

The Role of Technological Flexibility for the Distributive Impacts of Climate Change Mitigation Policy

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We analyze the relevance of technological flexibility on the regional distribution of mitigation costs in climate policy scenarios within a global multi-regional integrated assessment model. The scenarios consider different assumptions on the availability of low-carbon technologies and on the initial allocation of emission permits. We focus on a decomposition of regional consumption losses into contributions from three effects: domestic efforts, devaluation of tradable fossil energy endowments, and gains or losses on the emission permit market.

Our key results are: (i) The initial allocation scheme for emission permits has a greater impact on regional mitigation costs, when the application of the considered low-carbon technologies is restricted, because the monetary permit trade volume increases due to a higher global carbon price. (ii) Mitigation costs of the exporters of fossil energy carriers can largely be attributed to a devaluation of tradable fossil energy endowments. (iii) Assumptions on the availability of low-carbon technologies have a significant impact on both the regional shares in the global emission reduction effort and regional revenues from energy trade.

We draw the conclusion that the availability of a broad portfolio of low-carbon technologies could facilitate negotiations on the question which emission permit allocation schemes to adopt in a global cap-and-trade system.

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1 Introduction

An ambitious climate change mitigation policy leads to significant welfare redistributions among world regions. Several studies have recently assessed the regional costs of CO₂ emission reductions in different scenarios, in order to identify key factors and uncertainties that could explain the regional cost distribution ([2], [6], [15], [11], [14], [22]).

The flexibility of the energy system to redirect investments into low-carbon technologies has already been identified as a key influence factor even on global mitigation costs in studies which consider a globally aggregated structure ([2], [3], [8], [12]). The **technological flexibility** is higher, when more technological options are available. In general, this leads to lower carbon prices and hence a modification of the measures undertaken to comply with the climate policy goal.

More attention has recently been paid to the analysis of regional mitigation costs in multi-regional models. Besides technological flexibility, which applies in a similar way to individual regions and on a global aggregate, other key factors have been identified that arise from interactions among model regions. One key factor is the sharing of global emission reductions among regions. If a global cap-and-trade system is assumed, regional carbon prices level out. The pareto solution of a multi-regional model implies that the necessary emission reductions are shared among regions such that global welfare is maximized. If technological flexibility is reduced, regional shares can be assumed to change. In consequence, regional measures to reduce emissions are modified. We define this impact of the technological flexibility as the *domestic effect*, as it is not directly related to trade among world regions.

In a multi-regional model, further key factors arise from the trade with energy carriers ([15]): Due to the redirection of investments towards low-carbon technologies in regional energy systems, the global demand for fossil energy carriers decreases, resulting in a **devaluation of fossil energy endowments**. Assumptions on the availability of particular technologies have an impact on the strength of this devaluation. Especially, the availability of Carbon Capture and Sequestration (CCS) allows for an extended use of coal under climate policy. The devaluation of coal resources is reduced thereby. We define the consequences of devalued fossil energy carriers on regional mitigation costs as *energy trade effect*.

The regional **initial allocation with emission permits** has been identified as another key factor to explain regional costs ([14], [7], [20], [22]). The question arises whether this effect can be separated from the implications of technological flexibility. It has been shown that the initial allocation of emission permits does not affect regional shares of the global emission reduction, if a free flow of capital among regions is assumed ("separability of efficiency and equity", see [17] and references there in). In other words: From the perspective of a global cap-and-trade system, the initial allocation determines

Effect	Variation of Technology	Variation of Allocation
domestic	Regional shares in global reduction Regional mitigation measures	-
energy trade	Regional mitigation measures	-
permit trade	Carbon price Regional demand for permits	Regional supply with permits

Table 1: Potential linkages between a variation of technological flexibility and the initial permit allocation scheme to the three effects on regional mitigation costs.

the regional endowment with a tradable good. Revenues from permit export have a purely distributional effect on the consumption of regions without affecting their investment decisions.

The implications of technological flexibility on permit trade have also been analyzed ([15]). The availability of low-carbon technologies has an impact on regional expenditures or revenues on the permit market via two mechanisms: First, if low-carbon technologies are unavailable, a higher carbon price can be expected to result, in general, in higher monetary flows involved in permit trade. Second, by changing the regional measures to reduce emissions, the unavailability of technologies can be assumed to affect the regional demand for permits.

We define the contributions from permit trade on regional mitigation costs as *permit trade effect*. It comprises 1. the supply with permits (subject to initial allocation), 2. the demand for permits and 3. the carbon price (2. and 3. subject to technological flexibility). It is not clear *a priori* how the distributive impacts of allocation schemes are affected if the availability of technologies is reduced.

The joint impact of technological change and trade-related effects has recently been identified as a major reason for the regional distribution of the consumption losses associated with climate change mitigation ([15]). However, the effort to separate domestic effects, energy trade effect and permit trade effect, has to our knowledge not yet been undertaken in the literature.

Hence, the aim of this paper is to fill this gap. We quantify and discuss the relevance of the three effects that determine the distribution of total regional consumption losses, and we focus on the question how scenario assumptions on the availability of low-carbon technologies and on the initial permit allocation scheme affect the importance of the effects. Table 1 summarizes the mechanisms that we discussed above.

The significance of our study is twofold. First, it provides methodological insights into the consequences of regional interactions in multi-regional models on the interplay of technological flexibility and allocation schemes. Second, conclusions for policy making can be drawn from these insights, e.g., about the relevance of particular low-carbon technologies for the positioning of regions in the debate about a global permit allocation scheme. Our study contributes to the analysis of the set of choices that policy makers face, which is an urgent task of current integrated assessment modeling ([9], [10]).

