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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.

Keywords: regional mitigation costs, delayed cooperative action, burden sharing, integrated assessment models.

1 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 2 describes the methodology and scenario design. In the results analysis part, Section 3, at first, gives an overview on regional mitigation costs obtained from different scenarios. Section 4 and Section 5 then elaborate on the drivers of regional mitigation costs for immediate action scenarios. Section 6 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.

2 Methodology

2.1 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)*:

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

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), X_i^E, X^G, and X^P represent the net export of energy carrier *i*, generic good, and permits, respectively; P_i^E, P^G, and P^P are the corresponding present value prices derived from the shadow prices of the optimization.

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

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* (cp_i^E) and the current value price of permits (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:

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

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

We then formulate regional current accounts[1] (*CA*) as:

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

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.

2.2 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

[1] 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.

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:

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

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[2].

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):

$$\Delta M(r,t) = \Delta C(r,t) + \Delta CA(r,t) = \Delta Y(r,t) - \Delta I(r,t) - \Delta E(r,t) - \Delta A(r,t)$$
$$+ \sum_i \Delta\left(cp_i^E(t) X_i^E(r,t)\right) + \Delta\left(cp^P(t) X^P(r,t)\right) \quad \forall t, r \qquad (7)$$

[2] 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).

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[3]):

$$\overline{\Delta M}\ \ (r) = \left(\overline{\Delta Y}\ \ (r) - \overline{\Delta I}\ \ (r) - \overline{\Delta E}\ \ (r) - \overline{\Delta A}\ \ (r)\right)$$

$$+\left(\sum_t P_{REF}^G(t)\sum_i\left(cp_{i,REF}^E(t)\ X_{i,REF}^E - cp_{i,POL}^E(t)\ X_{i,POL}^E\right)\right)$$

$$+\left(\sum_t P_{REF}^G(t)(cp_{REF}^P\ (t)\ X_{REF}^P(r,t) - cp_{POL}^P\ (t)\ X_{POL}^P(r,t)\ )\right)\forall r. \qquad (8)$$

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).

2.3 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[4]. 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.

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[3] 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.

[4] 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.

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 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 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 2.2.

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 2.2 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 4.

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

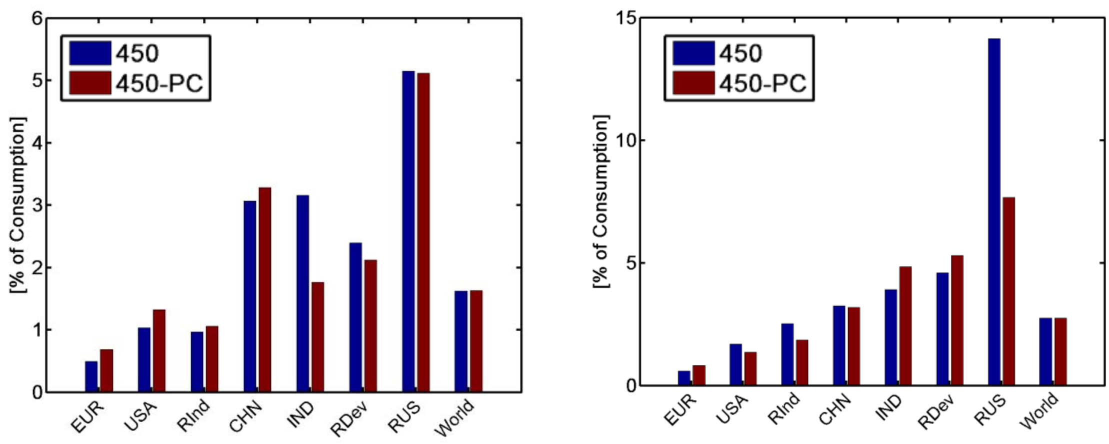

Figure 1: Discounted mitigation costs as a percentage of baseline consumption over regions: (a) 2010-2050 and (b) 2010–2100.

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.

4 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)

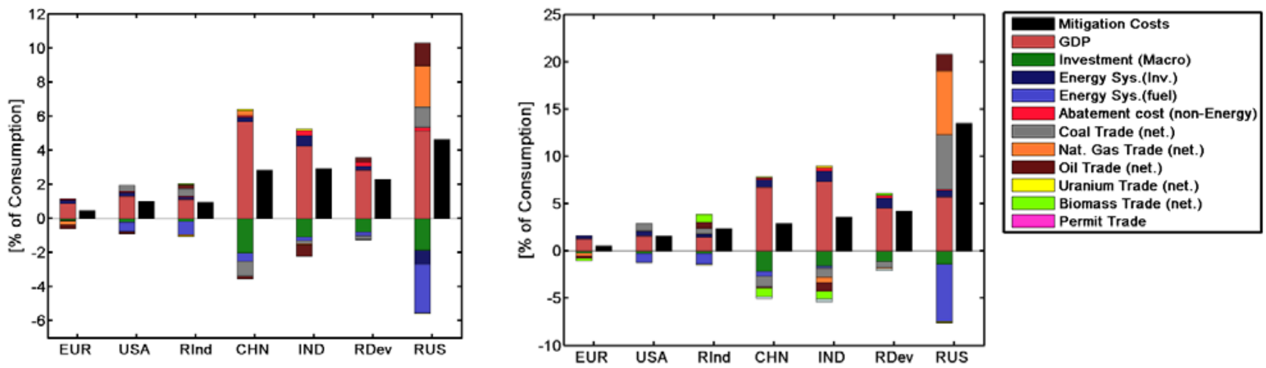

Figure 2: Decomposition of discounted mitigation costs for scenario "450" as a percentage of baseline consumption over regions: (a) 2010-2050 and (b) 2010-2100. (The black bar shows total mitigation costs, and the stacked bar to the left shows the components).

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.

5 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.

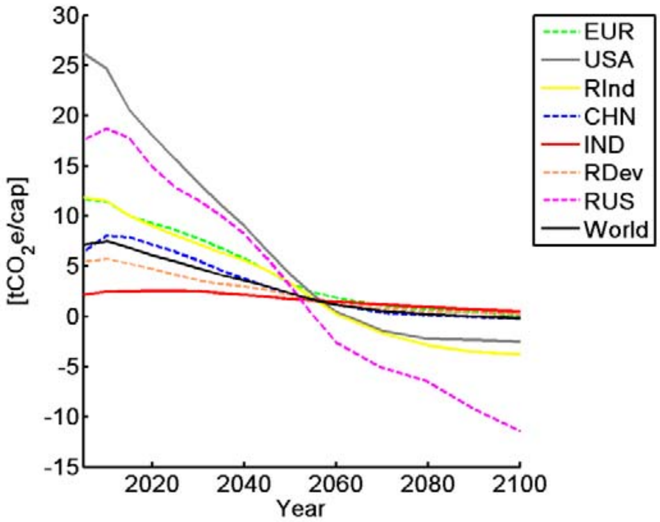

Figure 3: GHG per-capita emissions over regions and time in scenario "450-PC".

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.

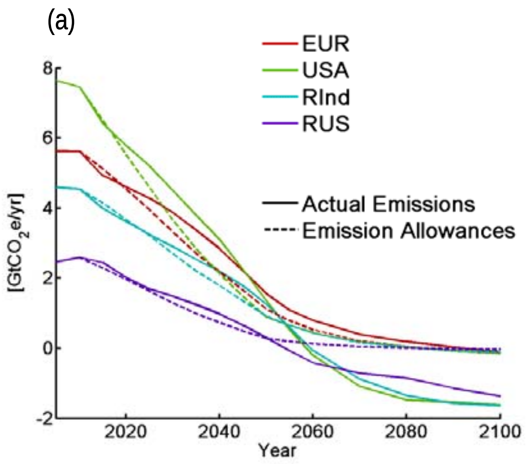

Figure 4: Emissions allowances versus actual GHG emissions over time for scenario "450-PC": (a) Industrialized regions and Russia, (b) Developing regions.

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 2.1). 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.

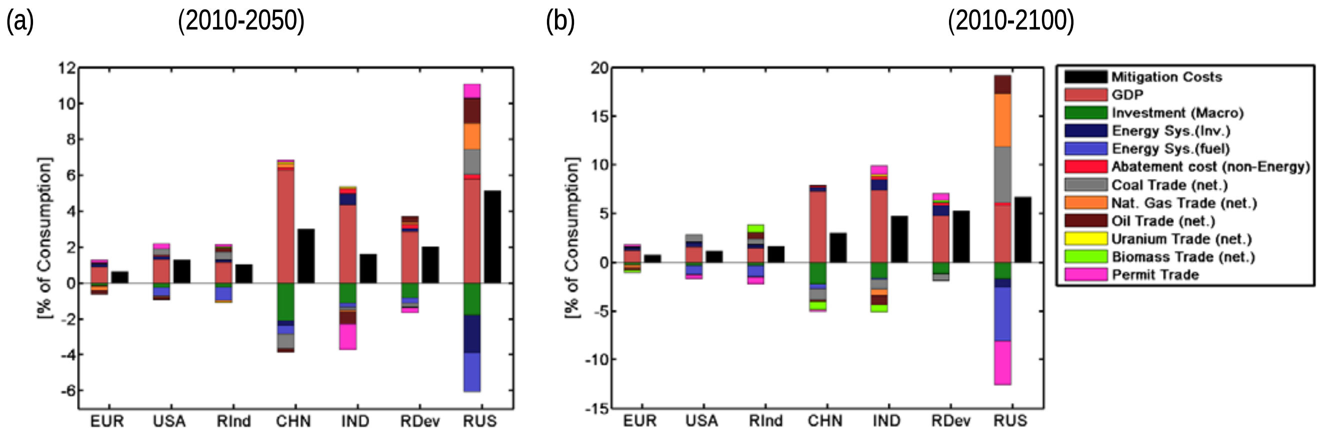

Figure 5: Decomposition of discounted mitigation costs for scenario "450-PC" as a percentage of baseline consumption over regions: (a) 2010-2050 and (b) 2010-2100. (The black bar shows total mitigation costs, and the stacked bar to the left shows the components).

6 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 6.2).

6.1 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.

6.1.1 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.

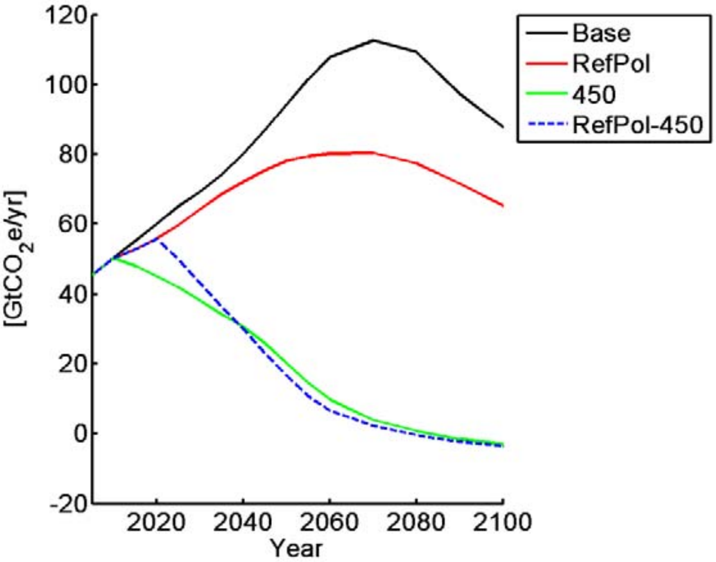

Figure 6: Global GHG emissions trajectories.

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 2.1); 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.

(a) (b)

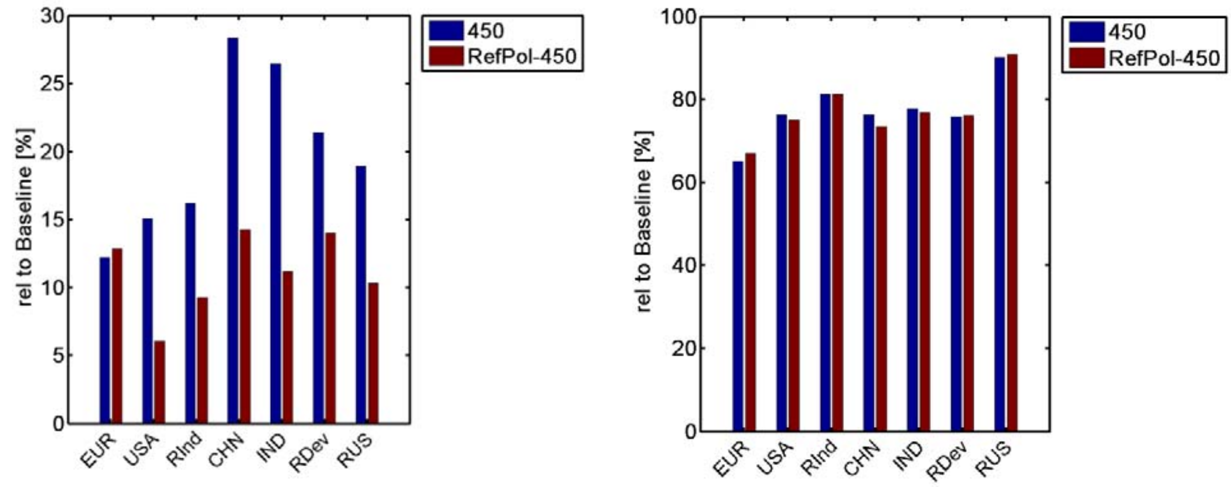

Figure 7: Cumulative GHG emissions reductions from baseline over regions: (a) 2005–2030, and (b) 2005–2100[5].

6.1.2 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-

[5] 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.

