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Report on the compensation and burden sharing for a 2°C policy

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1. Introduction and Overview

At the very heart of the response to climate change lies the need to reduce GHG emissions. In 2010, governments recognized the long term goal of limiting global mean temperature increase to below 2 degrees Celsius. The Conferences of Parties in Durban and Doha re-emphasized this target and concluded that by 2015 a post-Kyoto legally binding climate change control agreement should be achieved and become active from 2020 onwards. Behind this background it is most likely that one of the main challenges in all further negotiations will be the allocation of GHG emission reduction obligations across regions. With this report the LIMITS project aims to contribute to the discourse on distribution of the mitigation effort and specifically looks at two inter-regional burden-sharing schemes:

- The resource sharing scheme, which allocates emission allowances according to GHG emissions per capita for each region in 2020 and the evolution of the global average GHG emissions based on population-related criteria.
- The effort-sharing scheme, which attributes emission rights to regions according to their individual GDP and the world's total climate policy costs and economic development.

The papers presented in this report look at the burden-sharing issue from different angles:

- multi-model perspective on distribution effort across major economies.
- single-model perspective on distribution effort with an additional focus on the decomposition of regional mitigation costs, including the contribution of burden sharing regimes, and the effects of delayed cooperative action.
- single-model perspective on distribution effort with an additional focus on limitations in carbon permits trade.

The distribution of the major economies' effort in the Durban platform scenarios

This paper is based on a set of coordinated scenarios, simulated by six integrated assessment models (IAM). It looks at three schemes for allocating the mitigation effort: a uniform carbon pricing and no transfer payments, a resource sharing scheme based on long-term convergence of per capita emissions and an effort sharing scheme which equalizes regional policy costs. It comes to the conclusion that the first would lead to an uneven distribution of policy costs, with below global average costs for OECD countries and above global average costs for developing and exporting economies; the second would lead to a more equal distribution of policy costs in the short run, but not resolve distributional conflicts in the long-term; the third leads to an equal distribution of costs by definition. In both resources sharing schemes, the size of the international carbon market would need to substantially exceed the one framed by the Clean Development Mechanism and thus would require a major institutional and management effort.

On the regional distribution of climate mitigation costs: the impact of delayed cooperative action

The paper is based on the results of the REMIND model and analyses costs for establishing global action to limit global warming to 2°C by 2020 or 2030. Mitigation costs at the regional level vary substantially, and are affected by a delay in climate policy. With a decomposition method, the paper identifies the determinants of regional mitigation costs, namely economic output and investments, energy system expenditures and changes in trade. Some regions see an increase of domestic costs due to delay, caused by the lock-in with carbon-intensive infrastructure and subsequent increase of investment costs for decarbonising the energy system. Variations also depend on the over- or under-allocation of emission allowances. Regions with allowances exceeding their emissions will benefit from delay, while others will suffer from higher carbon process caused by the delay.

Emission Certificate Trade and Costs under Regional Burden Sharing Regimes for a 2°C Climate Change Control Target

This paper reports the results from the TIAM-ECN model on the impacts of the two burden-sharing schemes. The study shows that to reach the 2°C target overall GHG emissions need to become negative at the end of the century and for some regions and sectors already before in order to compensate for GHG emissions in regions and sectors where abatement is too costly. Also, the amount of certificates traded under the resource-sharing scheme is three times higher than in the effort-sharing scheme, as allocation of permits in the latter is closer to the allocation under a least-cost reference mitigation scenario. Furthermore, the study investigates the effects of possible limitations in international carbon permit trade. Global climate policy costs rise by up to 20% in the short to mid-term in the study, since alternative climate change mitigation measures such as additional abatement have to be realised within the regions to keep on track with a global 2°C climate stabilisation pathway. Trade restrictions would impose higher policy costs in the resource-sharing scheme than in the effort-sharing scheme, due to the larger amount of certificate trading under the former.

This report provides new insights into the regional implications of 2°C climate policies and as such represents a major novelty compared to most IAM studies. It constitutes a major advancement compared to the existing literature, by analysing the the impacts of near-term, fragmented mitigation efforts and burden sharing regimes on the regional distribution of long-term mitigation costs in a multi-model comparison setting. Another important contribution is the improved assessment and interpretation of modelling results by providing a cost decomposition method and a sensitivity analysis on the effect of possible limitations in global trade of carbon certificates.

2. The distribution of the major economies' effort in the Durban platform scenarios

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2.1. Abstract

The feasibility of achieving climate stabilization consistent with the objective of 2°C is heavily influenced by how the effort in terms of mitigation and economic resources will be distributed among the major economies. This paper provides a multi-model quantification of the mitigation commitment in ten major regions of the world for a diversity of allocation schemes. Our results indicate that a policy with uniform carbon pricing and no transfer payments would yield an uneven distribution of policy costs, which would be lower than the global average for OECD countries, higher for developing economies and the highest, for energy exporters. We show that a resource sharing scheme based on long-term convergence of per capita emissions would not resolve the issue of cost distribution. An effort sharing scheme which equalizes regional policy costs would yield an allocation of allowances comparable with the ones proposed by the Major Economies. Under such a scheme, emissions would peak between 2030 and 2045 for China and remain rather flat for India. In all cases, a very large international carbon market would be required.

2.2. Motivation and study design

In spite of the accelerating trend of climate change, no significant progress in international climate policy-making has been observed over the past few years. This has led many analysts and policy-makers to focus on more bottom-up and decentralized approaches to climate change mitigation, which try to reconcile emissions reductions with national and subnational objectives such as economic growth, pollution reduction, and energy security, or provide alternatives to mitigation such as adaptation and geo-engineering. Though such approaches are likely to dominate the political agenda for climate change mitigation in the next few years, the discussion about coordinated action to reduce greenhouse gas emissions will ultimately remain a central one. This is because harmonizing mitigation effort is crucial for ensuring that climate change is tackled efficiently and effectively.

In the next few years, international climate policymaking will be focused on the negotiation process under the Durban platform for enhanced action. This platform provides an interesting opportunity for discussing post-2020 emission reduction commitments beyond the traditional divide of developed versus developing countries. A refocus on the major economies might help achieve more than expected, and calls for new thinking about the best policy instruments which can be put into place to provide adequate incentives to join the coalition. Climate clubs are known to increase the likelihood of the stability of the international agreement, but the need for coordination and for transfer payments will remain a pre-requisite for the coalition to be effective. Global cooperative action implies that some regions with larger mitigation potential undertake a greater mitigation effort to achieve the cheapest global solution. Forming a coalition on climate action will therefore require some form of burden sharing mechanism, which would compensate such countries for the extra costs of CO_2 policies.

Integrated assessment models are extensively applied to assess the global implications and the interactions of climate mitigation policies, and they play an increasing role in the scientific debate about climate change mitigation. Since models vary considerably in the assumptions and methodologies, multi-model ensembles have emerged in the past few years as the best way to identify insights which are robust across a range of assumptions and methodologies. Several of these assessments have included climate stabilization policies which are compatible with maintaining global temperature increase below 2°C (Clarke et al., 2009; Edenhofer et al., 2010; Kriegler et al., Submitted), quantifying the mitigation effort in terms of changes of the energy and land use system, and of their impacts on economic growth. However, few coordinated studies have set forth to assess the distribution of this effort across the major economies for different ways of sharing the mitigation commitments (see below for a literature review). The LIMITS study aims to fill this gap.

2.3. Study design

The LIMITS project (http://www.feem-project.net/limits/), which has led to this article and to the overall special issue, has taken on as one of the objectives the issue of regional burden sharing. To this end, a set of coordinated scenarios have been simulated by six integrated assessment models (see the editorial article and the article by Kriegler et. al of this special issue for a detailed description of the participating models). Table 1 summarizes the 4 scenarios, which will provide the backbone of the analysis for this paper. More information about the assumptions underlying each scenario is provided in Table SO1 in the supporting online material.

Scenario Type	Near-term Target / Fragmented Action	Fragmented Action until	Long-term Target / Global Action	Burden Sharing Scheme	NAME in the paper
Baseline	None	N/A	None	None	Base
Climate Policy	Weak	2020	450 ppm CO_2-eq	None	RefPol-450
Climate Policy	Weak	2020	450 ppm CO_2-eq	Per Capita Convergence	RefPol-450-PC
Climate Policy	Weak	2020	450 ppm CO_2-eq	Equal Mitigation Efforts	RefPol-450-EE

Table 1: Scenarios relevant for this paper

The Base scenario is a counterfactual baseline development without climate policy against which climate policy scenarios are evaluated. It portrays a pessimistic view of the future in which no climate change mitigation is carried out, and also in which energy policies are extremely limited. In the project we have also considered two additional 'reference' scenarios, with varying degrees of climate and energy policies; but for simplicity this paper will take as reference the counterfactual baseline. The interested reader is referred to (Kriegler and al., 2013, this issue) for further information.

The RefPol-450 is a scenario which aims at stabilizing climate at a level which would ensure to attain the 2°C objective with a relatively high probability (>60-70%). In particular, the equivalent concentrations of greenhouse gases in the atmosphere are set in 2100 at 450 ppm CO_2-eq. This target can be exceeded before 2100, leading to an overshoot of concentrations. The policy is implemented starting immediately after 2020 (thus, 2025/2030 depending on the model time resolution) via a carbon price which is applied uniformly to all regions and which covers all greenhouse gases. Fragmented action with different regional commitments is implemented before the policy kicks in. This scenario represents the standard cost efficient solution after 2025 with equalization of marginal abatement costs throughout the world and no distribution of emission allowances. No trade of carbon across regions is thus foreseen in this scenario[1].

In order to include the possibility of burden sharing, the multi model ensemble has considered two additional scenarios which can be categorized as *'resource-sharing'* and *'effort-sharing'* respectively (see den Elzen and Höhne (2008, 2010) for a overview of allocation approaches).

The RefPol-450-PC is based on a *resource sharing* allocation scheme in which emission rights are eventually allocated according to equalized GHG emissions per capita, This regime is based on both the sovereignty and egalitarian equity principles (Rawls, 1999). The convergence to the per capita equalization of emission rights takes place from 2020 onwards and is attained by 2050. The regional shares of global emissions are calculated according to the following linear interpolation schedule:

$$\frac{E_r(t)}{E_w(t)} = \frac{T_2-t}{T_2-T_1} * \frac{E_r(T_1)}{E_w(T_1)} + \frac{t-T_1}{T_2-T_1} * \frac{P_r(t)}{P_w(t)} [1]$$

Er(t): Regional emissions allowances in time step t

Ew(t): World emissions in time step t

Pr(t): Regional population in time step t

Pw(t): World population in time step t

T1: Reference year for grandfathering (here: 2020)

[1] Equivalently, this scenario can be seen as one in which allowances are allocate to regions equally to their cost effective abatement levels. As a consequence, there is no incentive to trade.

T2: Target year for convergence (2050)

In addition, we have investigated an *effort-sharing* scheme in which relative climate policy costs are equalized across regions, RefPol-450-EE. This means that at every point in time (from 2025/2030 onwards) all regions within each individual model incur the same policy costs as the global average, ensuring a flat distribution of effort. Policy costs are calculated as percentage of consumption losses from baseline over GDP for macro-economic models, and as mitigation costs (measured as the area under the Marginal Abatement Cost curve or as the additional energy system costs) plus net gains or losses due to permit trading over GDP for energy system models. The following formula summarizes the equal effort rule:

$$\left(\frac{C_r}{Y_r}\right)_t = \left(\frac{C_w}{Y_w}\right)_t \qquad \forall t \in \{2020, 2030, \dots, 2100\} \text{ [2]}$$

C_r: Regional absolute policy costs

C_w: World absolute policy costs

Y_r: Regional GDP

Y_w: World GDP

This allocation scheme represents a novel contribution of this project to the literature, with the exception of Harrison and Rutherford, 1999. The scheme does not attempt to resolve the difficult ethical questions which characterize burden sharing, such as who is responsible for historical emissions and who is likely to suffer the most damage from climate change. Indeed, the equal effort scheme might be seen as unjust from the perspective of those countries – many of which developing ones- which have or will contribute to the climate change problem to a limited extent, or which will suffer most of its adverse consequences. The value of the equal effort scheme is to provide a reference level in terms of emission allocations for which no region is worse off than any other in terms of mitigation costs relative to economic output. It provides a reference for a "level playing field" in which all countries take on similar mitigation costs. This means that countries who fare worse under GHG mitigation (such as energy exporters who lose export revenue) are compensated for their losses through a global carbon market. The outcome of this scenario will be a set of emission allocations which are model-dependent, since different models are likely to foresee a different regional distribution of costs.

All three schemes represent idealized policy contexts, none of which will be entirely implemented, even in the rosiest outcome of international climate policies. This simplicity however allows us focusing on the key elements. The approach taken in this paper reflects the importance of including three key elements which have been dubbed as essential for an effective international climate policy: "a framework to ensure that key industrialized and developing nations are involved in differentiated but meaningful ways, an emphasis on an extended time path for emissions targets, and the inclusion of flexible market-based policy instruments to keep costs down and facilitate international equity" (Olmstead and Stavins, 2012).

Throughout the paper, we show results for 10 representative regions (see Box1 in the supporting information for a detailed description of these regions). The choice of regional aggregation is not an univocal one, since different models have different native regions. The one adopted here has been chosen with the aim of best mapping all models native regions into 10 representative regions, but approximations for some specific regional compounds was unavoidable.

2.4. Relation to the literature

Effort sharing refers to a differentiation of commitments of reducing global greenhouse gas emissions to avoid dangerous climate change. In general, approaches are based on some sort of equity principle in accordance with their common but differentiated responsibilities and respective capabilities (UNFCCC, article 3). See Ringius et al. (2002), Rose et al. (1998) and Berk and den Elzen (2001) for a discussion of different equity principles. Many effort-sharing approaches have been proposed and discussed in the literature, each with different participation levels, timing of reductions, as well as stringency and type of commitments (See an overview of proposals in e.g. Bodansky, 2004; Gupta et al., 2007; Kameyama, 2004; Philibert, 2005). The equal effort scheme proposed in this paper (RefPol-450-EE) can be related to the GreenHouse development right framework (Baer et al., 2009). The framework allocates emission reductions based on an index, which encompasses both historic responsibility and economic capacity, whereas in this paper we focus only on the latter. Other papers have proposed and tested burden sharing schemes based on the division of effort across members (see Elzen and Höhne (2008, 2010) (Ekholm et al., 2010)).

Furthermore, there is a broad literature on the environmental and economic impacts for specific countries or world regions of such approaches. See for example den Elzen and Lucas (2005) for an assessment of a broad range approaches using the FAIR model, den Elzen and Höhne (2008, 2010) for a meta-analysis of scientific literature focussing on Annex-I and non Annex-I reductions requirements and van Ruijven et al. (2012) for a meta-analysis of the scientific literature focussing reduction requirements and cost implication for China and India. However, few studies have looked at effort sharing in the context of a multi model ensemble. Existing studies include Edenhofer et al. (2010) and Johansson et al. (submitted) who discuss a single regime using different global and national models. While Edenhofer et al. took a global perspective, Johansson et al. focused on China and India only. Luderer et al (2012) investigated four distinct burden sharing regimes with three global models, but concentrated on a stabilization target which is laxer than the one assessed here. They showed that regional mitigation costs are highly dependent on the choice of model and regime, pointing to the need for further research on regional mitigation costs and compensation mechanisms.

The equal effort scheme proposed in this paper can be related to the Greenhouse development right framework (Baer et al., 2009). The framework allocates emission reductions based on an index, which encompasses both historic responsibility and economic capacity, whereas in this paper we focus only on the latter. Other papers have proposed and tested burden sharing schemes based on the division of effort across members (see Elzen and Höhne

(2008, 2010) (Ekholm et al., 2010)). An important difference, however, is that the equal effort scheme analysed here is distributes the effort in terms of mitigation costs, while virtually all other approaches proposed in the literature distribute the effort in terms of emission reductions relative to baseline, or distribute the remaining permissible emissions.

2.5. Main questions to be addressed

This paper will address the following three main issues:

1. In order to ensure economic efficiency and minimize costs, a policy framework which harmonizes carbon pricing across regions is ideal. But what are the consequences of this arrangement for the distribution of costs between regions? In other words, who are the regional winners and losers in a “cost-effective” set up without regional side payments? We will tackle this issue in Section 2.
2. Alleviating the distributional implications of climate policies while retaining economic efficiency will invariably require allocating different regions with different endowments of carbon permits. What would be the distribution of emission endowments if either the carbon space or the economic effort were shared equally across regions? And to what extent do different endowments of permits mitigate the diverse distribution of effort in terms of mitigation and costs? We will look into this in Section 3.
3. Allocating permits would create endowments which would be traded and distributed across regions, and which would require establishing a global market for CO_2. What would the size of this market be, and which positions each region take with respect to net permit-trading? Section 4 will focus on this.

The final section will conclude and highlight future research avenues. Throughout the paper, we will examine the implications of 10 major countries which cover the whole world. This regional aggregation has been designed to best match the different native regional details across models, which is relatively coarse in terms of spatial disaggregation. The regional definition can be found in the supporting online material.

This paper is related to the other overview article of the special issue of the LIMITS project (Kriegler and al., 2013).. The paper by Kriegler and al., 2013 provides an in depth evaluation of the Durban scenarios with a focus on emissions reduction requirements, the consistency with the 2˚C target and global economic impacts, whereas this article is centred around the discussion of the regional costs under different ways of sharing the burden of the climate policy.

2.6. The diversity of effort across regions in a cost minimizing setting without compensation

It is instructive to start from a framework in which each region undertakes mitigation based on the same incentive to abate carbon, but without the establishment of a market for GHG emissions endowments. This is the setting of the carbon tax scenario RefPol-450. Pricing carbon equally across regions ensures that the ideal mitigation options are picked irrespectively of where they are located, and that as a result the most efficient outcome is achieved globally. In a world of scarce resources and limited political capital for the cause of climate change, it seems that cost containment should be a top policy priority. However, this method is blind to the issue of distribution of costs; in principle, if a region hosted all the cheaper abatement options (even at the margin), it would carry out the totality of abatement, and face all the costs.

Indeed, the distribution of the mitigation effort –measured in costs- of a carbon tax scenario is quite unevenly distributed, as shown in Figure 1[2]. The chart emphasizes a significant variation of policy costs across regions, and across models in some instances, but reveals a rather clear three-tier pattern. Advanced economies such as Europe, US and Pacific OECD bear a cost which is lower than the global average. Fast growing economies, including Latin America, Southeast Asia, India and Africa, pay a larger fraction of the cost. Finally, energy-exporting countries like Russia and the Middle East bear a policy costs which can be several times the global one[3].

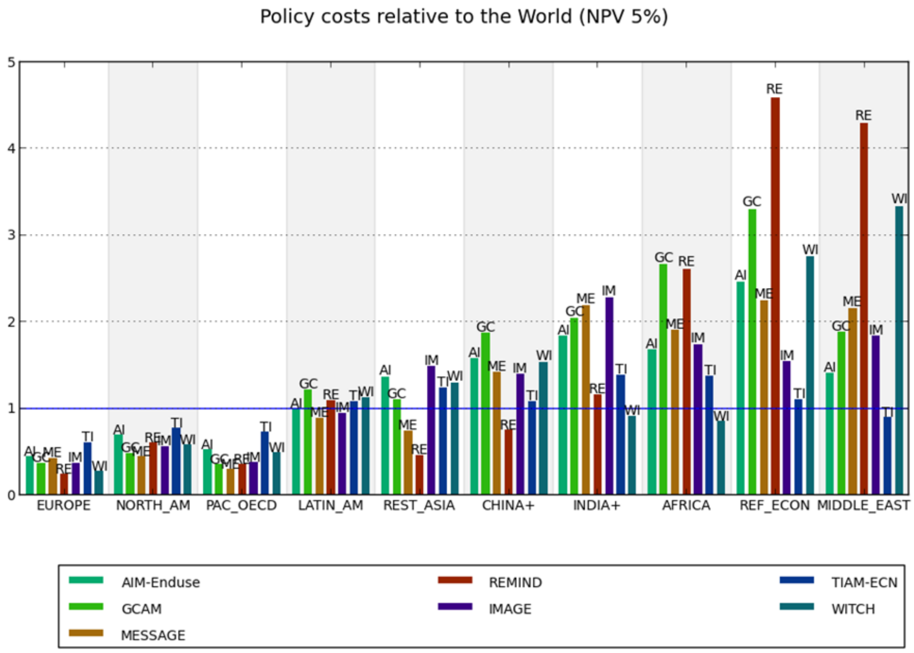

Figure 1: The uneven distribution of regional policy costs. The chart shows regional policy costs across models in the carbon tax scenario (RefPol-450), relative to the global level (indicated by the blue line at 1). Costs (see Footnote 3) are actualized in Net Present Value (NPV) from 2020 to 2100 using a 5% discount rate.

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[2] Throughout the paper policy costs are calculated in accordance with equation 2. They are consumption losses over GDP for models with a macro-economic component (MESSAGE; REMIND; WITCH). For REMIND, mitigation costs include, in addition to consumption losses, changes net foreign assets due to changes in current accounts induced by climate policy (for more information, see Aboumahboub et al., this issue). Abatement costs over GDP are used for AIM-Enduse, IMAGE and GCAM, and energy system costs over GDP is used for TIAM-ECN. GDP is expressed in market exchange rates (MER) for all models except TIAM-ECN, who uses purchasing power parity (PPP).

[3] The only model which does not show this last effect is TIAM-ECN. This is due to the assumption about trade of physical CO_2 in the model (though this possibility is also allowed in the GCAM model). This additional element of flexibility provides a source of revenue to energy exporting countries, who can count on a large storage potential, and thus can, at least partly, compensate reduced revenues from decreasing fossil fuel exports by providing CO_2 storage capacity to other regions. For more information see Kober et. al. 2013, this issue.

The regional discrimination in terms of economic effort to achieve a 2°C climate change control target via a uniform carbon tax policy instrument is robust to different cost metrics. As Table 2 indicates[4], the regional ordering is almost unchanged when measuring costs in a variety of different ways[5]. *OECD* remains the ones *below global costs; fast growing economies* are generally *above global costs*; and *energy exporting* countries are *well above global costs*. The use of different discount rates suggests that this ranking is rather persistent over time.

	NPV_5	NPV_3	NPV_0	max2050	max2100	NPV_5 PPP
MIDDLE_EAST	2.6	2.5	2.3	2.3	2.3	1.1
REF_ECON	3.0	3.0	3.1	3.0	3.5	0.9
AFRICA	2.1	1.9	1.6	1.6	1.4	1.2
INDIA+	2.0	1.7	1.5	1.4	1.4	1.2
CHINA+	1.6	1.5	1.3	1.5	1.4	0.8
REST_ASIA	1.3	1.2	1.1	1.1	1.2	0.8
LATIN_AM	1.2	1.2	1.1	1.1	1.2	0.7
NORTH_AM	0.7	0.7	0.8	0.8	0.9	0.5
PAC_OECD	0.5	0.6	0.7	0.7	1.1	0.4
EUROPE	0.5	0.5	0.6	0.5	0.7	0.4

Table 2: Robust ordering of regional costs. The table reports policy costs relative to the global average (as in Figure 1) for different cost metrics. Figures are average across models. Npv_5, npv_3 and npv_0 are NPV calculations of costs in the period 2020-2100 at yearly discount rates of 5%, 3% and 0% respectively. Max_2050 and max_2100 is the maximum costs in the periods 2020-2050 and 2020-2100. In the last column, costs are calculated based on PPP

[4] Note that Table 2 displays averages across participating models. Though models project different distribution of costs because of different assumptions, as shown in Figure 1 the ranking of the regions is quite robust across models. The use of averages is thus justified.

[5] The regional difference is less evident for the PPP case, though the ranking remains unchanged. However, given the different cost metric and different set of models included, the values in this column cannot be directly compared to the other columns.

GDP[6] (for the models reporting it, IMAGE, MESSAGE, and TIAM-ECN). Red colouring is used for costs above global average (e.g. >1) and blue colouring for below the global average (e.g. <1).

There are various reasons why policy costs differ so widely across regions. And given the given the characteristics of the group of countries identified above, likely candidates include variables which characterize regional economic and energy/land use systems, such as: *economic growth, energy intensity, fossil energy trade exposure, low carbon resources*.

Table 3 provides a decomposition of regional costs to such factors. We use a simple linear regression in which regional policy costs (in log) are explained by abatement, total emissions in the BAU, the energy intensity of the economy, and dummies for groups of regions (EEX and Developing Countries) and for general equilibrium versus partial equilibrium models[7]. In order to control for the potential multi-collinearity of the explanatory variables, different specification are reported[8].

The results of the regression show that relative abatement, as well as the size of regional BAU emissions and energy intensity, are significant and all affect policy costs positively. When controlling for modelling and regional differences, the coefficient of baseline emissions becomes more significant and higher. This is mostly due to the fact that developing countries have a larger size (see specification 4). Energy intensity is not significant with the full specification (number 2), because of its relation with the energy exporting dummy variable (see the specification number 3).

The results of the dummy variables also confirms the intuition: General Equilibrium models are found to be more expensive compared to the other models (and not to be statistically different from each other)[9], due to larger feedback of the energy sector on the economy[10]. For bottom up, partial equilibrium models, IMAGE and MESSAGE are cheaper than GCAM[11], and TIAM-ECN is not significantly different. Finally, regional patterns are also identified: energy exporting countries show have policy costs which are statistically higher than the ones in the OECD[12], highlighting the role of terms of trade effects for these regions.

	(1)	(2)	(3)	(4)

[6] Given the different cost metric and different set of models included, the values in this column cannot be directly compared to the other columns.

[8] Correlation between coefficients is at any rate rather modest, never exceeding 0.5-

[9] The dummy for WITCH has been automatically dropped from the regressions. Thus, the coefficient for REMIND must be interpreted as relative to WITCH.

[10] MESSAGE is treated as a 'partial equilibrium' model despite its link to a macro-economic module, and the fact that policy costs are calculated as consumption losses, similarly to WITCH and REMIND. But the economic module is not hard linked as in WITCH and REMIND, and the model is linear, and it has a more detailed representation of the mitigation technologies.

[11] The dummy for GCAM has been automatically dropped from the regressions. Thus, the coefficient for the other bottom up models must be interpreted as relative to GCAM.

[12] The dummy for the OECD has been automatically dropped from the regressions. Thus, the coefficients for EEX and DCs must be interpreted as relative to the OECD.

	Cost (log)	Cost (log)	Cost (log)	Cost (log)
Abatement	3.112***	3.528***	3.247***	3.065***
	(9.42)	(12.25)	(10.35)	(9.26)
Emi_BAU	0.296*	0.638***	0.410**	0.293*
	(2.01)	(4.39)	(2.69)	(2.09)
Enint_BAU	86.81***	-21.58	105.5***	
	(6.48)	(-0.89)	(7.26)	
IMAGE		-0.543**	-0.0942	-0.548**
		(-3.06)	(-0.48)	(-2.80)
MESSAGE		-0.625**	-0.252	-0.558*
		(-3.20)	(-1.14)	(-2.38)
REMIND		-0.0110	-0.0791	-0.0127
		(-0.07)	(-0.41)	(-0.05)
TIAM-ECN		0.224	-0.0532	0.103
		(1.45)	(-0.35)	(0.65)

GE		0.534**	0.937***	0.592**
		(3.15)	(5.31)	(2.87)
DC		0.285	-0.271	
		(1.91)	(-1.95)	
EEX		1.664***		
		(6.49)		
Constant	-3.364***	-3.634***	-3.717***	-2.807***
	(-12.34)	(-13.55)	(-13.35)	(-9.89)
N	227	227	227	227
adj. R^2	0.463	0.671	0.588	0.505

t statistics in parentheses (based on robust standard errors)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3: Results of the linear regression of the log of policy costs (NPV 5%) with respect to abatement (cumulative to 2100 and relative to the BAU), total emissions in the BAU (cumulative to 2100), and the energy intensity of the economy (computed from cumulative values as well). Some of the 4 specification also include a dummy variable for energy exporting countries (EEX) and one for developing countries (DC), as well as a dummy for the two general equilibrium models WITCH and REMIND (GE). The regression has been done on 4 scenarios (2 policy baselines and 2 climate stabilization targets) in the LIMITS data set[13].