For the purpose of this analysis, a modeling framework is needed that combines a detailed representation of energy transformations with an adequate description of trade flows. We use the multi-regional integrated assessment model REMIND-R for this analysis to simulate mitigation strategies under different assumptions on the availability of technologies and on the initial allocation of emission permits.

The paper is structured as follows. In Section 2, we describe the model REMIND-R used in this analysis. The definition of model scenarios is documented in Section 3. We present our results in Section 4. We focus on a decomposition of regional mitigation costs into the effects introduced above. Finally, Section 5 contains a discussion of the results and their implications for future climate negotiations.

2 The Model REMIND-R

REMIND-R, as introduced in [15], is a global multi-regional hybrid model which couples an economic growth model with a detailed energy system model and a simple climate model.¹ The hard-link between the energy system and the macroeconomic systems guarantees a simultaneous equilibrium of energy and capital market and follows the method in [1].

The model regions consist of the following groups of countries:

1. USA - USA
2. EUR - EU27
3. JAP - Japan
4. CHN - China
5. IND - India

¹On <http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/remind-code-1> the technical description of REMIND-R is available. REMIND-R is programmed in GAMS. The code is available from the authors on request. Compared to the model version documented in [15], the calibration of the model has been revised; most importantly, macroeconomic efficiency growth parameters have been re-calibrated to allow for a higher GDP growth. The restrictions on capacity increases in the energy system used in [15] are not included in the model for our study.

6. RUS - Russia
7. AFR - Sub-Saharan Africa (incl. Republic of South Africa)
8. MEA - Middle East and North Africa
9. OAS - Other Asia
10. LAM - Latin America
11. ROW - Rest of the World (Canada, Australia, Rest of Europe).

The time horizon of the model is the period 2005 to 2150 with a temporal resolution of 5 years.

The macroeconomic module is a Ramsey-type growth model. The aggregate good is produced by combining capital, labor and various final energy types, described by a nested CES production function. A Macro economic Budget Equation balances the production output Y with net exports of the aggregate good X_G , consumption C , investment into the macroeconomic capital stock I , and energy system costs G_{ESM} :

$$Y(t, r) - X_G(t, r) = C(t, r) + I(t, r) + G_{ESM}(t, r) \quad \forall t, r \quad (1)$$

The energy system module follows a bottom-up approach. It comprises all relevant primary and secondary energy carriers and their transformations. Transformation capacities are described by detailed techno-economic parameters. Carbon Capture and Sequestration (CCS) can be applied in fossil-based electricity generation and on coal- or biomass-based production of transportation fuels or hydrogen. In case of innovative technologies, learning-by-doing allows for a partial reduction of investment costs following a learning curve approach.

Trade between two regions is induced by differences in relative factor endowments and technologies, supplemented by the possibility of intertemporal trade: Each export of goods qualifies the exporting region for a future import (of the same present value), but implies for the current period a loss of consumption. Capital mobility and trade in capital, represented by trade in the composite good, causes factor price equalization and guarantees an intertemporal and interregional equilibrium. Tradable goods are Coal, Gas, Oil, Uranium, Composite good (aggregated output of the macro-economic system), and emission permits. The sums of exports and imports of each good add up to zero in each time step. Prices of tradable goods are derived as shadow prices from these trade balances. Trade implies an exchange of ownership in REMIND-R. Tradable primary energy carriers constitute endowments of exporting regions. The increase of extraction costs, when cumulated extraction rises, is anticipated by exporters, so that scarcity rents are endogenously calculated and added to extraction costs.

In order to co-ordinate the export and import decisions of the individual regions, and to achieve an equilibrium solution for trade flows, REMIND-R uses the Negishi-approach ([16], [13]). The Negishi-algorithm calculates the

intertemporal trade deficit of each region, $B(r)$, as the product of present value price p_i and net export X_i of each tradable good (marked by index i), summed over all tradable goods and time steps:²

$$\sum_t \sum_i (p_i(t)X_i(t, r)) = B(r) \quad \forall r \quad (2)$$

The algorithm ensures that the trade deficits converge towards zero.

The model REMIND-R calculates a pareto solution between regions. The necessary emission reductions are carried out at minimal costs and all trade interactions are directed at increasing welfare in general and lowering mitigation costs in particular (*where-flexibility*).

By hard-link coupling of the energy system model to a simple climate model, a defined temperature target leads to a welfare-maximizing timing of the reduction of CO₂ emissions (*when-flexibility*). For CO₂ emissions from land-use change and other anthropogenic forcings rather modest reductions are assumed, so that the reduction of CO₂ emissions from the energy system under a 2°C temperature target is rather strong.

3 Scenarios

In the reference scenario, no climate policy target is assumed, and the full portfolio of technologies is available. In the default climate policy scenarios, the global temperature increase is limited to 2.0°C.

Four climate policy scenarios with different assumptions on the availability of technologies (**technology scenarios**) are considered:

- **default**: The full portfolio of low-carbon technologies is available.
- **nucfix**: The use of nuclear power is restricted to levels in the reference scenario.
- **renewfix**: The use of renewable energy sources (wind, solar, hydro and geothermal energy) is restricted to the respective levels in the reference scenario. Biomass use is not restricted.
- **ccsmin**: The use of carbon capture and storage (CCS) is limited to a total cumulated amount of 100 GtC.³

Within each technology scenario, four **permit allocation schemes** are considered:

- **default**: Emission permits are initially allocated such that the allocation equals the actual emissions for each region. Hence, no trade in

²The present value price is the marginal value of the physical trade balances. The consideration of present value prices assures an appropriate discounting in the intertemporal balance.