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

(a) (b) (c)

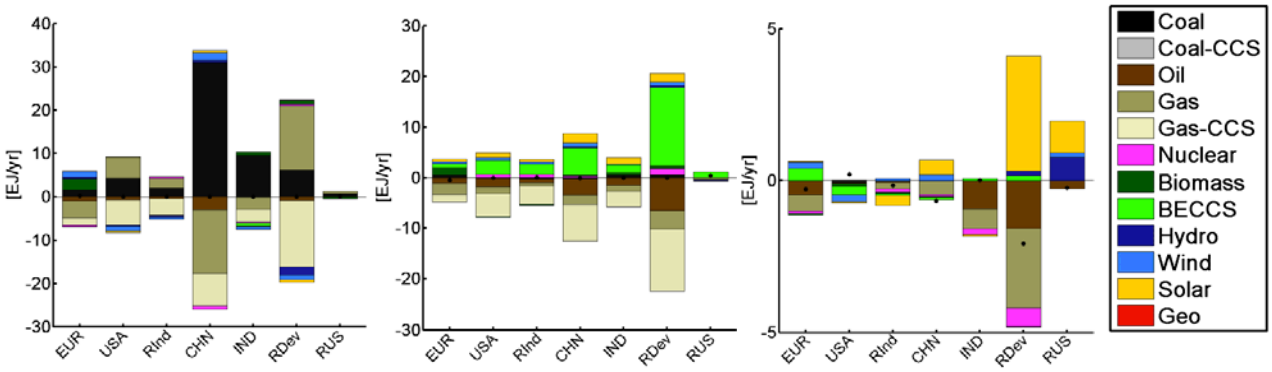

Figure 8: Difference in primary energy supply between the “RefPol-450” scenario and the “450” scenario over regions: (a) 2030, (b) 2050, and (c) 2100. (Positive values indicate higher production in “RefPol-450” compared to “450”).

6.2 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.

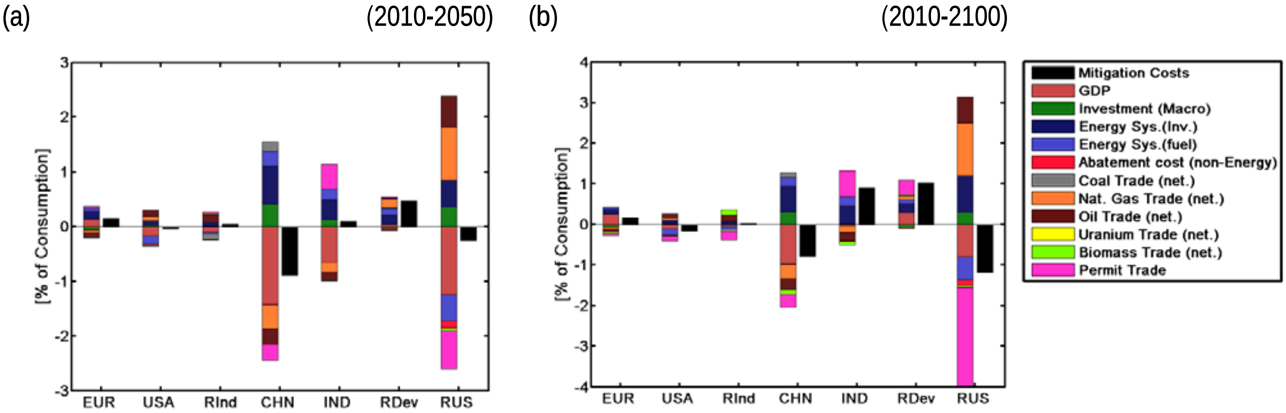

Figure 9: Decomposition of discounted mitigation costs differences between "RefPol-450-PC" and "450-PC" scenarios over regions: (a) 2010-2050 and (b) 2010-2100. (Positive values indicate higher mitigation costs in "RefPol-450-PC" scenario compared to "450-PC"; the black bar shows total differences in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

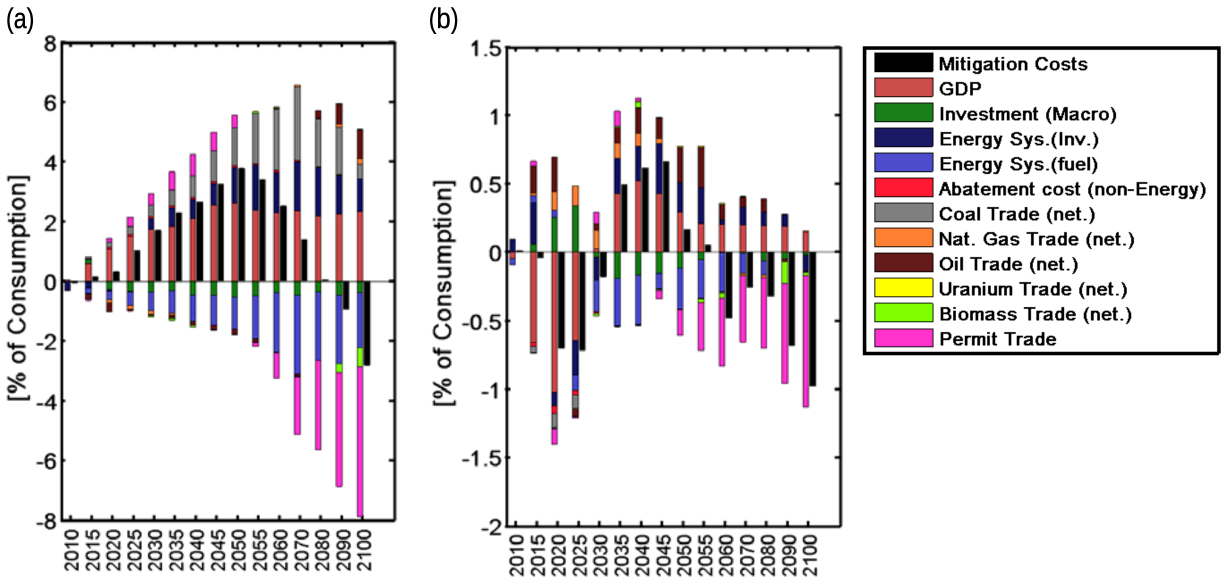

Figure 10: Decomposition over time for USA: (a) Decomposition of mitigation costs for scenario "450-PC"; (b) Decomposition of mitigation costs differences between "RefPol-450-PC" and "450-PC" scenarios. (Positive values indicate higher mitigation costs in "RefPol-450-PC" scenario compared to "450-PC").

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).

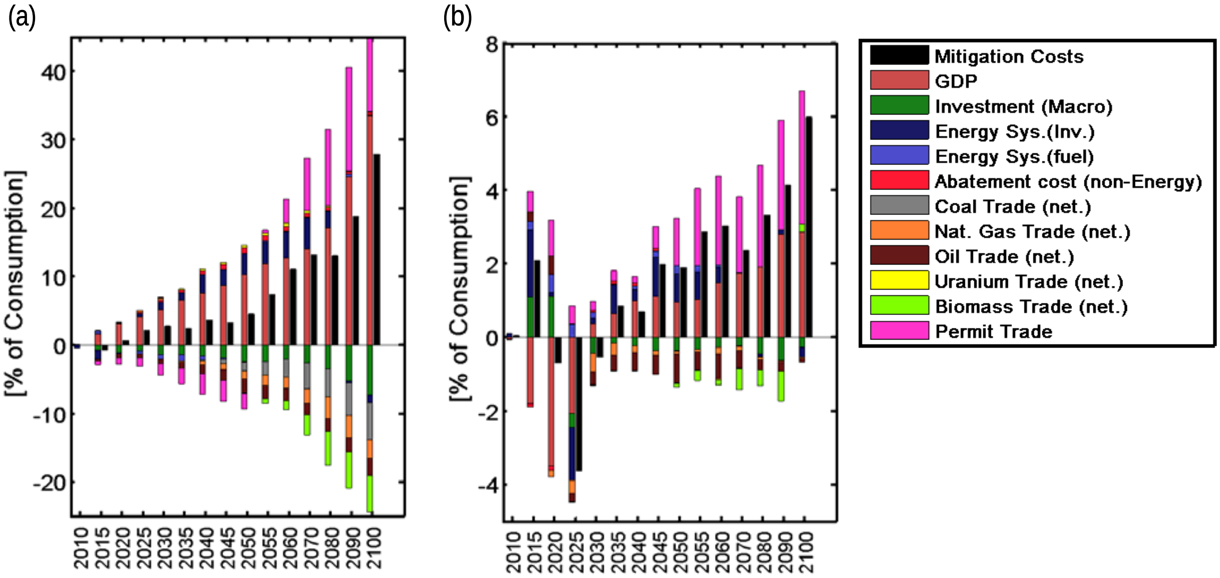

Figure 11: Decomposition over time for India: (a) Decomposition of mitigation costs for scenario "450-PC"; (b) Decomposition of mitigation costs differences between "RefPol-450-PC" and "450-PC" scenarios. (Positive values indicate higher mitigation costs in "RefPol-450-PC" scenario compared to "450-PC").

7 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 CO_2-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 (cf. Figure S11).

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 5). 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).

8 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 5). 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[6] 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.

[6] 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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Supplementary online material

Model description

Table S1: Conversion Technologies in REMIND

		PRIMARY ENERGY CARRIERS						
		Exhaustible				Renewable		
		Coal	Oil	Gas	Uranium	Solar, Wind, Hydro	Geothermal	Biomass
SECONDARY ENERGY CARRIERS	Electricity	PC, IGCC	DOT	NGCC	LWR	SPV, WT, Hydro, *CSP*	HDR	BIGCC
	H2	C2H2		G2H2				B2H2
	Gases	C2G		GasTR				B2G
	Heat	CoalHP, CoalCHP		GasHP, GasCHP			GeoHP	BioHP, BioCHP
	Liquid fuels	C2L	Refin.					B2L Bioethanol
	Other Liquids		Refin.					
	Solids	CoalTR						BioTR

Abbreviations:
B2G = biogas
B2H2 = biomass to hydrogen
B2L = biomass to liquids
BIGCC = biomass IGCC
BioCHP = biomass combined heat and power
Bioethanol = biomass to ethanol
BioHP = biomass heating plant
BioTR = biomass transformation
C2G = coal to gas
C2H2 = coal to hydrogen
C2L = coal to liquids
CoalCHP = coal combined hat power
CoalHP = coal heating plant
CoalTR = coal transformation
CSP = concentrating solar power
DOT = diesel oil turbine
G2H2 = gas to hydrogen
GasCHP = gas combined heat power
GasHP= gas heating plant
GasTR = gas transformation
GeoHP = geothermal heating pump
HDR = hot-dry-rock
Hydro = hydro power
IGCC = integrated coal gasification combined cycle
LWR = light water reactor
NGCC = natural gas combined cycle
PC = conventional coal power plant
Refin. = Refinery
SMR = steam methane reforming
SPV = solar photovoltaic
WT = wind turbine

Table S2: Techno-economic parameters of conversion technologies

	Lifetime [years]	*Investment costs [US$2005/kW]*	*Fixed O&M [% of Investment]*	*Variable O&M [US$2005/kWa]*	*Conversion efficiency*	*Availability factor*	*Couple production**	*Capture rate*
BioCHP	40	1375	4	30.11	0.43	0.46	0.72 Heat	
BioHP	40	400	4	25	0.80	0.4		
BIGCC	40	1860	4	31.5	0.42	0.8		
BIGCC CCS	40	2560	4	50.50	0.31	0.8		80%
B2G	40	1000	4	10.90	0.55	0.91	0.0 Heat	
B2H2	35	1400	10	10.60	0.61	0.9		
B2H2 CCS	35	1700	10	10.60	0.55	0.9		90%
Bioethanol	35	2380	7	97.27	0.36	0.9	0.15 Elec.	
B2L	35	2500	4	0	0.4	0.91	0.16 Elec.	
B2L CCS	35	3000	4	10.60	0.41	0.91	0.14 Elec.	48%
BioTR	*35*	*150*	*0*	*0*	*1*	*0.9*		
CoalHP	*40*	*400*	*3*	*30*	*0.70*	*0.4*		
CoalCHP	*40*	*1350*	*3*	*60*	*0.40*	*0.7*	*0.61 Heat*	
CoalTR	*35*	*100*	*3*	*0*	*0.95*	*0.9*		
C2G	*35*	*900*	*3*	*0*	*0.60*	*0.9*		
C2H2	*35*	*1260*	*3*	*4.6*	*0.59*	*0.8*	*0.08 Elec.*	
C2H2 CCS	*35*	*1430*	*3*	*5.3*	*0.57*	*0.8*	*0.05 Elec.*	*90%*
C2L	*35*	*1000*	*5*	*36*	*0.4*	*0.85*		
C2L CCS	*35*	*1040*	*6*	*36*	*0.4*	*0.85*		*70%*
CSP	30	9500	3	0	1	1		
DOT	25	400	3	10	0.3	0.4		
GasHP	*35*	*300*	*3*	*20*	*0.75*	*0.4*		
GasCHP	*35*	*800*	*3*	*35*	*0.45*	*0.6*	*0.42 Heat*	
G2H2	*35*	*498*	*3*	*1.8*	*0.73*	*0.9*	*- 0.01 Elec.*	
G2H2 CCS	*35*	*552*	*3*	*2.4*	*0.70*	*0.9*	*-0.04 Elec.*	*90%*
GasTR	*35*	*50*	*3*	*25*	*1.0*	*0.9*		
GeoHP	25	1000	6	0	1	0.4		
HDR	30	3000	4	0	1	0.9		
Hydro	70	2500	2	0	1	1		
IGCC	*40*	*1650*	*3*	*31.5*	*0.43*	*0.75*		
IGCC CCS	*40*	*2050*	*3*	*50.5*	*0.38*	*0.75*		*90%*
LWR	40	3000	3	30.53	4.41	0.8		
NGCC	*35*	*650*	*2*	*12.6*	*0.56*	*0.75*		
NGCC CCS	*35*	*1100*	*2*	*25.2*	*0.48*	*0.85*		*90%*
PC	*40*	*1400*	*3*	*25.2*	*0.45*	*0.75*		
PC CCS	*40*	*2400*	*3*	*63.1*	*0.36*	*0.85*		*90%*
Refin2D	40	222	3	10	0.75	0.9		
Refin2P	40	494	3	10	0.75	0.9		
SPV	30	5300	2	0	1	1		
WT	25	1400	2	0	1	1		