We further elaborate on energy exporting countries in Figure 3, which shows the effect of stabilization on energy export revenues. All the models show that there is a decrease in energy export revenues for the Middle East and

[13] The two policy baselines represent two scenarios with moderate and stringent policies, based on extrapolation of the Copenhagen pledges. The two climate stabilization targets are the 450 ppm-eq considerated in this paper, as well as a 500 ppm-eq. See Kriegler et. al 2013, this volume, for the description of the scenarios. The database has 6 models, 4 scenarios and 10 regions, yielding a total of 240 observations, of which only 227 are included, given that negative policy costs have been dropped when taking the logarithm.

Reforming Economies. However, while the effect on export revenue as a proportion of GDP is fairly consistent for the Middle East region, the results for the Reforming Economies differ by an order of magnitude. Export revenues for the Middle East drop by between 14 and 48 trillion dollars over the century or 1% and 6% of GDP. For the Reforming Economies, most models agree that the drop in export revenues would be between 0.4 and 3 trillion dollars or 1% and 6% over the century[14].

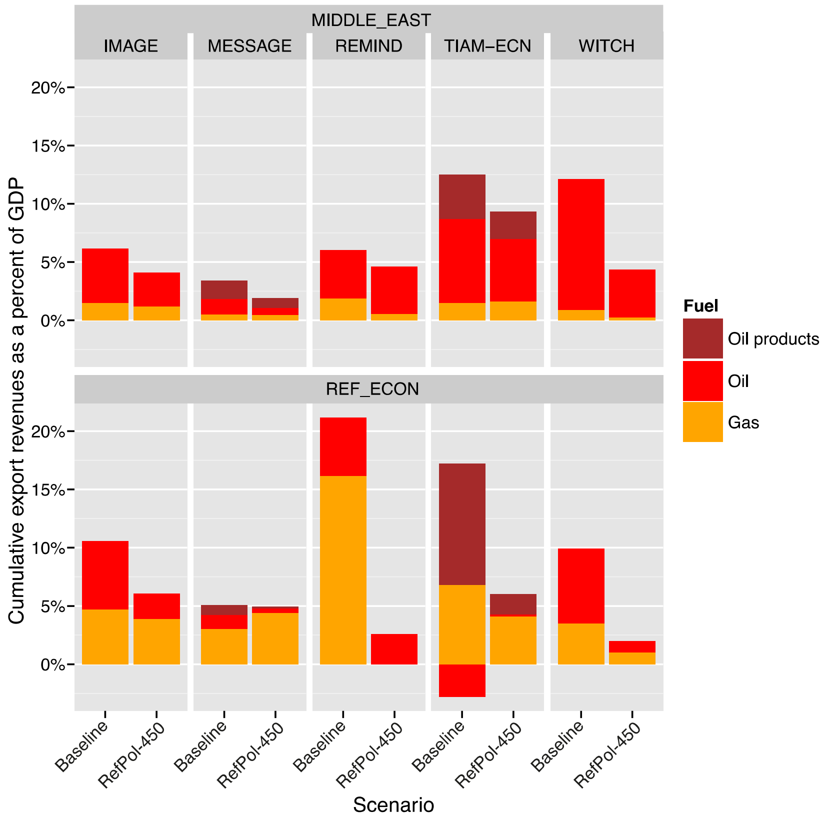

Figure 3: Energy export revenue for the Middle East and the Reforming Economies in BAU versus RefPol-450.

[14] ReMIND is a clear outlier. Its Reforming Economy region only includes Russia which according to ReMIND would lose over 5 trillion dollars of 20% of the region's GDP from lost export revenues. This high drop is due to the fact that in ReMIND the baseline leads to a high proportion of gas use (and as a result gas trade), which is primarily supplied by Russia. In contrast, under ReMIND's 450 scenarios, gas is phased out by the end of the century and the region does not benefit from these export revenues.

2.7. The impact of different emission allocation schemes on the distribution of allowances & the policy costs

The previous section has highlighted the regional variation in economic costs mitigation in a setting where carbon is priced efficiently but which does not allow for compensating the mitigation effort. The results highlight a tension between efficiency and equity. As standard in economics, this tension can be alleviated by designing an appropriate market for emissions which allows for financial transfers between countries. In a world with no transaction costs and perfect markets, as is the one normally represented by integrated assessment models, the creation of endowments of carbon allowances and the possibility to freely exchange them allows to perfectly separate efficiency and equity. This independence property, originally formulated in (Coase, 1960), is particularly convenient when analysing international climate regimes, despite its limited predictive power. There are many reasons why the Coase theorem might not perfectly hold in practice. These include transaction costs, market power, institutional and political factors, etc. See (Hahn and Stavins, 2010) for a review of the relevance of these factors.

This section focuses on the two burden sharing schemes analysed in the LIMITS project, the per capita convergence and the equal effort schemes. It quantifies the initial allocations of permits associated with those, in relation to the cost effective emission reductions. This comparison is shown in Figure 4, for the year 2030. The chart shows that OECD countries would receive a higher GHG reduction obligation, compared to their optimal mitigation level, for both the resource and effort sharing schemes. This result for effort sharing is intuitive since as we have shown previously the carbon tax scenario induces lower mitigation costs in the industrialized regions; the chart makes the additional point that the OECD emission reductions in the tax scenarios are also lower than the ones prescribed by the Rawlsian principle of equality of carbon space in the atmosphere. Given their fast growing economies and associated emissions, Latin American and Asian countries have to undertake to less stringent mitigation to current levels in the tax case and the burden sharing regimes (but not necessarily to their baseline). The three allocation schemes show relatively similar commitments for these regions, with the noticeable exception of China: the per capita convergence scheme appears to be particularly disadvantageous to China, which would receive an allocation which is below todays values already in 2030 (and significantly so). The resource sharing per capita scheme is also quite stringent for the energy exporting countries in 2030, while the opposite holds for the equal effort, since as we have seen in the previous sections these regions incur the highest mitigation costs, and would need to be compensated when aiming at an equalization of mitigation efforts.

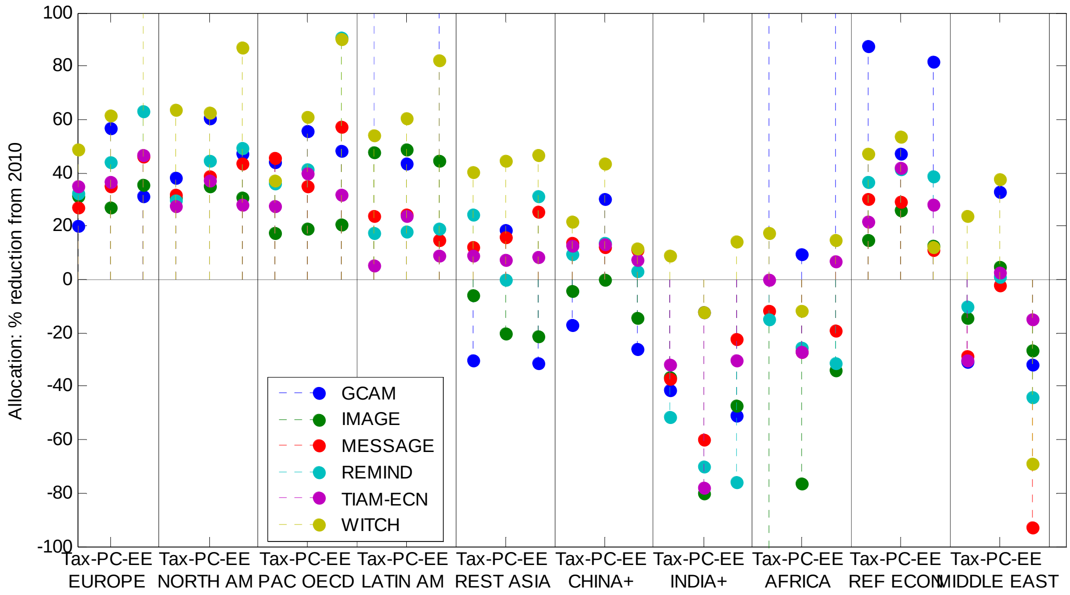

Figure 4: Allocation of allowances for the three different sharing scenarios (Tax, Per Capital convergence, and Equal Effort). Emissions allocations are expressed in reductions in 2030 from 2010 values. The scale of the y-axis has been limited at +/-100%[15].

The variation across models reflect different regional assumptions about baseline emissions, global emissions pathways consistent with the 2°C objective, and regional abatement potential (see also van der Zwaan et al., 2013, this issue). This is especially important for models which foresee large mitigation potential already early in the century for specific parts of the world: for example GCAM finds allowances reductions from todays' levels which largely exceed 100% for regions like Latin America and Africa, which are endowed with large biomass potential and can achieve significant net negative emissions already in 2030 due to massive reforestation programmes in the tropics.

The econometric analysis in the previous section has indicated relative abatement from baseline to be the most important explanatory variable for policy costs, all other things equal. In order to understand the economic implications of the burden sharing schemes, it is thus instructive to look into the distribution of allocation across schemes and time. Table 4 reports how the allocation effort is distributed, showing a high level of agreement across models. In the per capita scheme, the allocation effort would be beard in a similar way between OECD countries, China and the energy exporting countries. Developing countries with current low per capita emissions, such as Africa and India, would get a less stringent target, but only in the first half of the century. During the second half, when

[15] Some of the outliers show an allocation of net negative emissions in 2030. This is due to assumptions – most notably in the GCAM model- about large mitigation potential in the tropics via afforestation practices.

emissions cuts are deeper, the distribution is almost even, with all regions undertaking mitigation exceeding 90% from baseline. These figures already suggest that the per capita scheme is unlikely to resolve the distributional conflicts identified so far in this paper, a result on which we will elaborate more in the following.

	PC				EE			
	2020-2050		2050-2100		2020-2050		2050-2100	
	Mean	*CV*	mean	*CV*	Mean	*CV*	Mean	*CV*
MIDDLE_EAST	65.7	*0.1*	96.7	*0.0*	33.3	*0.2*	81.5	*0.1*
REF_ECON	69.0	*0.1*	97.6	*0.0*	51.4	*0.4*	92.5	*0.2*
AFRICA	32.1	*0.5*	90.7	*0.1*	62.4	*0.6*	86.8	*0.1*
INDIA+	46.6	*0.2*	94.3	*0.0*	54.2	*0.2*	87.1	*0.1*
CHINA+	65.9	*0.2*	96.8	*0.0*	55.1	*0.2*	95.9	*0.1*
REST_ASIA	51.3	*0.2*	95.1	*0.0*	54.8	*0.3*	94.4	*0.1*
LATIN_AM	60.7	*0.1*	95.8	*0.0*	68.5	*0.5*	109.8	*0.2*
NORTH_AM	69.3	*0.1*	97.8	*0.0*	72.1	*0.2*	114.1	*0.1*
PAC_OECD	63.2	*0.2*	97.6	*0.0*	85.6	*0.3*	115.5	*0.1*
EUROPE	62.6	*0.1*	96.3	*0.0*	79.5	*0.2*	109.8	*0.1*

Table 4: Allocation of allowances in the first and second half of the century, for both burden sharing schemes (Per Capita, left, and Equal Effort, right). Emission allocations are expressed in % reductions from Baseline, in cumulative terms from 2020 to 2050, and from 2050 to 2100. Figures are averages across models. Red and blue colouring are used for emissions reductions above and below 80% respectively. The coefficient of variation (CV) is also shown: dark green indicates high confidence (<0.5), light green medium confidence (0.5-1), and white low confidence (>1).

The equal effort provides a more diverse allocation of abatement across countries, with OECD regions always bearing a significantly higher mitigation effort, which would exceed 100% in the second half of the century. The energy exporting countries, especially in the Middle East, would receive significant lower mitigation targets, as a way to make up for the large economic losses incurred otherwise.

In all cases, emissions reductions in the latter part of the century would be very significant; this is a result of the very tight carbon budget which allows meeting 2C with sufficiently high probability, roughly of about 1200 GtCO2[16].

Looking more specifically at the equal effort scenario –given its novelty-, we plot the temporal allocation of emissions allowances in Figure 5 for four major economies. The chart shows that -on average across models- Europe and North America would receive an emission allocation roughly 50% below todays' levels in 2030, ramping up to 80%-100% in 2050. The latter target is quite consistent with the aspirational targets delineated at the Major Economies Forum meeting in 2009. For Europe, this profile resembles quite closely the one proposed in the EU low carbon roadmap. Regarding China, the larger consensus across models is that allowances would be equal to today's values between 2030-2040. These patterns are somewhat more ambitious than the low carbon scenario for China developed in (Kejun et al., 2010). Finally, India would receive a rather flat allocation of allowances over time, which for most models is always above today's value, but which would grow to a 50% emission reduction with respect to BAU by mid-century (not shown on the graph). This is due to relatively high mitigation costs in the country mostly due to continued growth in emissions due to population and economic increase and a lower abatement potential due to CCS and renewable limitations[17].

[16] Throughout the paper, emissions include all Kyoto gases, and are thus expressed in CO2 equivalent levels.
[17] With the exception of WITCH, which foresees a higher mitigation potential in earlier periods.

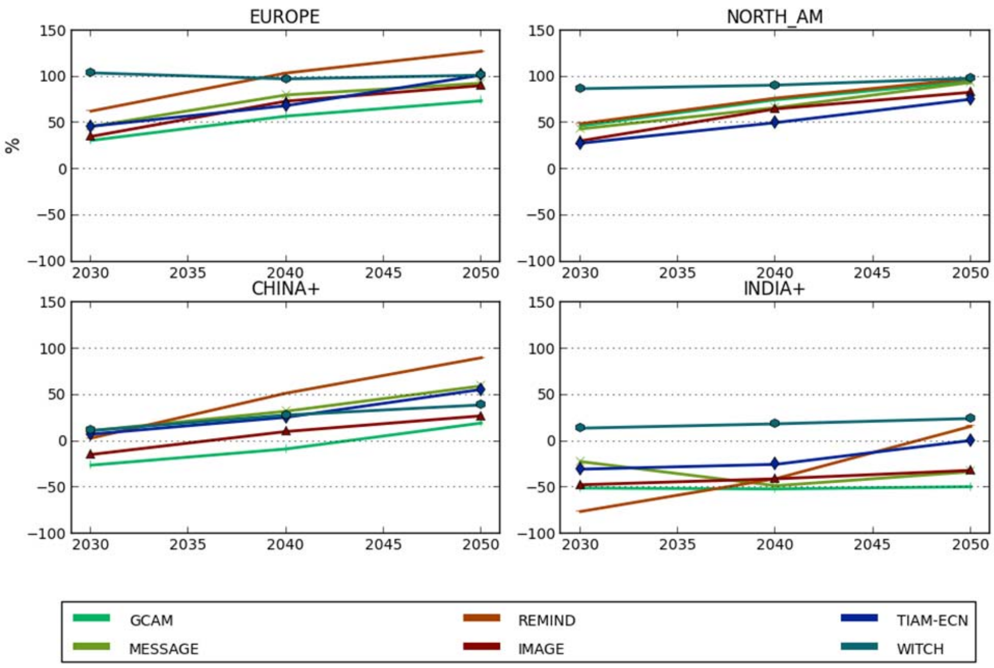

Figure 5: Emission allowances over time for the equal effort scenario, expressed in reductions from 2010 values.

In Figure 6, we show how the allocation of carbon permits compares to the optimal level of abatement for 4 major economies. This provides an immediate intuition on the direction of trade in the carbon market, a topic which will be discussed in more detail in the next session. The figure clearly indicates that both the EU and North America would be endowed with an emission allocation significantly below the cost effective mitigation level, implying that both countries will find it convenient to purchase the additional emission reductions on the global carbon market. For most models, China would on the other hand sell emission credits, though in a rather contained fashion. India would receive an allocation rather close to the optimal level, with limited need to resort to the global CO_2 permits market.

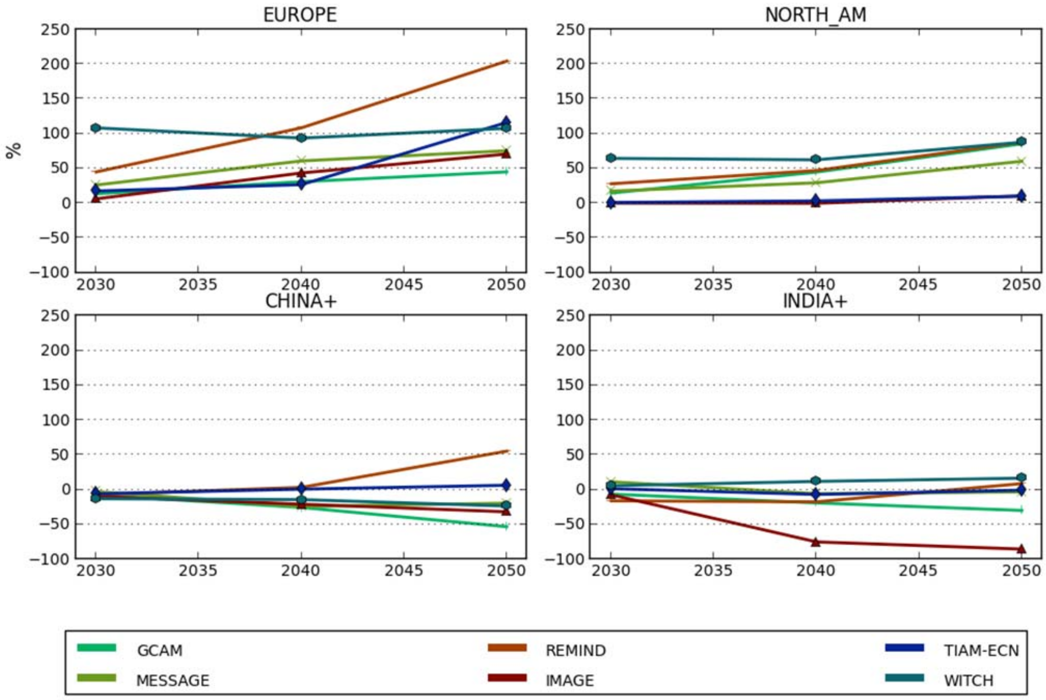

Figure 6: Emission allowances over time for the equal effort scenario, expressed in reductions from the optimal mitigation levels.

The different initial allocation of emission permits has no influence on the global policy costs due to the independency property of efficiency and equity. This requires the appropriate certificate trading platform, otherwise, without full carbon certificate trade, policy cost impacts can be expected (see carbon certificate trade sensitivity analysis in Kober et al., 2013, this issue). However, the initial allocation of certificates, even in a perfect carbon certificate market, has a direct impact on the regional costs: indeed, it is designed to do so to make sure that either resources or efforts are shared in a responsible manner.

Table 5 shows the extent to which the skewed distribution of costs outlined in Table 2 is smoothed for the per capita scheme (by design, it is equalized in the equal effort case). The table indicates that the per capita, resource sharing, scheme does not seem to alleviate the problem of distribution of costs across regions. Developing countries with low per capita emissions and growing populations –such as India and Africa- benefit from the per capita schemes in the early decades of the century (se the PC/Max 2050 cost metric), but eventually suffer from them, as reflected in significantly higher than average long term (maximum) costs. For some models, this is a direct consequence of their high carbon intensity of the economy through long-term periods affected by their limited CCS and renewable potential relative to their high growth of final energy demand. However, for Africa, there is substantial disagreement across models, especially with respect to costs as net present value, making a definitive statement not possible. China appears to even be worse off under a per capita scheme than under a tax, in line with previous findings (Luderer et. al, 2012).

	PC/NPV5		PC/Max2050		PC/Max2100	
	Mean	*CV*	Mean	*CV*	Mean	*CV*
MIDDLE_EAST	3.8	*0.3*	3.4	*0.2*	3.0	*0.4*
REF_ECON	2.5	*0.8*	3.7	*0.5*	3.1	*0.6*
AFRICA	1.2	*2.4*	0.5	*1.5*	3.1	*0.8*
INDIA+	2.1	*0.6*	0.9	*0.7*	2.6	*0.7*
CHINA+	2.0	*0.5*	1.9	*0.4*	1.9	*0.8*
REST_ASIA	1.3	*0.6*	1.0	*0.5*	1.3	*0.4*
LATIN_AM	0.4	*4.0*	1.2	*0.8*	1.0	*0.9*
NORTH_AM	0.6	*0.3*	1.1	*0.3*	0.7	*0.3*
PAC_OECD	0.4	*1.2*	0.9	*0.6*	0.7	*0.4*
EUROPE	0.5	*0.6*	0.7	*0.5*	0.7	*0.6*

Table 5: The table reports policy costs relative to the global average (as in Table 2) for the Per Capita convergence allocation, and different cost metrics (NPV at 5% d.r. and maximum by 2050 and 2100). Figures are averages across models. Red colouring is used for costs above global average (e.g. >1) and blue colouring for below the global average (e.g. <1). The coefficient of variation (CV) is also shown: dark green indicates high confidence (<0.5), light green medium confidence (0.5-1), and white low confidence (>1).

Overall, the same ordering and division into 3 main groups (OECD below global costs, fast growing economies above global costs, and energy exporters well above global costs) is preserved under the per capita allocation scheme. This results somewhat contradicts the existing literature, which traditionally showed higher than average costs for OECD countries, for 2050 (Hof et. al 2009). The difference can be attributed to various factors. First, baseline emissions have been updated in several models, with a redirection towards more growth in developing countries. Second, the Durban Action Platform scenarios considered in this paper achieve 2C with sufficiently high probability (>60-70%) and assume a more realistic transition towards full cooperation after 2025; as a result, the carbon budget is very limited, and very deep cuts in emissions are needed everywhere, including in the developing countries. Finally, models heavy reliance of negative emissions has shifted the emissions reduction profile over time, putting at further disadvantage future generations, especially in countries with fast growing economies. Overall, these results suggest a tension between equity –measured by the distribution of effort- and climate safety – measured by the stringency of the climate objective, which is of direct relevance for policy (Tavoni et. al 2012).

2.8. The carbon and financial transfers in the carbon market

The creation of emissions rights immediately translates into financial flows trading across regions. Given the models' assumption about a frictionless international carbon market, regions sell and buy permits freely without incurring extra costs (e.g. such as transaction costs), depending only on their relative marginal abatement costs and to the permits endowments of a given allocation scheme.

As a result, very significant trading of emissions occurs across regions. Already in 2030[18], physical transfers of carbon permits under the PC regime range between 2 and 13 $GtCO_2$ (see Figure 7), covering 10-25% of global abatement. The size of the market tends to contract in the EE case, where it never exceeds 6 $GtCO_2$/yr. The magnitude of these transactions is very sizeable compared to the experience of present day carbon markets. For example, the total number of carbon credits issued to date in the Clean Development Mechanism is about 1.2 GtCO2, and the total supply is estimated to reach 8 GtCO2 by 2020 (UNFCCC[19]). But these are cumulative numbers over the whole duration of the respective periods, whereas the figures indicated by the models suggests that similar levels of trading would occur each year from 2030 onwards. Needless to say, managing a carbon market of this size would require a major institutional effort in many countries.

[18] For brevity, from now on, quantities will be described as belonging to 2030, 2040 or 2050 even if they actually represent decadal averages over the periods 2025-2035, 2035-2045 or 2045-2055 respectively.
[19] http://cdm.unfccc.int/Statistics/Public/files/201305/CER_potential.pdf

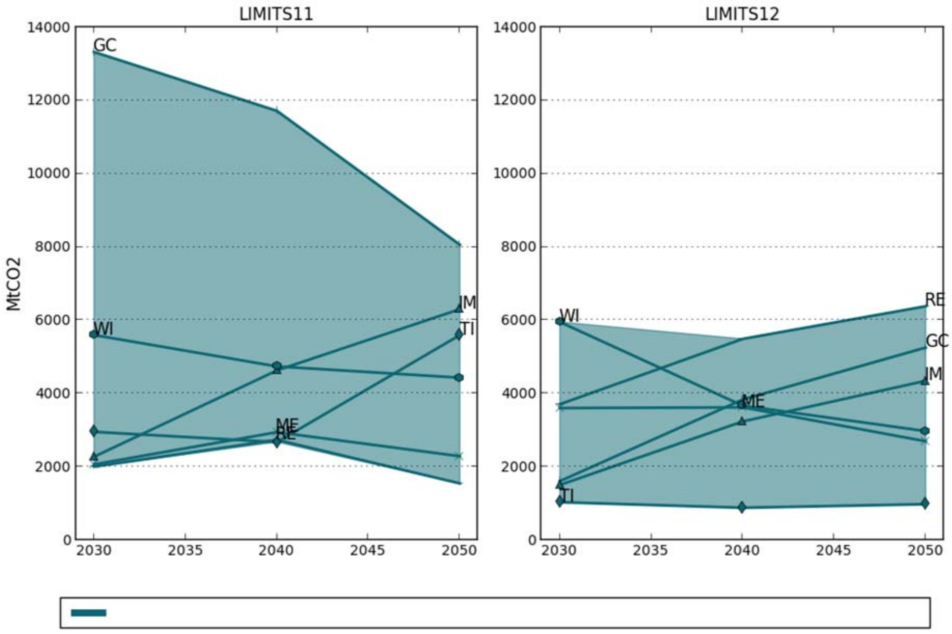

Figure 7: Global emission trade volumes (PC left, EE right).

The financial flows associated with these trading would also be considerable, due to the large trading volumes and the sustained carbon prices needed to attain policies compatible with 2°C (see Kriegler et. al, this issue, for more information on carbon prices). Figure 8 quantifies the financial exchanges tied to the carbon market in 2030 for all the major economies. In both schemes, in 2030 OECD countries would be net buyers of permits worth up to and more than 100 USD Billions. Permits would be sold mostly by India and Africa in the per capita allocation scheme, and by all non-OECD countries in the equal effort scheme. In the per capita case, China would be either neutral or even a permit buyer in 2030, whereas it would be a net seller in the equal effort case. Energy exporting countries would be net buyer of permits in the per capita scheme, thus further exacerbating the impact of climate policies on their economies.

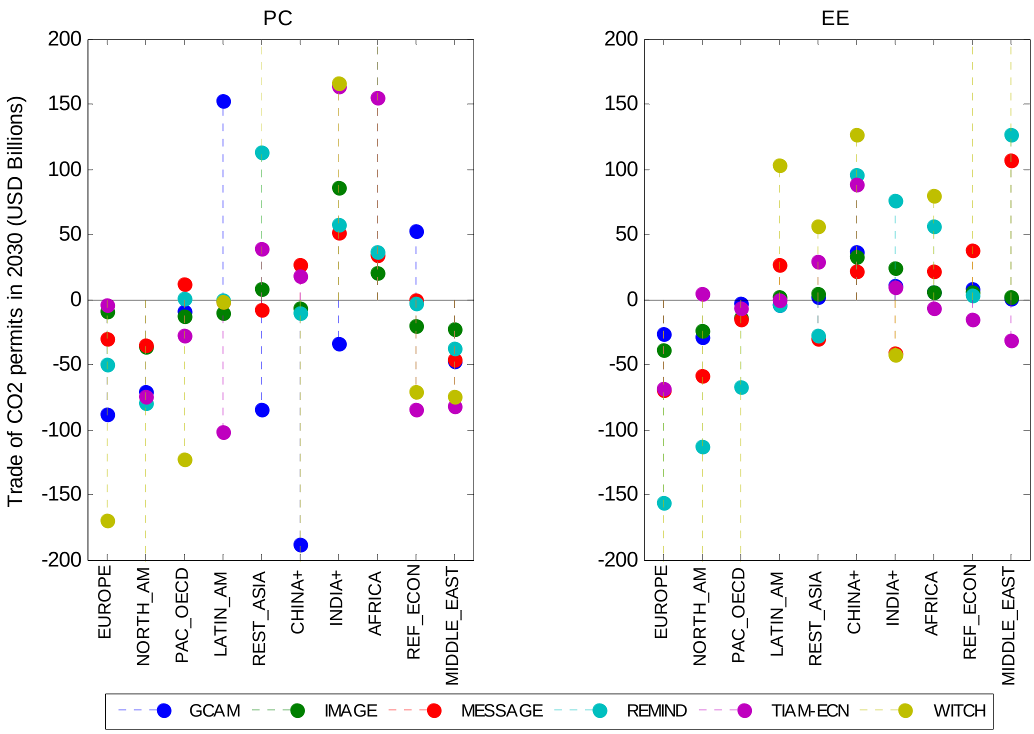

Figure 8: Regional trade flows of GHG emission permits in 2030 for the PC and EE schemes (positive=selling, negative=buying).The y axis is truncated at +/- 200 USD Billions.