³This compares to about 600 GtC in the default scenario.

emission permits occurs, and permit trade effects on regional consumption losses are zero. In the absence of uncertainty, this setting is equal to a global tax regime with regional revenue recycling.

- **C&C**: Contraction and convergence allocation scheme⁴.
- **intensity**: In proportion to regional GDP.
- **equal per capita**: In proportion to regional population.

The sum of the regional initial allocations equals the global optimal emissions in all four schemes.

4 Results

We present our results in four steps: First, we briefly introduce major characteristics of the four technology scenarios (Subsection 4.1). Then we turn to mitigation costs and provide an overview of the regional costs we find in the technology scenarios (Subsection 4.2). To assess the role of technological flexibility, we discuss the decomposition of regional costs into contributions related to different domestic and trade-related effects (Subsection 4.3). Up to this point, we restrict the discussion to the default permit allocation scheme, as revenues from permit trade constitute an additional component without affecting the other effects. Finally, we consider the distributive consequences from different permit allocation schemes on regional consumption losses and analyze how the technological flexibility affects the results (Subsection 4.4).

4.1 Major Characteristics of the Technology Scenarios

The compliance to the 2°C target requires an articulated reduction of CO₂ emissions and a redirection of investments in the energy system towards low-carbon technologies. Global CO₂ emissions are reduced to zero by 2070. Afterwards, the use of biomass with CCS even allows for negative global emissions of almost 2 GtC/a in 2100. In the scenario *ccsmin*, emission reductions in the first half of the century are more pronounced, but negative emissions reach only about 0.5 GtC/a in 2100.

In the default technology scenario, the global carbon price (measured in current value terms) increases smoothly throughout the 21st century and reaches 1100 \$/tCO₂ by 2100 (see Figure 1). Restrictions on renewable and nuclear technologies cause moderately higher carbon prices of 1200 \$/tCO₂ and 1450 \$/tCO₂, respectively (scenarios *nucfix* and *renewfix*, resp.).⁵ A

⁴As of 2050, the same per capita emission rights are allocated in this scenario. Between 2010 and 2050, there is a smooth transition of the regional shares between grandfathering and equal per capita emissions. 2000 is assumed to be the reference year for grandfathering. The Contraction and convergence allocation scheme has been developed by [18].

⁵The price increase in scenario *renewfix* compared to the default is moderate, because renewable energy contributes a large share of energy even in the reference case.

limitation of CCS, however, leads to a remarkably higher price of up to 3900 $\$/\text{tCO}_2$ in 2100 (scenario *ccsmin*).

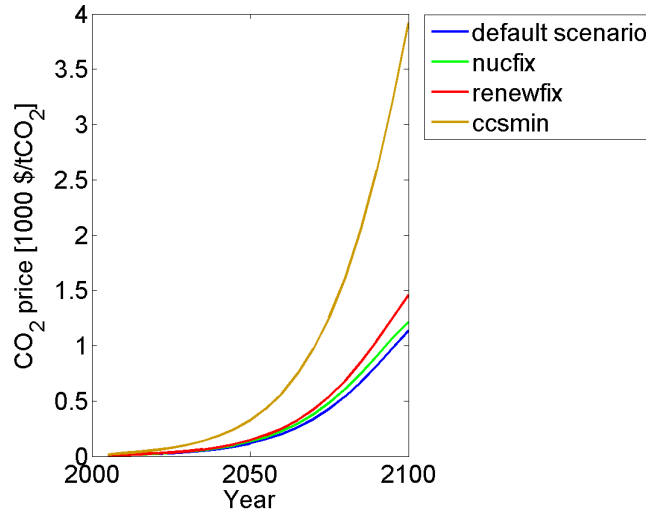


Figure 1: Global carbon prices in the technology scenarios.

The primary energy consumption increases from almost 470 EJ in 2005 to more than 1400 EJ in 2100 in the reference scenario and about 1000 EJ in the default climate policy scenario (see Figure 2). Without climate policy, the primary energy mix is mostly based on fossil sources. Especially, the use of coal increases strongly. Consumption of oil and coal is significantly reduced in the default climate policy scenario. It is partly substituted by biomass, wind and nuclear energy in the short- to mid-term. In the long term, solar energy and coal with CCS are widely used. In the middle of the century, natural gas use in the default climate policy scenario exceeds the respective values in the reference scenario. Natural gas is consumed as a transitional option to reduce specific emissions in comparison to coal. The option to generate negative emissions by using biomass with CCS allows for extending the utilization of oil, which is more difficult to substitute than coal.

A restriction of the usage of low-carbon technologies leads to changes in the global primary energy mix (see Figure 3). Compared to the default policy scenario, the consumption of coal, mostly with CCS, increases in the scenarios *nucfix* and *renewfix* to replace nuclear energy and solar energy, respectively. In the scenario *ccsmin*, however, the consumption of coal is reduced, as the remaining CCS potential is fully used together with biomass. This is partially compensated by additional use of solar and nuclear energy. Oil and natural gas are also consumed less, as the potential of biomass with CCS to generate negative emissions is reduced by the storage restriction. The