Abbreviations:
BioCHP = biomass combined heat and power plant
BioHP=biomass heating plant
BIGCC = biomass IGCC
B2G = biogas
B2H2 = biomass to hydrogen
Bioethanol = biomass to ethanol
B2L = biomass to liquids
BioTR = biomass transformation
CoalHP = coal heating plant
CoalCHP = coal combined hat power
CoalTR = coal transformation
C2H2 = coal to H2
C2L = coal to liquids
CSP=concentrating solar power
DOT=diesel oil turbine
GasHP= gas heating plant
GasCHP= gas combined heat and power plant
G2H2=gas to hydrogen
GasTR = gas transformation
GeoHP = geothermal heating pump
HDR = hot-dry-rock
Hydro = hydro power
IGCC = integrated coal gasification combined cycle
NGCC = natural gas combined cycle
PC = conventional coal power plant
Refin2D=Refinery oil to diesel
Refin2P=Refinery oil to petrol
SPV= solar photovoltaic
WT = wind turbine

C2G = coal to gas	LWR=light water reactor

** defined as units of couple product that can be additionally produced per unit of main product. Sources: Iwasaki (2003), Hamelinck (2004), Ragettli (2007), Schulz (2007), Uddin and Barreto (2007), Takeshita et al. (2006), Gül (2008), Brown et al. (2009), Klimantos et al. (2009).*

Table S3: Total renewable energy potential and CO_2 storage potential for REMIND Regions

REMIND Region	Wind [EJ/year]	PV [EJ/year]	CSP [EJ/year]	Hydro [EJ/year]	CO_2 storage [GtC]
AFR	29.6	248	194	7	62.5
CHN	26	254	199	8	100
EUR	21.8	17	13	3	48.5
IND	12.9	40	31	2	50
JPN	3.6	2	1	1	18.75
LAM	35.3	327	248	10	150
MEA	45	537	426	3	125
OAS	20.9	130	103	5	50
ROW	66.8	336	264	6	100
RUS	52.5	18	13	6	250
USA	53.7	231	180	2	125

Abbreviations:

AFR = Sub-saharan Africa excluding South Africa
CHN = China
EUR = EU27
IND = India
JPN =Japan
LAM = Latin America, also including Mexico
MEA = Middle East and North Africa, also including Kazachstan,Turkmenistan, Usbekistan, and Tajikistan
OAS = Other Asia, also including Pakistan
ROW = Rest of World, including Australia, Canada, South Africa, Turkey and some more
RUS = Russia
USA = United States of America
CSP = Concentrating solar power
Hydro = Hydro power
PV = Solar photovoltaic

Sources: Bauer (2005), Brückl (2005), EEA (2009), Hoogwijk (2004), Hoogwijk and Graus (2008), Horlacher (2003), Trieb et al. (2009), Tzscheutschler (2005), WGBU (2003), and communication with German Aerospace Center DLR

Table S4: Mapping of REMIND regions

REMIND Region	Aggregated Region
AFR	RDev
CHN	CHN
EUR	EUR
IND	IND
JPN	RInd
LAM	RDev
MEA	RDev
OAS	RDev
ROW	RInd
RUS	RUS
USA	USA

Abbreviations:
AFR = Sub-saharan Africa excluding South Africa
CHN = China
EUR = EU27
IND = India
JPN = Japan
LAM = Latin America, also including Mexico
MEA = Middle East, North Africa, and Central Asia
OAS = Other Asia, also including Pakistan
ROW = Rest of the World
RUS = Russia
USA = United States of America
RDev = Rest of developing countries
RInd = Rest of industrialized countries

Economic decomposition method

We convert the budget balance of the baseline scenario to present value prices by multiplying Eq. (1) by the macroeconomic good price of the reference scenario. Then, we sum the discounted macroeconomic budget over time and replace the trade of generic good with financial flows from trade of energy carriers and emissions permits and the current account effect according to Eq. (5):

$$\begin{aligned}\sum_t P_{REF}^G(t)\; C_{REF}(r,t) = {} & \sum_t P_{REF}^G(t)\; Y_{REF}(r,t) - \sum_t P_{REF}^G(t)\; I_{REF}(r,t) - \sum_t P_{REF}^G(t)\; E_{REF}(r,t) \\ & - \sum_t P_{REF}^G(t)\; A_{REF}(r,t) + \sum_t P_{REF}^G(t) \sum_i cp_{i,REF}^E(t)\, X_{i,REF}^E(r,t) \\ & + \sum_t P_{REF}^G(t)\, cp_{REF}^P(t)\, X_{REF}^P(r,t) - \sum_t P_{REF}^G(t)\, CA_{REF}(r,t) \qquad \text{(S.1)}\end{aligned}$$

Equation (S.2) represents a short form of the equation above, where the bar sign represents the discounted terms based on the good price of the baseline scenario that are summed over the whole time horizon:

$$\begin{aligned}\overline{C}_{REF}(r) = {} & \overline{Y}_{REF}(r) - \overline{I}_{REF}(r) - \overline{E}_{REF}(r) - \overline{A}_{REF}(r) - \sum_t P_{REF}^G(t)\, CA_{REF}(r,t) \\ & + \sum_t P_{REF}^G(t) \sum_i cp_{i,REF}^E(t)\, X_{i,REF}^E + \sum_t P_{REF}^G(t)\, cp_{REF}^P(t)\, X_{REF}^P(r,t) \qquad \text{(S.2)}\end{aligned}$$

Similarly, we convert the budget balance of the policy scenario to present value prices by multiplying Eq. (1) by the macroeconomic good price of the baseline scenario and sum it over time. We then replace the trade of generic good with financial flows from trade of energy carriers and emissions permits as well as the current accounts:

$$\begin{aligned}\sum_t P_{REF}^G(t)\; C_{POL}(r,t) = {} & \sum_t P_{REF}^G(t)\; Y_{POL}(r,t) - \sum_t P_{REF}^G(t)\; I_{POL}(r,t) - \sum_t P_{REF}^G(t)\; E_{POL}(r,t) \\ & - \sum_t P_{REF}^G(t)\; A_{POL}(r,t) + \sum_t P_{REF}^G(t) \sum_i cp_{i,POL}^E(t)\, X_{i,POL}^E(r,t) \\ & + \sum_t P_{REF}^G(t)\, cp_{POL}^P(t)\, X_{POL}^P(r,t) - \sum_t P_{REF}^G(t)\, CA_{POL}(r,t) \qquad \text{(S.3)}\end{aligned}$$

Equation below represents a short form of Eq. (S.3), where the bar sign represents the discounted terms using the good price of the reference scenario, which are summed over the whole time horizon:

$$\begin{aligned}\overline{C}_{POL}(r) = {} & \overline{Y}_{POL}(r) - \overline{I}_{POL}(r) - \overline{E}_{POL}(r) - \overline{A}_{POL}(r) - \sum_t P_{REF}^G(t)\, CA_{POL}(r,t) \\ & + \sum_t P_{REF}^G(t) \sum_i cp_{i,POL}^E(t)\, X_{i,POL}^E + \sum_t P_{REF}^G(t)\, cp_{POL}^P(t)\, X_{POL}^P(r,t) \qquad \text{(S.4)}\end{aligned}$$

We then take the difference between the two scenarios by subtracting Eq. (S.4) from Eq. (S.2):

$$\left(\overline{C}_{REF}(r) - \overline{C}_{POL}(r)\right) + \left(\sum_t P_{REF}^G(t)\; CA_{REF}(r,t) - \sum_t P_{REF}^G(t)\; CA_{POL}(r,t)\right)$$

$$= \left(\overline{\Delta Y} \quad (r) - \overline{\Delta I} \quad (r) - \overline{\Delta E} \quad (r) - \overline{\Delta A} \quad (r) \right)$$

$$+ \left(\sum_t P^G_{REF}(t) \left(\sum_i \left(cp^E_{i,REF}(t)\, X^E_{i,REF} - cp^E_{i,POL}(t)\, X^E_{i,POL} \right) \right) \right)$$

$$+ \left(\sum_t P^G_{REF}(t) (cp^P_{REF}\,(t)\, X^P_{REF}(r,t) - cp^P_{POL}\,(t)\, X^P_{POL}(r,t)\,) \right) \qquad (\mathrm{S.5})$$

We replace the $P^G{}_{REF}$ in the second bracket on the left side of Eq. (S.5) from:

$$\Delta P^G(t) = P^G_{POL}(t) - P^G_{REF}(t) \qquad \text{(S.6)}$$

We then reformulate it as below:

$$\sum_t P^G_{REF}(t)\;\; CA_{REF}(r,t) - \sum_t P^G_{REF}(t)\;\; CA_{POL}(r,t) =$$

$$\sum_t P^G_{REF}(t)\;\; CA_{REF}(r,t) - \left(\sum_t P^G_{POL}(t)\;\; CA_{POL}(r,t) - \sum_t \Delta P^G(t)\, CA_{POL}(r,t) \right) =$$

$$\overline{CA}_{REF}(r) - \overline{CA}_{POL}(r) + \sum_t \Delta P^G(t)\;\; CA_{POL}(r,t) \qquad (\mathrm{S.7})$$

When summing over the complete horizon, the first and second term reaches zero according to the inter-temporal trade balance. On this basis, the difference in time-aggregated mitigation costs between the two scenarios can be decomposed:

$$\overline{\Delta M} \quad (r) = \left(\overline{C}_{REF}(r) - \overline{C}_{POL}(r) \right) + \left(\sum_t \Delta P^G(t)\, CA_{POL}(r,t) \right)$$

$$= \left(\overline{\Delta Y} \quad (r) - \overline{\Delta I} \quad (r) - \overline{\Delta E} \quad (r) - \overline{\Delta A} \quad (r) \right)$$

$$+\left(\sum_t P^G_{REF}(t)\sum_i\left(cp^E_{i,REF}(t)\,X^E_{i,REF}-cp^E_{i,POL}(t)\,X^E_{i,POL}\right)\right)$$

$$+\left(\sum_t P^G_{REF}(t)(cp^P_{REF}\,(t)\,X^P_{REF}(r,t)-cp^P_{POL}\,(t)\,X^P_{POL}(r,t)\,)\right)\forall r. \qquad (S.8)$$

It is worth mentioning that the second bracket on the left side of Eq. (S.8) arises due to variations in the model-endogenous interest rates (which are implicit to the development over time of the present value price of the generic macro-economic good ΔP^G) induced by climate policies. It represents the variations of interest payments on net foreign assets. We refer to this effect as the capital market effect; this is in general relatively small compared to other components.

Weak policy scenario

The weak policy scenario is designed based on a collection of regional 2020 targets for emissions reductions, renewable portfolio standards as well as renewable and nuclear capacity targets (cf. Table S5). The stringency level of these regional targets is extrapolated beyond 2020 by using average improvement rates of GHG emissions intensity, i.e., GHG emissions per unit of GDP. In the weak policy, the 2020 emissions (intensity) reduction commitments correspond to the lower end of Copenhagen pledges. Plausibility considerations were applied in cases, where Copenhagen pledges appeared to be ambitious (mostly developing country emissions reductions relative to baseline). For the USA, the 2020 emissions reduction target has been taken from an assessment of the impact of existing US regulations (Bianco and Litz, 2010). Country targets were extrapolated to larger regions under the assumption that neighboring countries follow the example of regional leaders. If, for a given region and period, the emissions (intensity) reduction target in 2020 and/or the emissions intensity improvement rates after 2020 are less ambitious than projected by REMIND in the baseline scenario, the emissions in the baseline are adopted also for the weak policy scenario. This requirement implies that no region has higher emissions than baseline in the weak policy scenario. The weak policy targets adapted to REMIND regions are represented in Table S6.