When looking at the overall patterns aggregated over the whole century, terms of trade in the carbon markets change as a result of the changing allocation and the rising price of permits at which carbon permits are traded. Table 6 shows that in net present value, OECD countries would slightly be net seller of permits in the per capita scheme, and net buyers in the equal effort scheme. For energy exporters, the pattern is reversed. China is a net-buyer in in the per-capita scheme and a net-seller in the equal-effort one while India is a net buyer in both.

	PC		EE	
	Mean	CV	Mean	CV
MIDDLE_EAST	-2.3	1.5	3.0	1.6
REF_ECON	-0.4	13.4	3.5	1.2

AFRICA	1.2	4.4	0.4	5.2
INDIA+	-0.4	2.9	-0.2	6.6
CHINA+	-1.6	2.4	0.4	2.4
REST_ASIA	0.6	3.5	-0.3	2.9
LATIN_AM	1.9	2.6	0.1	2.5
NORTH_AM	0.4	1.6	-0.5	1.2
PAC_OECD	0.2	2.6	-0.5	1.1
EUROPE	0.0	18.9	-0.9	1.3

Table 6: Trade of CO2 permits as % of GDP for the PC and EE schemes (actualized in NPV at 5% d.r.). Positive (red) = selling. Negative (yellow)=buying. Also reported is the coefficient of variation across models.

In all cases, there is a disagreement across models, testified by the high coefficients of variations[20]. In many circumstances, different models disagree on the sign of the total trading, as a result of different projections about regional mitigation potential and different carbon prices. Nonetheless, this variation testifies that the financial flows associated with the carbon markets would be considerable as compared to the economy, representing several percentage points of regional economies. As a point of reference, all foreign direct investments (FDI) in China currently represent around 3-4% of the economy.

Such trading patterns could have profound economic and social repercussions -such as dutch-disease, corruption, etc.- and would require the existence of strong property rights and institutions, all of which is ignored in the model assessment presented in this paper. In this respect, the experience of CDM –despite being on a much smaller scale- has already emphasized the difficulty of implementing market mechanisms in key emitting countries, due to difficulties in verifiability and correct implementation (Wara, 2007).

2.9. Discussion and Conclusions

This paper provides a multi-model assessment of the regional implications of three post-2020 climate regimes consistent with the objectives enunciated in the Durban platform for enhanced action. It uses the results of a subset of the scenarios designed in the LIMITS project to assess the distribution of effort across 10 major economies, contributing with the largest consistent study on burden sharing for 2C policies. We provide a contribution to the rich quantitative discussion about effort sharing in international climate negotiations (den Elzen and Höhne (2008,

[20] Please not that the some of the coefficient of variation are high as a result of the mean being close to zero.

2010),Clarke et al., 2009; Ekholm et al., 2010; Johansson et al., 2012; Luderer et al., 2012), taking advantage of a multi-model ensembles of scenarios with different burden sharing regimes and fully consistent with the 2°C target. We assess a regime without transfers, and compare it to a resource burden sharing scheme based on long-term convergence of per capita emissions and an effort sharing scheme which equalizes policy costs across regions. Our analysis provides a number of important insights, which can be summarized as follows:

- With a carbon tax and no transfers between regions, the economic effort to achieve 2°C would be widely differentiated across regions, with a clear grouping of regional costs relative to the global average costs: below global average for the OECD, somewhat above global average for the fast growing developing economies, and well above global average for energy exporting countries. These patterns are well explained by a series of factors, which include abatement, baseline emissions, energy intensity and regional characteristics.
- The asymmetric distribution of costs could be alleviated only to a limited extent when endowing regions with emission permits based on convergence to per capita by 2050, and allowing free trade of such permits. Developing countries with current low per capita emissions would benefit in the next few decades, but would nonetheless be penalized in the longer term. China and the energy exporting countries would always be worse off.
- An allocation scheme based on the equalization of climate policy costs across regions would allocate OECD with emission reductions compatible with those enunciated by the Major Economies Forum and the European Commission. China would receive emissions allowances which return to today's levels by 2030 to 2040. India would receive a rather flat allocation of allowances over time, generally above today's values.
- The size of the carbon permit trade market would be significant in all the assessed regimes, exceeding by far the experience of CDM. The main actors on the market would differ between the two burden sharing schemes.

All in all, these results emphasize the distributional challenge of achieving 2C, in terms of balancing costs across the different regions.

While we found a number of robust patterns and insights, the uncertainty in regional mitigation cost estimates, and estimates of the effect of alternative burden sharing regimes, remains substantial. These variations reflect uncertainties about future development pathways in different regions and their mitigation potentials. We also identify areas where more analysis is needed. Focusing on the interplay between partial cooperation and effort sharing, and on the best way to link multiple coalitions and to harmonize different policy instruments and different carbon markets could yield important insight which are relevant given the current fragmentation in international climate policy. The relation between transfers originating from burden sharing schemes and side payments which are needed to ensure the stability of the coalition would also link the two strands of literature. Since carbon trade flows are projected to be a significant portion of regional output, giving rise to a number of institutional challenges for implementing a global burden sharing scheme, further research is needed that goes beyond the idealized assumption of full separability of efficiency and equity. Going beyond this approach is likely to exacerbate the distributional tensions identified in this paper.

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LIMITS

3. On the regional distribution of climate mitigation costs: the impact of delayed cooperative action

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3.1. Abstract

This paper analyzes the results of the climate-energy-economy model, REMIND, to assess the regional costs of climate-change mitigation for reaching the 2˚C target with a medium to high likelihood. We assume that the global climate regime remains fragmented until 2020 after which a global mitigation target is adopted. We decompose the regional mitigation costs into (a) domestic and energy trade effects and (b) permit trade effects. Delaying cooperative action affects domestic costs by increasing the energy system's costs as a consequence of lock-in of carbon-intensive infrastructures. This is particularly true in developing countries with low near-term emissions reduction commitments. In a global cap-and-trade system, the effect of delayed action highly depends on whether or not the regions are over- or under-allocated with emissions allowances in the long-term. Those with allowances exceeding their long-term emissions will likely benefit from the delay, while others suffer the consequences of higher long-term carbon prices.

3.2. Introduction

The ultimate objective of the United Nations Framework Convention on Climate Change is to limit anthropogenic interference with the climate system. In its Copenhagen Accord, the international community broadly agreed on the long-term objective of limiting the increase of the global mean temperature to a maximum of 2˚C relative to pre-industrial levels. This target was re-emphasized in the subsequent Cancun and Durban climate conferences. Earlier studies have indicated that achieving such a temperature target with a high likelihood requires deep emissions reductions and substantial changes to energy production and consumption patterns, even if all nations take action immediately with full flexibility of when and where to undertake the emissions abatement (Clarke et al., 2007; Van Vuuren et al., 2007; Edenhofer et al., 2010). However, in view of current negotiations, it seems rather unlikely that a full agreement with globally binding targets on greenhouse gas (GHG) emissions will materialize in the near future. It has been illustrated that even the most ambitious national pledges leave a gap between the expected 2020 emissions levels and the emissions levels projected in cost-efficient, immediate action scenarios that stay below the 2°C target with high likelihood (den Elzen et al., 2010; Dellink et al., 2011; UNEP, 2011, 2012).

The implications of weak or non-existent emissions reduction commitments in the near-term for the achievability of ambitious, long-term climate-mitigation targets have been explored in several integrated assessment modeling studies (Clarke et al., 2009; Jakob et al., 2012; Van Vliet et al., 2012; Luderer et al., 2013b; Riahi et al., 2013). The EMF22 study partly addressed the nature of international participation in emissions mitigation and concluded that a failure to develop a comprehensive international approach will constrain efforts to meet ambitious climate targets (Clarke et al., 2009). Jakob et al. (2012) explored the consequences of a delay in global mitigation effort on regional climate-mitigation costs. According to their findings, postponing a global agreement to 2020 while only Annex 1 countries undertake early climate policies significantly raises global mitigation costs, while a delay until 2030 renders ambitious climate targets infeasible. Van Vliet et al. (2012) explored the implications of delay in climate mitigation starting from the 2020 Copenhagen Accord pledges for the attainability of the 2°C target. They concluded that an ambitious realization of Copenhagen pledges implies higher cumulative discounted mitigation costs, while weaker reduction commitments reduces the probability of achieving the target.

Another strand of literature analyzes the effects of different burden sharing rules on regional mitigation costs in the context of a global cap-and-trade system considering different time horizons and regional scales (Den Elzen et al., 2008; Leimbach et al., 2010a; Lueken et al., 2011; Luderer et al., 2012b; van Ruijven et al., 2012). Van Ruijven et al. (2012) presented an analysis of the scientific literature on how different burden sharing rules affect the mitigation costs in China and India through the first half of the century. Over a time horizon from 2010 to 2050, India can expect to gain or incur low costs from climate policy due to financial revenues from selling permits. The cost implications of different post-Kyoto climate regimes are also addressed in (Den Elzen et al., 2008), considering a time horizon towards the mid-century and two stabilization targets of 450 and 550 ppm CO_2-equivalent.

A central question, merely touched upon in the existing literature, relates to the economic impacts of near-term, fragmented mitigation efforts on the regional distribution of climate-mitigation costs to achieve ambitious, long-term climate stabilization targets. This paper addresses this question by providing a decomposition analysis of regional mitigation costs — using the example of the integrated assessment model REMIND — to identify the determinants of these costs and the effects of delayed action. The application of the cost decomposition method is a new contribution to the literature, which enhances our understanding of regional mitigation costs by attributing costs to changes in economic output, macro-economic investments, energy system costs, and trade in energy resources as well as financial transfers induced by the carbon market. Our study also takes into account the long-term consequences of burden sharing rules, which has often been ignored, as most studies have focused on a time horizon until 2050. To account for national emissions reductions and low-carbon technology deployment pledges, we designed the weak policy scenario. This determines the level of near-term action while in delayed action scenarios, ambitious global climate targets are adopted only after 2020. This also enhances the existing literature, in which the effects of delayed participation are studied in the complete absence of climate policies before adoption of the global climate regime. This study draws on the scenario design of the LIMITS multi-model comparison exercise of the Durban Platform architectures (Kriegler et al., 2013a; Tavoni et al., 2013).

The paper proceeds as follows: Section 3.3 describes the methodology and scenario design. In the results analysis part, Section 3.4, at first, gives an overview on regional mitigation costs obtained from different scenarios. Section 3.5 and Section 3.6 then elaborate on the drivers of regional mitigation costs for immediate action scenarios. Section 3.7 explores the implications of near-term fragmented mitigation policies in the context of long-term climate-stabilization targets. Section 7 and an extensive part of the supplementary material address the sensitivity of our results to various parameters and scenario assumptions. Finally, Section 8 concludes and discusses the implications of the findings.

LIMITS

3.3. Methodology

3.3.1. The integrated assessment model, REMIND

The Regionalized Model of Investment and Technological Development (REMIND) (Leimbach et al., 2010a,b; Bauer et al., 2012a,b; Luderer et al., 2012a; Luderer et al., 2013a) is a global multi-regional integrated assessment model that couples a top-down macroeconomic growth model with a detailed bottom-up energy system model and a simple climate model. To obtain a detailed evaluation of the climate implications of the scenarios, the model is further coupled with the climate module, MAGICC6 (Meinshausen et al., 2011). The following paragraphs briefly describe the features of the model that are of particular relevance to this study. For an elaborated description of the REMIND model we refer to (Luderer et al., 2013a).

In REMIND, the macroeconomic output, i.e., gross domestic product (GDP), of each region is determined by a "constant elasticity of substitution" (CES) function of the production factors, which include labor, capital, and end-use energy. The produced GDP *(Y)* is used for consumption *(C)*, net exports of aggregated good *(X^G)*, investments into the macroeconomic capital stock *(I)*, non-energy system abatement costs *(A)*, and energy system costs *(E)*, which are comprised of investment costs, fuel costs, and operation and maintenance costs. Table S11 gives an overview of the symbols used throughout this paper. The balance of GDP distribution (Eq. 1) forms the budget constraint, which is satisfied for each region *(r)* at every time step *(t)*:

$$\boldsymbol{Y(r,t) - X^G(r,t) = C(r,t) + I(r,t) + E(r,t) + A(r,t) \quad \forall t, r.} \qquad (1)$$

The methodological approach for the representation of trade is of particular relevance for this study. The REMIND model represents the world in eleven regions. In general, regions interact by trading aggregated macro-economic output, exhaustible non-renewable energy carriers (coal, natural gas, oil, and uranium), and biomass. Under climate policies, regions also interact by trading emissions rights in a global cap-and-trade system. The initial allocation of emissions rights is determined by a burden-sharing rule. The global carbon market allows emissions reductions to be performed where they are cheapest, leading to an optimal market allocation of permits that is divergent from initial endowments. The emissions permits are then exported from regions that emit less than their endowment to countries with higher emissions.

The inter-temporal trade balance (Eq. 2) ensures that the inter-temporally aggregated value of exports and imports are balanced over the modeled time horizon for each region. In Eq. (2), $\boldsymbol{X_i^E}$, $\boldsymbol{X^G}$, and $\boldsymbol{X^P}$ represent the net export of energy carrier *i*, generic good, and permits, respectively; $\boldsymbol{P_i^E}$, $\boldsymbol{P^G}$, and $\boldsymbol{P^P}$ are the corresponding present value prices derived from the shadow prices of the optimization.

$$\boldsymbol{\sum_{t=0}^{T} \left(\sum_i P_i^E(t)\, X_i^E(r,t) + P^G(t)\, X^G(r,t) + P^P(t)\, X^P(r,t) \right) = 0 \quad \forall r.} \qquad (2)$$

Note that in this formulation interest payments are implicit by using present value prices in the accounting, which already embody discounting of the value of goods traded in the future relative to present. The current value price of energy carrier *i* ($\boldsymbol{cp_i^E}$) and the current value price of permits ($\boldsymbol{cp^P}$) can then be obtained by expressing energy and permit prices relative to the price of the generic macro-economic good, which serves as a numéraire in our framework:

$$\boldsymbol{cp_i^E(t)} = \boldsymbol{P_i^E(t)} / \boldsymbol{P^G(t)} \qquad \forall \boldsymbol{t}. \tag{3}$$

$$\boldsymbol{cp^P(t)} = \boldsymbol{P^P(t)} / \boldsymbol{P^G(t)} \qquad \forall \boldsymbol{t}. \tag{4}$$

We then formulate regional current accounts[21] (*CA*) as:

$$\boldsymbol{CA(r,t)} = \sum_i \boldsymbol{cp_i^E(t)\, X_i^E(r,t) + X^G(r,t) + cp^P(t)\, X^P(r,t)} \qquad \forall \boldsymbol{t, r}. \tag{5}$$

For each good *j*, the sum of trade balances across regions is zero at every time step. Therefore, regional current accounts sum up to zero at each point in time, i.e., regions with a current account deficit are counterbalanced by regions with a current account surplus. Through an iterative procedure — using the Negishi approach — the model finds a Pareto-optimal solution, which corresponds to the market equilibrium in the absence of non-internalized externalities (cf. Manne and Rutherford, 1994).

Technology availability is another key factor influencing the mitigation costs of climate change. REMIND's energy system module covers a broad set of technologies that are represented with detailed techno-economic parameters and CO_2 emissions factors (cf. Table S1 and Table S2). REMIND assumes endogenous technology learning for wind, solar photovoltaic (PV), concentrating solar power (CSP), fuel cells, and electric vehicles. Region-specific technical potentials, classified into different grades, limit the deployment of non-biomass renewables (cf. Table S3). A global upper limit of 300 EJ/yr is assumed for bioenergy in the REMIND default setting. This limit applies to modern second-generation biomass and residues, but does not cover traditional biomass. The prices for biomass are derived from the regional supply curves of the high-resolution land-use model, MAgPIE (Model of Agricultural Production and its Impact on the Environment), (Lotze-Campen et al., 2008, 2010; Popp et al., 2010). Furthermore, the application of carbon capture and storage (CCS) technologies is subject to regional constraints on CO_2 storage potential (cf. Table S3).

It is worth mentioning that the independency of efficiency and allocation is fulfilled in REMIND and other similar models (cf. Manne and Stephan, 2005; Lueken et al., 2011; Luderer et al., 2012b). The allocation of emissions permits only affect regional consumption patterns, but have (almost) no effect on regional GDP. According to the formulation of the production function in REMIND, energy demand is linked to GDP but not to consumption; therefore, patterns of energy use and emissions as well as energy trade flows are not affected by the allocation scheme.

[21] This is equivalent to regional temporal trade balances; in order to use a more common terminology, we refer to it as current account throughout this paper. The model inter-temporally balances debts and assets, accruing from trade over the time horizon considered.

3.3.2. Economic decomposition method

In a general equilibrium framework as the one applied in REMIND, the costs of climate change mitigation can be quantified by comparing the macro-economic consumption in the policy scenarios with those of a no-policy baseline scenario. However, in the presence of capital trade and perfect foresight, as represented in REMIND, regions respond to climate policies by adjusting trade patterns, to smoothen consumption variations over time. While this has (almost) no effect on the inter-temporally aggregated consumption over the modeled time horizon, it can result in a substantial redistribution of consumption over time. We present further insights on this "consumption smoothening" effect in Section 6.2 based on the model results for selected regions and scenarios.

In order to explicitly account not only for consumption losses, but also for the effects of climate policies on foreign assets, we define regional mitigation costs (*M)* as differences in macro-economic consumption adjusted by the effects on current accounts:

$$\boldsymbol{M(r,t)} = (\boldsymbol{C_{BASE}(r,t)} - \boldsymbol{C_{POL}\,(r,t)}) + (\boldsymbol{CA_{BASE}(r,t)} - \boldsymbol{CA_{POL}\,(r,t)}) \qquad (6)$$

It is important to note that with this formulation, global mitigation costs are equivalent to consumption losses, as the sum of regional current accounts vanishes. Similarly, regional mitigation costs aggregated over the full time horizon are approximately equal to aggregated consumption losses, as the inter-temporal trade balance ensures that the discounted sum of each region's current account equals zero[22].

The economic decomposition method then allows us to differentiate the underlying factors of mitigation costs at a detailed level. This approach is an extension of the methodology presented by Lueken et al. (2011). Based on the budget constraint (Eq. 1), the difference in regional consumption between the two scenarios can be explained by the variations in macro-economic output and investments, energy system expenditures, and changes in the trade of macro-economic good. Using Eq. (5), we integrate financial flows from trade of energy carriers and emissions permits as well as the effect of current account. On this basis, the regional mitigation costs (or the difference in mitigation costs if two policy scenarios are compared) can be decomposed at every time-step (Δ represents the variations between the two scenarios):

$$\Delta\boldsymbol{M(r,t)} = \Delta\boldsymbol{C(r,t)} + \Delta\boldsymbol{CA(r,t)} = \Delta\boldsymbol{Y(r,t)} - \Delta\boldsymbol{I(r,t)} - \Delta\boldsymbol{E(r,t)} - \Delta\boldsymbol{A(r,t)}$$

$$+\sum_{\boldsymbol{i}}\Delta\left(\boldsymbol{cp_i^E(t)X_i^E(r,t)}\right) + \Delta\left(\boldsymbol{cp^P(t)X^P(r,t)}\right) \qquad \forall \boldsymbol{t,r} \qquad (7)$$

To decompose the inter-temporally aggregated regional differences in mitigation costs, we convert Eq. (7) into its present value prices and sum it over time (the bar sign represents the inter-temporally aggregated values[23]):

[22] Due to variations in the model-endogenous interest rate between different scenarios, a small deviation between inter-temporally aggregated mitigation costs and consumption losses remains, see Eq. (S.8).

[23] Note that discounting in Eq. (8) is implicit by using present values prices of the reference scenario $P_{REF}^{G}(t)$ in the inter-temporal aggregation.

$$\overline{\Delta M}\ (r) = \left(\overline{\Delta Y}\ (r) - \overline{\Delta I}\ (r) - \overline{\Delta E}\ (r) - \overline{\Delta A}\ (r)\right)$$
$$+ \left(\sum_t P^G_{REF}(t) \sum_i \left(cp^E_{i,REF}(t)\, X^E_{i,REF} - cp^E_{i,POL}(t)\, X^E_{i,POL}\right)\right)$$
$$+ \left(\sum_t P^G_{REF}(t)\left(cp^P_{REF}\,(t)\, X^P_{REF}(r,t) - cp^P_{POL}\,(t)\, X^P_{POL}(r,t)\,\right)\right) \forall r. \qquad (8)$$

The first bracket on the right side of Eq. (8), covering the reaction of regional energy systems and macro-economies, is referred to as the domestic mitigation costs. The second bracket includes the net trade effects of energy carriers due to changing prices and traded volumes. The domestic and energy trade effects are chiefly a function of the global mitigation target and only depend weakly on the allocation rule (Lueken et al., 2011; Luderer et al., 2012b) (cf. Section 2.1). The third bracket provides the inter-temporally aggregated carbon trade effect, i.e., revenues or expenditures arising from emissions trading. This component depends on the allocation rule and the carbon price path. A detailed description of the decomposition methodology can be found in the supplementary online material (SOM).

3.3.3. Scenario design

This study is based on an extension of a set of scenarios designed in the context of the LIMITS study (Kriegler et al., 2013a; Tavoni et al., 2013). Focusing on the main climate policy scenarios: "450", "RefPol-450", "450-PC", and "RefPol-450-PC", we investigate the costs of reaching the 2˚C target with a high likelihood (> 70%) by assuming a flexible choice of energy conversion technologies. Early decommissioning is allowed in the modeled scenarios for all no-CCS fossil technologies used for the transformation of primary energy to secondary energy[24]. We briefly explain the main scenarios below; for detailed descriptions of the complete set of scenarios we refer to Kriegler et al. (2013a) and Tavoni et al. (2013). We also explore a further set of scenarios for the purpose of sensitivity studies, which are introduced and analyzed in Section 7 and in the SOM.

a) No-policy baseline scenario (Base) This scenario has no climate policy after 2010 and serves as a common reference case for all climate policy scenarios. In REMIND, the population growth, regional GDP growth, and fossil resources are based on the AMPERE default assumptions (Kriegler et al., 2013b).

b) Weak policy scenario (RefPol) The weak policy scenario is based on a collection of national targets and Copenhagen pledges — mostly specified until 2020 — and an extrapolation of the level of stringency beyond 2020 based on emissions intensity (GHG emissions per unit of GDP). This scenario describes situations in which regions enact domestic climate

[24] The implemented constraint is in the form of a smooth phase-out constraint to avoid immediate retirement with a limit on the share of the capital stock that can be retired in one year.

policy actions without emissions trading or other international climate policy mechanisms. The weak policy scenario differentiates GHG emissions reduction targets, renewable energy shares in power generation or final energy, and renewable and nuclear capacity installation targets (cf. Table S5 and Table S6).

c) Immediate cooperative climate policy action (450 and 450-PC)
These scenarios consider immediate, globally cooperative climate policy action from 2010 onwards aiming for reaching atmospheric GHG concentration at roughly 450 ppm CO_2-equivalent in 2100. Overshoot of the stabilization target before 2100 is allowed. This setup serves as an idealized benchmark case for understanding the influences of delayed action. We consider a uniform global carbon tax regime as the reference permit-allocation scheme. This implies the equalization of marginal mitigation costs across regions without the inter-regional trade of emissions rights; therefore, monetary transfers from the carbon market are zero. We also consider the per-capita convergence (PC) allocation scheme as an alternative burden sharing, in which the per-capita allocation of emission rights converges from the level at the start year of the global climate agreement to equal per-capita emissions rights in 2050. The regional shares of global emissions are thus calculated according to the following linear relation:

$$\frac{E_r(t)}{E_w(t)} = \frac{T_2 - t}{T_2 - T_1} * \frac{E_r(T_1)}{E_w(T_1)} + \frac{t - T_1}{T_2 - T_1} * \frac{P_r(t)}{P_w(t)}\,. \tag{9}$$

where $E_r(t)$ *and* $E_w(t)$ is regional emissions and global emissions at time step t, respectively, $P_r(t)$ *is* regional population, and $P_w(t)$ represents the world population at time step t; T_1 is the reference year for grandfathering (2010 for immediate action scenarios), and T_2 is the target year for convergence (2050).

d) Delayed cooperative climate policy action following weak policy until 2020 (RefPol-450 and RefPol-450-PC)
In these scenarios, the global mitigation effort is delayed until 2020. Prior to the start year of global cooperative action, regions follow the weak policy scenario without anticipation of the long-term climate-mitigation target. In the post-2020 development stage, we consider a uniform global carbon tax regime as a reference permit-allocation scheme in scenario “RefPol-450”. In scenario “RefPol-450-PC”, we assume the PC scheme as an alternative burden sharing, in which the convergence to the per-capita equalization of emissions rights starts after 2020 and is attained by 2050.

This regional analysis focuses on the major contributors in climate policy negotiations (USA, EUR – European Union, CHN – China, IND – India, and RUS – Russia) as well as the rest of the industrialized countries (RInd) and the rest of the developing countries (RDev). Table S4 maps the REMIND regions to the regions we use in this analysis. It is important to note that in the following sections, the term “delay” refers to the “delay of cooperative action” and not the “delay of climate policy.”

3.4. Regional distribution of mitigation costs

For the analysis of regional mitigation costs, we start out with a comprehensive overview and analysis of the global and regional mitigation costs obtained from selected scenarios. In the following Sections 4, 5 and 6, we elaborate on the economic mechanisms behind the scenario results by decomposing the regional mitigation costs into their main contributors through applying the methodology described in Section 3.3.2.

Figure 1 depicts the global and regional mitigation costs aggregated over different time horizons expressed as a percentage of baseline consumption. As described in Section 2.1, the inter-temporal capital trade represented in REMIND gives rise to model-endogenous discounting, which is implicit in the development of the present value price of the generic macro-economic good over time, which serves as a numéraire in our framework. Hence, to ensure consistency with the model-internal dynamics, we use this model endogenous discount factor for the ex-post evaluation of inter-temporally aggregated mitigation costs. This approach is also required for the purpose of decomposition analysis (cf. Section 3.3.2 and SOM). Furthermore, due to different rates of per-capita consumption growth, there is a non-negligible discrepancy between discount rates in baseline and climate policy scenarios and also between policy scenarios with different burden sharing schemes (cf. Table S8 and Table S9). In our analysis, we therefore adopted the convention of using the discount rates from the baseline scenario as the standard, common reference case in computation of time-aggregated mitigation costs for all policy scenarios (see also Lueken et al., 2012).

