r * CL^0$$

From that we can derive the regional permit emission share

$$S_r = \frac{E_r + \frac{DC_r - CL_{glob}\frac{GP_r}{GP_{glob}}}{p}}{\sum_{r=1}^{n} E_r}.$$

A.3 Historic responsibility

With baseline and policy emissions E^{BAU} and E^{pol}, and the contribution SHR of each region to the temperature increase until 2005, we compute the regional permit emission share associated with the burden sharing according to the historic responsibility by

$$S_r = \frac{E_r^{BAU} - SHR_r \cdot \sum_{r=1}^{n}\left(E_r^{BAU} - E_r^{pol}\right)}{\sum_{r=1}^{n} E_r^{pol}}.$$

A.4 Results from ex-post analysis

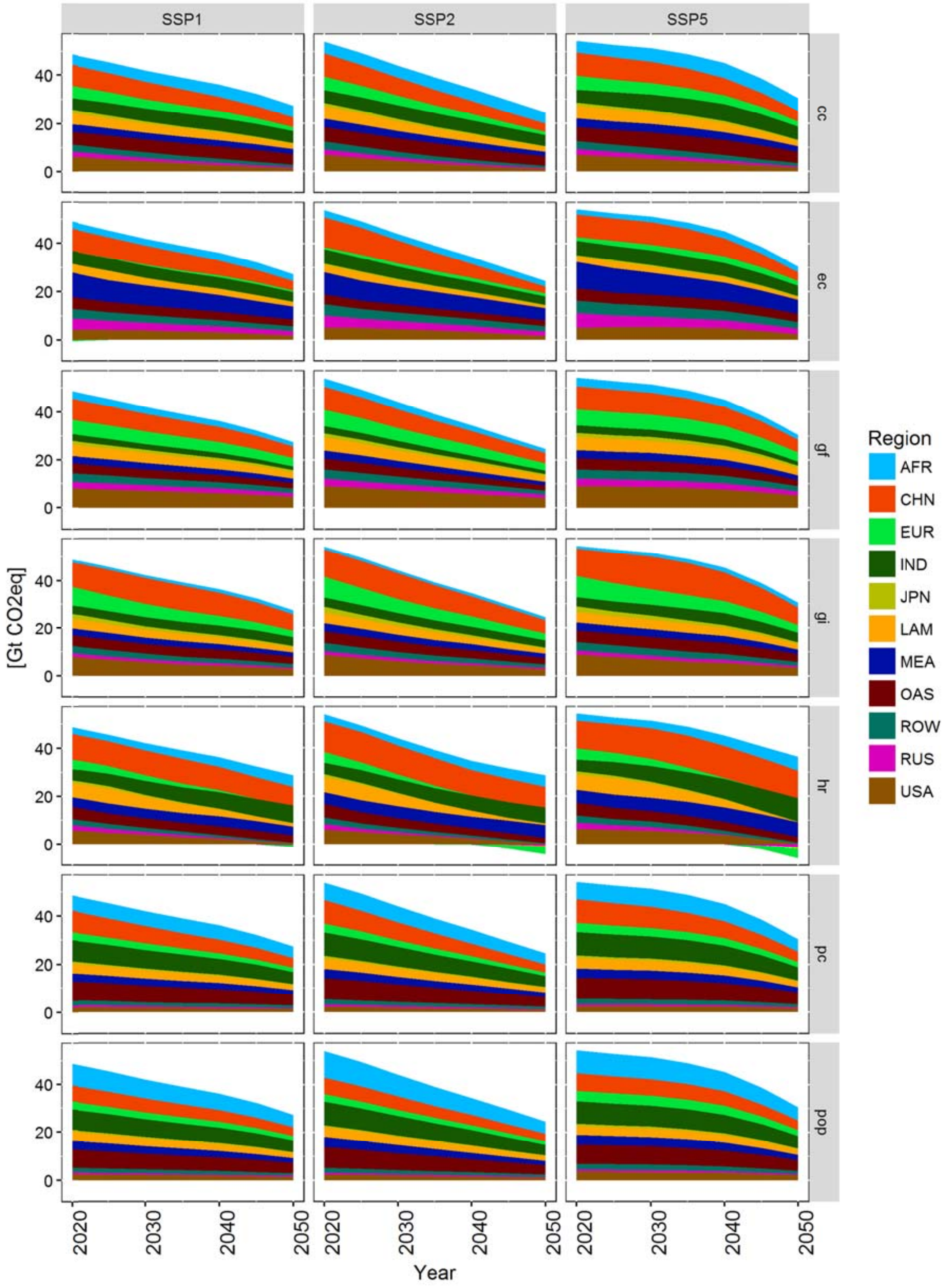


Fig. S.1: Distribution of emission allowances until 2050 under different burden sharing schemes and SSPs