Table S5: Targets in weak policy scenario for 25 world regions

Region	GHG emissions reduction in 2020[(1)]	GHG intensity reduction in 2020[(2)]	Modern Renewable share in electricity[(3)]	Installed renewable capacity in 2020 [(4)] (Wind, solar)	Installed nuclear power capacity [(5)]	Average GHG emissions intensity reduction after 2020[(6)]
EU27	-15% (2005)	N/A	20% (2020)	-	N/A	3%
China	N/A	-40%	25% (2020)	200 GW; 50GW	41 GW (2020)	3.3%
India	N/A	-20%	-	20 GW; 10GW	20 GW (2020)	3.3%
Japan	-1% (2005)	N/A	-	5 GW; 28GW	N/A	2.2%
USA	-5% (2005)	N/A	13% (2020)	-	N/A	2.5%
Russia	+27% (2005)	N/A	4.5% (2020)	-	34GW (2030)	2.6%
AUNZ	-13% (2005)	N/A	10% (2020)	-	N/A	3%
Brazil	-18% (BAU)	N/A	-	-	N/A	2.7%
Mexico	-15% (BAU)	N/A	17% (2020)	-	N/A	2.8%
LAM	-15% (BAU)	N/A	N/A	-	N/A	2.1%
CAS	N/A	N/A	N/A	N/A	N/A	2.6%
KOR	-15% (BAU)	N/A	-	8 GW; -	N/A	3.3%
IDN	-13% (BAU)	N/A	7.5% (2025)	-	N/A	2.1%
SSA	N/A	N/A	N/A	-	N/A	2.3%
CAN	-5% (2005)	N/A	13% (2020)	-	N/A	2.4%
EEU	N/A	N/A	N/A	N/A	N/A	2.6%
EFTA	N/A	N/A	N/A	N/A	N/A	3.5%
MEA	N/A	N/A	N/A	-	N/A	1.5%
NAF	N/A	N/A	20% (2020)	-	N/A	1.5%
PAK	N/A	N/A	N/A	N/A	N/A	1.9%
SAF	-17% (BAU)	N/A	N/A	N/A	N/A	2.8%
SAS	N/A	N/A	N/A	-	N/A	2.9%
SEA	N/A	N/A	15% (2020)	-	N/A	2.1%
TUR	N/A	N/A	-	20 GW;-	N/A	2.3%
TWN	N/A	N/A	N/A	N/A	N/A	3.3%

Abbreviations:
AUNZ = Australia and New Zealand
LAM = Latin America
CAS = Central Asia
KOR = South Korea
IDN = Indonesia
SSA = Sub-saharan Africa
CAN = Canada
EEU = Eastern Europe
EFTA = European Free Trade Association (Lichtenstein, Iceland, Norway, and Switzerland)
MEA = Middle East
NAF = North Africa
PAK = Pakistan
SAF= South Africa
SAS = South Asia
SEA = South-east Asia
TUR = Turkey
TWN = Taiwan

(1) Including Land-use Change, Land-use Change and Forestry (LULUCF) and relative to 2005 or business as usual (BAU) as specified in brackets. (If GHG emissions in baseline is lower, baseline trajectory is adopted for the region concerned.)
(2) Including LULUCF and relative to 2005 (If GHG intensity reduction in baseline is higher, baseline trajectory is adopted for the region concerned.)
(3) Reference quantity is always electricity production except for EU27 where it is final energy.

(4),(5) Capacity targets are minimum targets; target year is specified in brackets.
(6) %/year; GHG intensity improvement rates calculated based on Kyoto GHG equivalent emissions including LULUCF relative to GDP. (If GHG emissions (intensity) reduction in baseline is higher, baseline trajectory is adopted for the region and period concerned.)

Table S6: Targets in weak policy scenario adapted to REMIND regions

Region	GHG emissions reduction in 2020(1)	GHG intensity reduction in 2020(2)	Modern Renewable share in electricity(3)	Installed renewable capacity in 2020 (4) (Wind, solar)	Installed nuclear power capacity (5)	Average GHG emissions intensity reduction after 2020(6)
AFR	0% (BAU)	N/A	N/A	-	-	2.8%
CHN	N/A	-40%	25% (2020)	200GW; 50GW	41GW (2020)	3.3%
EUR	-15% (2005)	N/A	20% (2020)	-	-	3%
IND	N/A	-20%	N/A	20GW; 10GW	20GW (2020)	3.3%
JPN	-1% (2005)	N/A	N/A	5GW; 28GW	-	2.2%
LAM	25.8% (2005)	N/A	N/A	-	-	2.5%
MEA	0% (BAU)	N/A	N/A	-	-	1.8%
OAS	24.2% (2005)	N/A	N/A	-	-	2.3%
ROW	-5.3% (2005)	N/A	13% (2020)	20GW; -	-	2.6%
RUS	+27% (2005)	N/A	4.5% (2020)	-	34GW (2030)	2.6%
USA	-5% (2005)	N/A	13% (2020)	-	-	2.5%

Abbreviations:
AFR = Sub-saharan Africa excluding South Africa
CHN = China
EUR = EU27
IND = India
JPN = Japan
LAM = Latin America, also including Mexico
MEA = Middle East, North Africa, and Central Asia
OAS = Other Asia, also including Pakistan
ROW = Rest of the world
RUS = Russia
USA = United States of America

(1) Including Land-use Change, Land-use Change and Forestry (LULUCF) and relative to 2005 or business as usual (BAU) as specified in brackets. (If GHG emissions in baseline is lower, baseline trajectory is adopted for the region concerned.)
(2) Including LULUCF and relative to 2005 (If GHG intensity reduction in baseline is higher, baseline trajectory is adopted for the region concerned.)
(3) Reference quantity is always electricity production except for EUR, where it is final energy.
(4),(5) Capacity targets are minimum targets; target year is specified in brackets.
(6) Represented in %/ year GHG intensity improvement rates calculated based on Kyoto GHG equivalent emissions including LULUCF relative to GDP.

Sensitivity analysis

This section presents further sensitivity analysis of our results to other influencing factors and scenario assumptions as a complementary to Section 8 on the main text. The sensitivity analysis scenarios are described in Table S7.

Table S7: Sensitivity analysis scenarios

Scenario Name	Scenario Type	Near-term Target / Fragmented Action	Fragmented Action until	Long-term target	Burden sharing / convergence year	Global bio-energy potential
500	Immediate	None	N/A	500 ppm CO2e	TAX	300 EJ/yr
500-PC	Immediate	None	N/A	500 ppm CO2e	PC (2050)	300 EJ/yr
450-lowbio	Immediate	None	N/A	450 ppm CO2e	TAX	100 EJ/yr
450-PC-lowbio	Immediate	None	N/A	450 ppm CO2e	PC (2050)	100 EJ/yr
450-PC-2100	Immediate	None	N/A	450 ppm CO2e	PC (2100)	300 EJ/yr
RefPol-450-EE	Delay	Weak	2020	450 ppm CO2e	EE	300 EJ/yr
RefPol2030-450	Delay	Weak	2030	450 ppm CO2e	TAX	300 EJ/yr
RefPol2030-500	Delay	Weak	2030	500 ppm CO2e	TAX	300 EJ/yr
RefPol2030-450-PC	Delay	Weak	2030	450 ppm CO2e	PC (2050)	300 EJ/yr
RefPol2030-500-PC	Delay	Weak	2030	500 ppm CO2e	PC (2050)	300 EJ/yr

Burden-sharing

In addition to the reference tax regime and the PC convergence framework, we have investigated a new effort-sharing scheme, the so-called Equal Mitigation Efforts (EE), in which relative climate policy costs are equalized across all regions (cf. Tavoni et al., 2013). Therefore, in scenario “RefPol-450-EE”, after the target adoption (from 2020 onwards), at every model time step, all the regions incur the same amount of consumption losses from baseline per GDP as the world-average, ensuring an equal distribution of mitigation efforts:

$$\left(\frac{\Delta C(r,t)}{Y(r,t)}\right) = \left(\frac{\Delta C_{World}(t)}{Y_{World}(t)}\right) \qquad \text{(S.9)}$$

Figure S16 depicts the regional mitigation costs across different burden-sharing rules. In Figure S17, we compare the GHG allocations between the PC scheme and the EE framework. Differences in regional mitigation costs across various allocation schemes can then be explained by differences in regional reduction targets and domestic mitigation potentials.

Affected by its low-income levels, Russia receives higher emissions allowances under the effort-sharing regime compared to the tax and the PC scheme. As a result, Russia encounters very low mitigation costs in the EE framework. On the other hand, industrialized countries, Europe and USA, face higher mitigation costs in the EE framework corresponding to their higher reduction pledges in the effort-sharing scheme. When comparing the reduction targets in the EE framework versus the PC scheme, India receives lower emissions allowances through the first half and higher emissions allowances through the second half of the century. Correspondingly, compared to PC scheme, India encounters higher mitigation costs towards 2050 and lower 2010-2100 mitigation costs. The rest of the developing countries have lower mitigation costs than in the tax and PC scheme due to their lower reduction targets in the EE burden sharing. The EE framework implies higher reductions mainly from 2040 onwards for China compared to the PC scheme. As a result, it encounters higher mitigation costs in EE framework relative to the PC scheme and the tax case.

Convergence year

Since the results obtained from the PC scheme strongly depend on the convergence year chosen, this section explores the impact of a later convergence year than 2050 on the emissions allocations and mitigation costs. In this analysis, we thus consider a new scenario “450-PC-2100” with a later convergence in year 2100. Figure S18 compares the GHG allocations in scenario “450-PC-2100” with the previously analyzed scenario “450-PC” with convergence in 2050. The reference year for grandfathering is the year 2010 in both scenarios. A later convergence implies higher reductions for highly populated regions with a low initial share of global emissions such as India and the rest of the developing countries, while it results in much lower reductions for industrialized countries having a low share in global population but a high share of global emissions at the start of the international climate regime. This finding can be explained according to Eq. (9) and is in accordance with the literature (Leimbach et al., 2003; den Elzen et al., 2005). A high initial share of global emissions and descending share of global population distinguishes China from other developing countries. Correspondingly, the mitigation costs of India and the rest of the developing countries increase in scenario “450-PC-2100” relative to “450-PC”, while industrialized countries, Russia and also China benefit from a later convergence (cf. Figure S19).

Time of participation in global mitigation effort

As another dimension of our sensitivity analysis, we delay the time of participation in global mitigation effort until 2030. In scenario “RefPol2030-500”, the global mitigation costs over the whole century rises to 2.3% of global consumption in the baseline scenario versus 1.9% in the “500” scenario. Delaying cooperative action until 2030 in scenario “RefPol2030-450” raises the global mitigation costs to 3.7% versus 2.7% in scenario “450”. Thus, at the lower stabilization target, the impact of delay on an increase of aggregated mitigation costs is higher. This finding is in accordance with earlier studies (Clarke et al., 2009; Jakob et al., 2012).

Figure S20 shows the difference in regional primary energy supply between the "RefPol2030-450" and the "450" scenario. A longer term delayed action until 2030 results in a higher conventional usage of fossil fuels particularly in regions such as China, India and the rest of the developing countries with non-ambitious near-term reduction commitments in fragmented actions. On the other hand, it raises the application of BECCS and fluctuating renewables through long-term periods against a sooner implementation of a global climate regime in 2020.

Figure S21 shows the impact of a delay until 2030 on the regional climate-mitigation costs and its determinants. We elaborated on the consequences of a delayed action until 2020 in Section 6; here, we explain the marginal effects of a longer-term delay until 2030. At first, we conclude that if the time of participation in global mitigation effort is delayed until 2030, among domestic effects, higher energy system investment costs arise in all regions due to further lock-in with carbon-intensive technologies in the near to medium-term. Significant lock-in of carbon-intensive technologies in China and India continues even through long-term periods (cf. Figure S20). Furthermore, a longer-term delay results in higher emissions at early stages for regions with non-ambitious early reduction commitments in the weak policy scenario compared to a sooner target adoption in 2020. Therefore, India, as an exporter of permits towards the mid-century derives less revenues from emissions trading. Moreover, a longer-term delay further increases the carbon price after the target adoption. Aggregating over the complete horizon, this further increases the mitigation costs of importers of permits such as Europe, and importers of permits through the second half of the century such as India and the rest of the developing countries. On the other hand, this effect results in higher gains for net exporters of permits such as Russia.

Discount rate

The discount rate, which is used to make costs that occur in different points in time comparable by converting them to net present values, is a crucial factor in determining whether immediate action turns out to be beneficial. The total net costs of delayed action is regarded as a weighted average of additional mitigation costs relative to immediate action in all periods, with higher discount rates putting less weight on costs that materialize further in the future. Through the main text, we applied the price of macro-economic good as a discount rate for consistency with the model-internal discounting, and to ensure that the decomposition analysis as described in Section 2.2 is complete. The corresponding discount rates and discount factors are represented in Table S8 and Table S9 (see also Figure S22). Here, we analyse the influence of variations in the discount rate on regional mitigation costs and winners and losers from the delayed action. Table S10 shows the net costs of delayed action as a function of the discount rate for the periods 2010–2050 and 2010–2100 and different scenarios. It clarifies which regions gain while the others lose from a delayed action if various discount rates are applied. At the global level, an immediate action involves additional costs in the short run, which are counterbalanced by cost savings in the long run. Our results confirm the conclusion that the global net costs because of delayed action decrease with a higher discount rate as a large part of additional costs materialize in later periods (cf. Figure S23).

Table S8: *model-internal discount factors for baseline and selected climate-policy scenarios*

Scenario	2005	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Base	1.0	0.7958	0.4201	0.2275	0.1278	0.0734	0.0388	0.0270	0.0161	0.0102	$6.46\text{x}10^{-3}$
450	1.0	0.7958	0.4249	0.2334	0.1328	0.0774	0.0411	0.0287	0.0173	0.0109	$6.93\text{x}10^{-3}$
450-PC	1.0	0.7958	0.4200	0.2304	0.1310	0.0762	0.0404	0.0282	0.0169	0.0106	$6.77\text{x}10^{-3}$

Note: The discount factors are calculated as the price of macro-economic good at time step *t* relative to the price in the base year: $d(t) = {P^G(t)}/{P^G(2005)} \quad \forall t.$

Table S9: *model-internal discount rates in % p.a.*

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Base	5.742	6.387	6.143	5.790	5.675	4.935	5.022	5.023	4.691	5.383
450	5.715	6.221	6.013	5.637	5.536	4.914	4.995	4.994	4.663	5.331
450-PC	5.832	6.234	6.017	5.656	5.551	4.929	5.010	5.009	4.673	5.338

Note: The discount rates are calculated as: $\delta(t) = \left(\frac{d(t)}{d(t-1)}\right)^{\left(1/(ts(t)-ts(t-1))\right)} - 1 \quad \forall t.$

Europe incurs additional costs in the delayed action scenario "RefPol-450" due to ambitious early emissions reduction commitments in the weak policy scenario, but the costs of immediate action slightly exceeds the level of delayed action through later periods. Correspondingly, our results conclude that Europe's net costs of delayed action rises with increasing the discount rate. The net costs of delayed action remains nearly constant for the USA over the given ranges of discount rates, while for the rest of the industrialized countries it decreases when increasing the discount rate as a large part of additional costs materialize in later periods. For Russia, an immediate action involves additional costs in the short-term, but the costs of delayed action largely exceed the immediate action through later periods (cf. Figure S23). As a result, the net costs of delayed action largely reduce with increasing the discount rate, and the delayed action becomes even beneficial at high discount rates. Other regions with non-ambitious early commitments in the weak policy scenario such as India and the rest of the developing countries incur a similar correlation between the discount rate and the net costs of delayed action.