Regional mitigation costs deviate substantially from the global average. First, we focus on the uniform global carbon tax regime as an efficient climate policy scenario, in which the distribution of emissions reductions corresponds to the cost-optimal regional mitigation potentials. Russia has a high mitigation potential and bears the highest mitigation costs. On the other hand, as a fossil fuel exporter it also suffers from the devaluation of fossil resources. In the "450" scenario, industrialized countries face mitigation costs varying between 0.5%-1.0% towards the mid-century. They encounter mitigation costs of 0.6% (EUR), 1.6% (USA), and 2.5% (RInd) over the whole century. India and the rest of the developing countries encounter high mitigation costs varying between 2.3%-3.1% for the 2010-2050 time horizon, and 4.0%–4.5% until 2100. We present a cost decomposition analysis for the tax scenario in Section 3.5.

(a) (2010-2050) (b) (2010-2100)

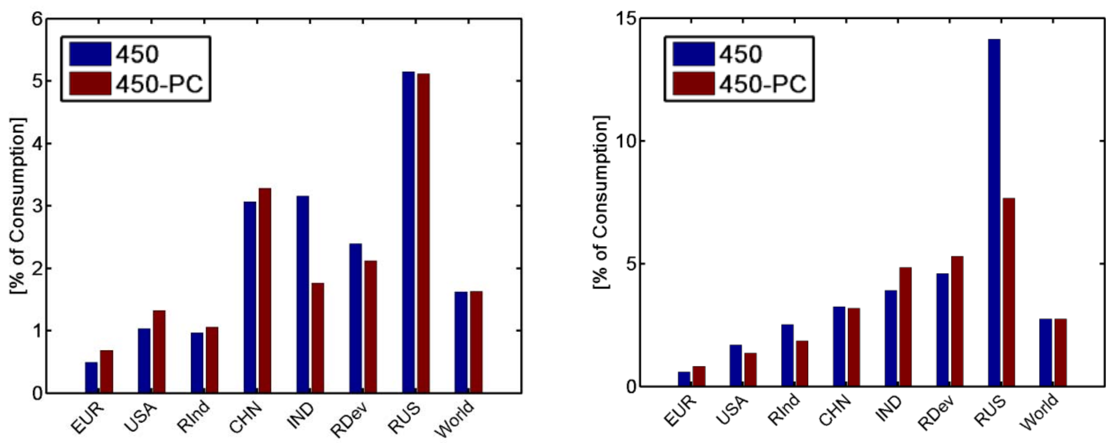

Figure 1: Discounted mitigation costs as a percentage of baseline consumption over regions: (a) 2010-2050 and (b) 2010–2100.

It is broadly accepted that globally uniform carbon pricing is an essential element for cost-effective climate change policies (Fischer et al., 1996). However, the regional cost pattern obtained from the tax scenario is unlikely to occur in the real world since it would result in very high costs for countries with high emissions abatement potentials. These countries will only be willing to realize their reduction potentials if they are at least partially compensated by other countries. Therefore, due to regional and international market distortions, it cannot be expected that this regional cost pattern will fully hold in the real world. Next, we focus on mitigation costs in a burden-sharing framework with the convergence of per-capita emissions rights in 2050. The Coase theorem (Coase, 1960) implies that the global costs of climate policy are independent of the allocation scheme, provided there are no other non-internalized externalities or market failures. Regional costs are redistributed in accordance with monetary transfers in the global carbon market.

Total mitigation costs expressed relative to consumption are highest for Russia in particular towards the mid-century. This is a direct consequence of Russia's relatively high per-capita emissions over the first half of the century (cf. Figure 3). This has also been concluded in earlier studies (Den Elzen et al., 2008). However, through the second half of the century, Russia encounters much less mitigation costs in PC scheme relative to the reference tax scenario. This occurs due to Russia's long-term negative per-capita emissions as a direct consequence of an extensive application of biomass with CCS (BECCS), which produces large amounts of negative emissions. Industrialized countries encounter mitigation costs varying between 0.7%-1.3% (2010-2050) and 0.8%-2.0% (2010-2100). The mitigation costs of USA are somewhat higher than Europe because of its higher per-capita emissions. As importers of permits, USA and the rest of the industrialized countries encounter higher mitigation costs in PC scheme relative to the tax scenario during the first half of the century.

The mitigation costs of India until 2050 are similar to the global average mitigation costs. The PC scheme thus leads to lower costs than the tax regime for India and the rest of the developing countries over this time horizon, since the domestic and energy import costs are partially compensated by revenues from emissions trading. This finding is in accordance with earlier studies (Den Elzen et al., 2008; Leimbach et al., 2010a; Luderer et al., 2012b; van Ruijven et al., 2012). However, for our scenario assumptions, we observe that in the PC scheme, the massive global efforts required to achieve near negative emissions result in significant additional costs in the second half of the century for India and Africa, which only have a low potential for generating negative emissions via BECCS. Scenario assumptions and input parameters have also a substantial impact on regional mitigation costs. A sensitivity study on key assumptions is thus provided in Section 7 and in the SOM. Further analysis of the results obtained from the PC scheme and elaboration on cost components appears in Section 5.

The impact of delayed action on the inter-temporally aggregated global mitigation costs is rather modest. In the "450" scenario, global mitigation costs aggregated from 2010 to 2050 reach 1.6%, and rise to 2.7% towards 2100. If a global cooperative regime is delayed until 2020, the aggregated global mitigation costs over 2010-2100 increase to 2.9%. Section 6 elaborates on the impacts of delayed action on regional distribution of mitigation costs.

3.5. Decomposition of mitigation costs – domestic and energy trade effects

As a first step towards the decomposition of mitigation costs, we focus on the regional mitigation costs obtained from the global carbon tax regime. This allows us to describe the drivers of domestic emissions reductions and energy trade effects in the absence of carbon-market induced compensations.

In Figure 2, we apply the economic decomposition methodology to the regional mitigation costs obtained from the scenario "450". Higher final energy prices due to climate policies result in a contraction of economic output. This is a dominant contributor to mitigation costs for most regions. Due to the reduced macroeconomic growth under climate policy, the investments into the macroeconomic capital stock are lower than in the baseline scenario, partly offsetting the reduction of economic output. In terms of energy system, moving towards emissions-free renewable energy sources as well as reduced prices of fossil fuels — as implied by the climate policy — reduces fuel expenditures. On the other hand, investing in capital-intensive low-carbon technologies such as CCS or renewable technologies leads to additional investment costs.

(a) (2010-2050) (b) (2010-2100)

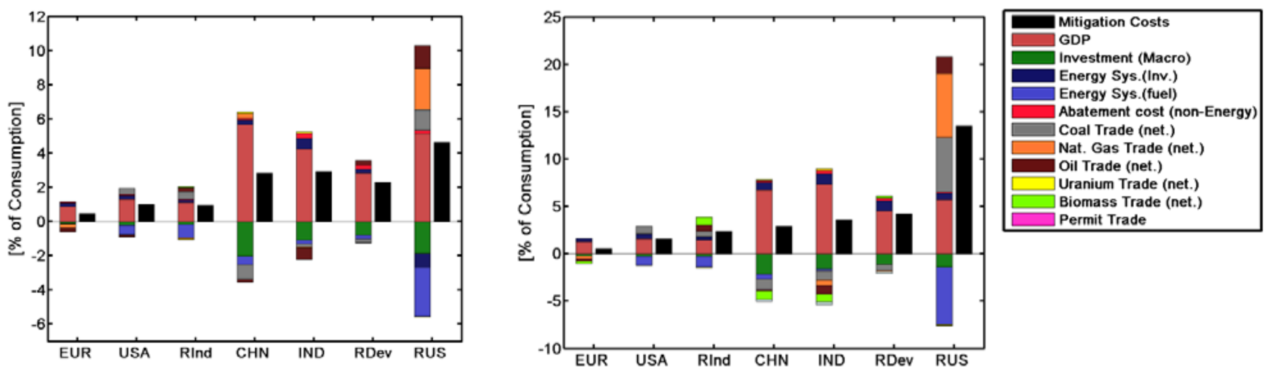

Figure 2: Decomposition of discounted mitigation costs for scenario "450" as a percentage of baseline consumption over regions: (a) 2010-2050 and (b) 2010-2100. (The black bar shows total mitigation costs, and the stacked bar to the left shows the components).

The impact of variation in the fossil-energy trade component is particularly significant for fossil fuel-exporters. Russia in particular is confronted with reduced revenues from fuel exports. This is a combined influence of the lower prices and the decreasing demand for fossil fuels under climate policy. It is important to note that these energy trade effects will occur independently of Russia's willingness to participate in the international climate regime (cf. Blanford et al., 2013).

For industrialized, resource-importing countries, GDP loss is the major contributor to mitigation costs. In Europe, this is partly counterbalanced by reduced oil and natural gas import costs due to lower prices and imported quantities. On the other hand, reduced revenues from coal exports result in further increase of mitigation costs for USA. Due to the lower carbon intensity of economic output, mitigation costs are lower than in the developing world.

In developing and emerging economies, the reduction of economic output also dominates the mitigation costs. Reduced coal import costs partially decrease the mitigation costs. Similarly, expenditures for importing oil and natural gas decrease.

3.6. Decomposition of mitigation costs - impact of permit trading

This section adds the influence of emissions trading on aggregated regional mitigation costs. Regions with emissions less than their endowment in the per-capita convergence framework derive revenues from the export of emissions rights. Regions that partially fulfill their reduction commitments by purchasing permits face additional costs, which raise their mitigation costs beyond the costs incurred for domestic abatement.

Figure 3 depicts the regional GHG per-capita emissions over time for the “450-PC” scenario. To provide a breakdown of the variations in per-capita emissions, Figure S2 and Figure S3 visualize the development of GHG intensity of final energy and per-capita final energy over time, respectively. From these figures, we can compare the pattern of each region against the world-average.

Currently, the USA and Russia are characterized by per-capita emissions that exceed the world average by a factor 4 and 2.5, respectively. By contrast, our results suggest that their per-capita emissions could fall far below the world-average under climate policy during the second half of the century. This is due to their high CCS and renewable energy potential (cf. Table S3). Russia in particular achieves deep negative per-capita emissions after 2050 because of the large-scale application of BECCS, which produces large amounts of negative emissions.

On the other hand, India and the rest of the developing countries have comparatively low initial per-capita emissions but exceed the world-average after 2050. The world-average GHG intensity of final energy reaches zero and becomes slightly negative through the second half of the period. In the long-term, CCS, bio energy use and the use of renewables dominate emissions reductions in all regions. However, the CCS and renewable energy potentials are limited in India and the rest of developing countries considering their high growth of final energy demand over time (Figure S1), resulting in a carbon intensity of final energy above the world average. Therefore, their long-term per-capita emissions are high despite relatively low levels of per-capita final energy demand. Finally, China’s per-capita emissions stay close to the world-average, and Europe’s per-capita emissions stay above the world-average over the whole century.

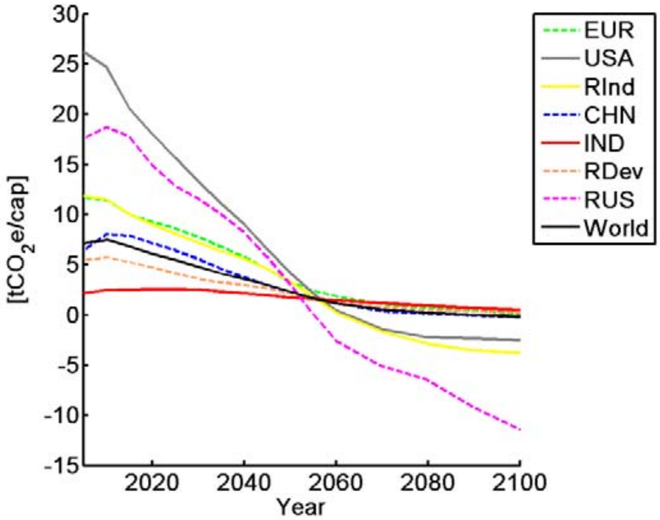

Figure 3: GHG per-capita emissions over regions and time in scenario "450-PC".

Figure 4 depicts a comparison between actual emissions and emissions allowances over time. This clarifies how the roles of different regions with respect to permit trading in a global cap-and-trade system vary over time. Corresponding to its below-average per-capita emissions in the long-term, Russia acts as a main seller of permits through the second half of the century. The USA meets part of its reduction obligations by importing permits over the first half and acts as a seller thereafter, which also corresponds to its long-term below-average per-capita emissions. Europe always acts as a buyer of permits to compensate for higher emissions than its endowments.

The emissions allowances based on the PC scheme in the "450-PC" scenario imply emissions reductions relative to baseline that are modest in the first decades but increase to 100% towards the end of the century for both China and India. For India, the reductions reach 17%, 36%, 72%, and 103% relative to baseline emissions in 2020, 2030, 2050, and 2100. The emissions allowances based on the PC scheme imply higher emissions reductions for China. This leads to a peak of emissions allowances around 2035/2040 for India but for China soon after their participation in 2020. Our results are in the ranges given in earlier studies focusing on low stabilization targets (van Ruijven et al., 2012). Our study particularly concludes that although these regions derive revenues from selling permits in the medium-term towards 2050, however, affected by their relatively high carbon intensity of the economy, they act as importers of permits through the second half of the century.

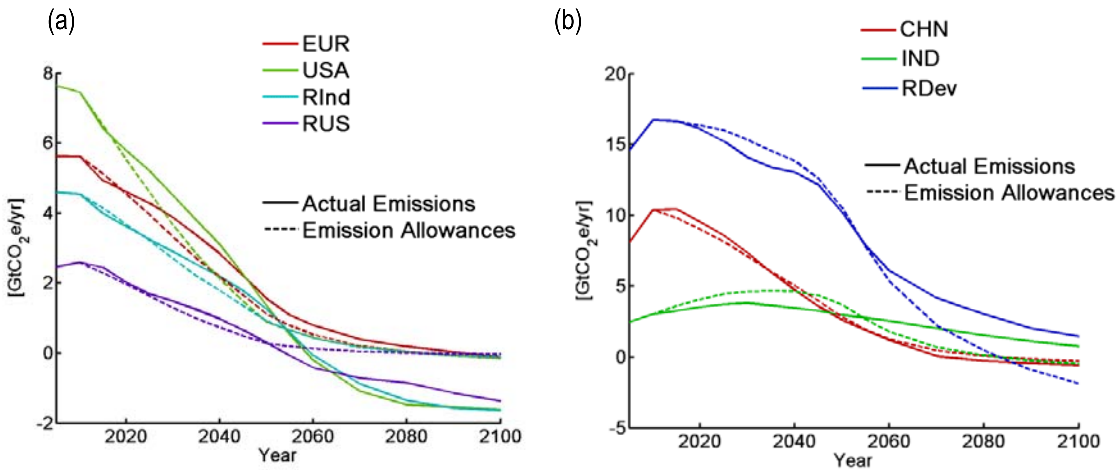

Figure 4: Emissions allowances versus actual GHG emissions over time for scenario "450-PC": (a) Industrialized regions and Russia, (b) Developing regions.

Figure 5 shows the decomposition of regional mitigation costs for the "450-PC" scenario. The domestic and energy trade effects remain unaffected by the allocation scheme (cf. Section 3.3.1). The carbon trade balance then determines the variations of mitigation costs against the reference tax scenario. In the 2010-2050 time span, total relative costs are high for Russia nearly at the level of the tax scenario as a direct consequence of its relatively high per-capita emissions through the first half of the century. However, Russia benefits from the surplus emissions allowances over the second half of the century, resulting in substantially lower 2010-2100 mitigation costs than in the tax scenario. Among industrialized countries, the USA and the rest of the industrialized countries slightly gain from selling emissions permits through the second half of the century, while Europe encounters slight additional costs due to purchasing permits.

India and the rest of the developing countries achieve revenues from selling emissions permits under the PC convergence framework and face lower mitigation costs relative to the tax regime over the period 2010-2050. This result is in accordance with earlier studies (Den Elzen et al., 2008; Leimbach et al., 2010a; Lueken et al., 2011; Luderer et al., 2012b; van Ruijven et al., 2012). Our results further conclude that the climate-mitigation costs are highly sensitive to the considered time horizon and is particularly influenced by the long-term effects arising through the second half of the century. Affected by the relatively high carbon intensity of their economies during the second half of the century, higher costs arise in India and the rest of the developing countries in the PC scheme relative to the tax regime when aggregated over the full century (2010-2100). Finally, China's mitigation costs can mainly be attributed to domestic and energy trade effects, while carbon trading plays a minor role.

(a) (2010-2050) (b) (2010-2100)

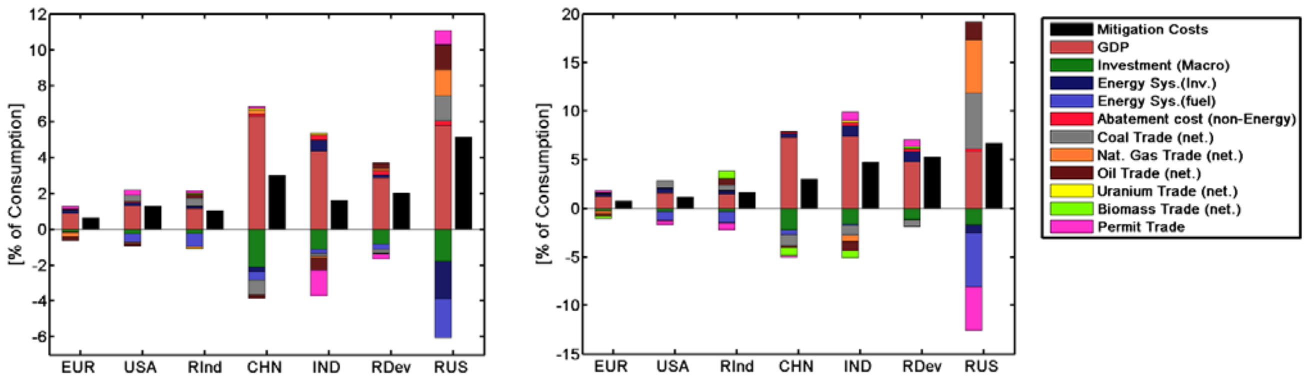

Figure 5: Decomposition of discounted mitigation costs for scenario "450-PC" as a percentage of baseline consumption over regions: (a) 2010-2050 and (b) 2010-2100. (The black bar shows total mitigation costs, and the stacked bar to the left shows the components).

3.7. Regional implications of delayed action

For the analysis of regional implications of delayed action, we first explore effects on regional transformation pathways (Section 6.1) followed by a decomposition analysis of induced changes in regional mitigation costs (Section 3.7.2).

3.7.1. The effect of delayed action on regional transformation pathways

This section focuses on mitigation pathways that limit atmospheric GHG concentrations at roughly 450 ppm CO_2-equivalent in 2100. It sheds light on heterogeneous consequences of weak near-term climate policies in terms of regional GHG emissions abatements and energy system transformations.

Emissions

Figure 6 presents the global GHG emissions trajectories. On a near- to medium-term perspective, global emissions in the delayed-action scenario exceed those of the immediate case. The excess emissions relative to the "450" scenario reaches 10 $GtCO_2e$ (23%) in the "RefPol-450" scenario by 2020. The excess emissions decline over time, but do not disappear before 2040. In the long-term, emissions in the delayed-action scenario go below the immediate action case to compensate for higher emissions at early stages.

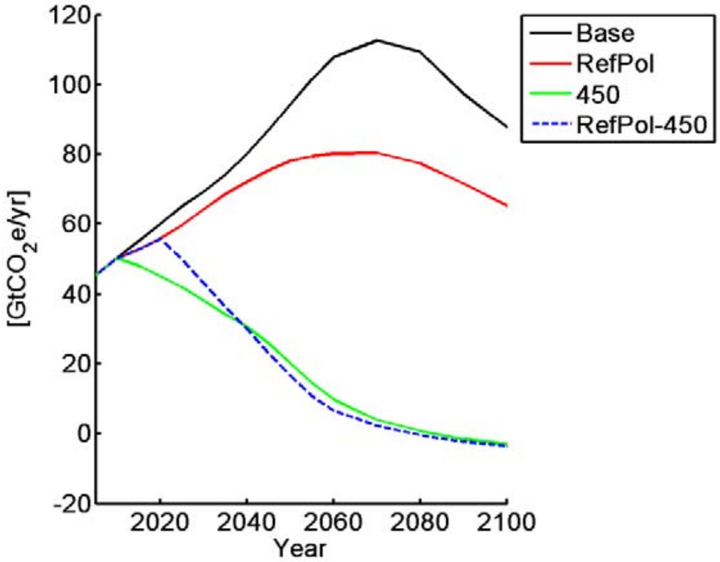

Figure 6: Global GHG emissions trajectories.

Figure 7 depicts the regional cumulative emissions reductions from baseline. For a given global stabilization target, the amount of emissions reductions performed in a region are independent of the allocation rule (cf. Section 3.3.1); therefore, it is only shown for the reference tax regime. Delayed action has a strong impact on near- to medium-term emissions reductions, as regional emissions trajectories are highly influenced by the weak policy scenario that is followed until 2020. Europe has medium-term emissions reductions that are similar to or even more ambitious than those implied by the idealized immediate action scenario, while reductions in other regions stay far below the immediate case. However, long-term reductions in cumulative emissions are less sensitive to near-term action, but rather reflect regional differences in mitigation potentials. Thus, in both scenarios, the relative abatement over the whole century is the highest for Russia, which has a high mitigation potential, while less potential exists in industrialized and developing countries.

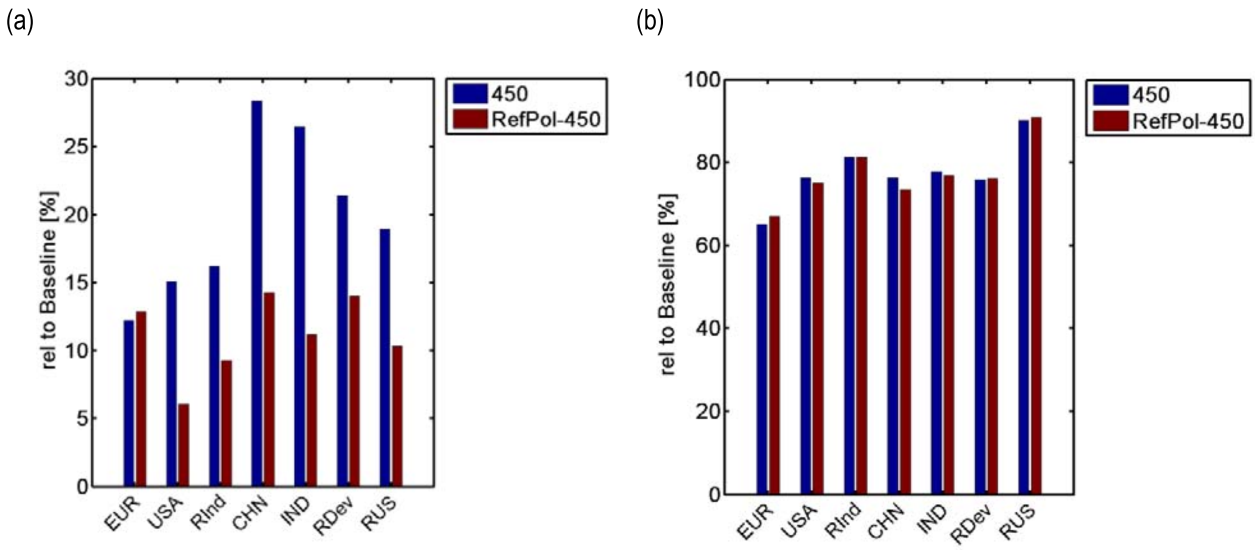

Figure 7: Cumulative GHG emissions reductions from baseline over regions: (a) 2005–2030, and (b) 2005–2100[25].

Energy supply

To clarify the implications of weak near-term climate policies for the future development of the energy sector, Figure 8 depicts the differences in regional primary energy supply between the "RefPol-450" and the "450" scenario (the regional primary energy mix of the "Base" and "450" are visualized in Figure S4 and Figure S5).

One consequence of delayed action is the lock-in of emissions-intensive fossil fuel-based capacities in the near- to medium-term. The total conventional usage of fossil energy in the delayed-action scenario remains above the immediate action case even until 2040 due to the inertia caused by long-living capacity stocks. Rapidly growing economies, particularly China and India as well as the rest of the developing countries without strong reduction commitments in the weak policy scenario have much higher conventional deployment of fossil energy in the near- to medium-term than in case of immediate action. This gives rise to a twin challenge in the delayed-action scenario. First, the energy system's capital stock at the start of the global mitigation effort is characterized by a higher share of carbon-intensive technologies compared to an immediate cooperative action. Second, given a particular climate-stabilization target, more rapid and aggressive emissions reductions must be achieved after the adoption of a global climate regime in case of delayed action compared to the immediate cooperative action (cf. Section 6.1.1).

The application of BECCS in the delayed action scenario exceeds the immediate action case from 2035 onwards and peaks around 2060. A higher penetration of fluctuating renewables dominated by solar energy is also noticed after

[25] Cumulative reductions from baseline over 2005-2100 implied by the delay are slightly higher than the immediate action in regions with ambitious short-term reduction pledges such as Europe, while it is less than the immediate case in regions such as China and India with low near-term reduction commitments in the weak policy scenario.

2050 because of higher carbon prices after the target adoption in the delayed-action scenario compared to the immediate action.

(a) (b) (c)

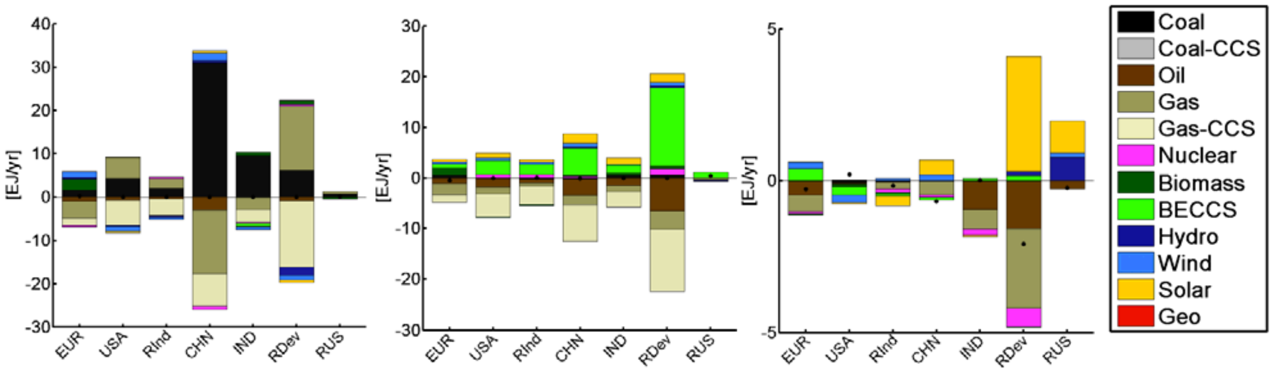

Figure 8: Difference in primary energy supply between the “RefPol-450” scenario and the “450” scenario over regions: (a) 2030, (b) 2050, and (c) 2100. (Positive values indicate higher production in “RefPol-450” compared to “450”).

3.7.2. Decomposition of mitigation costs

Having elaborated on the mitigation costs of immediate action scenarios in Sections 4 and 5, here, we particularly focus on the marginal economic impacts of delay. We thus decompose the difference in mitigation costs between the “RefPol-450-PC” and “450-PC” scenarios in Figure 9.

A combination of four main distinct effects determines the impact of delayed action on regional mitigation costs. First, regions with less stringent near-term reduction commitments in fragmented regimes bear a lower share of global mitigation effort and encounter lower aggregated mitigation costs compared to the idealized immediate action. This is most obvious from a smaller reduction of economic output. Second, the advantage of low reduction commitments at an early stage is countered by the increase in future mitigation costs due to higher prospective emissions reduction requirements combined with an exacerbated “lock-in” with carbon-intensive energy infrastructures (cf. section 6.1). This is confirmed by the decomposition analysis that shows additional energy system investment costs occurring in all regions. Third effect relates to the energy trade impacts of delayed action. Net fossil fuel exporters would incur less revenues, while net importers would gain because of a higher usage of coal, which replaces oil and natural gas particularly in regions with low near-term reduction commitments. Fourth, delayed action raises the global carbon price after adoption of the target above the level in the immediate action scenario to compensate for excess emissions in an early period. This has varying consequences for regional mitigation costs according to the role of the region in the global carbon market. In essence, delayed action harms sellers of permits in an initial period since they have fewer permits to sell due to the shortened time under a trading system and their own higher emissions, and buyers of permits in the long term when carbon prices are higher – and vice versa.