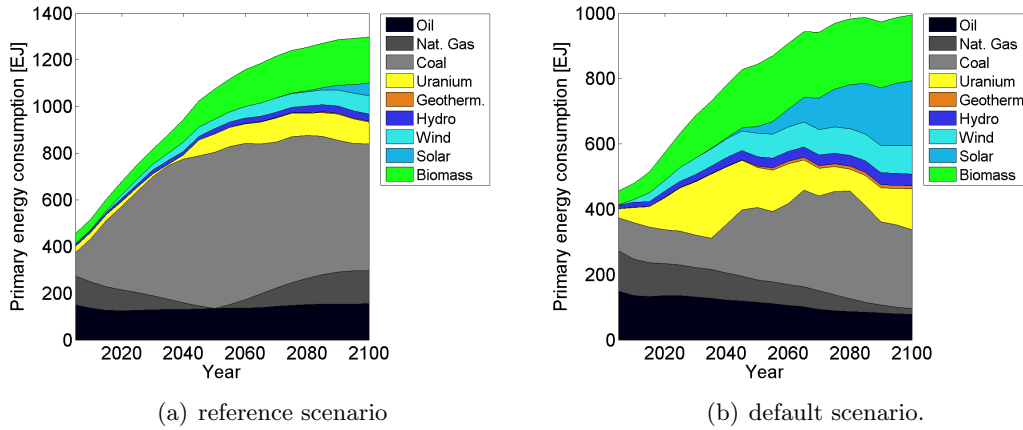


Figure 2: Global primary energy mix in the reference scenario and in the default climate policy scenario. Note the different scalings of the y-axis in the subfigures.

total primary energy consumption in scenario *ccsmin* is significantly reduced, and the same can be observed in the final energy production.

Accordingly, import and export flows of tradable energy carriers are significantly modified under climate policy. Compared to the reference scenario, the reduced global demand for coal and, to a smaller extent, for oil implies lower prices than in the reference scenario. An increased demand for natural gas in the middle of the century leads to an earlier increase of the natural gas price.

Figure 4 shows cumulated emissions over the century for each region in the different technology scenarios.⁶ The global cap-and-trade system ensures a cost-minimal allocation of mitigation efforts by leveling carbon prices among world regions. In consequence, the regional shares in the global emission reduction efforts change if low-carbon technologies are restricted. This effect is most obvious in scenario *ccsmin*: For example, RUS can increase its emissions by a factor of five compared to the default scenario, because the limitation of CCS implies a strong increase in its marginal costs of abatement. In turn, other regions (e.g., MEA) reduce their emissions in this scenario. This revision of regional contributions to the global emission reduction has significant consequences on regional consumption losses as we will discuss in Section 4.3).

4.2 Overview of Regional Mitigation Costs

We measure mitigation costs in terms of discounted consumption losses between reference scenario and the respective climate policy scenario, expressed

⁶Global sums are 352 GtC (default, *nucfix*, and *renewfix* scenario), and 331 GtC (*ccsmin* scenario), resp.

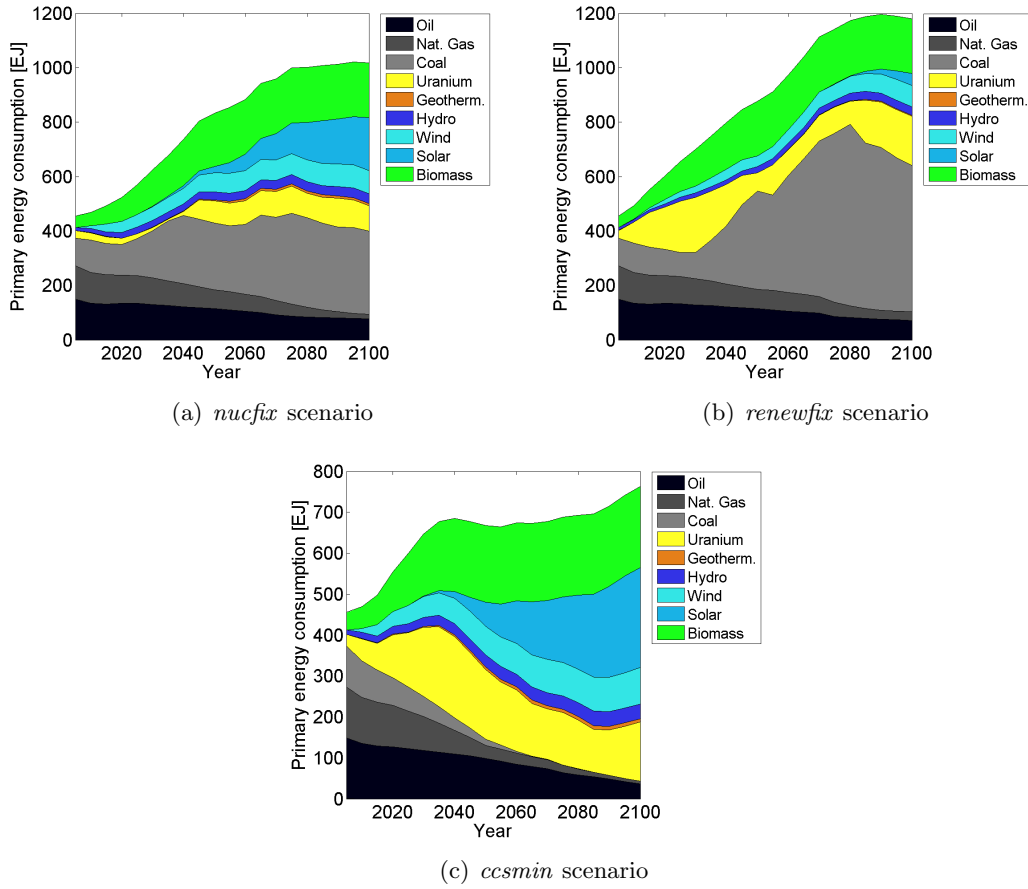


Figure 3: Global primary energy mix in the alternative technology scenarios. Note the different scalings of the y-axis in the subfigures.

as ratio per GDP of the reference scenario. Global consumption losses in the default scenario amount to 1%, but regional costs deviate from this value. RUS bears the highest costs of about 5% (see Figure 5). Limitations of low-carbon technologies lead to increasing global consumption losses, but also to a modulation of the regional losses. In general, higher global losses imply higher regional losses also. For some regions, however, the limitation of a technology leads to lower consumption losses than in the default case (e.g., RUS in the *ccsmin* scenario, see Figure 5).