Table S10: *Discounted net costs of delayed action as % of consumption*

	Scenario RefPol-450 rel. to 450								Scenario RefPol-450-PC rel. to 450-PC							
	2010-2050				2010-2100				2010-2050				2010-2100			
	3%	5%	10%	int.	3%	5%	10%	int.	3%	5%	10%	int.	3%	5%	10%	int.
EUR	0.2	0.4	0.7	0.1	0.1	0.2	0.7	0.1	0.1	0.2	0.5	0.2	-0.1	0.0	0.5	0.2
USA	0.1	0.1	0.2	-0.1	0.2	0.1	0.2	0.0	-0.3	-0.2	0.3	0.0	-0.5	-0.4	0.2	-0.2
Rind	0.2	0.1	-0.2	0.0	0.6	0.3	-0.2	0.2	-0.2	-0.1	0.1	0.0	-0.3	-0.2	0.1	0.0
CHN	-0.6	-0.5	-0.2	-0.6	-0.8	-0.6	-0.2	-0.5	-0.6	-0.5	-0.1	-0.9	-0.8	-0.7	-0.2	-0.8
IND	-0.2	-0.2	-0.4	-0.3	0.0	-0.2	-0.3	0.0	1.5	0.9	-0.6	0.1	2.5	1.7	-0.4	0.9
RDev	0.6	0.2	-0.5	0.4	1.2	0.7	-0.4	0.7	1.0	0.5	-0.9	0.5	2.4	1.4	-0.7	1.0
RUS	1.1	-0.5	-4.1	0.3	3.9	1.3	-3.7	1.0	-2.6	-1.9	-0.3	-0.2	-3.8	-2.7	-0.5	-1.2
World	0.2	0.1	-0.1	0.1	0.4	0.3	0.0	0.2	0.2	0.1	-0.1	0.1	0.4	0.3	0.0	0.2

Particularly, in the PC convergence framework, the time preference of monetary transfers from the global carbon market is a determining factor for the incremental costs or benefits of delayed action. Early action involves additional costs in early periods for Russia, while later on significant benefits arise from selling permits at higher prices in delayed action. Our results correspondingly indicate that the avoided mitigation costs resulting from a delayed action for Russia decrease if the discount rate rises. On the other hand, net costs of delayed action of India and the rest of the developing countries decrease at a higher discount rate as the costs of delayed action only materialize in later periods, which mainly arise from the higher costs paid for purchasing permits through the second half of the century. The delayed action becomes even beneficial in those regions at high discount rates. For China, the benefits of delayed action decrease at a higher discount rate as the cost savings of delayed action materialize in later periods. As a complementary to this analysis, Figure S24 depicts the regional mitigation costs of different scenarios at various discount rates.

Supplementary figures

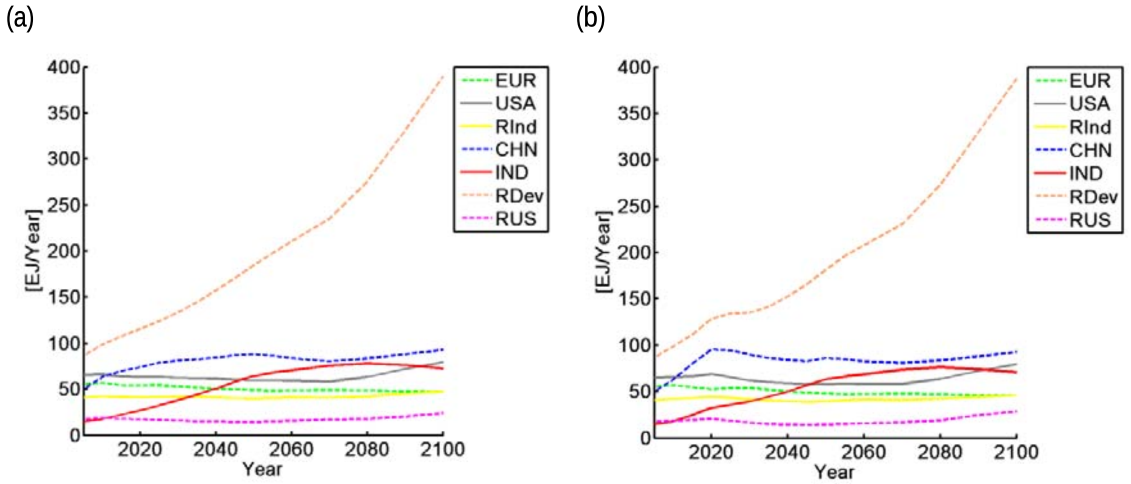


Figure S1: Final energy demand over regions and time: (a) Scenario "450-PC", and (b) Scenario "RefPol-450-PC".

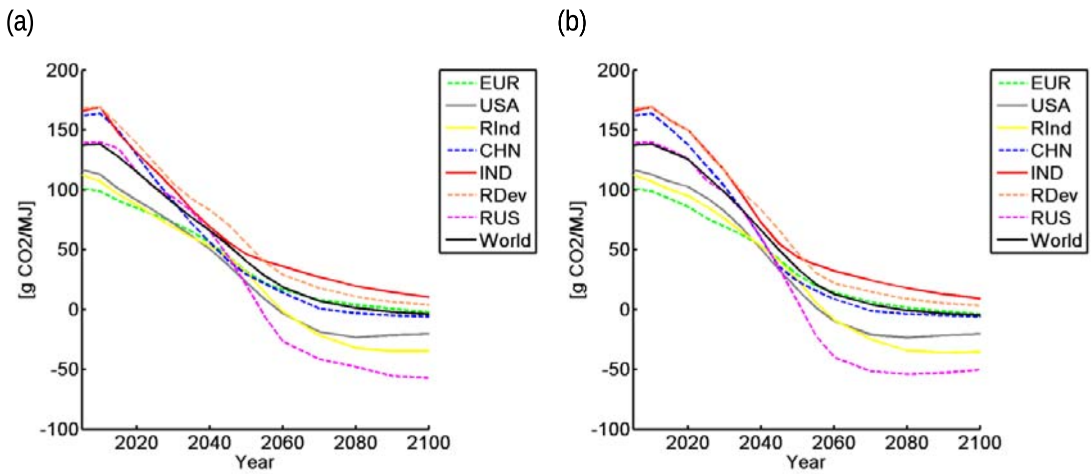


Figure S2: GHG per final energy over regions and time: (a) Scenario "450-PC", and (b) Scenario "RefPol-450-PC".

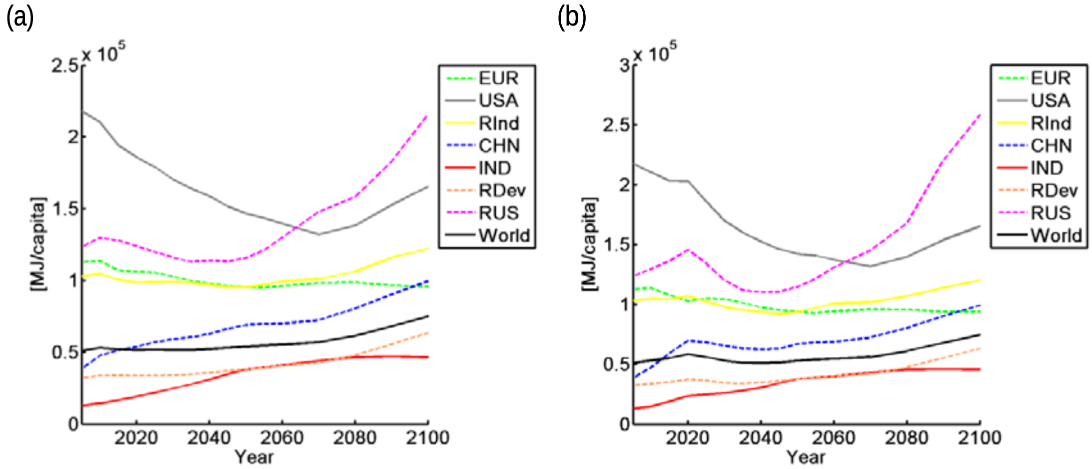


Figure S3: FE per capita over regions and time: (a) Scenario "450-PC", and (b) Scenario "RefPol-450-PC".

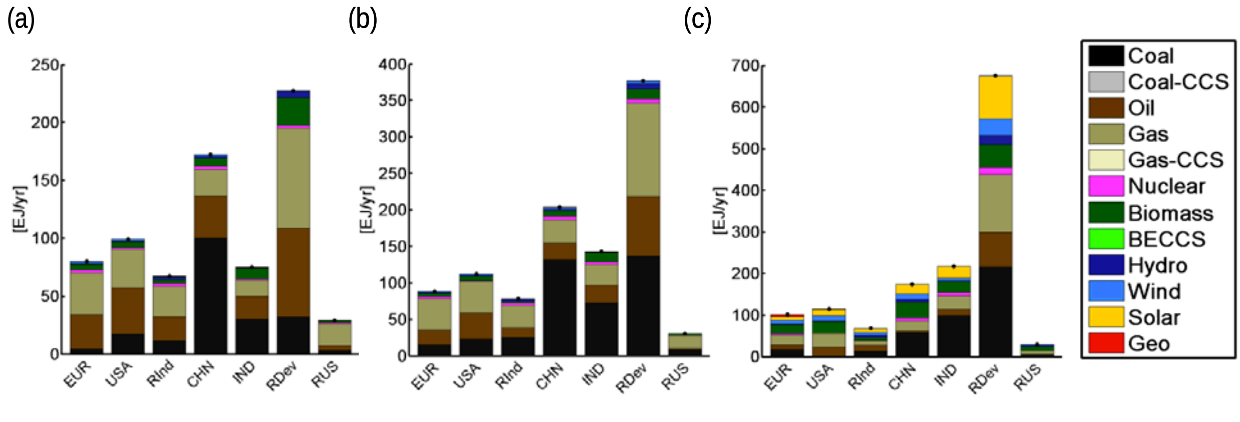


Figure S4: Primary energy mix over regions in scenario "Base": (a) 2030, (b) 2050, and (c) 2100.

(a) (b) (c)

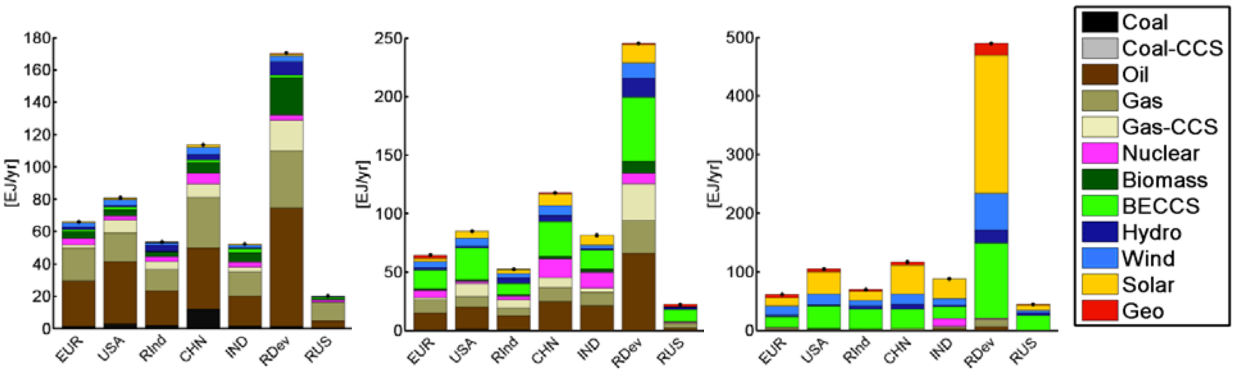


Figure S5: Primary energy mix over regions in scenario "450": (a) 2030, (b) 2050, and (c) 2100.

(a) (b)

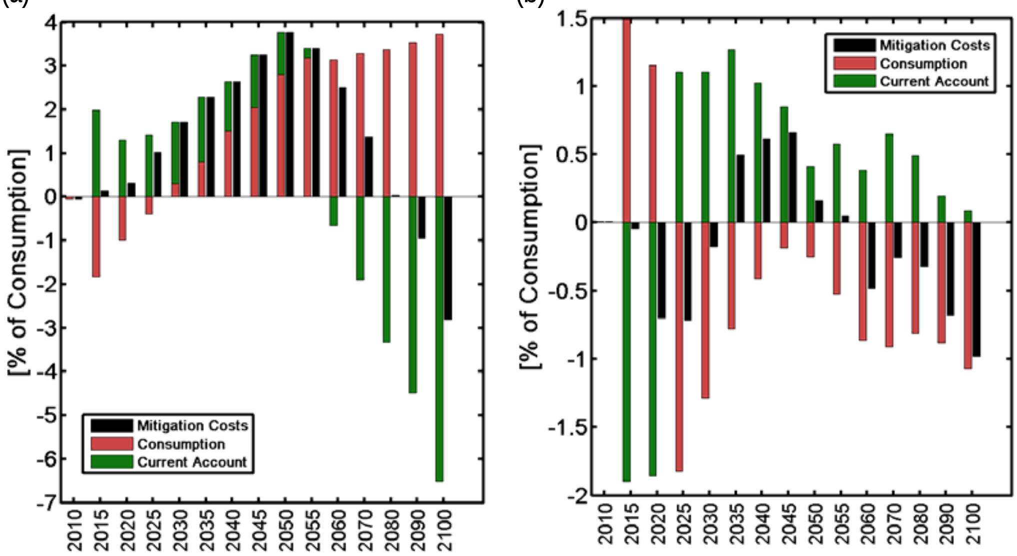


Figure S6: Mitigation costs over time for USA: (a) Decomposition of mitigation costs for scenario "450-PC"; (b) Decomposition of mitigation costs differences between "RefPol-450-PC" and "450-PC" scenarios. (Positive values indicate higher mitigation costs in "RefPol-450-PC" scenario compared to "450-PC"; the black bar shows total differences in mitigation costs, and the stacked bar to the left shows the components).