In particular, the delayed action raises the mitigation costs of India and the rest of the developing countries above the immediate action over both time horizons. The decomposition analysis shows the main underlying mechanisms. First, additional energy system costs occur as a direct consequence of unambitious, early emissions reduction commitments and subsequent “lock-in” effects. Second, the revenues obtained from selling permits contract over the 2010-2050 time span due to higher domestic emissions, while over the second half of the century they encounter higher costs for purchasing permits due to higher carbon prices resulting from delayed action. These cost components counterbalance the increase in economic output and also reduced oil and gas import costs in India.

On the other hand, China and Russia mainly gain from a delayed participation in global mitigation effort. In terms of 2010-2050 mitigation costs, China mainly gains, while over the complete horizon Russia benefits the most from delayed action. China’s net gain in delayed action can mainly be attributed to lower domestic and energy import costs. Delayed action results in a stronger deployment of coal without CCS and less application of oil and natural gas in China and India (cf. Figure 8). Correspondingly, expenditures for importing oil and natural gas reduce against the immediate action. It also obtains slight gains from the export of emissions permits due to both higher carbon prices and higher exported quantities. Reduced fuel import costs along with an increase in economic output and the revenues from emissions trading counterbalance the additional energy system costs and coal import costs in China. Russia chiefly gains from emissions trading, which stems from both higher carbon prices and higher quantities of exports. Other effects include the higher energy system investment costs and reduced revenues from oil and natural gas exports. These components offset the GDP gain and reduced fuel expenditures among the domestic effects.

(a) (2010-2050) (b) (2010-2100)

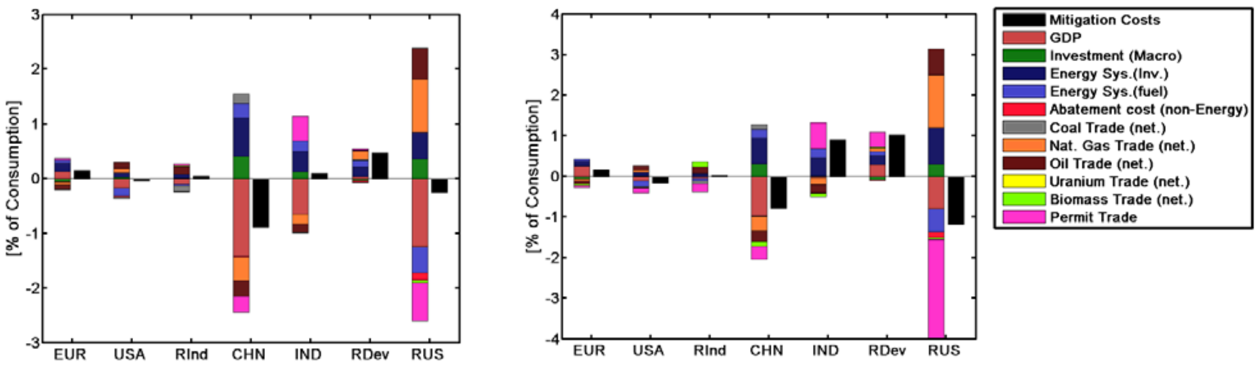

Figure 9: Decomposition of discounted mitigation costs differences between “RefPol-450-PC” and “450-PC” scenarios over regions: (a) 2010-2050 and (b) 2010-2100. (Positive values indicate higher mitigation costs in “RefPol-450-PC” scenario compared to “450-PC”; the black bar shows total differences in mitigation costs, and the stacked bar to the left shows the components).

So far, we addressed the mitigation costs on a time-aggregated basis. The decomposition of climate-mitigation costs over time yields further insights into the specific regional patterns of the costs' components. Smoothening effects on temporal variations of consumption arise from the inter-temporal trade balance.

To analyze the components of mitigation costs over time, we narrow the regional scope to the USA (with lower mitigation costs over the whole century) and India (with higher mitigation costs over the whole century) in the context of delayed action. Both countries can be considered as representatives of two different groups in the international burden-sharing regime: those with long-term allowances exceeding their long-term residual emissions (USA) and those with the opposite pattern (India). As discussed in detail below, delayed action is beneficial for the former group of countries while it is more costly for the latter group, mainly due to the associated increase of carbon prices in the long-term.

Figure 10.a shows the decomposition of mitigation costs over time for the USA in the "450-PC" scenario. The pattern of domestic factors of mitigation costs remains nearly unaffected over time, while revenues from the export of permits arise throughout the second half of the century. In the "RefPol-450-PC" scenario, revenues from the export of permits increase compared to its level in the "450-PC" scenario (Figure 10.b). This along with the reduced fuel expenditures offsets the mitigation costs arising from contraction of economic output, energy system investment, and import of fossil fuels. As a combined effect of all these factors, the USA encounters lower mitigation costs from 2060, compared to the immediate action.

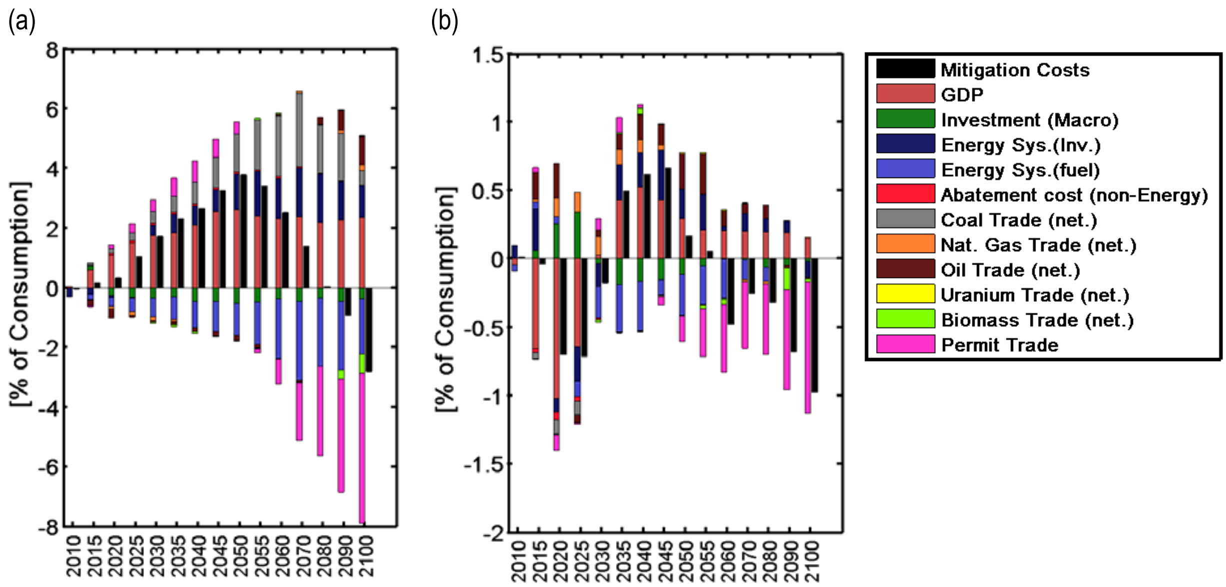

Figure 10: Decomposition over time for USA: (a) Decomposition of mitigation costs for scenario “450-PC”; (b) Decomposition of mitigation costs differences between “RefPol-450-PC” and “450-PC” scenarios. (Positive values indicate higher mitigation costs in “RefPol-450-PC” scenario compared to “450-PC”).

Figure 11 depicts the decomposition of mitigation costs over time for India. The contraction of economic output and energy system’s investment costs counterbalance the reduced macroeconomic investments and the lower import costs of fossil fuels as well as the revenues obtained from the export of permits throughout the first half of the century. Costs are paid for purchasing permits throughout the second half of the century (cf. Figure 11.a). In the “RefPol-450-PC” scenario compared to the “450-PC” scenario, exported quantities of permits reduce in the near to medium-term, while higher costs are paid for purchasing permits over the second half of the century. Correspondingly, after 2030, mitigation costs of India exceed the level of the immediate action.

It is worth mentioning that when looking into temporal variations of mitigation costs, the so-called “consumption smoothening” effect arises from the adjustments of capital trade over time. This is obvious when representing the mitigation costs over time based on its first set of constituents, consumption losses and variations in current accounts (see Eq. 6). Due to the perfect foresight assumed in the model, for instance, the USA, anticipates the gains arising from permit revenues in the long-term. Via inter-temporal adjustments of the current account, the benefits are spread over time, resulting in higher consumption and therefore lower mitigation costs in the near-term (cf. Figure S6.a). On the other hand, developing countries such as India while anticipating high costs of emissions reductions in the second half of the century, might build up foreign assets by increasing exports of goods in the near term, which allow them to offset costs incurred later by higher imports (cf. Figure S7.a).

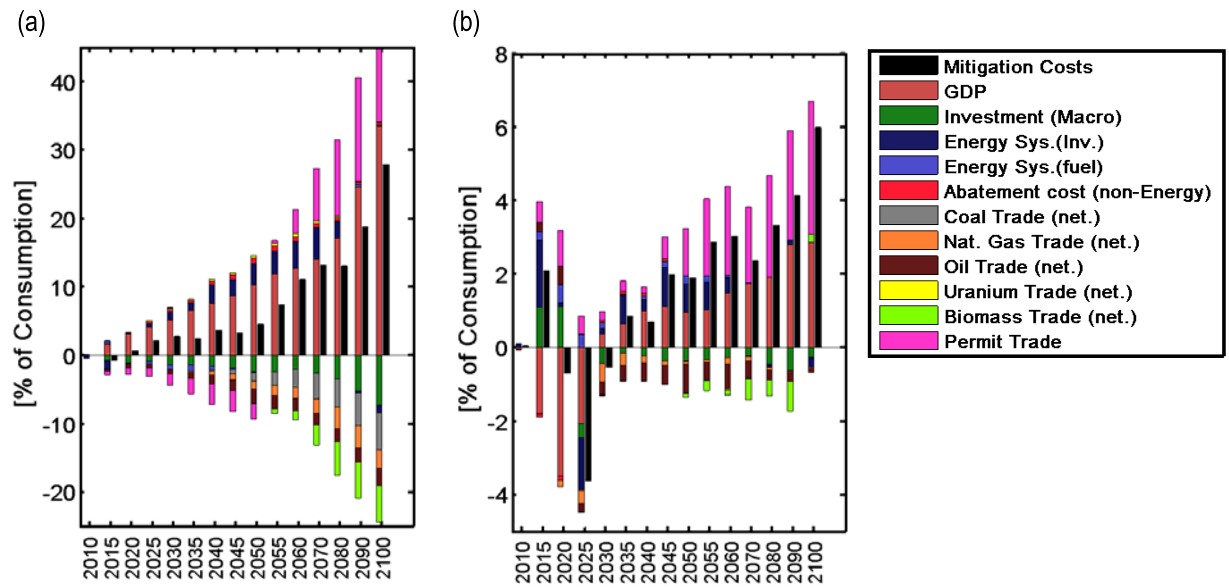

Figure 11: Decomposition over time for India: (a) Decomposition of mitigation costs for scenario "450-PC"; (b) Decomposition of mitigation costs differences between "RefPol-450-PC" and "450-PC" scenarios. (Positive values indicate higher mitigation costs in "RefPol-450-PC" scenario compared to "450-PC").

3.7.3. Sensitivity analysis

To provide an insight on key factors that their variations affect the regional mitigation costs the most and to investigate to what extent these costs depend on key assumptions about the mitigation and policy options, we present a sensitivity analysis of our results throughout this section followed by a further discussion and visualization of results in the SOM.

Climate stabilization target

We consider a less ambitious climate target of 500 ppm CO2-e in scenarios "500" and "500-PC" (cf. Table S7). The global mitigation costs reduce to 1.9% of global consumption in the baseline scenario. Under the global carbon tax regime, the mitigation costs reduce in all regions at the higher stabilization target (cf. Figure S10). The most obvious reduction of mitigation costs at the higher stabilization target occurs in Russia as a fossil fuel exporter and the rest of the developing countries. On the other hand, a lesser reduction of mitigation costs occurs in fossil fuel importing regions, i.e. Europe followed by the USA, China, and India. Among the domestic components, an increase in economic output is a major contributor to total consumption gains in all regions. The energy system investment costs reduce, while the fuel expenditures increase because of lower investments in capital-intensive low-carbon technologies and higher fossil fuel prices at the higher stabilization target. In particular, Russia benefits from higher fossil-energy export profits at the higher stabilization target.

Apart from the domestic and energy trade effects, the climate stabilization target affects the financial flows arising from emissions trading. This has a particular impact on regions such as India with a low domestic mitigation potential or Russia with an opposite pattern. In scenario "500-PC", the GHG per-capita emissions of India stay below the world-average even up to 2070 (cf. Figure S12). Correspondingly, India becomes a net exporter of permits over the complete horizon, resulting in lower mitigation costs in PC scheme relative to the tax scenario. This shows a different pattern against the previously analyzed "450-PC" scenario, in which India acts as an importer of permits through the second half of the century. On the other hand, the higher stabilization target adversely affects the emissions trading of Russia as a region with a high domestic mitigation potential. At the higher stabilization target, Russia derives less revenues from selling permits due to both lower prices and exported quantities. The impact of emissions trading is high enough that over the complete horizon, Russia encounters slightly higher mitigation costs in the "500-PC" scenario compared to "450-PC".

Bioenergy potential

As a next key determining factor, we investigate the consequences of limited availability of bioenergy towards ambitious climate-stabilization targets. We thus reduce the global bioenergy potential from the assumed level so far (300 EJ/yr) to 100 EJ/yr, while regional shares remain constant. Figure S13 depicts the global and regional mitigation costs across scenarios with different assumptions about bioenergy potential. The global mitigation costs rises to 4.1% (2010-2050) and 5.5% (2010-2100) at the lower level of bioenergy potential.

Decomposition of regional mitigation costs reveals that among the domestic factors, contraction of economic output and higher energy system investment costs dominate the mitigation costs in most regions. These components counterbalance the gain obtained from reduced macroeconomic investments and less fuel expenditures (cf. Figure S14).

Large-scale application of BECCS has led to long-term negative per-capita emissions particularly for Russia in scenario "450-PC" (cf. Section 3.6). However, due to limited availability of bioenergy in scenario "450-PC-lowbio", Russia cannot achieve negative emissions (cf. Figure S15). Correspondingly, Russia's revenues from emissions trading reduce through the second half of the century as compared to scenario "450-PC".

Furthermore, India's per-capita emissions stay below the world-average through the whole century in scenario "450-PC-lowbio" (cf. Figure S15), and it correspondingly acts as an exporter of permits over the complete time horizon. Furthermore, limited availability of bioenergy raises the global carbon price in scenario "450-PC-lowbio" relative to the "450-PC" scenario. Therefore, at the lower bioenergy potential, PC scheme is always favorable to India as it results in lower mitigation costs than the tax case chiefly due to the emissions trading effect. The influence of permit trading as a factor of China's mitigation costs increases in scenario "450-PC-lowbio" relative to the "450-PC" scenario due to both higher permit prices and higher quantities of exports. Therefore, China also obtains gains from selling emissions permits (cf. Figure S14).

3.7.4. Discussion and conclusions

In this article, we have analyzed the regional climate-mitigation costs under global emissions pathways stabilizing GHG concentrations at 450 and 500 ppm CO_2-equivalent by 2100, while near-term fragmented climate policies are adopted and the implementation of a global climate agreement is delayed to 2020. We explored the underlying economic mechanisms by decomposing the climate-mitigation costs into their various components. It is important to note that the adverse consequences of climate change were not part of this analysis due to the uncertainty of their size in financial terms. Therefore, the results presented here should be interpreted as a cost-effectiveness, rather than a cost-benefit, analysis.

First, our results show that following the weak, near-term fragmented actions until 2020 and a subsequent adoption of the 450-ppm CO_2e stabilization target is still feasible in the model framework, albeit at higher global costs. Our conclusion is in line with other studies addressing the impacts of delayed cooperative action while the near-term climate policies, which are already under way, are taken into account (Luderer et al., 2013b). Although the model results show the techno-economic feasibility of such pathways, their political and institutional feasibility remains ambiguous.

Our results indicate that regional mitigation costs may deviate substantially from the global average. In an immediate action towards 450-ppm CO_2e target, in the reference tax regime, Russia encounters the highest relative mitigation costs, while high costs also arise in India and rest of the developing countries. Europe, USA, and the rest of the industrialized countries encounter mitigation costs of around or below world-average. This general pattern was also found in the broader set of models participating in the LIMITS study (cf. Tavoni et al., 2013). Under the PC scheme, we found a range of emissions reduction targets similar to those quoted in earlier studies (cf. Section 3.6). Our analysis of different burden sharing rules and time horizons conclude that the considered regime and the time period has a particular impact on the regions with low domestic mitigation potential such as India and the rest of the developing countries or Russia with an opposite pattern, where the costs or revenues from emissions trading play an important role. Towards the mid-century, PC scheme leads to lower costs than in the tax regime for India and the rest of the developing countries as the domestic and energy trade costs are partly compensated by revenues from emissions trading. This finding is in accordance with earlier studies (Den Elzen et al., 2008; Leimbach et al., 2010a; Lueken et al., 2011; Luderer et al., 2012b; van Ruijven et al., 2012). Considering a time horizon until 2100 in this study allows us to explain divergent effects arising in the second half of the century. In our scenarios aiming at the 450-ppm CO_2e target, India and the rest of the developing countries derive revenues from selling permits in the medium-term until mid-century; however, they may become importers of permits in the second half of the century, due to their limited domestic mitigation potential. Russia is affected by its relatively high per-capita emissions through the first half of the century, and, therefore, bears high 2010-2050 mitigation costs in PC scheme at the level of the tax case; this is also correspondent to conclusions drawn in earlier studies (den Elzen et al., 2008). Our results furthermore indicate that over the whole century, Russia encounters much less mitigation costs in the PC scheme relative to the tax case due to the revenues obtained from emissions trading over the second half of the century. Russia in particular achieves deep negative emissions in the long-term due to large-scale application of BECCS.

Our sensitivity analysis further indicates the high dependency of regional mitigation costs to different parameters and scenario assumptions in particular to the climate-stabilization target and the bio-energy potential. Apart from domestic and energy trade effects, the climate stabilization target affects the costs or revenues arising from emissions trading. This has a particular impact on regions, where the costs or revenues from emissions trading play an important role. Our results show that at the higher stabilization target of 500-ppm CO_2e, India acts as an exporter of permits in PC scheme over the complete horizon and encounters lower mitigation costs relative to the tax scenario. On the other hand, the higher stabilization target adversely affects the emissions trading effect for Russia. In our main set of scenarios, we assumed a global bio-energy potential of 300 EJ/yr, while we limited the global potential to 100 EJ/yr in our sensitivity study. Affected by the limited availability of bioenergy, Russia cannot achieve negative emissions in the long-term, and, correspondingly, its revenues from emissions trading reduce over the second half of the century and encounters higher mitigation costs at the lower bioenergy potential. On the other hand, India's per-capita emissions stay below the world-average over the whole century in a scenario towards 450-ppm CO_2e target at the lower bio-energy potential, and it correspondingly acts as an exporter of permits over the complete time horizon. Furthermore, limited availability of bioenergy raises the global carbon price, and, therefore, India gains from emissions trading and encounters lower mitigation costs in PC scheme relative to the tax case over the whole century.

Our analysis of delayed-action scenarios concludes that a delay in cooperative action affects domestic costs on one hand by increasing the energy system investment costs, which is a direct consequence of lock-in with carbon-intensive infrastructures due to the myopic behavior[26] in the delay period. This is particularly relevant for developing countries such as China, India, and the rest of the developing countries with non-ambitious near-term emissions reduction commitments in the weak policy. However, additional energy system costs are compensated to different degrees by a lesser contraction of economic output and lower import costs of fossil fuels (due to higher usage of coal replacing oil and natural gas) arising from the delay. While the latter effects are dominant in China, it is superseded by the effect of permit trading in other developing regions. Assuming convergence of per-capita allowances in 2050, importers of permits through the second half of the century such as India and the rest of the developing countries suffer from higher mitigation costs, which chiefly stem from the higher costs paid for purchasing permits in delayed action. On the other hand, Russia benefits from a delayed action particularly over the second half of the century due to higher incomes from selling permits. Overall, our results suggest that the effect of delayed action on regional mitigation costs highly depends on whether or not the regions are over- or under-allocated with emissions allowances in the long run. Those with long-term allowances exceeding their long-term residual emissions will likely benefit from the delay, while others will suffer the consequences of higher long-term carbon prices. This creates greater institutional challenges for implementing burden-sharing regimes due to the higher importance and value of long-term emissions rights.

Several qualifications apply to our results. First, our modeling framework assumes a perfect foresight and the separability of efficiency and allocation. Further research is required to investigate the impact of delayed action on regional mitigation costs in less idealized settings with global-scale market imperfections and myopia. Second, we assumed a flexible set of energy conversion technologies in our scenario assumptions. According to our findings and also based on other studies (den Elzen et al., 2008; Lueken et al. 2011), CCS accounts for a major share of the emissions reductions. To analyze the impact of uncertainty relating to CCS capacity and its technical feasibility, the implications of restricted availability of this mitigation option (particularly bioenergy combined with CCS) for the costs of climate change mitigation specifically in delayed action scenarios must be explored further. We defer this important analysis to our future research.

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[26] Following the weak policy scenario until 2020 without anticipation of the long-term climate target thereafter, is referred here as the myopic behavior (cf. section 2.3).

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4. Emission Certificate Trade and Costs under Regional Burden-Sharing Regimes for a 2˚C Climate Change Control Target

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4.1. Abstract

In this article we explore regional burden-sharing regimes for the allocation of greenhouse gas emission reduction obligations needed to reach a 2˚C long-term global climate change control target by performing an integrated energy-economy-climate assessment with the bottom-up TIAM-ECN model. Our main finding is that, under a burden-sharing scheme based on the allowed emissions per capita, the sum of merchandised carbon certificates yields about 2000 billion US$/yr worth of inter-regional trade around 2050, with China and Latin America the major buyers, respectively Africa, India and Other Asia the main sellers. Under a burden-sharing regime that aims at equal cost distribution, the aggregated amount of transacted carbon certificates involves less than 500 billion US$/yr worth of international trade by 2050, with China and Other Asia representing the vast majority of selling capacity. Restrictions in the opportunities for international certificate trade can have significant short- to mid-term impact, with an increase in global climate policy costs of up to 20%.

4.2. Introduction

The much anticipated negotiations during the 15th Conference of the Parties (COP-15) of the United Nations Framework Convention on Climate Change (UNFCCC) in 2009 in Copenhagen failed to lead to a new binding agreement as successor to the 1997 Kyoto Protocol, designed to eventually “stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”. Since then, the climate policy community has generated a fragmented network of national and regional climate change mitigation measures. The main outcome of COP-17 in Durban in 2011 and COP-18 in Doha in 2012 was that by 2015 the negotiation of a new legally enforceable climate change control agreement should be achieved and become effective from 2020 onwards. The fundamental challenge for policy makers and government representatives from developed and developing countries, during multi-lateral negotiations the forthcoming years, will be to resolve the crux of equitable regional burden-sharing. This matter is one of the main research topics of the LIMITS project[27], which researches greenhouse gas (GHG) emission reduction strategies, globally and at the level of the world’s major economies, required to limit the anthropogenic atmospheric temperature increase to 2˚C in comparison to the average level in pre-industrial times (UNFCCC, 2010).

This article, produced in the context of the LIMITS project, investigates the cost and carbon certificate trade impacts of different regimes of inter-regional burden-sharing for the allocation of GHG emission reduction obligations needed to reach stringent global climate change stabilisation. In addition to inspecting the technological and structural changes required to adapt the energy systems of the world’s main economies, we analyse carbon certificate price effects as well as carbon market capital flows emanating from the introduction of equitable burden-sharing between

[27] See www.feem-project.net/limits

regions that undertake collective effort in mitigating global climate change. In section 2 of this paper we shortly describe the model that we use to perform our analysis, as well the approach and assumptions adopted for this study. Section 3 presents our main results, in terms of GHG emission reduction pathways and allocation of GHG emission allowances in two different kinds of regional burden-sharing regimes: resource-sharing respectively effort-sharing. In section 4 we investigate the impact of possible limitations in carbon certificate trade opportunities across the world between its main economies, in terms of quantity and timing of permit trade, inter-regional transfers of funds, carbon certificate prices, and overall climate policy costs. In section 5 we report our overall conclusions and proffer thoughts on the implications of our study for policy makers.

4.3. Approach and socio-economic assumptions

This paper is complementary to, and an extension of, another article on burden-sharing in this special issue, which unlike ours takes a cross-model perspective rather than a single-model view (see Tavoni *et al.*, 2013). Our article reports results from the TIAM-ECN model only, and puts sensitivity analyses with this model at centre stage. Moreover, our paper investigates the effects of possible limitations in international carbon permit trade. For details on the set-up and definition of scenarios analysed in our study we refer to Kriegler *et al.* (2013) in this special issue.

4.3.1. TIAM-ECN energy system model

TIAM-ECN is the TIMES[28] Integrated Assessment Model (TIAM) of the Energy research Centre of the Netherlands (ECN), used for long-term energy systems and climate policy analysis. It has a global scope with a world energy system disaggregated in 15 distinct regions. TIAM-ECN is a linear optimisation model, based on energy system cost minimisation with perfect foresight until 2100. It simulates the development of the global energy economy over time from resource extraction to final energy use. The objective function is represented by the discounted total energy system costs summed over all time periods and across all regions. The main cost components aggregated in the objective function are the investment costs and fixed plus variable operation and maintenance costs for various energy supply and demand options, including emission reduction measures. TIAM-ECN is based on a partial equilibrium approach with exogenous demands for energy services. These services, however, can respond to changes in their respective prices through end-use price elasticities. Hence, savings of energy demand and corresponding overall energy system cost variations are accounted for in our model. TIAM-ECN is operated with a comprehensive technology database that contains many possible fuel transformation and energy supply pathways, and encompasses technologies based on fossil, nuclear and renewable energy resources. Both currently applied technologies and future applicable advanced technologies, such as ultra-supercritical fossil-fuelled power plants, hydrogen technologies, a broad variety of renewable energy options, and carbon dioxide capture and storage (CCS) techniques in power plants and industrial applications, are available in the model's technology portfolio.

[28] TIMES is the acronym for The Integrated MARKAL-EFOM System, a model generator inspired by two bottom-up energy system models: the MARket Allocation model (MARKAL) and Energy Flow Optimization Model (EFOM).

TIAM-ECN simulates in detail three main types of GHGs (and does not inspect other GHG species): carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). GHG emissions related to energy conversion and industrial processes are modeled via a process-oriented approach with an endogenous emission calculation. For emissions of CH_4, CO_2 and N_2O that are not related to energy conversion or industrial activities, such as from agriculture, a reference pathway is determined outside the model and postulated as emission profile exogenously to the model. With regard to climate change mitigation measures, however, our model covers abatement options for *all* GHG emissions, i.e. for both energy- and non-energy related sources. For energy-related sources various low-emission technology options are available in the model, while for non-energy-related emissions cost-potential curves for GHG mitigation measures are simulated. More detailed model descriptions and examples of the application of TIAM-ECN can be found in Rösler *et al.* (2011; 2012), Keppo and van der Zwaan (2012), and van der Zwaan *et al.* (2013b), as well as several references therein. Since TIAM-ECN is an energy system model, it allows for analysing GHG reduction pathways over the entire energy supply chain up to end-use energy demand. Horizontal and vertical interdependencies and substitution effects of energy supply are thereby accounted for. For instance, the use of hydrogen in the transport sector as climate change mitigation measure depends, evidently, on the availability and price of hydrogen (vertical dimension). The nature and deployment scale of hydrogen production technology in industry has a significant impact on the supply costs of hydrogen, notably for the transport sector (horizontal dimension).