Table S.1: Cumulated Permit trade value (discounted by 5% per year) in 2100 (in bill. US$2005); positive values indicate net costs, negative values net revenues

		AFR	CHN	EUR	IND	LAM	MEA	OAS	RUS	USA
CC	SSP1	-440	-45	140	-8	176	255	-420	238	58
	SSP2	-422	86	435	-287	203	360	-289	182	-76
	SSP5	16	-357	1279	782	471	-465	-259	85	-394
EC	SSP1	-97	359	1801	-177	568	-2261	47	-763	708
	SSP2	68	-13	2117	-665	1456	-2497	821	-1294	744
	SSP5	762	1148	2666	-716	2552	-4433	201	-2346	1483
GF	SSP1	698	-307	-582	1423	-48	370	459	-200	-1424
	SSP2	1265	-334	-645	1793	-88	535	974	-434	-2186
	SSP5	1793	-608	23	3413	65	-277	1340	-693	-3058
GI	SSP1	971	-1381	-585	602	258	369	142	235	-699
	SSP2	1854	-1608	-834	800	292	438	582	180	-1332
	SSP5	2869	-3312	60	2088	711	-233	862	83	-1796
HR	SSP1	-2489	-1568	2831	-3269	1233	-1045	-291	1298	2028
	SSP2	-5577	-3901	7689	-5963	2905	-3929	-587	2224	4803
	SSP5	-16186	-8310	17751	-15513	9636	-8998	1143	7492	8954
PC	SSP1	-723	-29	474	-481	241	228	-719	363	727
	SSP2	-910	131	930	-1057	305	311	-771	392	903
	SSP5	-615	-302	1855	-224	626	-525	-884	370	812
POP	SSP1	-1089	310	433	-383	300	216	-646	374	596
	SSP2	-1730	781	1004	-965	378	258	-693	409	831
	SSP5	-1367	1031	2243	287	1412	-828	-864	662	113