(a) (b)

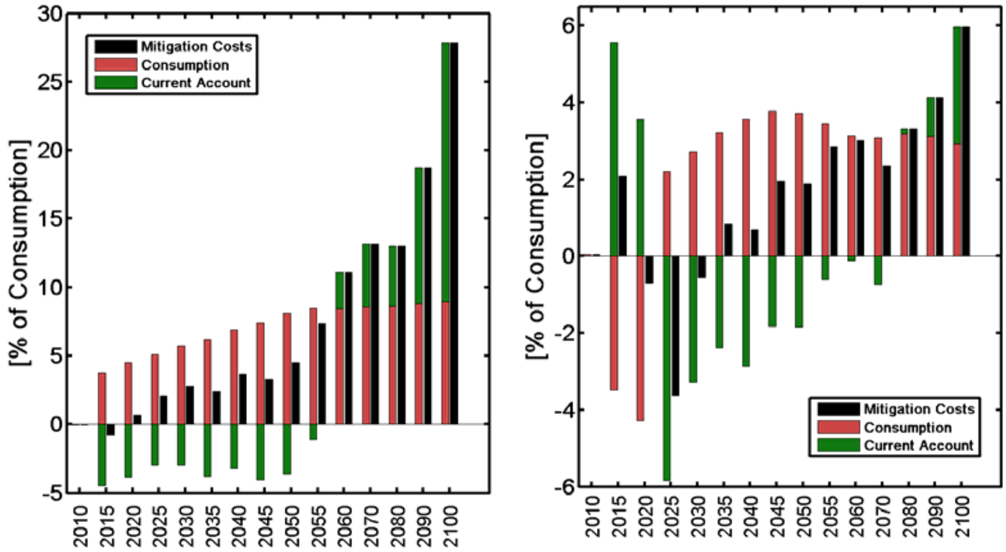


Figure S7: Mitigation costs over time for India: (a) Decomposition of mitigation costs for scenario "450-PC"; (b) Decomposition of mitigation costs differences between "RefPol-450-PC" and "450-PC" scenarios. (Positive values indicate higher mitigation costs in "RefPol-450-PC" scenario compared to "450-PC"; the black bar shows total differences in mitigation costs, and the stacked bar to the left shows the components).

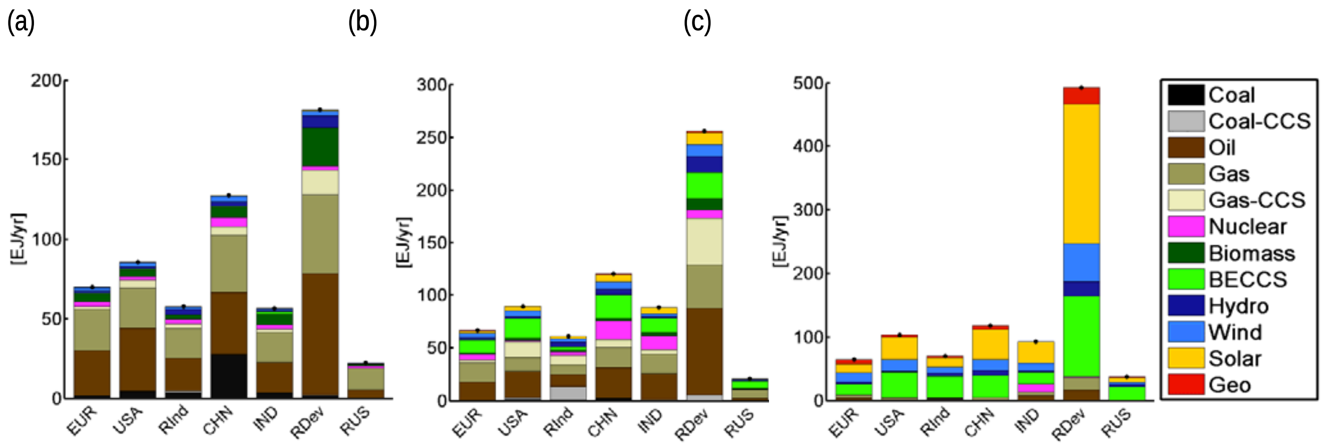


Figure S8: Primary energy mix over regions in the "500" scenario: (a) 2030, (b) 2050, and (c) 2100.

(a) (b)

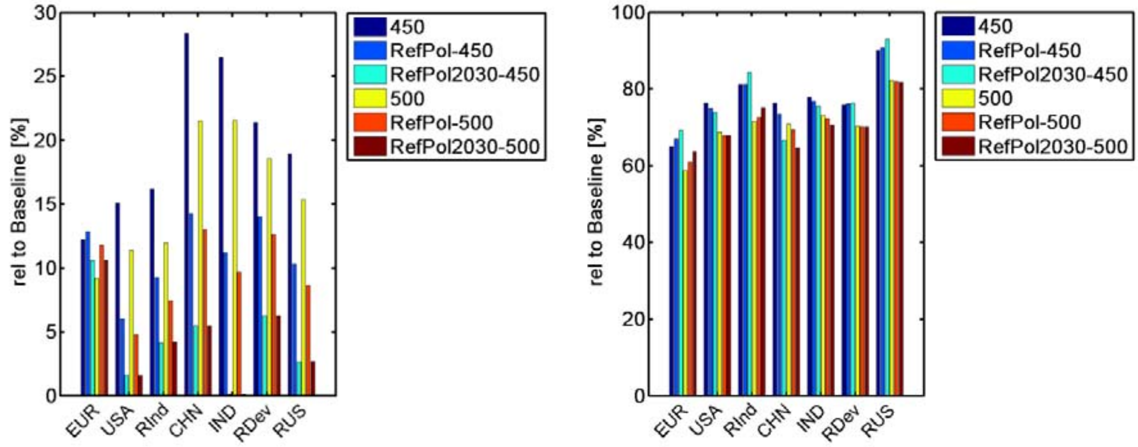


Figure S9: Cumulative GHG emissions reductions from baseline over regions: (a) 2005-2030, and (b) 2005-2100.

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

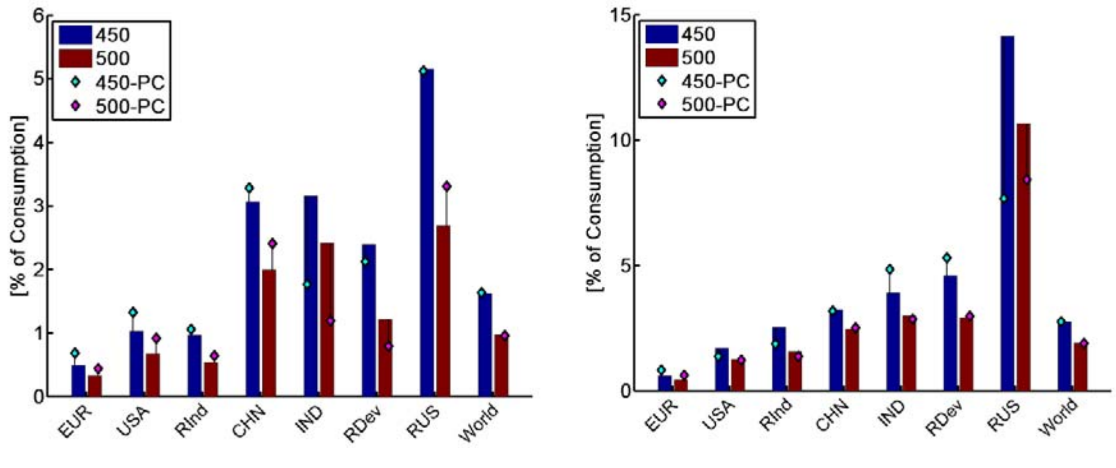


Figure S10: Discounted mitigation costs as a percentage of baseline consumption over regions, different time horizons and climate stabilization targets: (a) 2010-2050 and (b) 2010-2100.

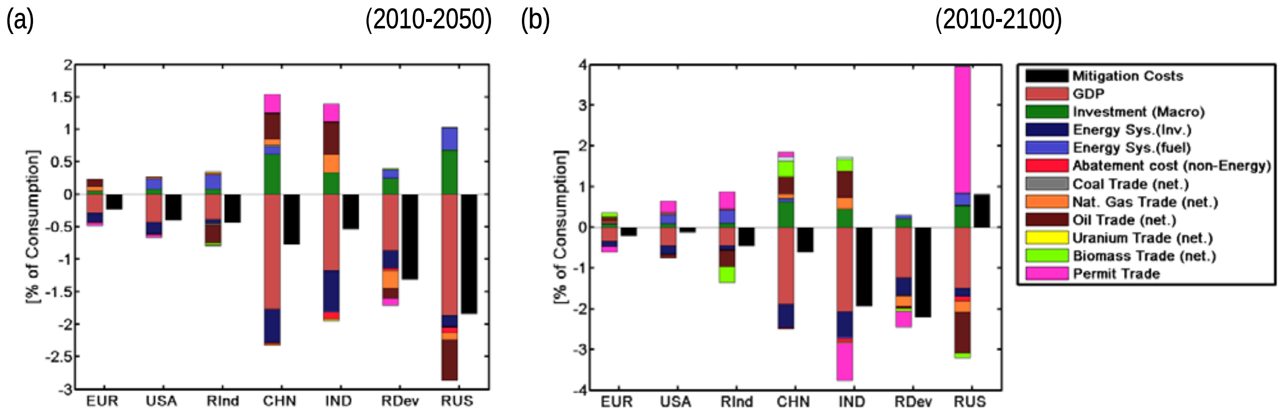


Figure S11: Decomposition of discounted mitigation costs differences between "500-PC" and "450-PC" scenarios over regions: (a) 2010-2050 and (b) 2010-2100. (Positive values indicate higher mitigation costs in "500-PC" scenario compared to "450-PC"; the black bar shows total differences in mitigation costs, and the stacked bar to the left shows the components).

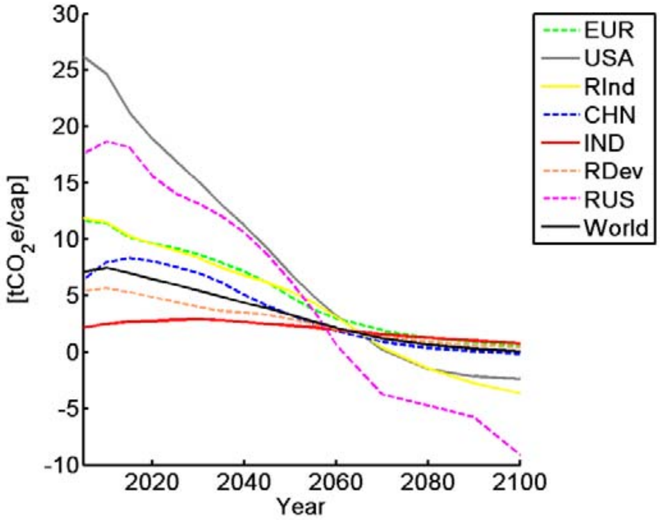


Figure S12: GHG per-capita emissions over regions and time in scenario "500-PC".

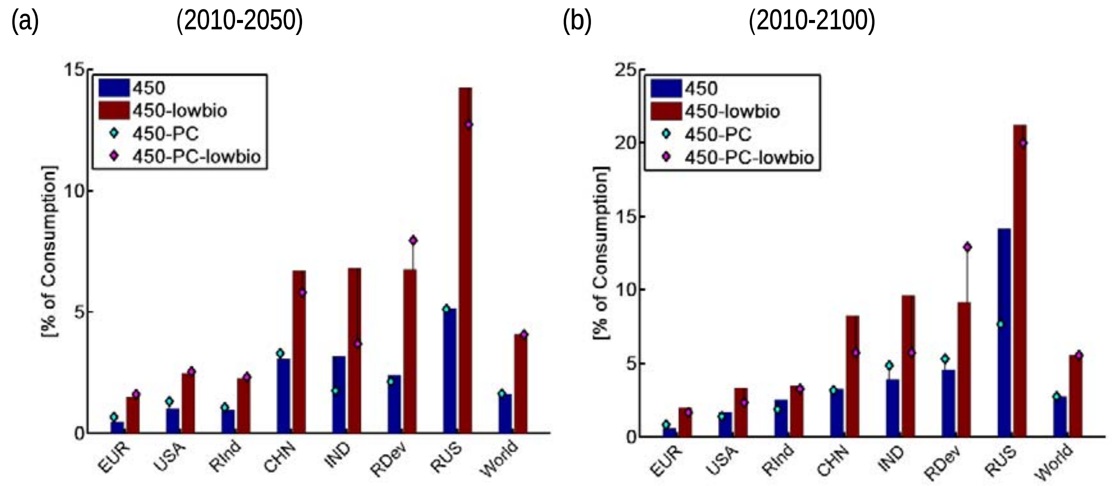


Figure S13: Discounted mitigation costs as a percentage of baseline consumption over regions: (a) 2010-2050 and (b) 2010–2100.