Besides this integrated systems approach, TIAM-ECN features details of energy extraction, conversion and demand, such as available fossil and renewable energy resources, potentials for storage of CO_2, and region-specific (energy) demand developments. Region- and sector-specific demands for end-use energy and industrial products are driven by socio-economic parameters. Globally we assume almost a tripling of gross domestic product (GDP) over four decades, from 68 tln US$ in 2010 to 247 tln US$ in 2050. World GDP increases further to 731 tln US$ in 2100 (see Table 1).[29] The world population is expected to grow rapidly in the first half of the century to reach 9 bln persons in 2050, and to remain at this level until the end of the century. This population development mimics the medium fertility projections of the United Nations (UN, 2011), and is characterised by strong population growth in three of the main economies: Africa to 2.1 bln persons in 2050, India to 1.7 bln persons in 2050 and Other Asia to 1.4 bln persons in 2050.[30] China's population is supposed to peak around 2025 at 1.4 bln people, and to decline afterwards down to 0.9 bln persons in 2100. The population development of most of the countries of the Organisation for Economic Cooperation and Development (OECD) is relatively stable, with a total average increase of 0.1%/yr for the period 2010-2100. In comparison to population growth, the increase of the number of households is more pronounced, as a result of changing living patterns towards smaller household sizes. The total number of households amounts to almost 4 bln in 2050 and 4.4 bln in 2100.

[29] GDP in this paper is expressed in terms of purchasing power parity (PPP), if not indicated otherwise. Monetary values are all in US$(2005).
[30] The latter do not include India, China, South Korea, Japan and Central Asian countries (formerly part of the Soviet Union).

Table 1: Global socio-economic assumptions

	2010	2020	2030	2050	2070	2100
GDP(PPP) [tln US$]	66.7	99.5	137.7	246.7	420.2	730.6
Population [bln persons]	6.9	7.6	8.3	9.2	9.4	9.1
Households [bln households]	1.9	2.3	2.9	3.9	4.4	4.4

Sources: IEA, 2012; World Bank, 2012; UN, 2011; Ironmonger *et al.*, 2000; own calculations.

4.3.2. Burden-sharing regimes

Against the background of expected socio-economic developments and in anticipation of international attempts to mitigate global climate change, meeting future generations' energy demand necessitates a fundamental restructuring of the current global energy system over the forthcoming decades. In comparison to an energy supply system not subjected to GHG emission reductions, a decarbonised energy system is more costly, as a result of the required investments in still relatively expensive low-carbon technologies. The additional cost can vary significantly across regions, for resource-potential, infrastructural, political and cultural reasons. For the most cost-efficient global GHG reductions scheme, ideally the least-cost climate change mitigation potentials worldwide are unlocked, independent of where they are geographically located. Undoubtedly significant expenditures are required in all regions, independent of their economic development status, but some regions may be more endowed with low-cost GHG abatement options than others. As a consequence, in order to exploit the least-cost options on a global scale as extensively as possible, some regions may need to disproportionally contribute to global climate change mitigation efforts, for which they would need to be compensated. Various approaches for regional compensation schemes exist that can shift climate policy costs across regions and thereby establish a more equitable distribution of the financial burdens associated with climate change mitigation. Alternative burden-sharing schemes can be based on different socio-economic variables, and/or varying energy- and emission-related parameters or cost factors. These differences determine the equity principle underlying each scheme as well as the way in which it can practically be implemented. Via an exchange of emission allowances on a carbon certificate market, both cost-efficient allocation of GHG emission reductions and financial compensation for more-than-obliged climate change mitigation efforts can be realised. For an overview of recent literature on different burden-sharing schemes we refer in particular to Tavoni *et al.* (2013), in which the two main schemes that we use for the present paper as well as their methodological background and relation to the literature are elaborately described. Comparative assessments of different burden-sharing principles have also been conducted, for instance, by den Elzen *et al*. (2008), Hof *et al*. (2008), Jacoby *et al*. (2008), and Ciscar *et al*. (2013). Subjects like the linkage between trade of emission allowances and technological innovation, as well as the coupling of different certificate markets, have especially been analysed in Driesen (2003), Babiker *et al*. (2004), de Sépibus (2008), and De Cian and Tavoni (2012).

The two different burden-sharing schemes analysed in this article relate to population development (referred to as "resource-sharing" scheme) respectively climate policy costs and economic development (the so-called "effort-sharing" scheme). Under the resource-sharing scheme, emission rights are allocated according to the level of GHG emissions allowed per capita. Through convergence of regional shares in global emission rights and uniform contraction of these global emissions (see Meyer, 2000, for an explanation of the terminology 'contraction and convergence') a transition from status quo regional emission levels in 2020 to a globally reduced average in 2050 is implemented. The regional shares of global emissions are calculated through Eq. 1, which formulates the convergence part of the resource-sharing method.

$$\frac{E_r(t)}{E_w(t)} = \frac{T_2 - t}{T_2 - T_1} * \frac{E_r(T_1)}{E_w(T_1)} + \frac{t - T_1}{T_2 - T_1} * \frac{P_r(t)}{P_w(t)} \qquad \textit{Eq. 1}$$

$E_r(t)$: Regional emissions at time step t

$E_w(t)$: World emissions at time step t

$P_r(t)$: Regional population at time step t

$P_w(t)$: World population at time step t

T_1: Reference year for grandfathering (2020)

T_2: Target year for convergence (2050)

The effort-sharing scheme aims at equalising the mitigation costs across regions, in the sense that all regions should incur the same climate change control costs in percentage terms of their GDP after emissions trading. From 2020 onwards, regional shares of total climate change mitigation costs (including revenues or expenses from carbon certificate trade) should be equal to the world average (see Eq. 2).

$$\left(\frac{C_r}{Y_r}\right)_t = \left(\frac{C_w}{Y_w}\right)_t \qquad \forall t \in \{2020, 2030, \dots, 2100\} \qquad \textit{Eq. 2}$$

C_r: Regional absolute mitigation costs

C_w: World absolute mitigation costs

Y_r: Regional GDP

Y_w: World GDP

The effort-sharing scheme is applied in TIAM-ECN via a pre-optimisation procedure that calculates each region's overall certificate allocation. For every region and period, target policy costs are calculated on the basis of the world total climate policy costs as percentage of global GDP and the GDP of each of the respective regions.[31] The difference between all regions' effort-sharing target policy costs and their policy costs under global least-cost climate change mitigation is divided by the global carbon certificate price. The resulting quantity represents for each region and period the amount of certificates that has to be added to the emission level calculated under least-cost mitigation criteria, which equals the regional effort-sharing certificate allocation.

Both burden-sharing schemes are investigated within a climate policy framework and corresponding annual GHG emission budgets apt to meet a long-term stabilisation of the global mean temperature increase at 2˚C with respect to the pre-industrial level. In the 2˚C climate stabilisation scenario without additional burden sharing arrangements, referred to as the 'reference' scenario, the regional allocation of GHG certificates is identical to each region's emissions under the conditions of a global least-cost GHG reduction pathway. The quantity of emission allowances allocated worldwide in each period equals in both burden-sharing regimes the global GHG emissions of the reference scenario. Neither methodology involves banking or borrowing mechanisms between trading periods. According to our model's time resolution, the duration of one trading period is 10 years.

4.4. Results

4.4.1. GHG emissions reduction without burden-sharing

As reference GHG emissions reduction pathway in this article we take one of the delayed-action scenarios developed in the LIMITS project: RefPol-450 (see Kriegler *et al.*, 2013). In this scenario, after a short period with fragmented weak national climate policies that reflect the unconditional Copenhagen pledges, from 2020 onwards a global treaty is in force that achieves climate stabilisation with a maximum of 2˚C average atmospheric temperature increase. This climate change control target is implemented through a maximum radiative forcing level of 2.8 W/m^2 in 2100[32]. A detailed description of this scenario can be found in Kriegler *et al*. (2013).

In the reference scenario global GHG emissions peak in 2020 at 51 GtCO$_2$e, decrease down to 21 GtCO$_2$e in 2050, and become negative to eventually reach -4 GtCO$_2$e by the end of the 21st century (see left panel in Figure 1). The majority of this large GHG emissions reduction profile materialises through CO$_2$ abatement, while CH$_4$ and N$_2$O emissions (primary from non-energy-related agricultural activities such as food production) decline by about a factor of 2 throughout the century. Agricultural emissions of CH$_4$ and N$_2$O develop mostly according to the combination of population growth and availability of mitigation potential in agriculture, for which we make assumptions based on

[31] Policy costs in the context of our bottom-up modelling approach refer to undiscounted costs for the entire energy system, including expenditures for technology investments, operation and maintenance, other variable costs as well as costs associated with changing demand patterns. Policy implementation and transaction costs are excluded. Climate policy costs are calculated as the difference between the total costs under certain policy conditions and the costs in the reference case.

[32] This forcing target refers to all anthropogenic radiative agents with the exception of three agents: nitrate aerosols, mineral dust aerosols, and land use albedo changes. According to our model approach we adjusted the forcing target to be applied to the three GHG emissions represented in the TIAM-ECN.

DeAngelo *et al.* (2006) and van Vuuren *et al.* (2006). In the agricultural sector, GHG emissions mitigation arises, for instance, from changes in soil management, adaptations in water control for rice production and advances in the use of fertilisers. The total worldwide mitigation potential we suppose for CH_4 and N_2O in 2100 of 7.8 $GtCO_2e$ (as expressed with respect to our population-driven business-as-usual assumptions) is fully exploited in this reference scenario, that is, we think that the remaining emissions of these gases are virtually impossible to abate. This is in line with a study on long-term non-CO_2 GHG mitigation potentials by Lucas *et al*. (2007), who provide a comprehensive analysis of this subject including abatement measures and costs.

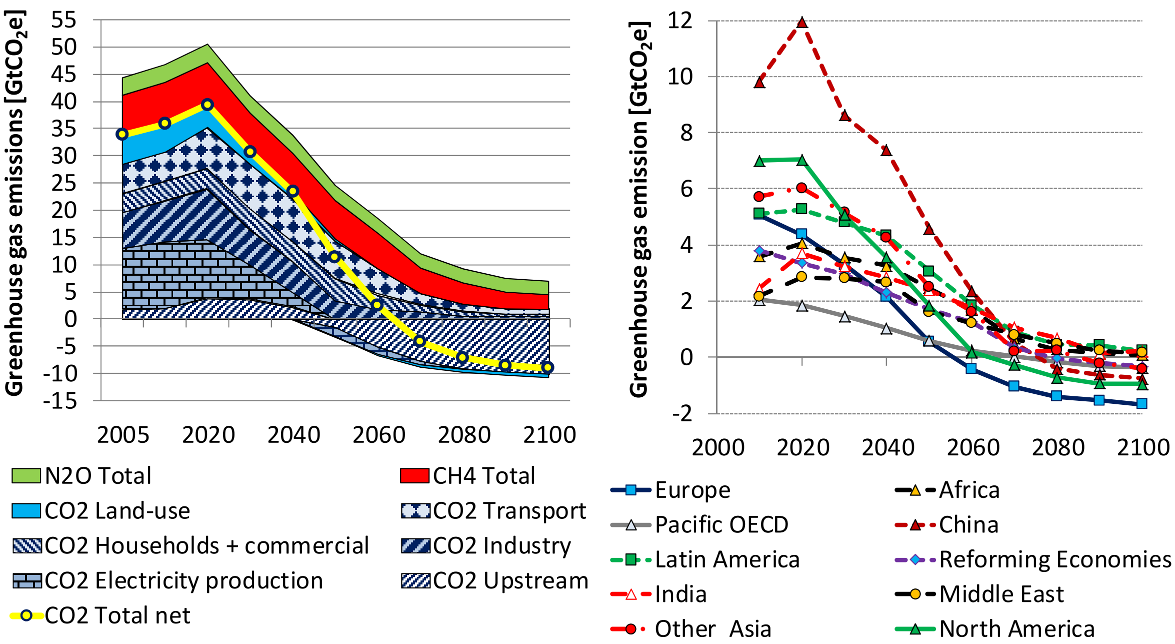


Figure 12: Global GHG emissions by type and sector (left) and by region (right) in the reference climate change control scenario with least-cost long-term GHG mitigation.[33]

Most anthropogenic CO_2 emissions derive from fossil-fuel-based combustion technologies. These emissions are curtailed significantly past 2020. Early emission reductions are notably realised in the power sector, which becomes a negative net GHG emitter on a global level from around the middle of the century. Also the upstream sector experiences a transition from positive net GHG emissions to negative ones around that time, but with eventually much larger quantities of negative GHG emissions. CO_2 emissions from land-use, land-use change and forestry (LULUCF) are eliminated before 2050 and become slightly negative during the second half of the century as a result of the implementation of afforestation measures. These three sectors together largely offset remaining positive GHG

[33] Results are given for the 10 LIMITS 'super-regions', for which our findings for the 15 TIAM-ECN regions have been aggregated.

emission contributions from other sectors during the last couple of decades of the century, especially CH_4 and N_2O from agricultural activities.

In order to cost-efficiently reach the 2˚C climate change control target, both industrialised countries and emerging economies have to cut their GHG emissions drastically (see right panel in Figure 1). In the Pacific OECD, North America, Reforming Economies, and Europe, GHG emissions never exceed 2010 emission levels. In other regions, mainly those with emerging economies, GHG emissions continue to increase until 2020 due to their economic development, population growth and as of yet limited national climate change mitigation efforts. Past 2020, however, GHG emissions decrease in these regions as well, in most cases rather rapidly. Similar to the off-setting effect between sectors, GHG emissions are levelled out between regions in the long run. In other words, regions that have sufficient mitigation potential to gain a negative net GHG emissions balance, can compensate for regions with positive net GHG emissions. Negative net GHG emissions on the regional level occur past 2050 in those regions with significant capacities for afforestation measures and biomass use in electricity generation and hydrogen production (where it is combined with CCS).

In our study we use relatively conservative estimates for global potentials of various types of biomass (representing about 150 EJ in total in 2100), which reflects our judgement that limited biomass may be available when sustainability criteria are accounted for and food price issues are prioritised (GEA, 2012, Hoogwijk *et al*., 2009; Thrän *et al*., 2010). We find that in the reference scenario more than 90 % of all biomass, used in the energy and non-energy sectors combined, is produced within the respective regions of consumption. In other words, unlike is the case for fossil fuel resources, biomass is mostly used domestically, and only relatively modest amounts of biomass are traded internationally. The main explanation for this outcome is our comparably conservative assumption on the availability of biomass resources. With larger biomass potentials, accompanied by excess of supply in certain regions, inter-regional biomass trade could in principle increase substantially in order to match production and consumption cost-efficiently. The costs of large-scale biomass collection within (and transport between) the respective regions, however, would co-determine the extent of such a possible increase. In our reference scenario Europe is one of the regions with the largest biomass net imports of up to 2 EJ/yr. Latin America and Other Asia, on the other hand, are the main biomass suppliers. For an in-depth assessment of the role of biomass at the regional level for reaching ambitious GHG reduction targets, based on a LIMITS multi-model scenario analysis that includes modelling results from TIAM-ECN, we refer to Calvin *et al*. 2013. For insights in the global, regional and sectoral deployment of low-carbon technology more generally (including biomass options) we refer to van der Zwaan *et al.* (2013) and van Sluisveld *et al.* (2013).

The carbon certificate price associated with reaching the 2˚C stabilisation target in our reference scenario, which is determined by the marginal costs of the mitigation options available in all sectors of the global energy system, rises from 70 US$/t$CO_2$e in 2020 via 130 US$/tCO_2e in 2030 to 390 US$/t$CO_2$e in 2050. During the second half of the century the price for emission permits increases substantially further, especially since negative GHG emissions have to be achieved: the certificate price increases to around 2000 US$/t$CO_2$e in 2080 and becomes about 5,000 US$/t$CO_2$e in 2100. The global annual policy costs to reach the 2˚C climate change control target add up to approximately 0.3 tln US$ in 2020, rise to around 4 tln US$ in 2050, and surge to 27 tln US$ in 2100. In total they accumulate to 77 tln US$ for the entire first half of the century, and to almost 1000 tln US$ for the second half of it.

4.4.2. Allocation of emission allowances under the resource-sharing regime

Along with our population development assumptions for the remainder of the 21st century, GHG emissions per capita (also called 'specific' emissions) for each region in 2020 and the evolution of the global average of GHG emissions (per capita) over the course of the century constitute the key input parameters for the calculation of the allocation of emission allowances according to the resource-sharing method. For the regional specific emissions in 2020 and the global average specific emissions from 2020 until 2100 we adopt those determined under the reference scenario, which are depicted as starting points respectively black line in the left panel of Figure 13. As can be seen in Figure 2, in 2020 North America has the highest specific emissions (19 $MtCO_2e$/capita) and India the lowest (3 $MtCO_2e$/capita), while the global average amounts to around 7 $MtCO_2e$. We observe that, from the regions' respective starting points, specific GHG emissions contract in subsequent decades and converge by 2050, as prescribed by the resource-sharing rule. During this time frame, the global average of specific GHG emissions declines to 2 $MtCO_2e$/capita. During the second half of the 21st century each region's amount of certificate endowments is determined by the region's exogenous population development as well as the further decreasing world average of GHG emissions per capita as calculated under the reference scenario. Against the background of deep global GHG emission reductions at an almost constant world population, the global level of per capita emissions continues to decline after 2050 to reach negative levels from about 2080 onwards.

The development in absolute terms of regional carbon certificate budgets during the course of the 21st century is depicted in the right panel of Figure 13. In early decades, the resource-sharing method favours regions with a high population growth. This can be seen in Figure 2 for Africa and India, for which the number of allocated certificates increases from 2020 to 2030, and for Africa also from 2040 to 2050. All other regions show decreasing certificate allocations from 2020 onwards. In the absence of high population growth rates, the number of emission rights of regions declines especially rapidly when the initially allocated amount of GHG emissions allowances is high, such as for China and North America. For Other Asia the decrease over time of allocated emission rights is clearly less steep, irrespective of their relatively high start, as a result of the initially high population growth in this region.

Scenarios involving negative global GHG emissions in the long run have special consequences for the regional allocation of carbon certificates and its development under the resource-sharing scheme. As pointed out in Figure 1, in order to achieve a 2˚C climate change control target under global cost optimisation criteria, some regions need to reach such a negative net GHG balance during the last decades of the century. The certificate allocation under the resource-sharing scheme in itself does not yield incentives to gain net negative GHG emissions within regions as long as worldwide GHG emissions do not become negative. If negative net emissions are required on a global level, however, as is the case in our reference scenario, the resource-sharing scheme imposes this obligation to all regions, which could as such be effectuated in principle in every region. For the long term, regions with a high population face strongest emissions reduction obligation in absolute terms. Consequently, in the long run the endowment of permits based on resource-sharing deviates from the reference emission levels especially for those *regions which have a positive net GHG emissions balance in the reference scenario and a large population (as a result of high population growth in early decades), like India and Africa, and likewise for those regions with significant negative net emissions in the reference scenario and relatively small populations (given moderate or zero population growth throughout the century), like Europe and North America (compare Figure 1 with Figure 2).*

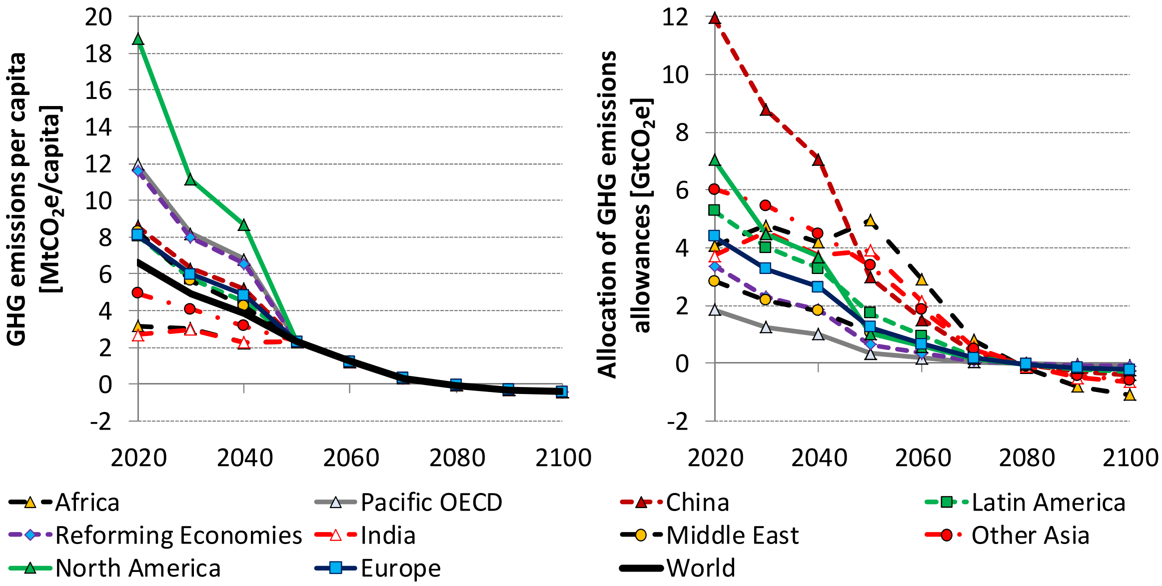


Figure 13: GHG emissions per capita as allowance allocation basis (left) and emission allowances allocation under the resource-sharing regime (right).

Trade of emission allowances occurs based on the allocation of GHG emission rights, on the one hand, and the region's technological potentials to reduce GHG emissions, on the other hand. This trade allows a return to the overall cost-optimal mitigation pathway, if one assumes the existence of a perfect carbon certificate market (as we here do). Trade of certificates in the resource-sharing scheme starts past the year of grandfathering in 2020, the results for which are reported in the left panel of Figure 14). A cumulative amount of certificates equivalent to 250 $GtCO_2e$ is traded until 2100. The total annually traded quantity of emission rights reaches its maximum in 2050, at 5.6 $GtCO_2e$, and decreases down to a value of 2.1 $GtCO_2e$ in 2070. This maximum in 2050, which represents about half of the global GHG emissions in that year, implies a significant divergence of allocated emission rights under the resource-sharing scheme in comparison to the overall cost-optimal mitigation pathway.

During the first half of the century the most important emission certificate selling regions are Africa and India. These two regions combined sell emission rights equivalent to a cumulative amount of 83 $GtCO_2e$ until 2050, which corresponds to about 75% of the total number of certificates sold in this period. Around 80% of the tradable permits in this time frame are bought by Latin America, China, the Middle East and the Reforming Economies, which can be explained by the high economic growth rates (hence rapidly increasing GHG emission levels) and modest or even negative population growth rates in these regions. In the long run, India and Africa become two major certificate-buying regions, because by then they have large economically developed populations but possess few options with which they can attain negative emissions, such as through biomass in combination with CCS. India and Africa buy allowances from regions that do have high biomass-CCS potentials, such as North America and Europe, which consequently become the negative net GHG emitting regions depicted in Figure 1. In 2100 Europe ends up selling carbon certificates up to an amount of approximately 1450 $MtCO_2e$/yr.

Unlike climate policy costs, which involve the sum of all costs required for the implementation of a climate policy target, the carbon capital flow is the monetary transfer associated with the total amount of certificates traded at the price prevailing at the global carbon market. The certificate price is determined by the marginal abatement cost amongst all GHG reduction options partaking in the global carbon market. We report policy costs, capital flows and carbon certificate prices as undiscounted values for their corresponding periods. We find that, as time proceeds, the carbon market capital flow is increasingly determined by the certificate price, rather than by the quantities of traded certificates, as a result of the exponential increase of the former towards the end of the century. The volume of the carbon market capital flow expands from 350-600 bln US$ in 2030-2040 via 2,200-2,600 bln US$ for the period 2050-2070 to about 15,000 bln US$ in 2100 (see right panel in Figure 14).

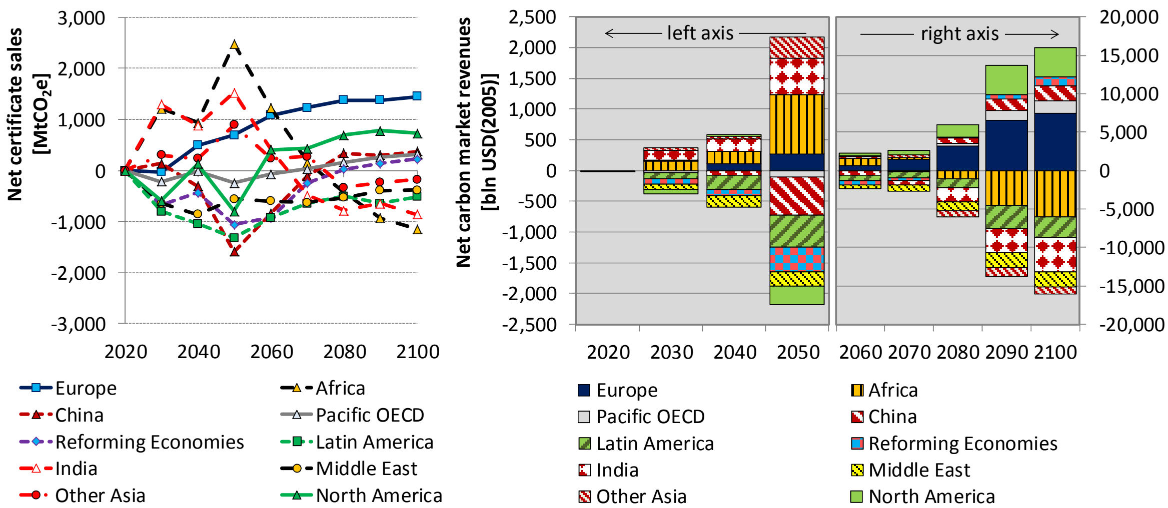
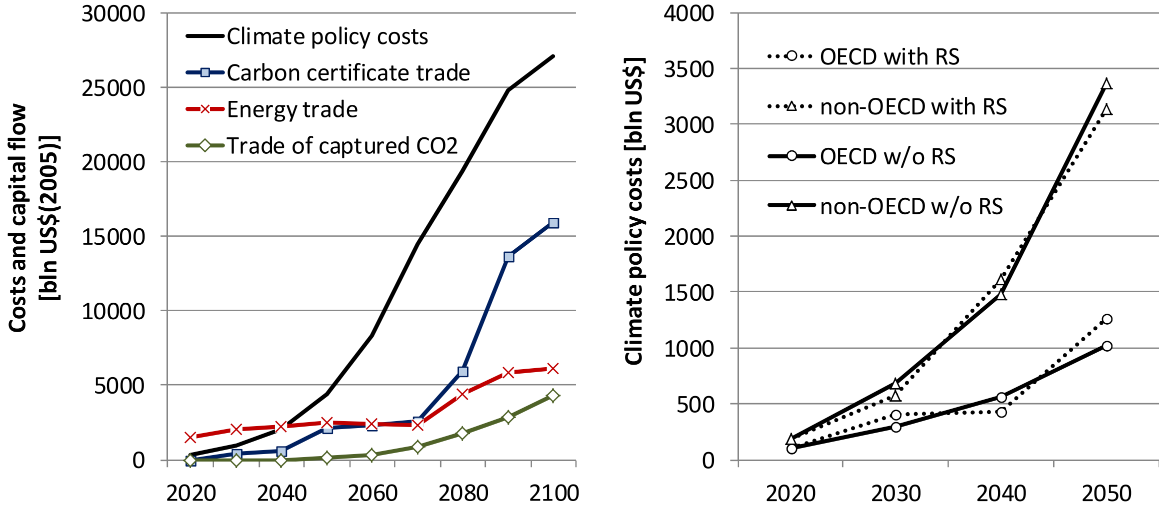


Figure 14: GHG emission certificates trade (left) and carbon market capital flow (right) in the resource-sharing scheme.