These observations lead us to the question: What are the underlying effects behind regional consumption losses? Our analyses in the next subsection provide useful answers to this question.

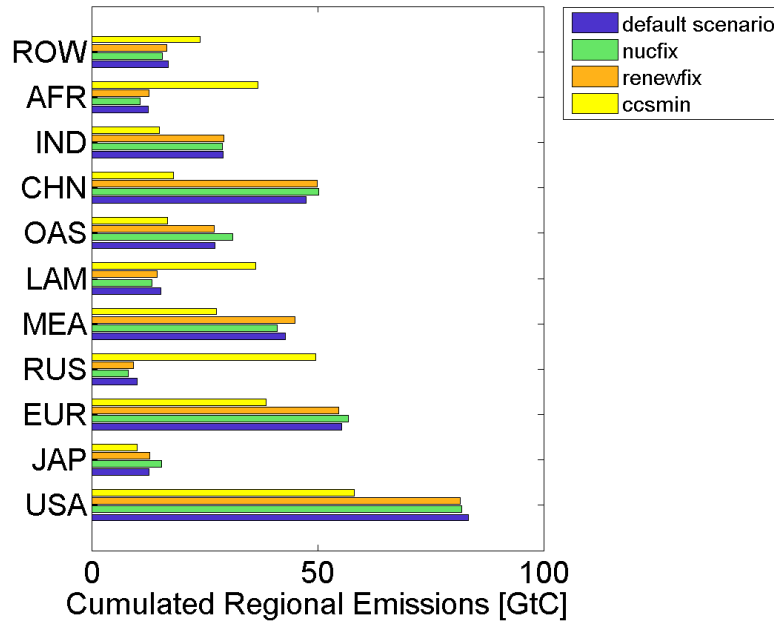


Figure 4: Cumulated regional emissions of CO₂ from the energy system in the period 2005-2100 in GtC.

4.3 Domestic and Fossil Trade Effects on Regional Consumption Losses

In this subsection, we present a decomposition of regional consumption losses into five components. The discussion of the results will allow us to separate and quantify the domestic effect and the energy trade effect. The first four of the components can be attributed to domestic effects, the fifth quantifies the energy trade effect:

1. Production: regional output of GDP
2. Investment: investments into the macroeconomic capital stock
3. Energy System (investment): investment costs into the regional energy system, including operation and maintenance costs
4. Energy System (fuel): extraction costs attributed to the *domestic* use of the extracted fuel. This applies to the use of fossil energy, uranium, and biomass
5. Energy Trade (net effect), differentiated by Oil, Coal Trade, Natural Gas and Uranium Trade: costs or revenues from the trade of the respective energy carrier. For exporters, the extraction costs attributed to the export of a fuel are subtracted, so that the net trade revenue is reported.

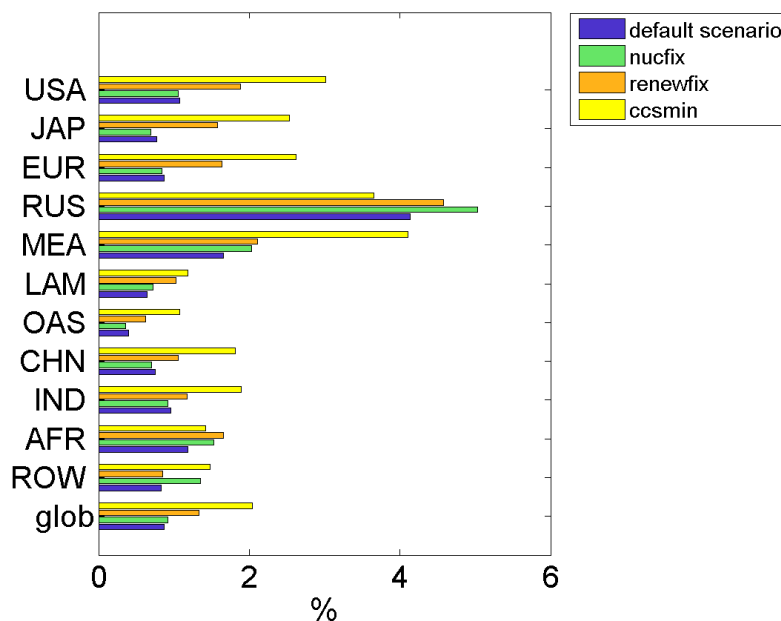


Figure 5: Mitigation Costs in the technology scenarios (default allocation). 'glob' denotes the global aggregate.

Please note that in this subsection we restrict the discussion on the default permit allocation, so that permit trade is zero by definition.

The method to decompose regional consumption losses into domestic and trade-related effects has already been applied by [4]. It is based on the analysis of the components in the Macro economic Budget Equation (1) and the Intertemporal Trade Balance Equation (2). A detailed description of the calculation can be found in the Technical Appendix.