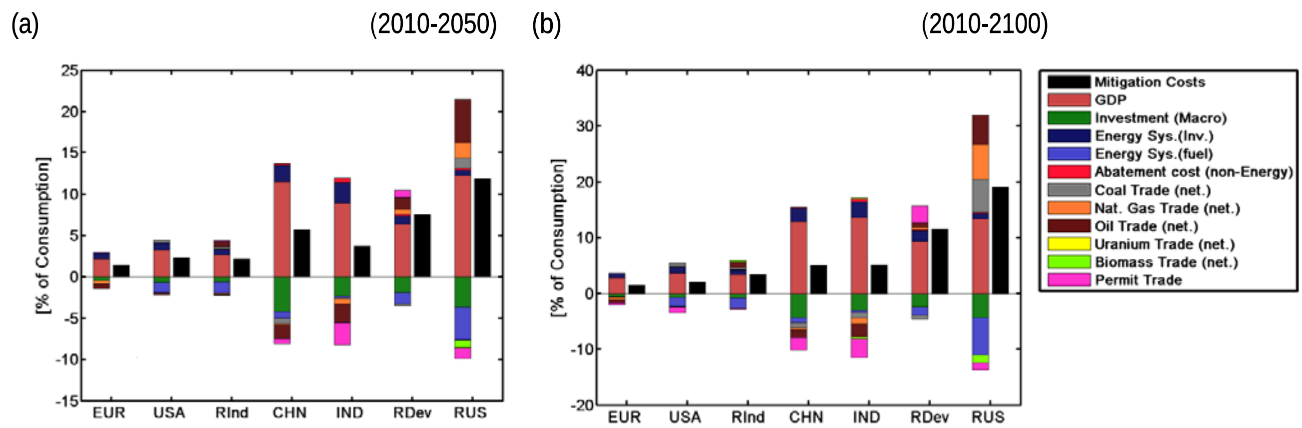


Figure S14: Decomposition of discounted mitigation costs for scenario "450-PC-lowbio" as a percentage of baseline consumption over regions: (a) 2010-2050 and (b) 2010-2100. (The black bar shows total mitigation costs, and the stacked bar to the left shows the components).

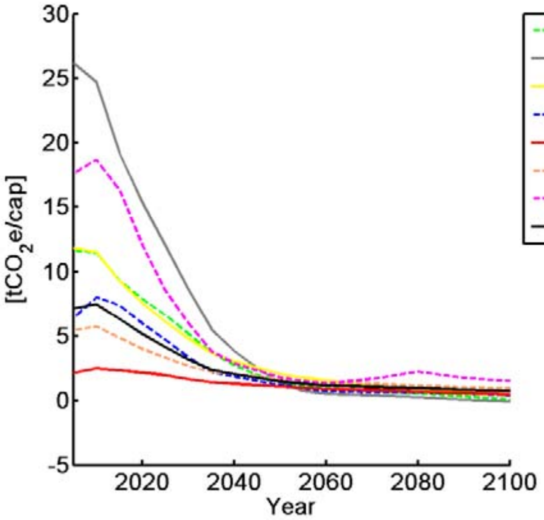


Figure S15: GHG per-capita emissions over regions and time in scenario "450-PC-lowbio".

(a) (b)

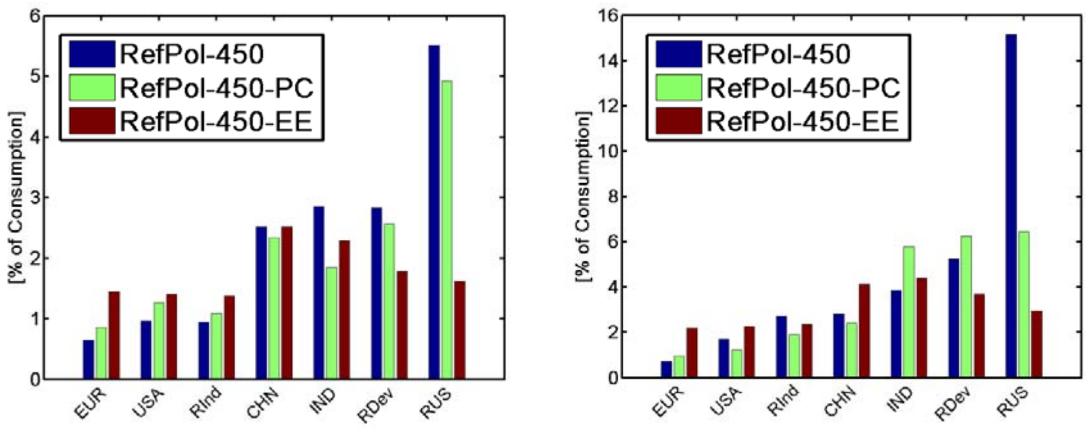


Figure S16. Discounted mitigation costs as a percentage of baseline consumption over regions: (a) 2010-2050 and (b) 2010–2100.

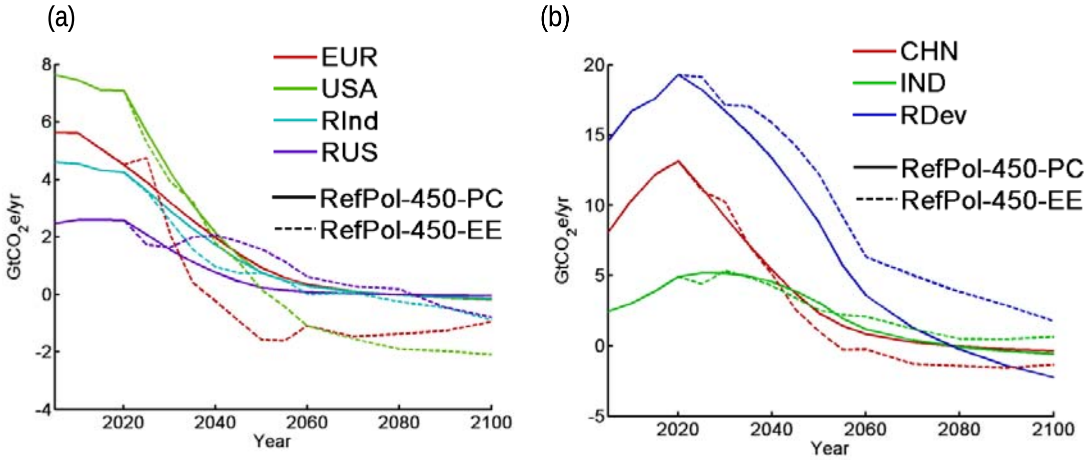


Figure S17: Emissions allowances in scenario “RefPol-450-EE” versus scenario “RefPol-450-PC”: (a) Industrialized regions and Russia, (b) Developing regions.

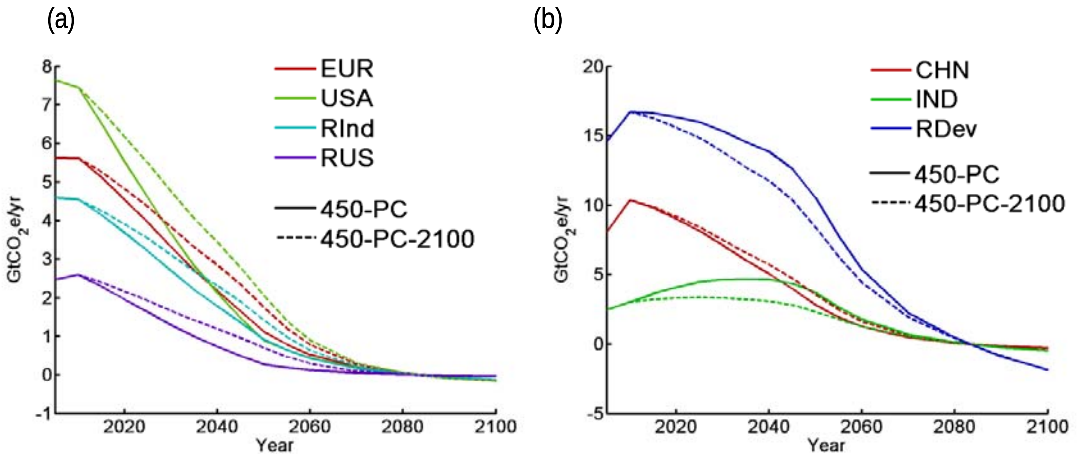


Figure S18: Emissions allowances in scenario “450-PC-2100” versus scenario “450-PC”: (a) Industrialized regions and Russia, (b) Developing regions.

(a) (b)

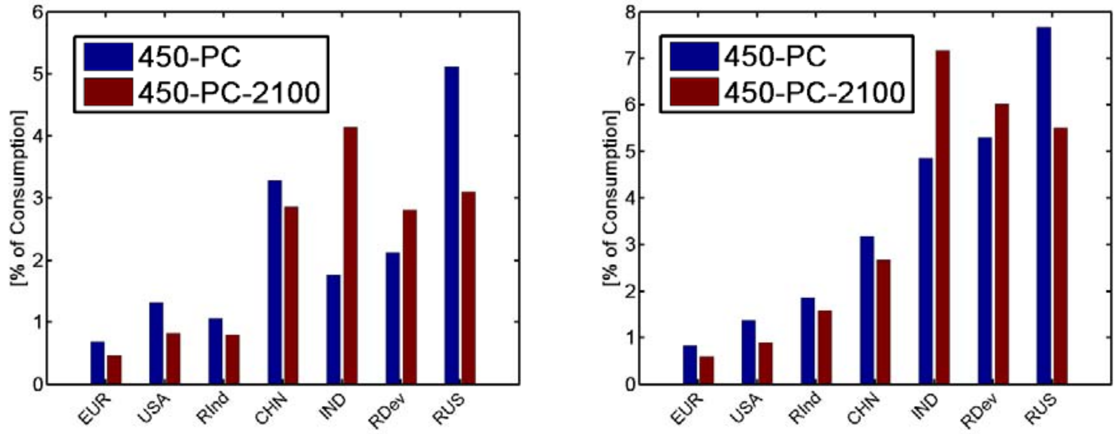


Figure S19: Discounted mitigation costs as a percentage of baseline consumption over regions: (a) 2010-2050 and (b) 2010–2100.

(a) (b) (c)

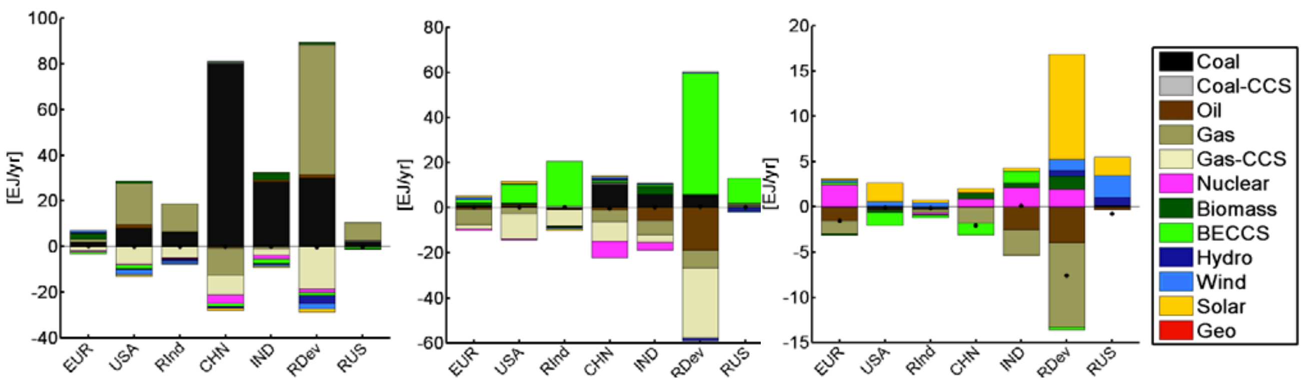


Figure S20. Difference in primary energy supply between the "RefPol2030-450" and "450" scenarios over regions: (a) 2030, (b) 2050, and (c) 2100. (Positive values indicate higher production in the "RefPol2030-450" scenario compared to the "450" scenario).

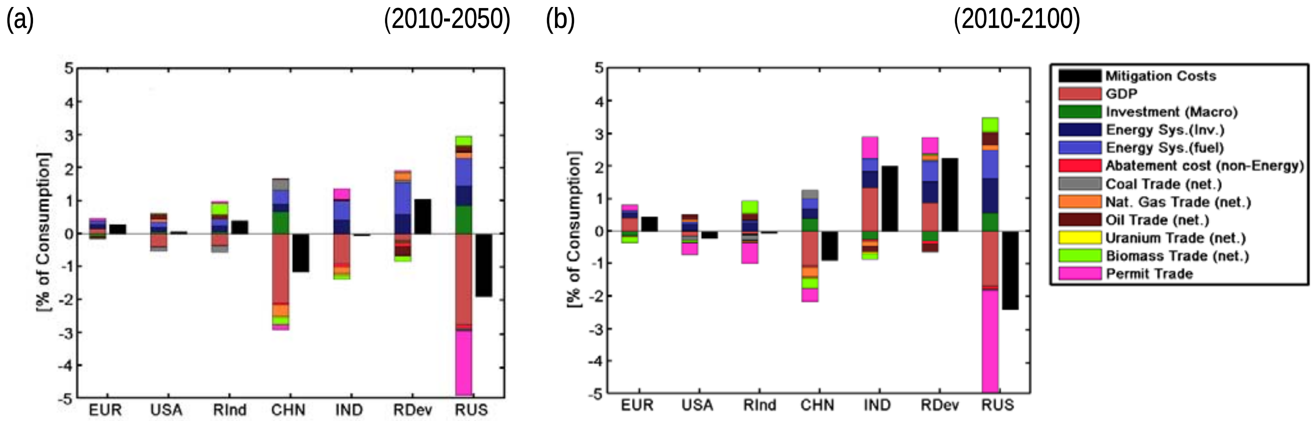


Figure S21: Decomposition of discounted mitigation costs differences between "RefPol2030-450-PC" and "450-PC" scenarios over regions: (a) 2010-2050 and (b) 2010-2100. (Positive values indicate higher mitigation costs in "RefPol2030-450-PC" scenario compared to "450-PC"; the black bar shows total differences in mitigation costs, and the stacked bar to the left shows the components).