A comparison between the annual global capital flows of the carbon certificate market with the costs needed to reach the 2˚C climate stabilisation target reveals several policy-relevant insights. In particular, it shows that the total capital flow of the world carbon market represents between 30% and 50% of the global policy costs associated with this climate target during the first half of the 21st century, and between 20% and 60% after 2050 (see left panel in Figure 15). Figure 4 also demonstrates that the total capital flow for trade of emission allowances reaches the level of energy market capital flows around the middle of the century, and exceeds them by almost three times by the end of it. This outcome underlines the outstanding importance of the carbon certificate market in the future, which within decades could become at least as important as the global energy market.

In terms of regional carbon certificate capital flows versus policy costs, much larger deviations can be observed than in the global case. The case of Africa, for example, shows that the total cumulative revenues of 13 tln US$ from allowances sold during the first half of the century are 2.5 times the cumulative climate policy costs (4.9 tln US$) in the same period. Conversely, the expenses for purchases of emission rights for the Reforming Economies are about 60% higher than their climate policy costs in the reference scenario for the period 2020 to 2050. This latter case indicates that the resource-sharing regime analysed in this study cannot compensate all developing and transition countries at once. Inversely, the former case shows that this scheme might overcompensate the financial efforts of GHG emission reduction measures of selected emerging regions. This overcompensation effect has also been observed in previous studies, e.g. by Jacoby *et al*. (2008), who find that a population-based burden-sharing scheme 'goes well beyond compensating for mitigation costs and turns the GHG mitigation policy into an instrument for global income distribution'.

For the group of non-OECD countries, only marginal effects of the resource-sharing scheme on the reduction of climate policy costs can be observed until 2050 (see right panel of Figure 15). In total 4% of their policy costs can be compensated by revenues from the carbon market during the first half of the century. This is the direct consequence of significant differences among non-OECD countries with regard to their expected socio-economic development and their capabilities to reduce GHG emissions, on the basis of which benefits in the resource-sharing regime are only generated for selected countries within this super-region. Hence, for the entire cluster of non-OECD countries, regional benefits and losses more or less level out, which indicates that the resource-sharing scheme is insufficient for compensating all non-OECD countries for their efforts to mitigate GHG emissions. One reason for this effect, and thereby drawback of the resource-sharing scheme, is the disregard of each region's technological capabilities and economic capacity to implement GHG emission reduction measures. In particular, regions with a moderate population growth and unfavourable GHG mitigation potential are hardly compensated for their climate control efforts irrespective of their macro-economic performance.



N.B. 1: RS: Resource-sharing

N.B. 2: Capital flows are based on trade among the 10 LIMITS regions. Market capital volumes would increase in case of a representation of our results with a higher geographical resolution.

Figure 15: Climate policy costs and capital flows for trade of carbon certificates, energy and captured CO_2 under the resource-sharing scheme.

4.4.3. Allocation of emission allowances under the effort-sharing regime

For the allocation of emission rights according to the effort-sharing scheme the development of climate policy costs in the reference scenario and the assumed GDP growth paths of each of the regions are the main determinants. Climate policy costs differ among regions, as a result of regional variations concerning the availability of GHG emission reduction options as well as trade patterns for energy and emission certificates. More specifically, drivers for such regional differences may be, for instance, the availability of renewable energy resources, the local feasibility of the diffusion of CCS, and the nature of national policies towards nuclear power. Recent insights vis-a-vis the global versus regional dimensions of technology deployment and diffusion of climate change mitigation measures can be found in studies by e.g. van der Zwaan et al. (2013) and van Sluisveld et al. (2013), both performed as cross-model comparison exercises. The left panel in Figure 16 (black line) depicts for our model the global annual average policy costs required to reach the 2˚C climate change control target, on which the calculation of carbon certificates allocation in the effort-sharing scheme is based. They are expressed in relative terms as shares of GDP: 0.3% in 2020, 1.8% in 2050 and 3.7% in 2100. As can be seen, the world average share of climate policy costs peaks in 2090 at 4.0% of GDP. The regional policy costs can reach up to 0.5% of GDP in 2020 and 6% during the second half of the century. In 2020, China and Latin America face the highest relative policy costs, which result from the large expected increases in their respective energy demands and thus massive investment requirements in renewable energy for power production and energy efficiency improvements on the demand side.

In the long run, effects connected to energy trade and the trans-boundary transport of captured CO_2 for storage abroad gain importance for each region's climate policy costs. Regions that have extensive net fossil fuel exports and possess few local GHG reduction measures, like the Middle East and Reforming Economies, face considerable reductions of these exports and hence the associated revenues when stringent climate policy is implemented. Their climate policy costs therefore increase. Inversely, a reduction of climate policy costs can be expected for regions that have large CO_2 storage capacity or bioenergy resources, if these potentials can be made available for other regions via trans-boundary CO_2 transport or biomass export. Traditional natural gas and oil producing regions can profit from their geological capabilities if their oil and gas fields (depleted or not) are adequate for CO_2 storage. The Middle East and Reforming Economies together hold about half of the estimated global CO_2 storage potential (see Figure 17). In order to make this large storage potential accessible for other regions with less advantageous CO_2 storage sites, CO_2 transport capacities of up to 16 $GtCO_2$/yr for each of these two regions are required under stringent climate change control targets. In that case the trans-boundary transport of CO_2 accelerates during the second half of the century, and then generates significant revenues for these two regions. As a result, the reduction of capital inflow from decreasing fossil fuel exports is compensated by selling CO_2 storage capacity to other regions, and climate policy costs are therefore partly levelised.

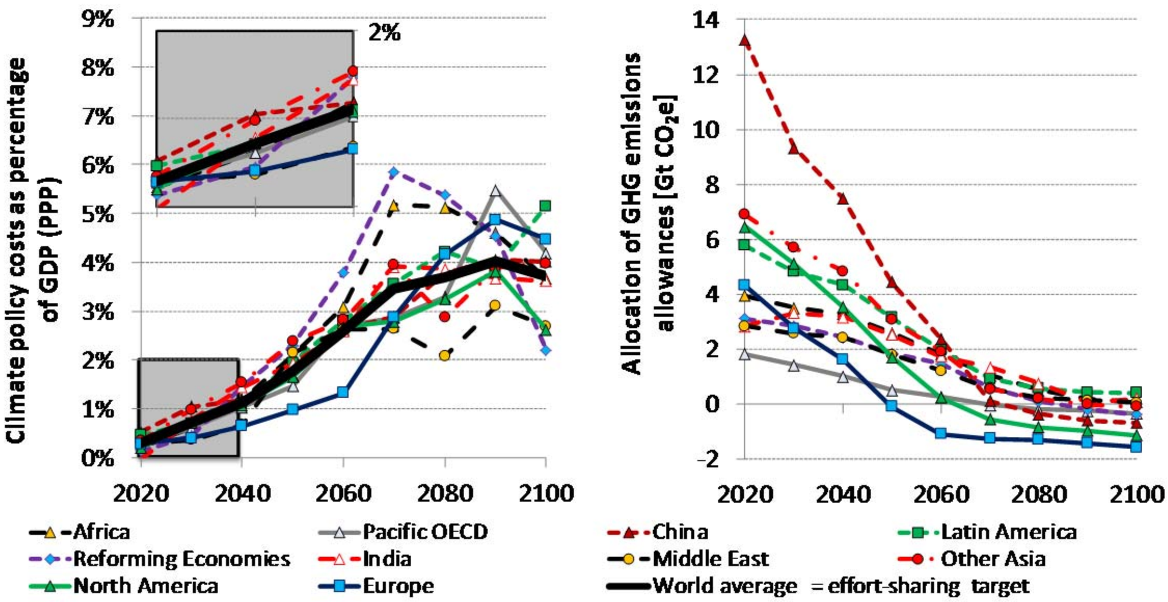


Figure 16: Regional climate policy costs under a global least cost GHG mitigation regime and effort-sharing regime (left) and emissions allowance allocation under this effort-sharing regime (right).

Besides the high climate policy costs observed for fossil fuel exporting regions, costs to mitigate climate change also represent a considerable share of GDP in regions with large GHG reduction potentials but with moderate economic growth, such as Africa and Latin America. For both these regions the share of climate policy costs in terms of GDP exceeds the world's average by up to 1.5%. The climate policy costs relative to GDP for India and China deviate little from the world average during the second half of the century. This outcome can be understood in view of the relatively high economic growth expected for both these countries even during the second half of the century (with average annual rates of, respectively, 4.8% and 1.2%). The absolute capital requirements for GHG emissions reduction in both these countries may thus be significantly higher than in other regions (amounting indeed for these two countries combined only to almost 40% of the global aggregated costs for the period 2050-2100), but in GDP terms they remain close to the global average.

The objective of the effort-sharing regime is to attribute emission rights to regions according to their individual GDP as well as the world's total climate policy costs in terms of global GDP. In this scheme, regions with higher relative policy costs in comparison to the world's average get additional carbon certificates allocated. Revenues from sales of excessive carbon certificates enable regions to compensate (at least partly) their local policy costs, which leads to an equalisation of climate change mitigation efforts across regions. The effort-sharing scheme starts in 2020, without any prior transition phase.

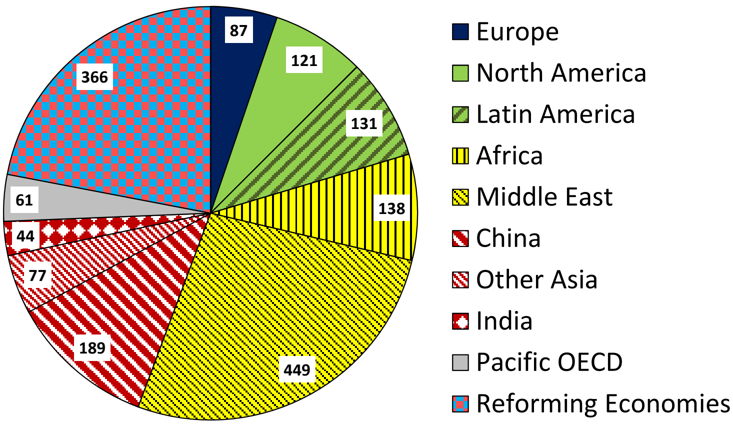


Figure 17: Potentials for CO_2 storage in geological formations by region (in $GtCO_2$), Source: Hendriks et al., 2004.

The cumulative emission rights allocated to China between 2020 and 2050 in the effort-sharing regime equal 256 $GtCO_2e$. This is 14 $GtCO_2e$ (6%) more than the level of GHG emissions in the reference scenario (see right panel in Figure 16). A similar increase applies to India, Latin America and Other Asia, which together profit from additionally available certificates worth about 11 $GtCO_2e$ until 2050. During the second half of the 21st century about 70% (142 $GtCO_2e$) of the total cumulative emission rights are allocated to three regions only: Latin America (53 $GtCO_2e$), India (49 $GtCO_2e$) and Africa (40 $GtCO_2e$). The cumulative certificate endowment of these three regions combined exceeds the GHG emissions level in the reference scenario by 15 $GtCO_2e$ between 2050 and 2100. The Reforming Economies and Other Asia also get allocated additional certificates with respect to their emissions in the reference scenario, worth some 9 $GtCO_2e$ for the period 2050-2100. In comparison to the resource-

sharing scheme, the allocation of emission certificates under the effort-sharing regime comes closer to each region's share in a global cost-optimal GHG emissions reduction pathway. Consequently, fewer certificates are traded in the effort-sharing scheme.

Between 2020 and 2100 the cumulative amount of certificates traded under the effort-sharing scheme is 70% (80 $GtCO_2e$) lower than the quantity traded under the resource-sharing scheme (left panel in Figure 18). Annual amounts of carbon certificate trade range from 250 $MtCO_2e$ in 2090 to 2,000 $MtCO_2e$ in 2020, which are lower values in comparison to those observed in the resource-sharing regime. This outcome has a direct influence on the level of financial flows in the carbon certificate market, particularly during the first half of the century: 80% less capital transfer is necessary in the effort-sharing scheme than under the resource-sharing regime. The annual carbon market volume peaks in the first half of the century at 400 bln US$, but increases strongly in the second half of the century up to a value of over 2,000 bln US$ in 2100.

In the near term, the capital flows into certificate selling regions accumulate to 140 bln US$ in 2020, of which China receives 95 bln US$, Latin America 35 bln US$, and Other Asia 10 bln US$. By 2050 Chinese revenues from the carbon market have decreased drastically, to such an extent that China has actually become a net buyer of emission rights. Regions such as India, Latin America, the Middle East, Other Asia, Reforming Economies and Africa receive capital inflows from the carbon market in 2050. During most of the second half of the century, Africa remains a net seller of certificates, with a peak at around 500 bln US$ in 2070 and 2080. Europe undergoes the transition from a net buying region until beyond the middle of the century to being a seller after 2070: it thus generates up to 500 bln US$/yr in 2090 and 2100. This value is less than 10% than that attained in the resource-sharing scheme. Reforming Economies can compensate their decreasing revenues from reduced fossil fuel exports partly by selling emission allowances on the certificate market during especially the second half of the century (while becoming a net buyer of emission rights in 2100). In addition, revenues from selling CO_2 storage capacity for CCS application in other regions increase, which overcompensate the decreasing income from fossil fuel exports. This effect is even more pronounced in the Middle East, where fossil fuel exports reduce significantly under global climate policy (but less so than in the Reforming Economies), while substantial growth takes place of storage of captured CO_2 from outside the Middle East. As a consequence, climate policy costs, and hence the amount of permits allocated to the Middle East, are comparably low for this region. This implies that the Middle East becomes the most important certificate buying region during the second half of the century, with annual expenditures of up to 680 bln US$. Despite these large expenditures, the total net capital balance in the Middle East, based on trade of energy, captured CO_2 and emission certificates, remains positive. In other words, capital inflow for this region stays higher than the outflow.

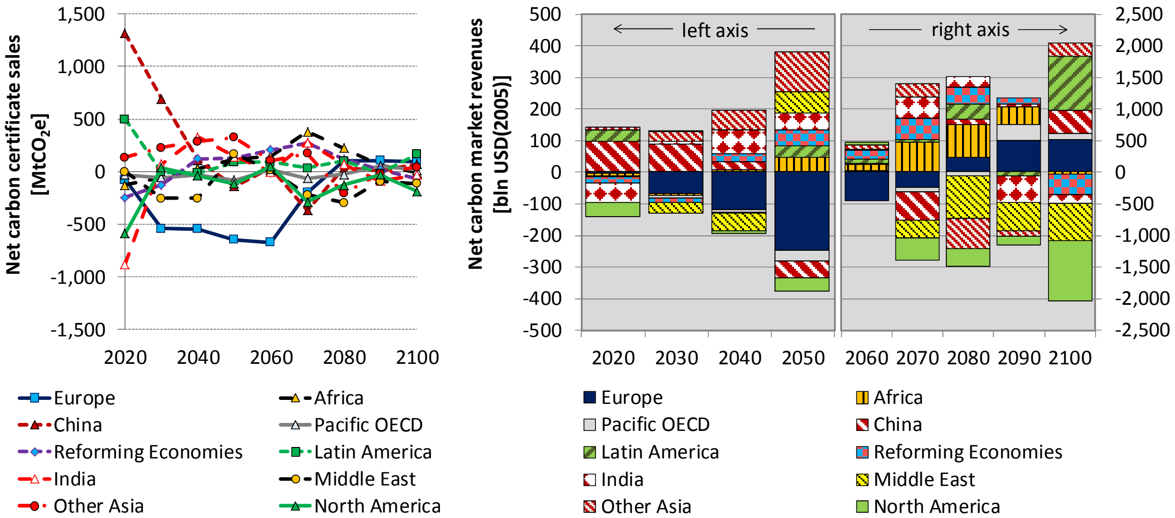
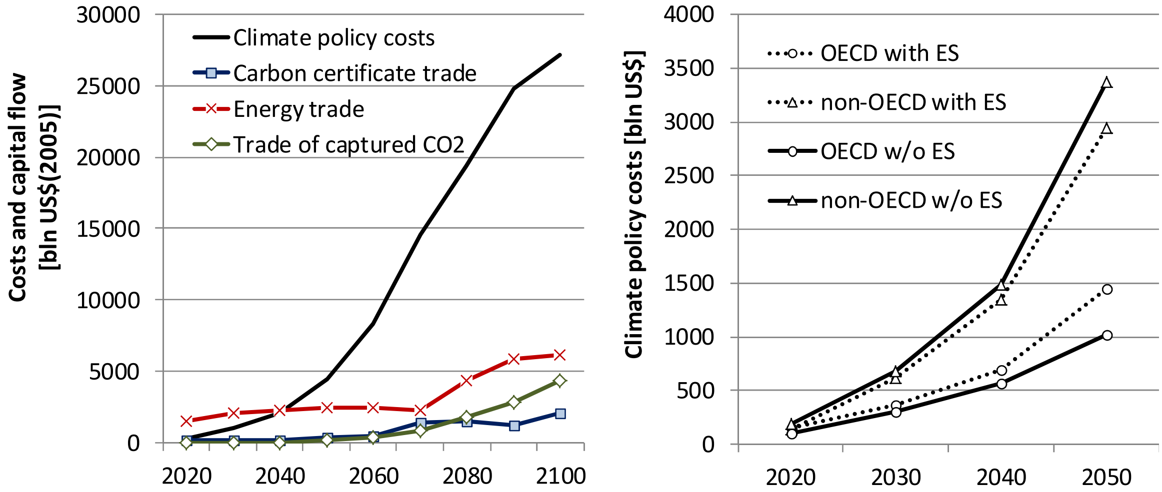


Figure 18: Carbon certificate trade (left) and corresponding market capital flows (right) under the effort-sharing scheme.

The capital volume of the carbon certificate market as percentage of the global climate policy costs declines from 50% in 2020 to 9% in 2050 and remains low for the remainder of the century with values between 5% and 10% (see left panel in Figure 19). By comparing Figure 4 with Figure 8, one observes that the cumulative carbon market capital flow from 2020 to 2100 as share of the total climate policy costs is much lower in the effort-sharing scheme (7%) than under the resource-sharing regime (55%), which reveals much less compensation of regions' climate policy costs in the former than in the latter. In the long run the total capital transferred on the carbon certificate market is significantly lower than the financial transfers involved with energy trade under the effort-sharing regime, unlike in the resource-sharing scheme, where during the last decades of the century the former is substantially larger than the latter. In the effort-sharing scheme, towards the end of the century, the overall value of the carbon market remains so low that even the capital flows associated with the physical transport of CO_2 between regions exceed the aggregated capital flow of emission allowances. For both burden-sharing schemes the main beneficiaries of the CO_2 transportation market are the Middle East and Reforming Economies, given their vast CO_2 storage potentials. As for the carbon certificate market over the next few decades, Africa, India and Other Asia are the main beneficiaries in the resource-sharing scheme, while China, India and Other Asia are so for the effort-sharing scheme. Hence, we find that under either burden-sharing scheme both the CO_2 transportation and carbon certificate markets represent compensation mechanisms for the policy costs associated with GHG reduction efforts incurred by non-OECD economies.

Substantial differences exist between individual regions in terms of the share of their carbon market capital flow of their climate policy costs. In 2020 the revenues from the carbon certificate market cover almost all the climate policy costs for China and Latin America, and one third for Other Asia. Also, the overcompensation observed for Africa under the resource-sharing scheme is less significant under the effort-sharing regime. As can be seen in Figure 8 (right panel) for the effort-sharing regime, for all non-OECD countries combined, about 12% of their climate policy costs can be covered by revenues from the carbon certificate market during the first half of the century, with a maximum of 27% in 2020 and a minimum of 9% in 2040. In comparison to the resource-sharing scheme, the effort-sharing regime is better capable of compensating less developed economies for their costs incurred to mitigate climate change. Indeed, a comparison between Figures 4 and 8 demonstrates that the effect of burden-sharing – generating generally and especially in the long run higher policy costs for the cluster of OECD countries and lower ones for non-OECD countries – is larger for the effort-sharing scheme than the resource-sharing scheme.



N.B. 1: ES: Effort-sharing

N.B. 2: Capital flows are based on trade among the 10 LIMITS regions. Market capital volumes would increase in case of a representation of our results with a higher geographical resolution.

Figure 19: Climate policy costs and capital flows for trade of carbon certificates, energy and captured CO_2 under the effort-sharing scheme.

4.5. Limitations in carbon certificate trade

The results presented in the previous section indicate that carbon certificate trade plays an important role in burden-sharing schemes to cost-efficiently reach climate change mitigation goals. We so far assumed a perfectly functioning carbon market. It might be hard, however, to establish perfect carbon market conditions, and market distortions of many different types could arise (see e.g. Straub-Kaminski *et al.*, 2013). Carbon market obstacles can result from an inadequate institutional framework, low regulatory transparency, transaction costs, information asymmetry, and other imperfections on financial markets. The objective of this section is to further investigate various aspects of carbon certificate trade, in particular in terms of (1) timing issues, (2) regional implications, (3) certificate price effects, and (4) global climate policy costs. We therefore conduct a sensitivity analysis, and study what may happen to the overall quantities of carbon certificate trade if emission allowances are allocated according to a specific burden-sharing regime but with constrained possibilities to trade permits on an international market. Similar research has been conducted by De Cian and Tavoni (2012), who researched restrictions in carbon certificate trade and their implications for technological innovation and low-carbon technology deployment. Contrary to their study, however, we here assume fixed exogenous technology cost reduction rates and do not assess interdependencies between certificate trade and technological learning. Hence we do not analyse the positive effects on innovation that may result within a region from a (complete or partial) decoupling of its internal market from the global one. The subject of our sensitivity tests is the total cumulative quantity of traded certificates between 2020 and 2100 in each of the two burden-sharing regimes. Under the resource-sharing regime in total about 250 $GtCO_2e$ are traded between 2020 and 2100 among the 10 regions defined in the LIMITS project. Under the effort-sharing regime this figure amounts to around 80 $GtCO_2e$. With as starting point these quantities that apply under perfect trade conditions, different trade (restriction) levels are analysed, in the sense that we constrain the total cumulative quantity of certificate trade while we leave the allocation among regions and the timing of trade endogenous to our model.[34]

4.5.1. Timing issues

Since under full trade conditions the total number of tradable certificates (cumulatively, as well as at each point in time from 2030 onwards) is more than three times higher in the resource-sharing regime than in the effort-sharing regime, the same trade level restrictions in relative terms represent different reductions of tradable certificates in absolute terms under these two burden-sharing schemes (see Figure 20). We find that the minimal permissible trade level under the resource-sharing scheme (left panel in Figure 9) is 20%. At more stringent trade restrictions, TIAM-ECN yields infeasible results. This trade limitation involves a cumulative amount of traded GHG emission permits until 2100 of 48 $GtCO_2e$, hence about five times lower than under full trade conditions. In the effort-sharing scheme (right panel in Figure 9) the minimal allowable trade level is found to be 30%, which corresponds to a cumulative amount of tradable certificates of 24 $GtCO_2e$, i.e. approximately three times lower than in a world with perfect trade. Under the resource-sharing scheme a limitation of the cumulative amount of tradable certificates down to 20% leads to a world in which the number of available carbon permits is conserved for trade during mostly the last few decades of the century only. This reveals that in this case certificate trade is indispensable in especially the second half of the century, given the depth of GHG emission cuts required after 2050 and the correspondingly rapid increase of mitigation costs by then. In the long run, the global carbon certificate market is particularly important to offset emissions from countries with positive net GHG emissions, by those countries possessing the capabilities to establish a negative net GHG balance. Hence even if stringent restrictions apply on the global carbon market, international trade allows to exploit cost-efficiently the climate change mitigation potentials of all respective regions. In the effort-sharing scheme we observe a different evolution of carbon certificates trade over the 21st century: from a peak in 2020 global trade gradually winds down until the end of the century. The explanation is the fact that under this regime (that is operational from today onwards) national climate policies out-shadow the importance of global climate change control policy, which generates an early reallocation (i.e. trade) of emission permits according to nationally stipulated GHG reduction targets (see also Kriegler *et al.*, 2013). We do not observe this effect under the

[34] Another approach could have been to reduce the tradable amount of carbon certificates by equal shares across periods and/or regions. This alternative method, however, which we may still inspect in the future, would by definition have provided less insight with regard to possible shifts in international certificate trade over time and space.

resource-sharing regime: no certificate trade arises there in 2020, which is a direct consequence of the contraction and convergence procedure applied from only the status quo situation in 2020 onwards.

For the resource-sharing scheme, carbon certificate trade reaches an all-time peak in 2050 for trade levels above 60% (see left panel in Figure 20). Trade patterns in 2050 alter significantly when trade levels are limited from 60% down to 40%. Inversely, the exchange of carbon permits expands substantially in 2050 when trade possibilities increase from a level of 40% to 60%, in which case the traded number of certificates more than doubles from 1.3 $GtCO_2e$ to 3.3 $GtCO_2e$. This strong increase at intermediate trade levels can be interpreted as the high relevance of carbon certificate markets, especially around the middle of the century, and demonstrates the importance of carbon certificate trade in particular under the resource-sharing regime. In the effort-sharing scheme (see right panel in Figure 20), in contrast to the resource-sharing scheme, no particular decade exists with exceptionally high influence of constrained certificate trade. The impact of limited trade under this regime is distributed relatively uniformly from 2030 onwards.

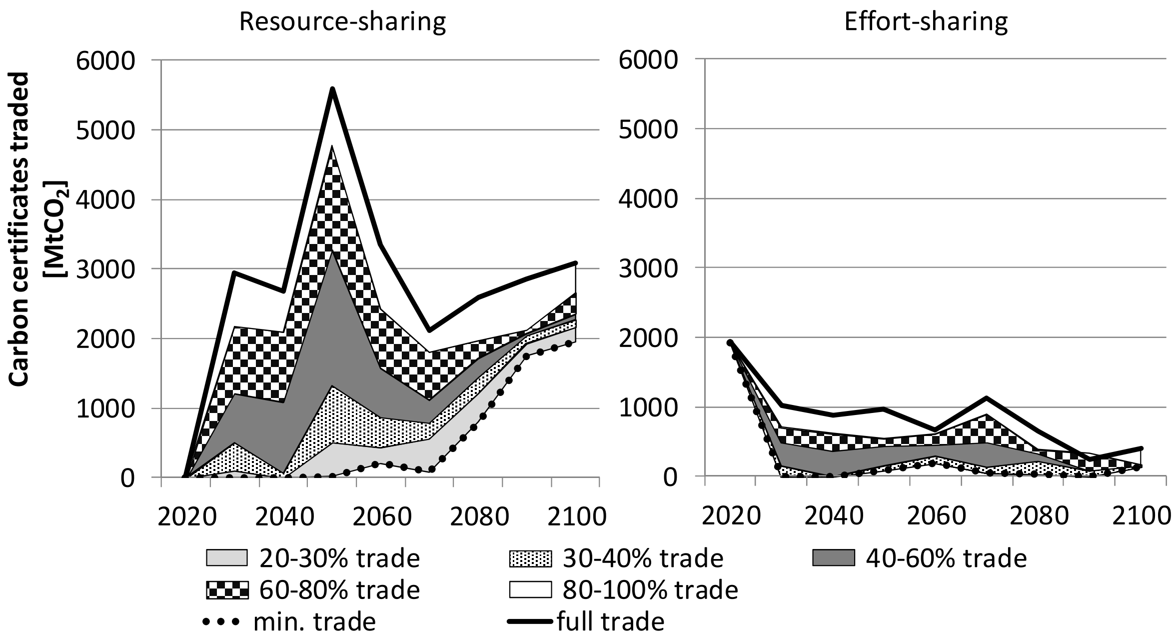


Figure 20: Global number of tradable carbon certificates under different trade levels in the two burden-sharing schemes.