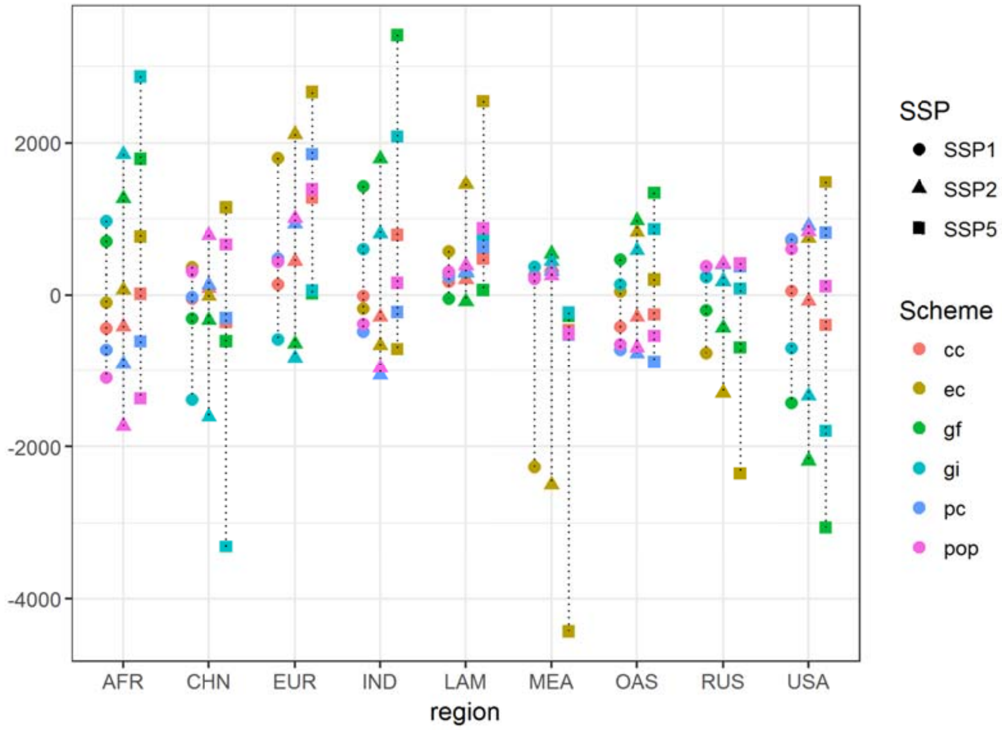


Fig. S.2: Cumulated Permit trade value (discounted by 5% per year) in 2100 (in bill. US$2005); positive values indicate net costs, negative values net revenues

Table S.2: Contribution of permit trade to overall mitigation costs (in percentage points)

		AFR	CHN	EUR	IND	LAM	MEA	OAS	RUS	USA
CC	SSP1	-0.8	0.0	0.0	0.0	0.2	0.4	-0.5	1.0	0.0
	SSP2	-0.9	0.1	0.2	-0.6	0.2	0.6	-0.4	0.8	0.0
	SSP5	0.0	-0.2	0.4	1.2	0.5	-0.6	-0.3	0.3	-0.1
EC	SSP1	-0.2	0.3	0.6	-0.3	0.6	-3.3	0.1	-3.2	0.3
	SSP2	0.2	0.0	0.7	-1.3	1.7	-3.9	1.1	-5.6	0.3
	SSP5	1.2	0.7	0.8	-1.1	2.6	-6.1	0.2	-8.5	0.4
GF	SSP1	1.4	-0.2	-0.2	2.4	0.0	0.5	0.5	-0.8	-0.5
	SSP2	2.8	-0.3	-0.2	3.5	-0.1	0.8	1.3	-1.9	-0.8
	SSP5	2.9	-0.4	0.0	5.1	0.1	-0.4	1.4	-2.5	-0.9
GI	SSP1	1.9	-1.0	-0.2	1.0	0.3	0.5	0.2	1.0	-0.3
	SSP2	4.1	-1.3	-0.3	1.6	0.3	0.7	0.8	0.8	-0.5
	SSP5	4.6	-2.1	0.0	3.1	0.7	-0.3	0.9	0.3	-0.5
HR	SSP1	-4.8	-1.1	0.9	-5.5	1.4	-1.5	-0.4	5.5	0.7
	SSP2	-12.4	-3.2	2.7	-11.6	3.4	-6.1	-0.8	9.7	1.8
	SSP5	-26.2	-5.3	5.1	-23.2	9.9	-12.3	1.2	27.3	2.6
PC	SSP1	-1.4	0.0	0.2	-0.8	0.3	0.3	-0.9	1.5	0.3
	SSP2	-2.0	0.1	0.3	-2.1	0.4	0.5	-1.0	1.7	0.3
	SSP5	-1.0	-0.2	0.5	-0.3	0.6	-0.7	-0.9	1.3	0.2
POP	SSP1	-2.1	0.2	0.1	-0.6	0.3	0.3	-0.8	1.6	0.2
	SSP2	-3.8	0.6	0.4	-1.9	0.4	0.4	-0.9	1.8	0.3
	SSP5	-2.2	0.4	0.4	0.2	0.9	-0.7	-0.6	1.5	0.0

A.5 POP-07 scenarios

Capital mobility in REMIND ensures that capital moves (i.e. is traded) between all regions until the rates of return of capital equalize. The Keynes-Ramsey rule applies, according to which the growth rate of per capita consumption in the balanced growth path is equal across all regions (assuming all regions have the same pure rate of time preference).

An upper bound on consumption losses, as in the POP-07 scenarios (section 6.1), may cause a distortion of the balanced growth path as demonstrated in Figure A.2. Whereas in the SSP5-POP scenario all trajectories of consumption losses are parallel to each other, this does not hold any longer for the consumption losses in the SSP5-POP-07 scenario.