The results are presented in Figures 6, 7 and 8. For each region and technology scenario, the figures show the regional consumption difference (equal to those shown in Figure 5) and, on the left to it, the components as defined above, which add up to the consumption difference.⁷

We will present the results along three groups of regions, as we find similar patterns within these groups: First, we discuss the effects for the resource-importing industrialized regions (USA, JAP, and EUR, see Figure 6), then for the major exporters of fossil energy carriers (RUS, MEA, and ROW, see Figure 7), and finally for the developing and emerging economies (LAM, OAS, CHN, IND and AFR, see Figure 8).

⁷A small residual value remains between the sum of the components and the respective consumption difference. This residuum is explained and quantified in the Technical Appendix.

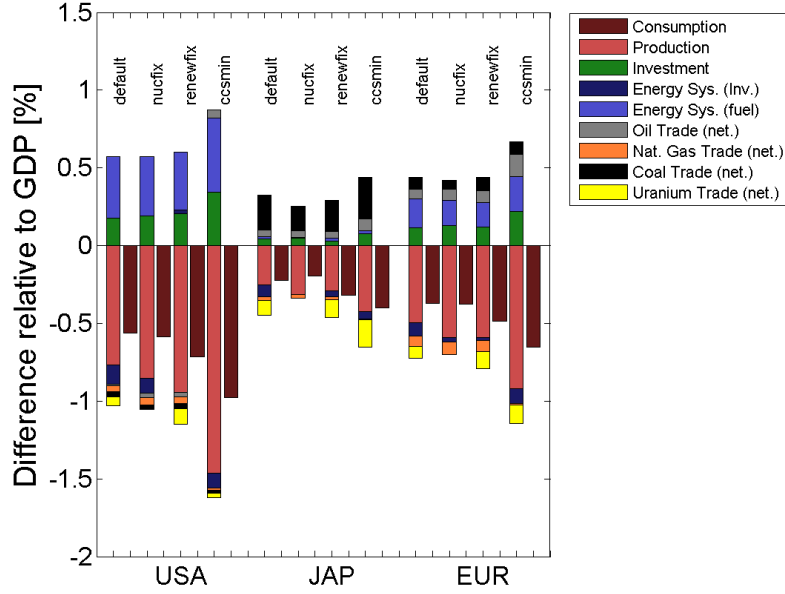


Figure 6: Decomposition of consumption losses for the resource-importing industrialized regions (USA, JAP and EUR). For each region and technology scenario, the brown bar shows the consumption loss and the other bars left to it show the components, which add up to the consumption loss.

In the default scenario, the consumption losses of **resource-importing industrialized regions** are between 0.2% (JAP) and 0.6% (USA). They can be mostly attributed to a decrease in GDP and higher investments into the energy system, partly counterbalanced by reduced expenditures for the investment into the macroeconomic capital stock and for domestic extraction costs. The reason is that GDP growth as well as the capital and energy input into the macroeconomic production function are reduced under climate policy, and that investments into the energy system are redirected from fossil fuel-based technologies to more capital-intensive low-carbon technologies.

Now we turn to the trade-related effects. Except for the coal trade component in JAP, the trade-related effects are less pronounced than the domestic effects. All industrialized regions have extra expenditures for the import of uranium and natural gas to cover the higher usage of these energy carriers under climate policy. The USA is an exporter of coal in the first decades of the century and thus faces minor losses from lower coal demand and price. JAP and EUR, to the contrary, are importers of coal, but reduce their import expenditures under climate policy. JAP and EUR decrease their oil demand under climate policy and thus save import expenditures.

Next, we compare the results of the default scenario and the other technology scenarios. In the scenario *nucfix*, nuclear capacities cannot exceed the respective values in the reference scenario. In consequence, regional expenditures for uranium imports are the same as in the reference scenario, so that a difference of zero is reported in Figure 6. In JAP, the restriction on nuclear is compensated by a larger usage of CCS, so that the reduction of coal import expenditures is smaller than in the default scenarios. In EUR and USA, a reduced GDP is the major effect compared to the default scenario.

In the scenario *renewfix*, the restriction on renewable energy is mostly compensated by higher usage of nuclear power, which goes along with higher uranium import expenditures. Furthermore, all regions face a further decrease of their GDP compared to the default scenario as a result of reduced energy input, partly counterbalanced by reduced investments into the regional energy systems, as investments into capital-intensive renewable technologies are restricted. The USA even has less energy system investment costs than in the reference scenario.

The most pronounced changes to the default scenario occur in the scenario *ccsmin*. In comparison to the default scenario, the major effect is, again, a further decrease of GDP along with reduced energy and capital input. As the constraint on CCS reduces the potential for the use of coal with CCS, JAP benefits from a reduced coal price. All regions increase their additional expenditures for uranium imports.

In summary, domestic effects constitute a major part of the regional consumption losses of industrialized regions, independent from the technology scenario. Trade-related effects play a smaller role, except for the uranium component in the *nucfix* scenario, and the coal component for JAP in all scenarios. Reductions of technological flexibility generally lead to moderately higher consumption losses, especially due to further reductions of the GDP.

Now we analyze the results for **major fossil fuel exporting regions** (RUS, MEA and ROW, see Figure 7). As exporters of coal and oil, MEA and RUS face the highest consumption losses of all model regions (namely 3% and 4%, resp.) due to the decrease in global fossil fuel demand and prices.⁸ In consequence, reduced net income from coal and oil exports amounts to approx. 3% of GDP for RUS (mainly coal), 1% for ROW (mainly coal), and 1% for MEA (mainly oil). In contrast, RUS and MEA receive small extra gains of approx. 0.1% of GDP from natural gas exports due to an increased global demand in the middle of the century.