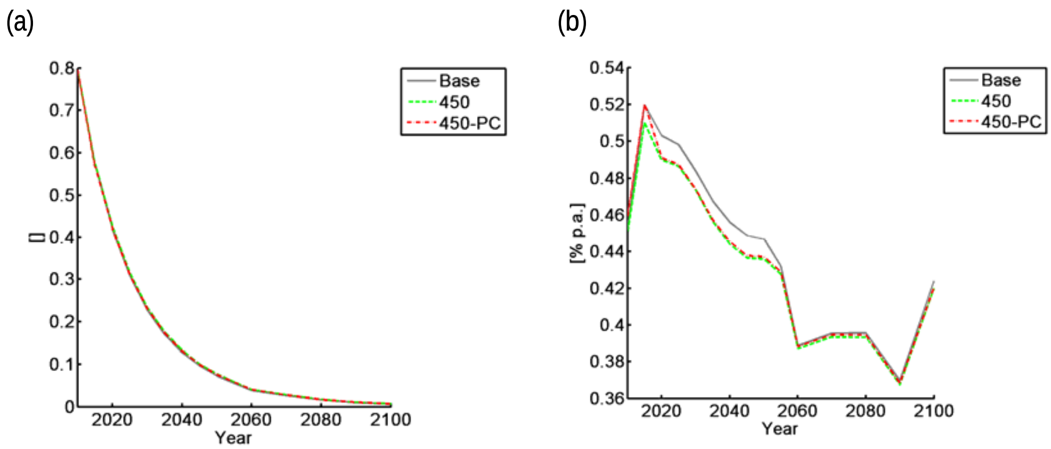


Figure S22: (a) model-internal discount factors, (b) model-internal discount rates.

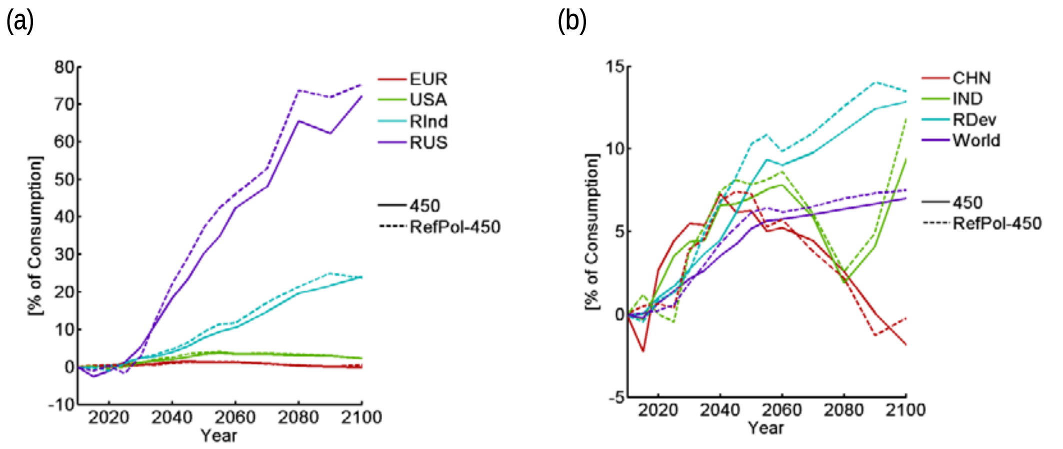
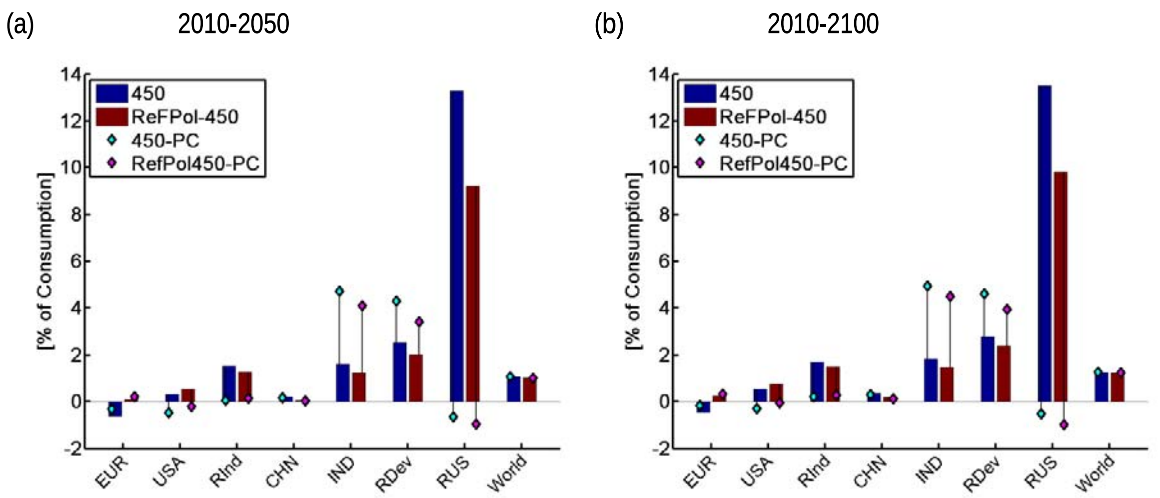


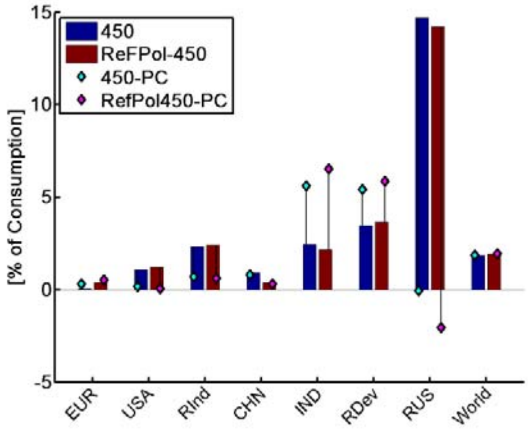
Figure S23: Mitigation costs over time for selected regions in "450" and "RefPol-450" scenarios: (a) Industrialized regions and Russia, (b) Developing regions and the world.

Figure S24: Discounted mitigation costs as a percentage of baseline consumption over regions: 2010-2050 (left) and 2010-2100 (right); 10% discount rate (a, b), 5% discount rate (c, d), 3% discount rate (e, f), and model-internal discount rate (g, h).

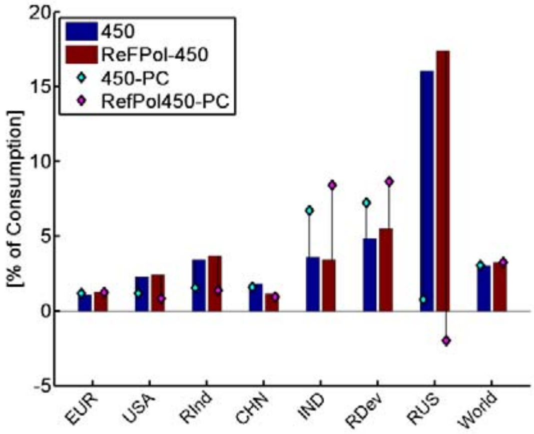


LIMITS

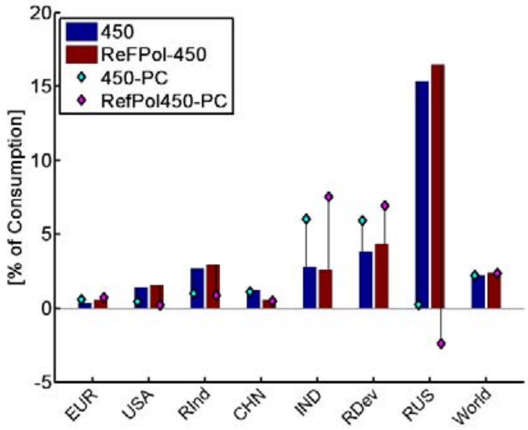
(c)



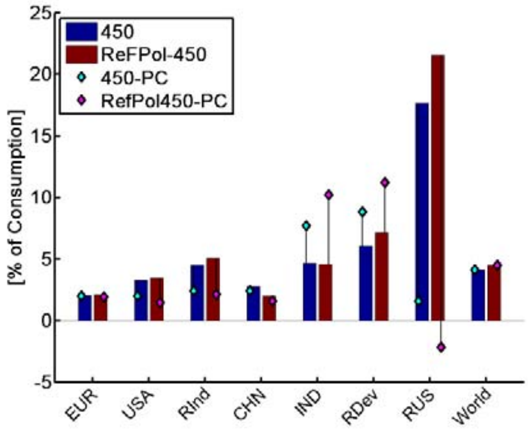
(d)



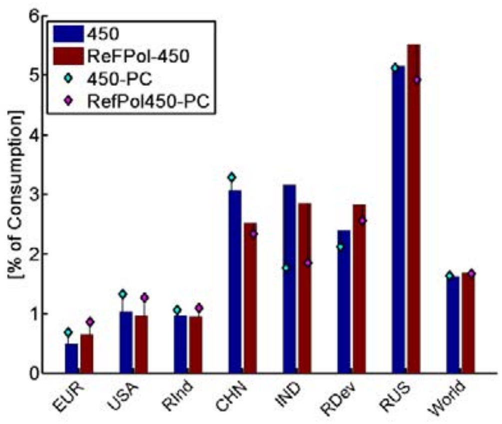
(e)



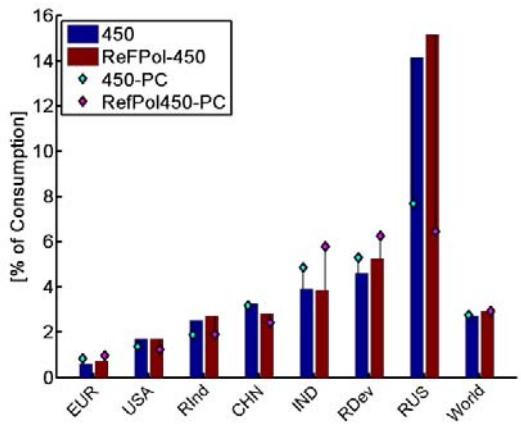
(f)



(g)



(h)



Definition of main symbols

The main symbols used in the model formulation and the units are represented in Table S11.

Table S11*: Definition of main symbols*

Symbol	Description	Unit
A	Non-energy system abatement costs	billionUS$2005/yr
C	Consumption	billionUS$2005/yr
CA	Current Account	billionUS$2005/yr
cp_i^E	Current value price of energy carrier i	US$2005/GJ
cp^P	Current value price of permits	US$2005/t CO_2
d	Discount factor	-
δ	Discount rate	-
E	Energy system costs	billionUS$2005/yr
E_r	Regional GHG emissions	Mt CO_2-e
E_W	Global GHG emissions	Mt CO_2-e
I	Macroeconomic capital stock investments	billionUS$2005/yr
M	Mitigation costs (when the policy scenario is compared against the baseline.)	billionUS$2005/yr
P_i^E	Present value price of energy carrier i	US$2005/GJ
P^G	Present value price of macroeconomic good	-
P^P	Present value price of permits	US$2005/t CO_2
P_r	Regional population	Million capita
P_W	Global population	Million capita
r	Region	-
T	Total optimization period	100 years
T_1	Reference year for grandfathering in PC scheme	-
T_2	Target year for convergence of per-capita emissions rights	-
t	Time	Year
ts	Model time step	5 years
X_i^E	Net export of energy carrier i	EJ/yr
X^G	Net export of aggregated good	billionUS$2005/yr
X^P	Net export of permits	Gt CO_2-e/yr
Y	GDP	billionUS$2005/yr
ΔA	Difference in non-energy system abatement costs	billionUS$2005/yr
$\overline{\Delta A}$	Inter-temporally aggregated difference in non-energy system abatement costs	billionUS$2005
ΔC	Difference in consumption	billionUS$2005/yr
$\overline{\Delta C}$	Inter-temporally aggregated difference in consumption	billionUS$2005
ΔCA	Difference in current account	billionUS$2005/yr
ΔE	Difference in energy system costs	billionUS$2005/yr
$\overline{\Delta E}$	Inter-temporally aggregated difference in energy system costs	billionUS$2005
ΔI	Difference in macroeconomic investments	billionUS$2005/yr
$\overline{\Delta I}$	Inter-temporally aggregated difference in macroeconomic investments	billionUS$2005
ΔM	Difference in mitigation costs (when two policy scenarios are compared.)	billionUS$2005/yr
$\overline{\Delta M}$	Inter-temporally aggregated difference in mitigation costs	billionUS$2005

ΔY	Difference in GDP	billionUS$2005/yr
$\overline{\Delta Y}$	Inter-temporally aggregated difference in GDP	billionUS$2005
ΔP^G	Difference in present value price of macroeconomic good	-
BASE	No-policy baseline scenario	-
POL	Policy scenario	-
REF	Reference scenario in comparison	-

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