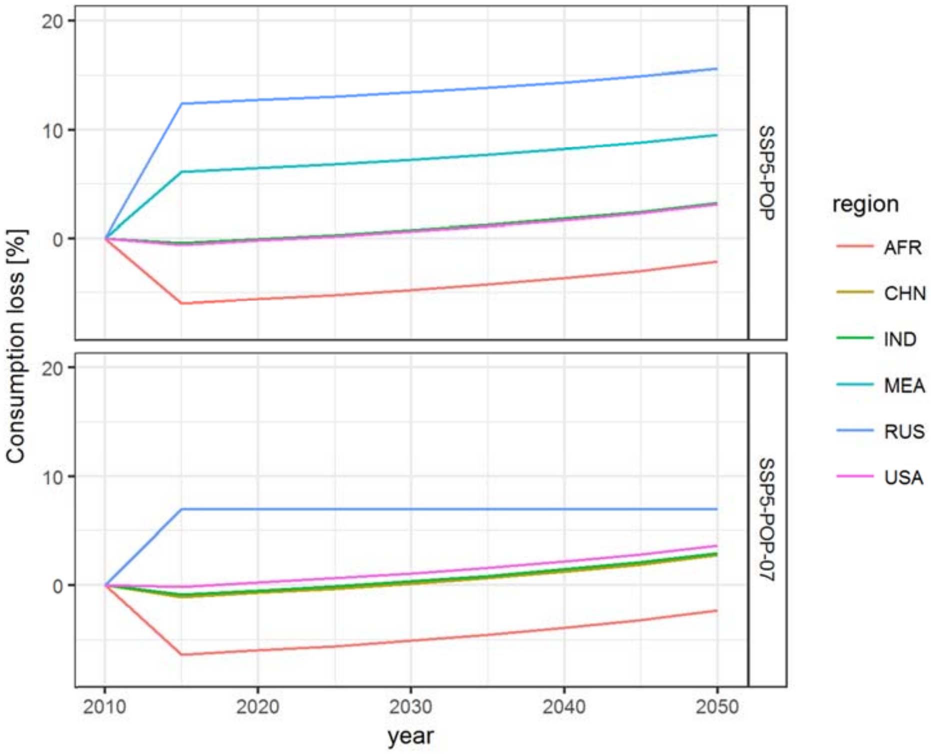


Fig. S.3: Consumption losses over time in SSP5-POP (upper panel) and SSP5-POP-07 scenario (lower panel)

The applied bound prevents in the case of MEA and Russia a further outflow of capital that would be needed in order to meet the intertemporal budget constraint. This directly follows from the interaction of consumption *C* and capital export *X* in the budget constraint and the contribution of capital (composite good) exports in the intertemporal trade balance. In the reduced form, the budget constraint reads as

$$C_t = Y_t + M_t^g - X_t^g - I$$

(with *Y* representing GDP, *M* import of composite good *g*, and *I* macroeconomic investments).

The intertemporal trade balance sums up net exports of the composite good and other goods *o* evaluated by respective net present value prices *p*:

$$B = \sum_t \left(p_t^g \left(X_t^g \ - M_t^g \right) + \sum_o \ p_t^o (X_t^o - M_t^o) \right)$$

With C* as the optimal consumption in the unconstrained model it holds:

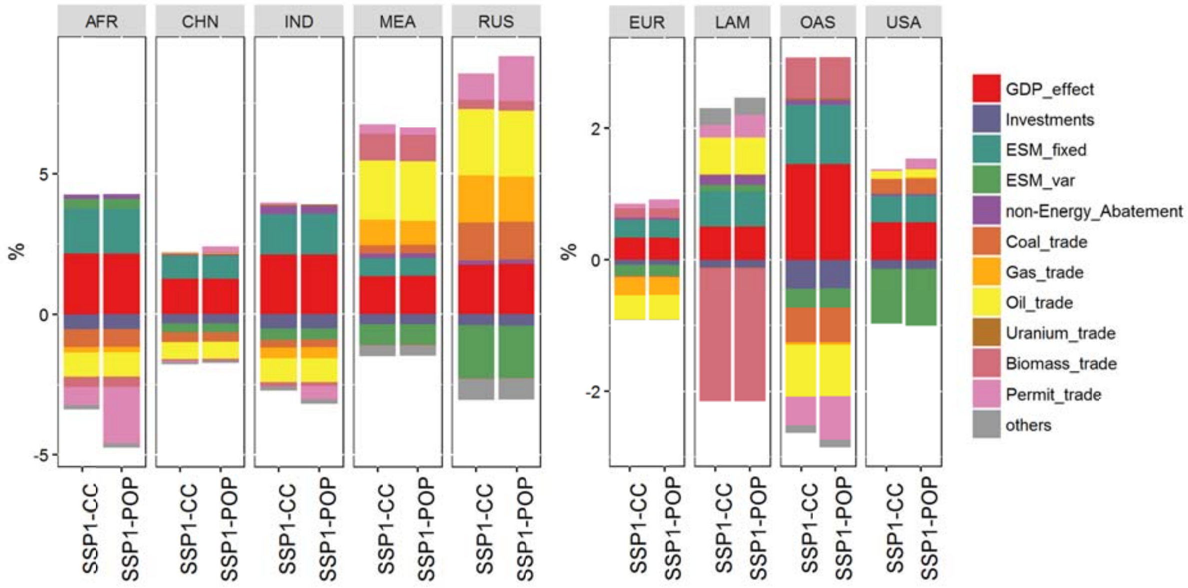
if $C_t > C_t^*$ then $B < 0$.

In the POP-07 scenarios, the model solution converges to a point where MEA and Russia accumulate a deficit (*B<0*) and all other regions a surplus in the intertemporal trade balance. We interpret this deficit as a financial transfer by the surplus regions that confines the consumption losses in the deficit regions according to the specified bound.

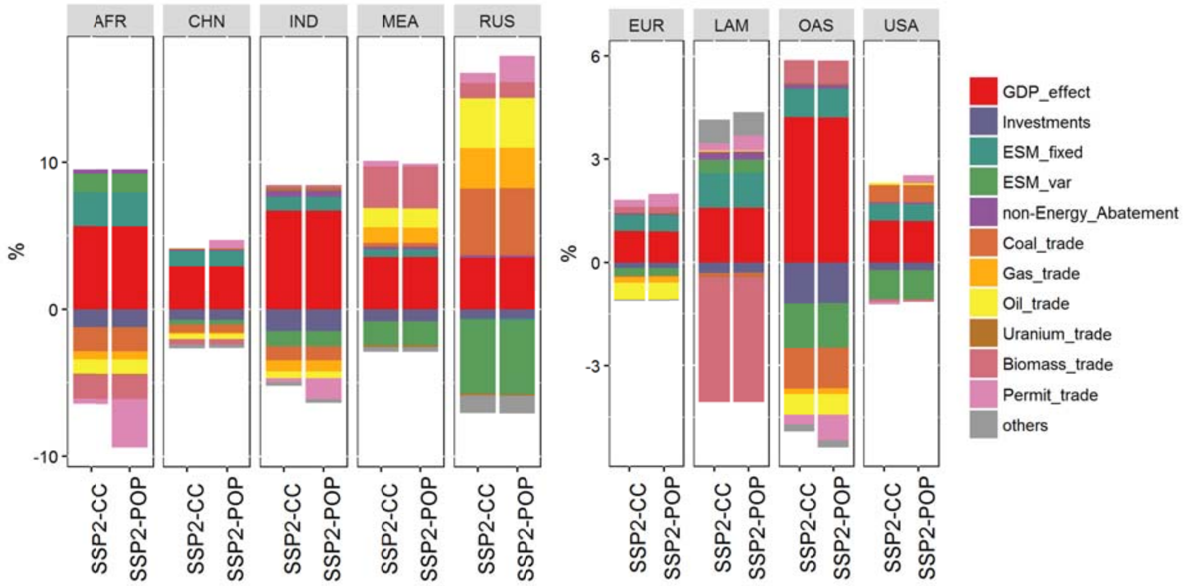
A.6 Decomposition analysis

A decomposition technique as described in Aboumahboub et al. (2014) is applied. The decomposition of mitigation costs is discussed by illustrations of the CC and POP scenarios (see Fig. S.4). The decomposition for the TAX scenarios is equal to the two discussed scenarios for all components but the permit trade. The same applies to the burden sharing schemes analyzed in section 5. The permit trade value is zero in the TAX scenarios. This equivalence of the decomposition is due to a property of REMIND as general equilibrium model with intertemporal capital trade which allows the separation of equity and efficiency (cf. section 3.2).