4.5.2. Regional implications

We find that limitations in carbon certificate trade rarely inverse a region's position on the carbon market within a period, that is, they seldomly switch a region from being a seller to becoming a buyer of emission permits, or vice versa. The amounts of certificates sold or bought on the carbon market, however, may shrink dramatically in response to trade restrictions, and sometimes regions may even entirely decouple from the global certificate market as a result of them. Figure 21 depicts the cumulative net regional sales of carbon certificates between 2020 and 2050 at different trade levels under the resource-sharing and effort-sharing regimes. As can be seen, under the resource-sharing scheme, Africa is in relative terms less affected by trade restrictions in its certificate selling capacity than regions like India and Other Asia. The explanation for this outcome is twofold: 1) Africa gets allocated an excess of carbon certificates under the resource-sharing scheme with respect to the reference scenario GHG emissions; 2) Africa possesses larger domestic GHG reduction potentials than the other two main certificate selling regions. Given its abundant natural gas and renewable energy resources, climate change mitigation can be realised at lower costs in Africa than in regions with less favourable potentials for low carbon energy supply such as India and Other Asia. Adequate institutional, financial and energy policy frameworks would obviously need to exist in Africa to unlock its large GHG emission reduction potentials, and our model assumptions critically hinge on whether these frameworks will be implemented in practice. In absolute terms, Latin America, the Reforming Economies and the Middle East are the largest buyers of certificates, amounting to cumulative purchases of, respectively, 10 $GtCO_2e$, 7 $GtCO_2e$ and 5 $GtCO_2e$ worth of emission permits, when trade is restricted down to 60%. In relative terms, North America reduces its certificate purchases most, by more than 50% if trade is reduced down to 60%. The reason is that North America possesses domestic climate change mitigation measures with relatively low costs, which allows it to affordably compensate for limitations of certificates on the global carbon market. Domestic GHG mitigation options in the Middle East, on the contrary, are quite costly, so that it only starts significantly reducing its purchases of emission certificates when international trade is almost completely obstructed.

Under the effort-sharing regime limitations in carbon certificate trade reduce in particular the number of certificates sold by China and Other Asia (cumulatively about 6 $GtCO_2e$ for each of these two regions, when trade is restricted down to 40%). Similarly it decreases especially the amount of certificates purchased by Europe and the Middle East (in total about 17 $GtCO_2e$). The limited availability of emission certificates is compensated in these two regions through the implementation of domestic climate change mitigation measures, such as additional CCS and renewables deployment in the power sector (in Europe) and enhanced CO_2 and CH_4 emissions abatement in the upstream sector (in the Middle East). For Europe we also observe an increased consumption of electricity (+10%) and hydrogen (+15%) in the energy end-use sectors if carbon certificate trade is restricted down to 40%. These developments on the demand side in Europe are accompanied by a reduced CO_2 emissions intensity for the production of electricity and hydrogen in the energy supply sector. In 2050, fossil fuel based electricity generation in Europe is reduced by 60 TWh, while the contribution of renewable energy increases by 450 TWh when carbon certificate trade diminishes down to 40%. For Europe and other oil and gas importing regions, the intensification of domestic GHG mitigation efforts, especially in the transport sector, has a positive impact on their fossil fuel import dependency, and corresponding consequences for global energy trade.

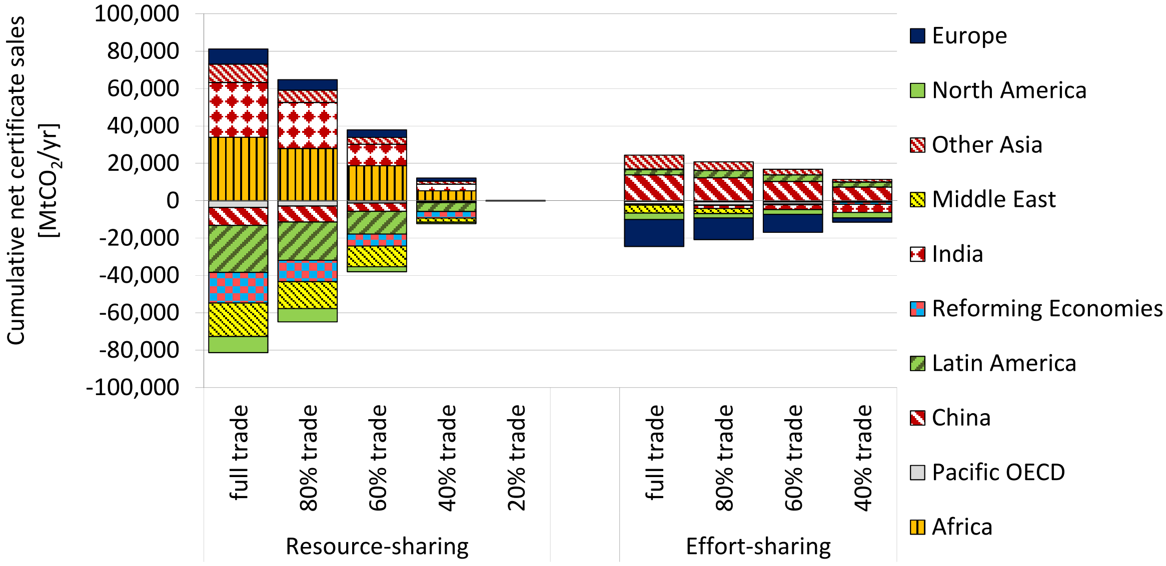
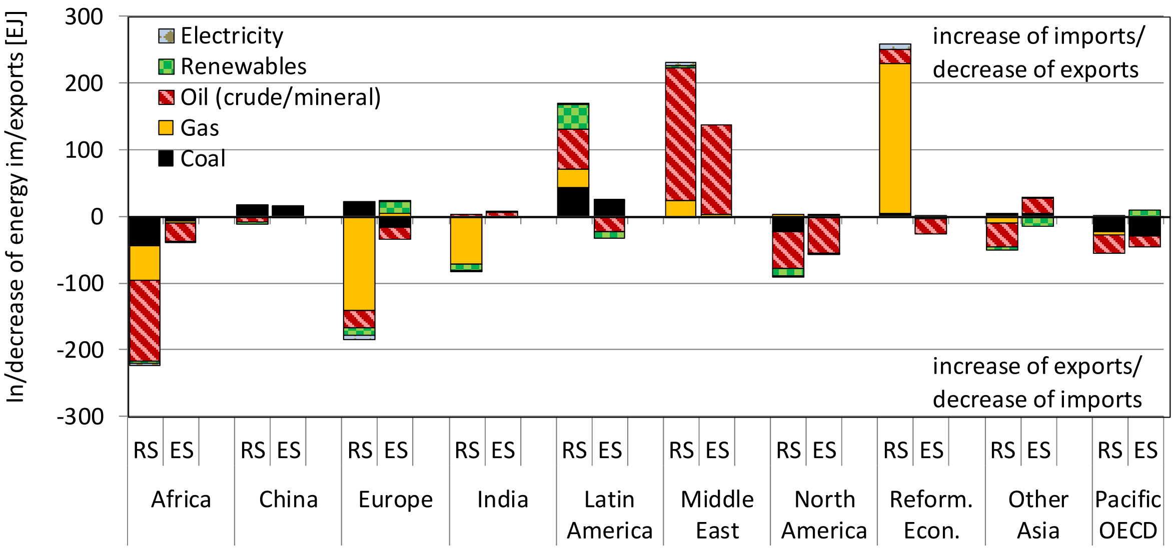


Figure 21: Cumulative net sales of carbon certificates between 2020 and 2050 at different trade levels under the resource-sharing and effort-sharing schemes.

Our model results imply that limitations in the trade of carbon certificates down to 40% reduce global energy trade by 11% under the resource-sharing scheme and by 2% under the effort-sharing scheme. Hence the effect is stronger for the former than the latter burden-sharing regime. Also at the regional level the impact of limited carbon trade tends to be higher under the resource-sharing than the effort-sharing regime, as can be seen in Figure 22 for most regions. The largest changes can be observed in the trade of oil and natural gas. Under the resource-sharing regime global oil consumption declines on average by 2%/yr between 2020 and 2050 if certificate trade is limited to 40%. Consequently oil exports decline, in particular from the Middle East, by a cumulative value of 200 EJ until 2050 (see Figure 22). Inversely, Africa, which is currently also an oil-exporting region and has an excess of emission allowances under the resource-sharing regime, experiences less stringent GHG reduction obligations, can therefore increase its oil production, and is thus able to export more oil (with a cumulative increase of 120 EJ between 2020 and 2050). For the major oil importing regions, i.e. North America, Other Asia, Pacific OECD and Europe, limitations of carbon certificate trade under the resource-sharing scheme lead to a reduction of their oil import dependency, which is mainly driven by a decrease in their oil consumption and partly by a larger use of domestic oil resources. In Latin America, a reduction of available emission certificates on the global carbon market to 40% under the resource-sharing regime obliges the region to implement more GHG emission reduction measures domestically, including fossil fuel savings and especially a reduction of the local production of fossil fuels. As a result, its net imports of fossil fuels must increase during the first half of the century to match domestic demand for these fuels, with 60 EJ for oil, 44 EJ for coal and 27 EJ for natural gas. In the same period exports of biomass products are curtailed drastically in favour of their domestic consumption, e.g. in the form of alternative fuels for the transport sector in Latin America.

Shifts of natural gas trade patterns under the resource-sharing scheme can mainly be observed for Europe and the Reforming Economies. Net natural gas imports to the former decline by about 140 EJ cumulatively until 2050 if carbon certificate trade is restricted to 40%. Since the Reforming Economies are net certificate buyers under the resource-sharing scheme during the first half of the century, a strong limitation of carbon certificate trade opportunities enforces these countries to collectively cut GHG emissions from natural gas production. We find that in the upstream sector in total 1.8 $GtCO_2e$ is reduced between 2020 and 2050 for this region. As a consequence, natural gas prices increase and it becomes less attractive to import natural gas into Europe. Europe's domestic natural gas reserves become thereby competitive and substitute some of the foregone imports from the Reforming Economies. Meanwhile overall natural gas consumption in Europe decreases, which favours an increase in coal demand. In the effort-sharing scheme, on the other hand, we observe negligible shifts in the trade of natural gas under restrictions of the carbon certificate trade. These limitations under this regime influence primarily the imports and exports of crude oil and oil products, with similar regional effects as obtained for the resource-sharing scheme. For the Middle East, the reductions in net oil exports accumulate to 135 EJ until 2050 if the global carbon certificate trade is limited down to 40% under the effort-sharing regime.



N.B. 1: RS: Resource-sharing, ES: Effort-sharing
N.B. 2: Reform. Econ.: Reforming Economies

Figure 22: Decrease of cumulative net energy exports or increase of cumulative net energy imports under carbon certificate trade limitations down to 40% for the resource-sharing and effort-sharing schemes between 2020 and 2050.

Along with shifts in energy trade, capital flows change as well. Our analysis shows that a limitation of carbon certificate trade has, for the period 2020 to 2050, a stronger influence on the worldwide capital transfer on the carbon certificate market than on the total capital involved with energy trade. If the global carbon certificate trade under the resource-sharing scheme is reduced down to 40%, the capital flow on the carbon market diminishes cumulatively by about 18 tln US$ until 2050, while the revenues from energy trade decline by some 8 tln US$ over the same period. Under the effort-sharing scheme the corresponding capital volumes decrease by 4 tln US$ on the carbon certificate market and by 3 tln US$ for trade in energy. On the regional scale, the impact of limited certificate trade appears rather heterogeneous. Regions exist for which changes in the capital flows associated with energy trade are larger than those for carbon certificate trade, such as the Middle East, Latin America, the Reforming Economies and Africa under the effort-sharing scheme. Under the resource-sharing scheme, however, we observe for almost all regions stronger implications for carbon market capital flows than for energy trade flows. Our results for the resource-sharing regime demonstrate that Africa can compensate about 40% of its reduced revenues from the carbon certificate market by increased revenues from energy exports if global certificate trade is limited to 40%. The reverse effect can be seen for the two main fossil fuel exporting regions. As a consequence of the decline in energy trade the revenues from energy exports decrease until 2050 cumulatively by about 3.0 tln US$ for the Middle East and some 2.7 tln US$ for the Reforming Economies, if carbon certificate trade under the resource-sharing regime is reduced to 40%. Simultaneously, these regions' expenses for the purchase of emission allowances reduce, to such extent that the resulting gain compensates for the decline in revenues from energy trade.

4.5.3. Certificate price effects

Under full trade conditions, regional certificate prices equal the price of permits on the global carbon market at any point in time. In that case these prices are independent of whether the resource-sharing or effort-sharing scheme is adopted, as indicated by the red line in both plots of

Figure 23. Limitations in opportunities for global certificate trade influence the carbon price within regions due to a partial decoupling of regional markets in GHG emission permits from the global marketplace. This decoupling generates certificate price decreases in permit selling regions and increases in permit buying regions. With constrained global trade of emission allowances, GHG reduction measures available within regions increasingly determine each region's carbon certificate price. In other words, domestic climate change mitigation capabilities and their costs are stronger determinants of the locally prevailing carbon price when the global certificate market is limited.

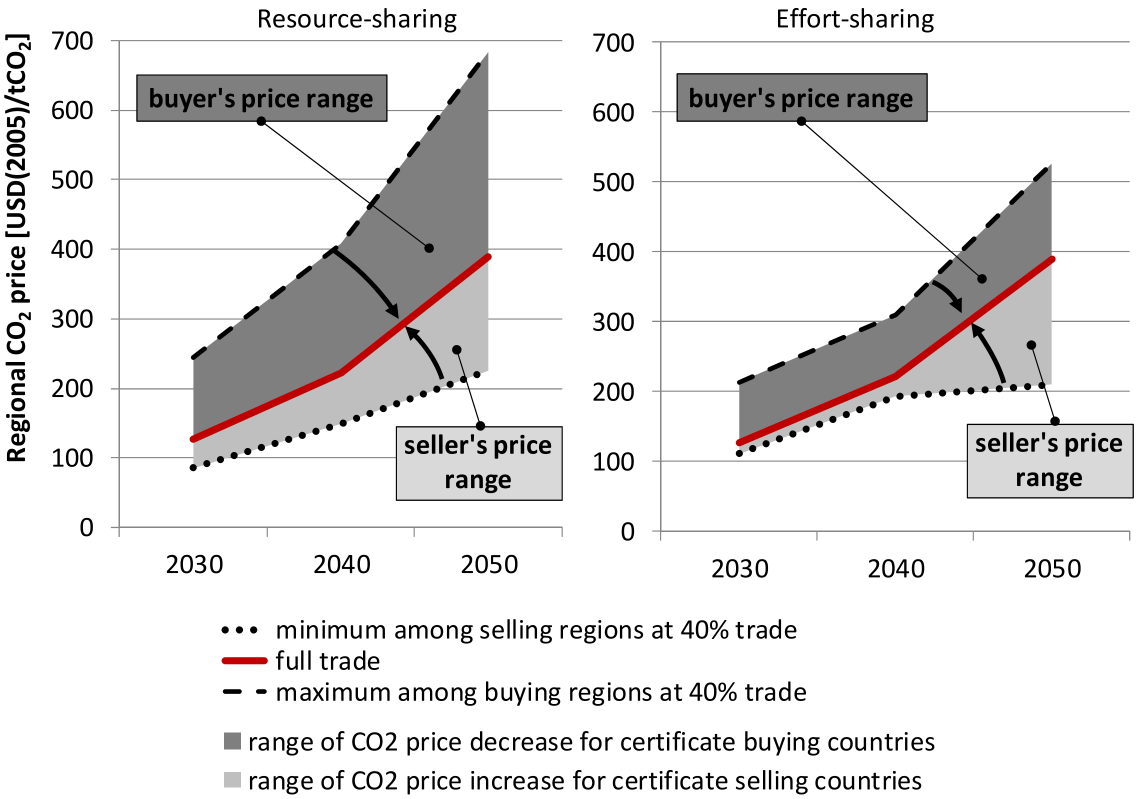


Figure 23: CO_2 price ranges for certificate buying and selling regions at trade levels between 40% and 100% for the the resource-sharing and effort-sharing regimes.

Figure 23 depicts the CO_2 price range under both burden-sharing regimes for total certificate trade levels higher than 40% during the period from 2030 to 2050. Except during the last decade of this time frame in the effort-sharing scheme, the seller's price range is smaller than the buyer's one, which shows that the effects of limited trade on the carbon price are generally more severe in certificate buying than in selling regions. Under the resource-sharing scheme, the minimum CO_2 price of the selling regions at a 40% overall certificate trade level is in 2030 about 40 US$/t$CO_2$ below the global carbon price at full certificate trade. In 2050 this difference amounts to about 160 US$/t$CO_2$. Our model runs reveal that the minimum CO_2 price of the selling regions is primarily driven by the marginal GHG abatement costs prevailing in Africa. The maximum CO_2 price of the certificate buying regions under the resource-sharing regime exceeds the full-trade global carbon price by about 120 US$/t$CO_2$ in 2030 and by some 300 US$/t$CO_2$ in 2050 if carbon permit trade is constrained down to 40%. We find that these higher certificate prices are determined by the regional marginal GHG abatement costs in predominantly China, the Middle East, North America and the Reforming Economies.

Under the effort-sharing regime less than one third of the emission permits are traded in comparison to the resource-sharing scheme. Consequently, the maximum CO_2 price of the buying regions at a trade limitation of 40% deviates less from the full-trade global carbon price than the difference we observe for the resource-sharing scheme: 90 US$/t$CO_2$ in 2030 and 140 US$/t$CO_2$ in 2050. This indicates that under an effort-sharing scheme carbon market distortions resulting from reduced certificate trade opportunities have in our model a lower impact on domestic carbon markets of selected regions than in a resource-sharing scheme. The explanation for this finding is that the allocation of allowances in the effort-sharing scheme is closer to the cost-optimal solution in comparison to the allocation under the resource-sharing regime. The outcome of our model runs is that the maximum of the price range of certificate buying regions in the effort-sharing scheme is mainly determined by the costs of GHG mitigation options realisable in Europe. This result supports an enhanced linkage of the European Emissions Trading Scheme (EU-ETS) to other regional markets for GHG emission permits trade, on the basis of which stringent global GHG reduction targets can be achieved significantly more efficiently. For the near term, similar findings are derived by Ciscar *et al*. (2013), who determine a maximum allowance relief of about 50 US$ for the year 2020 if the EU-ETS is fully integrated into an international certificate market.[35] We find that among the certificate selling regions under the effort-sharing regime the lower boundary of the CO_2 price range is set by GHG abatement technologies implementable in Africa, China and India.

4.5.4. Global climate policy costs

Diminished opportunities to trade emission allowances internationally yield increases in the total costs to mitigate global climate change, since no globally cost-optimal allocation of GHG reduction obligations can be established and costly alternative mitigation measures have to be utilised within regions that otherwise would not have been employed. Contrary to the previously described effects on the regionally prevailing CO_2 certificate price, global climate policy costs are not directly based on marginal GHG abatement costs, but rather reflect additional capital investments, operation and maintenance costs, fuel costs and other energy supply and demand costs such as associated with the transportation of energy carriers. Given the larger amounts of certificate trading in the resource-sharing than in the effort-sharing scheme, trade limitations cause a more extensive deployment of alternative local GHG reduction measures within regions to compensate for a lack of internationally tradable emission permits in the former than in the latter. As a result, as can be seen in Figure 14, incomplete international markets engender a stronger increase of global climate policy costs under the resource-sharing than under the effort-sharing regime.

Under the resource-sharing regime, if global carbon certificate trade is limited by as much as 60%, an extra amount of approximately 200 bln US$ has to be spent worldwide in 2030 on deploying alternative regional mitigation measures in order to reach the 2˚C climate change control target (see Figure 24). This represents a relative increase of global climate policy costs by about 20%. Similarly, in 2050 an additional figure of some 1,000 bln US$ would need to be spent, which corresponds to about 23% of total climate control expenditures in the full-trade scenario. After 2050 the share of additional policy costs would decrease down to 4% in 2070 (+570 bln US$) and to 2% in 2100 (+610 bln US$). Under the effort-sharing scheme additional climate policy costs amount to around 80 bln US$ in

[35] The number of 50 US$ is based on a conversion factor from €(2012) to US$(2005) of 1.1.

2030 and 4 bln US$ in 2050 when the trade of emission allowances is restricted down to 40%. In comparison to the full-trade case, this corresponds to about 8% of global climate policy costs in 2030 and less than 1% in 2050. During the second half of the century these shares are roughly equal to those we found in the resource-sharing scheme, that is, about 4% in 2070 and 2% in 2100.

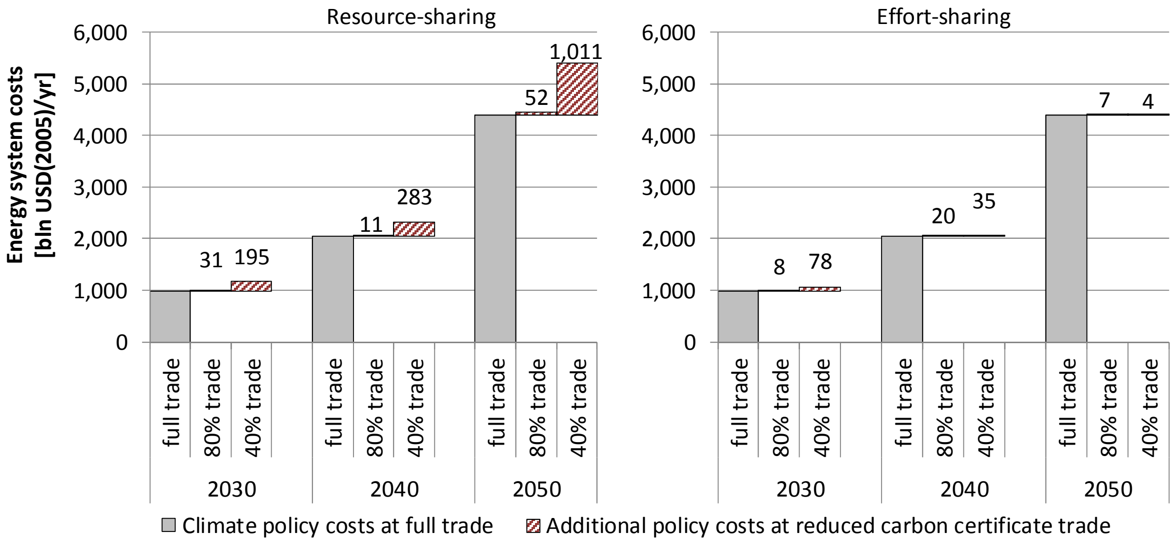


Figure 24: Impact of different carbon certificate trade levels on global climate policy costs, expressed as annual undiscounted energy system costs, under the resource-sharing and effort-sharing regimes.

The additional climate policy costs reported in Figure 14 probably represent a lower estimate of what extra costs could prove to be in reality under the presence of trade restrictions, since we left the timing of trade limitations endogenous to our model, while in practice the timing could be stipulated by political realities as well so that it would need to be exogenously treated in our model. Our model operates under a cost-minimisation paradigm in which the overall optimal certificate trade patterns are determined including in terms of when and between which regions trade of emission allowances takes place. We expect that if we were to limit another degree of freedom of TIAM-ECN by also straight-jacketing the timing of trade limitations, the global climate policy costs would further increase. It is even possible that staying on track of the GHG emissions reduction pathway needed to meet the 2˚C climate change control target becomes significantly curtailed.

4.6. Conclusions

In this paper we analysed the impacts of two different international burden-sharing schemes in terms of the regional allocation of GHG emission allowances, carbon certificate trade patterns between regions, and the corresponding aggregated carbon market capital flows, in the context of a global climate policy adopted to achieve a long-term stabilisation of the global mean temperature increase with respect to the pre-industrial level at 2˚C. Our first main finding is that, on a global least-cost mitigation pathway, overall GHG emissions must become negative by the end of the century if the 2˚C climate target is to be reached with high (i.e. 70%) probability. In order to compensate for GHG emissions in sectors in which abatement is costly, such as agriculture, industry and transportation, emissions have to become negative for e.g. electricity generation and fuel production from already around the middle of the century onwards. From approximately 2060, total GHG emissions in regions such as Europe and North America will need to become negative in order to balance positive emission levels of, for instance, Latin America and India, where cheap mitigation options deplete more quickly than in the former regions. Under a resource-sharing regime, in which every region's endowment in emission certificates is based on population-related criteria, the allocated emission rights deviate more from the allocation under a least-cost reference mitigation pathway scenario than observed in an effort-sharing scheme, which aims at equal distribution of the economic burden across regions. This translates into a large difference between these respective regimes in the volume of certificates traded on a global certificate market: for the period between 2020 and 2100 the number of certificates traded under the resource-sharing regime is approximately three times higher than under our effort-sharing regime.

The resource-sharing regime favours regions with a strong population growth, such as Africa, India and Other Asia, which assumes a net seller's position on the certificate market with cumulative sales of permits equivalent to 73 $GtCO_2e$ until 2050. This trade volume corresponds to an aggregated capital flow of 18 tln US$, which roughly covers the climate policy costs of these three regions combined until 2050. In the long run (post 2070), Europe and North America become the main certificate selling regions, given their high potentials for reducing GHG emissions. Particularly these two regions manage to realise net negative emissions as a result of their use of biomass plus CCS technologies. The most important certificate-buying regions in the near and medium term are China, Latin America and North America. The explanation for this outcome is their low or even negative population growth. In the long term, Africa and India become the major permit-buying regions, as a result of their relatively low potentials to achieve a net negative GHG emissions balance, against a background of strong population growth rates.

Under the effort-sharing regime, the quantities of regionally allocated certificates are determined by every region's climate policy costs relative to its local economic growth. In the near term (2020), particularly China and Latin America face high climate policy costs, but which they can almost entirely offset (by more than 90%) by selling emission certificates, given their high GDP growth rates. In the long run, climate policy costs are increasingly influenced by changes in fossil fuel trades that occur following global fuel shifts and demand reductions. Especially for the principal fossil fuel exporting regions (Middle East and Reforming Economies) these changes result in substantial reductions of import revenues. These climate policy costs can be offset, however, if revenues can be generated from providing CO_2 storage capacity for CCS applications operating in other regions. The Reforming Economies are significant carbon certificate sellers under the effort-sharing regime during the second half of the 21st century, and can balance their decreasing revenues from fossil fuel exports partly with annual revenues from the carbon market by up to 340 bln US$/yr. On the contrary, the Middle East becomes one of the main certificate buying regions during the second half of the century, plus loses revenues from decreasing oil and gas exports, which it can both compensate by gaining significant revenues from storing CO_2 capture in foreign CCS installations. China's position on the carbon market changes from being a seller of certificates during the first half of the century to becoming a buyer during the second half of it, as a result of its strong economic growth and comparable advantage in terms of its GHG emissions reduction potential.

Appropriate certificate trading mechanisms need to be in place when functioning burden-sharing schemes are to be established. Full carbon certificate trade enables most efficiently the unlocking of the world's least-cost GHG reduction potentials and GHG emission abatement options, since it allows proffering compensation for some regions' disproportional efforts to implement climate change control measures. Our sensitivity analysis with regard to possible limitations in global trade of carbon certificates has shown that the policy costs required to reach the global 2˚C climate change control target could increase by more than 20% in the short- to mid-term (i.e. around 2030) if carbon certificate trade is significantly restricted (by up to 60%). Substantially restricted carbon certificate trade tends to impose higher additional climate policy costs for the resource-sharing than the effort-sharing scheme, due to the larger amount of certificates traded under the former.

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