Now we turn to the import-related trade effects of the three regions. MEA reduces its coal imports compared to the reference scenario. All three regions suffer from a worsening of their terms of trade on the uranium market: Com-

⁸Given fixed supply, a demand decrease always coincides with a lower price, even if we do not point out this double effect explicitly in the following.

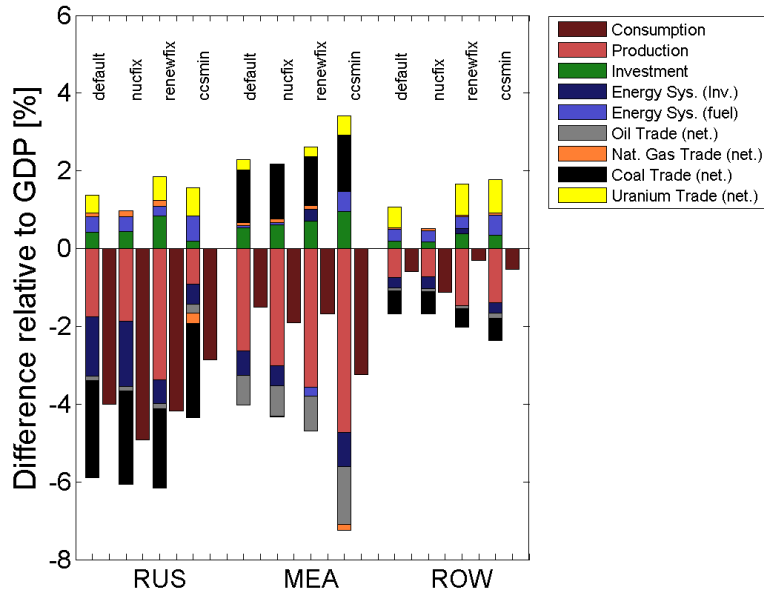


Figure 7: Decomposition of consumption losses for the major fossil fuel exporting regions (RUS, MEA and ROW). For each region and technology scenario, the brown bar shows the consumption loss and the other bars left to it show the components, which add up to the consumption loss.

pared to the reference scenario, increased demand of other regions, especially the resource-importing industrialized regions, leads to an increased uranium price. In turn, RUS, MEA and ROW decrease their uranium imports.

The fossil exporting regions face a reduction of GDP under climate policy and higher investments into their energy system on the one hand, and reduced investments into the macroeconomic capital stock and reduced fuel costs for domestic use on the other hand. GDP losses in RUS and MEA amount to almost 2% and 3%, resp., which is significantly higher than the GDP losses in resource-importing industrialized regions. For RUS, the total consumption loss is, however, even higher than the GDP loss.

The *nucfix* scenario implies a restriction of nuclear energy usage on the level of the reference scenario for all regions. This means a reduction of uranium import for most regions, especially the resource-importing industrialized regions. In turn, the fossil exporting regions can increase their uranium imports (compared to the default scenario) back to the level in the reference scenario, although this leads to higher consumption losses than in the default scenario. For ROW, this implies that the consumption loss exceeds the GDP loss.

In the *renewfix* scenario, a higher global demand for coal leads to a reduction of the losses from coal exports in the fossil exporting regions. However, GDP losses are higher compared to the default scenario due to a reduced energy input. In total, this leads to slightly higher (RUS, MEA) or even lower (ROW) consumption losses in the *renewfix* scenario.

In the *ccsmin* scenario, the devaluation of fossil endowments has stronger effects compared to the default scenario. The reduction of income from oil imports is significantly higher due to a reduction of global oil demand compared to the default scenario. This explains higher consumption losses in MEA. Losses in coal export for RUS and ROW are slightly higher than in the default scenario, as coal cannot be used largely with CCS anymore. Natural gas export does not provide extra revenues as in the other scenarios.

For RUS, we find a clear reduction of mitigation costs in the *ccsmin* scenario, mainly because GDP losses are only half as strong as in the default scenario. This can be explained from the pareto-optimal sharing of the global mitigation effort in REMIND-R: RUS uses a lot of biomass with CCS in the default scenario. Hence, emission reductions are shifted to other regions in the *ccsmin* scenario, leaving RUS with higher emissions and less GDP losses. In total, RUS profits from the modified sharing of the global emission reduction in a scenario with restricted CCS option.⁹

To summarize the results for the major fossil exporting regions, their consumption losses are to a large extent defined by the devaluation of their coal and oil endowments, whereas natural gas endowments are slightly revalued if the CCS option is not restricted.¹⁰ A restriction of the CCS option also leads to an increase of the devaluation of oil endowments. Due to competition with other regions on the uranium market, the major fossil exporters face higher consumption losses, if nuclear energy usage is restricted.

Finally, we discuss the results for **emerging and developing economies** LAM, OAS, CHN, IND and AFR (see Figure 8). Consumption losses in the default scenario range from 0.5% (LAM) up to 1.2% (IND, AFR). As for the resource-importing industrialized regions, the domestic effect of reduced GDP and a redirection of investments from the macroeconomic capital stock towards capital-intensive low-carbon energy technologies constitutes the major effect on regional consumption losses, together with reduced expenditures for coal and oil imports. CHN and IND reduce their domestic fuel costs which

⁹Please note that this result refers to domestic and energy trade effects. Hence, in other permit allocation schemes the total effect on regional consumption is modulated by the permit trade effect. This remark applies to the whole subsection, but for the implications of the availability of CCS for RUS it is of special importance.