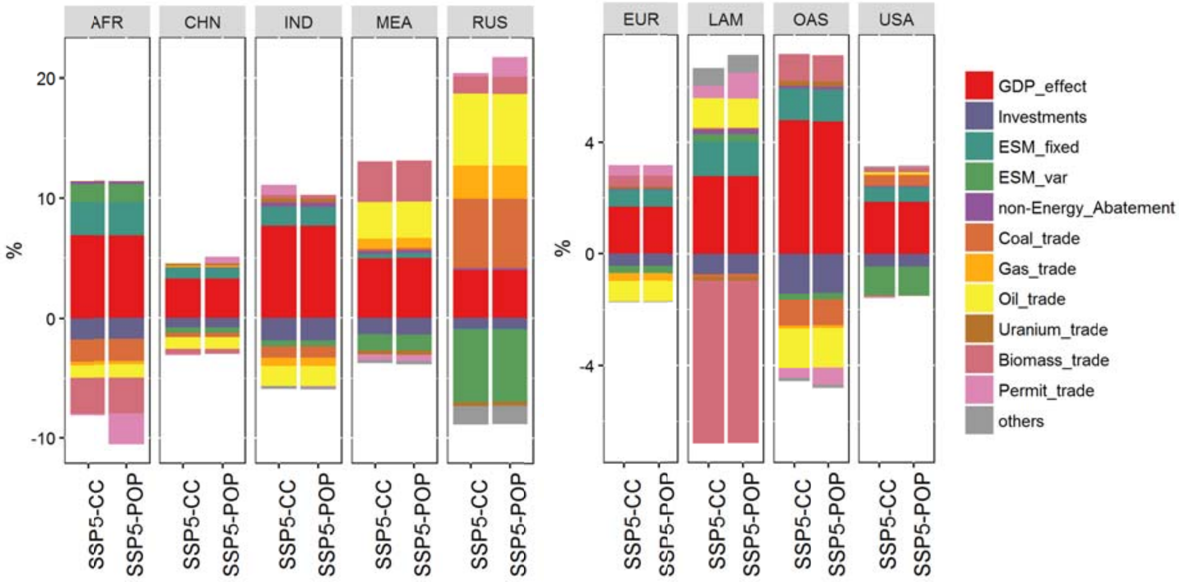
a.



b.



c.



S. 4: Decomposition of mitigation costs (panel a: SSP1, panel b: SSP2, panel c: SSP5)

Qualitatively, the decomposition shows a similar pattern across all SSPs. Overall, direct GDP losses represent a major part in all regions. However, despite similar GDP growth in SSP1 and SSP2, mitigation costs due to GDP losses are smaller in SSP1 because of higher energy efficiency and a higher preference for renewable energy. Both components reduce the carbon dioxide emission per unit of GDP already in the baseline. Mitigation costs contributions from trade are also large. Negative consumption effects due to decreasing fossil resource prices can be seen in MEA and Russia (to a smaller extent also in USA), and positive effects in AFR, China, India, OAS and EUR. In Russia and MEA, trade effects account for around 50% of the mitigation costs in all scenarios. Figures are even higher in Russia when permit imports are additionally taken into account. In both regions biofuels substitute fossils, hence biomass imports increase in policy scenarios. Consequently, the negative trade effect overcompensates savings from lower extraction and fuel costs. The only significant difference between the different scenarios of the same SSP type concerns the permit trade effect. It will be discussed in the next section.

In how far do differences in the mitigation cost composition mirror differences in the socio-economic assumptions across regions and across SSPs?

AFR and India show the highest direct growth impact (GDP effect), which is due to the assumption of relatively high growth rates in all scenarios (Dellink et al., 2017). The slightly lower economic growth rates and the contained population growth in SSP1 (cf. KC and Lutz, 2017) result in a somewhat lower contribution of the GDP effect in SSP1. On the other hand, a higher share of mitigation costs, compared to SSP2 and SSP5, is due to energy system investment costs (ESM_fixed). This indicates first that additional investments in carbon-free technologies are requested independently of the economic growth rate. Secondly, risk aversion on external environmental effects associated with large-scale biomass technologies (e.g. loss of biodiversity, reduction of food security) results in SSP1 in a preference to other forms of carbon–free energy technologies, like solar and wind, which have a higher fixed cost share than biomass technologies. With respect to the trade effects, AFR and India profit from lower prices on the energy markets – in particular with oil imports in SSP1. With a higher energy demand in SSP2 and in particular SSP5 (Bauer et al. 2017, Kriegler at al. 2017, Fricko et al., 2017), biomass plays a more important role – mainly as a unique technology of generating negative emissions, which are needed to compensate for remaining fossil fuel emissions. A higher share of negative mitigation costs is generated in AFR in SSP2 and SSP5 by revenues from biomass exports (both due to higher export quantities and higher prices). The biomass trade effect is most pronounced for LAM. LAM is the major exporter of biomass and profits from a price increase. A higher global demand for biomass in SSP5 based on a higher preference for this energy carrier and the need to compensate for initial higher fossil fuel consumption, enable LAM to scale up related trade benefits. Consequently, LAM faces even lower mitigation costs in SSP5 than in SSP1.

In all other regions, we see the same variation across the SSPs with respect to the GDP effect (lower share in SSP1) and energy system investment costs (higher share in SSP1), like in AFR and India. While China, OAS, and EUR also demonstrate a similar pattern regarding the energy trade effect (higher negative shares in SSP1), the opposite (higher positive shares in SSP1) applies to MEA and the USA. In particular, the major oil exporter MEA faces a higher share of mitigation costs due to losses in oil trade in SSP1. In Russia, the gas trade has an equal share of the mitigation costs in SSP1 as the oil trade, whereas the coal trade effect takes a much higher share in SSP2 and SSP5. This is a direct consequence of the high level of coal consumption globally in the baselines of SSP2 and SSP5 and related to the abundance of cheap coal in both scenario worlds. Compared to other regions, the USA exhibits a high negative share (i.e. gains) from lower fuel expenditures in SSP1. Overall, the decomposition analysis uncovers significant differences as well as qualitative similarities in the mitigation cost structure across the SSP scenarios.

A.7 Permit trading

Permit trading and in particular the allocation of permits are key components of burden sharing. Based on an agreed allocation of emission permits, transfers on the carbon market represent a well-defined form of climate finance. However, any type of climate finance implying the same transfers will yield the same burden sharing result.

Fig. S.5 presents the trade pattern in scenarios with a large amount of permit trade – SSP2-POP and SSP5-POP, peaking at 4.2 and 3.7 Gt CO_2eq in 2025, respectively. The SSP1-POP scenario peaks at a lower level of around 3.3 Gt CO_2eq in 2025. The trade pattern is the same in all POP scenarios: highest trade level in the beginning, a decreasing trade level until 2060 and a slight increase and stabilization at moderate levels towards the end of the century. The permit trade is much lower in the first half of the century in the CC scenarios (it hardly exceeds 1.5 Gt CO_2eq in SSP5-CC and even less in SSP2-CC and SSP1-CC), but the trade structure (i.e. the distribution of exporters and importers) is similar. This includes the switch of exporters and importers in 2060, which in particular holds for the big players on the carbon market: AFR, India, OAS, USA and China.

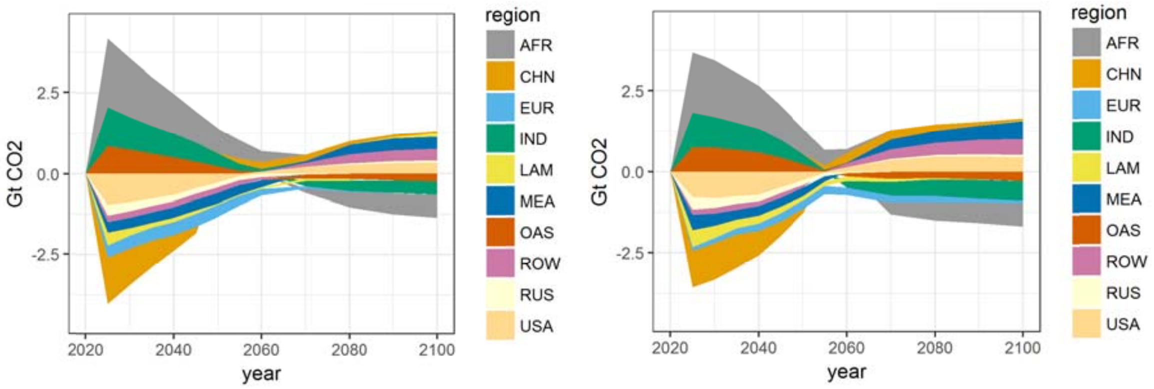


Fig. S.5: Permit trade (in Gt CO_2eq); left panel: SSP2-POP; right panel: SSP5-POP

The switch of exporters and importers does not at all mean that the contribution of the permit trade to the mitigation costs is well-balanced. The contribution of the permit trade depends on the carbon price as well as on the discount factor. The effects of both nearly cancel out each other. Thus, the areas in Fig. S.5 roughly illustrate for which regions we may expect positive or negative contributions to mitigation costs.

While details on these contributions are provided in Table S.2, another important information should be highlighted – the magnitude of revenues and transfers. Details on the cumulative amount of transfers are shown in Table S.1 and Fig. S.2. Furthermore, as Table S.3 demonstrates, transfers can be huge measured as share of GDP. Figures are high in the short term due to the large amount of permits traded and in the long term as a result of high carbon prices. Due to the initial existence of a fragmented climate policy regime, we see highest relative transfer levels with the beginning of the emissions trading system in 2025 and 2030. In SSP5-POP and SSP2-POP, we see maximum values of around 20% of GDP for AFR; for India the initial revenues are between 4% and 5% of GDP. These revenues on the carbon market are accompanied by payments that amount in 2030 to around 4% of

GDP for Russia, around 2% of GDP for China and MEA, and around 1% of GDP for LAM and USA (see Table S.3). Later in the century, substantial transfers flow in the opposite direction.

Table S.3: Share of Permit trade value on GDP in 2030, 2050 and 2100 (in %)

		AFR	CHN	EUR	IND	LAM	MEA	OAS	RUS	USA
SSP1-POP	2030	8.6	-0.6	-0.1	1.9	-0.4	-0.6	1.1	-1.8	-0.4
	2050	3.1	-0.2	-0.3	0.8	-0.3	-0.7	0.9	-2.0	-0.4
	2100	-2.0	0.2	0.3	-3.9	0.0	2.9	-1.4	1.2	2.1
SSP1-CC	2030	3.1	-0.3	0.0	0.5	-0.1	-0.8	0.6	-0.5	-0.1
	2050	2.5	-0.1	-0.3	1.0	-0.3	-0.8	0.9	-2.0	-0.4
	2100	-2.3	2.4	0.2	-3.8	0.1	2.9	-1.3	1.4	2.0
SSP2-POP	2030	18.8	-1.4	-0.4	4.6	-0.7	-1.3	2.1	-3.0	-0.8
	2050	7.1	0.0	-0.7	2.2	-0.2	-2.0	0.9	-3.0	-0.5
	2100	-7.4	1.3	0.0	-7.3	2.1	8.8	-3.4	8.2	4.3
SSP2-CC	2030	6.3	-0.7	0.0	1.6	-0.2	-1.8	1.1	-0.5	-0.2
	2050	5.4	0.3	-0.7	2.5	-0.2	-0.2	1.0	-3.0	-0.6
	2100	-8.0	2.1	0.0	-7.2	2.3	8.7	-3.4	8.3	4.2
SSP5-POP	2030	17.6	-1.3	-0.2	4.3	-1.2	-1.6	2.1	-3.2	-0.8
	2050	5.7	-0.3	-0.5	1.5	-0.7	-1.7	0.9	-2.8	-0.5
	2100	-7.0	1.3	-0.7	-11.1	0.4	15.4	-4.1	9.6	3.3
SSP5-CC	2030	7.2	-0.6	0.0	1.6	-0.3	-1.9	1.3	-0.5	-0.4
	2050	4.8	0.0	-0.7	2.0	-0.5	-1.5	1.1	-2.7	-0.8
	2100	-8.0	3.6	-1.0	-10.3	1.1	15.4	-3.5	10.3	2.8

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