¹⁰Please note that the net export losses shown in our analysis are calculated by subtracting saved extraction costs from the export losses. Due to the extraction cost curve approach in REMIND-R, extraction costs should be regarded as an upper limit, so that the net losses of fossil export are a lower limit.

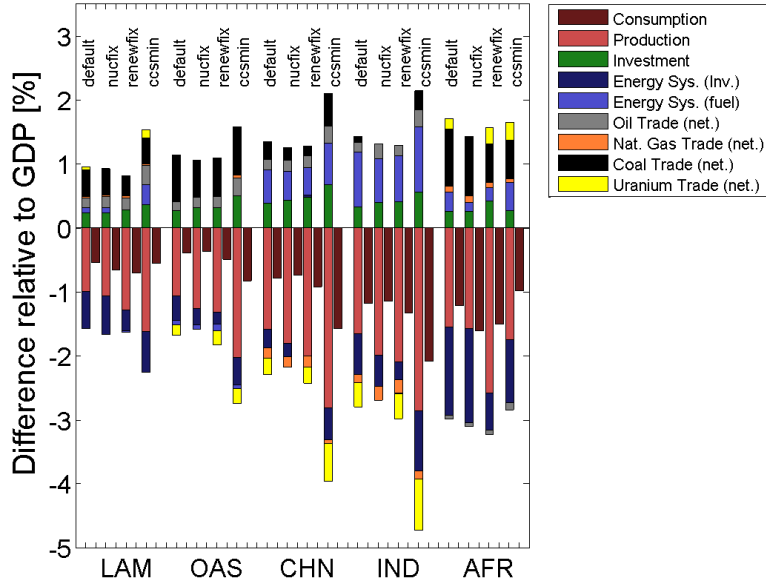


Figure 8: Decomposition of consumption losses for developing and emerging economies (LAM, OAS, CHN, IND and AFR). For each region and technology scenario, the brown bar shows the consumption loss and the other bars left to it show the components, which add up to the consumption loss.

is also mainly due to less coal usage under climate policy. LAM and AFR profit from increased natural gas and uranium export revenues.

In the *nucfix* scenario, regional expenditures for uranium imports and revenues from exports are the same as in the reference scenario, so that a difference of zero is reported. In consequence, the uranium exporters, AFR and LAM, face slightly higher consumption losses. For uranium importers, OAS, CHN and IND, the savings in uranium import are compensated by higher production losses, so that consumption losses are almost the same as in the default scenario.

In the *renewfix* scenario, higher consumption losses are mainly due to increased GDP losses, and reduced energy system investment costs. In the *ccsmmin* scenario, GDP and consumption losses increase even more. CHN and IND have significantly higher expenditures for uranium import. LAM and AFR have lower consumption losses in the *ccsmmin* scenario compared to the default scenario, similar to what has been observed for RUS. The main reason is a lower increase in energy system investments for AFR, and higher gains from uranium export and less fuel costs for domestic use for LAM.

In summary, the consumption losses of emerging and transition economies are mainly shaped by domestic effects. Expenditures and revenues from coal and uranium trade are the major trade components.

Up to this point, we can conclude that assumptions on the availability of low-carbon technologies influence regional consumption losses via domestic effects, especially changes in regional GDP. In general, the GDP loss is partly counterbalanced by the sum of the other components, so that the consumption loss is lower than the GDP loss. On the contrary, the opposite is true for RUS in all scenarios, and for ROW in scenario *nucfix*. This can be explained by the relatively high relevance of energy trade components in their intertemporal trade balance.

Some regions benefit from a reduced availability of certain technologies, especially RUS from a limitation of CCS. For the fossil exporting regions, the devaluation of coal and oil endowments constitutes a major reason for their relatively high consumption losses in all technology scenarios.

4.4 Permit Trade Effects on Regional Consumption Losses

In this subsection, we present the results of technology scenarios with different initial permit allocation schemes. We analyze the influence of the allocation scheme on regional consumption losses and ask how this influence is modified by the technological flexibility.

If the initial allocation of permits does not match the optimal emission levels of the regions, permits will be traded among regions, creating an extra contribution in the intertemporal trade balances of the regions without changing domestic or energy trade contributions to regional mitigation costs ("separability of efficiency and equity", see introduction).

Figure 9 shows the regional consumption losses in all technology scenarios, taking the permit trade component into account. We will discuss the plenitude of information in this figure by taking the following steps: First, we provide an overview about implications of the allocation schemes without considering the aspect of technology. Second, we analyze how the range of redistribution implied by the allocation schemes compares to technology-induced effects as discussed in the previous subsection. Third, we discuss how reduced technological flexibility affects the range of redistribution. Fourth, we make some special remarks on the implications of scenario *ccsmin* in the context of different allocation schemes.

We start with the first step. Implications of the considered allocation schemes on regional consumption differences are as follows: For the default allocation scheme, consumption differences coincide with those discussed in the previous subsection (see Figures 6-8).¹¹ Each region loses consumption

¹¹Please note that the default allocation implies different regional emission amounts in different technology scenarios, as shown in Figure 4.

under the default allocation scheme. The other allocation schemes cause a redistribution of consumption due to permit trade. The colored bars in Figure 9 represent the corresponding size of redistribution given the four allocation schemes considered here.

The intensity allocation is in general favorable for industrialized regions, whereas the equal per capita allocation is more attractive for low-income regions (esp. AFR and IND). The C&C allocation has a position in between. If a region is endowed with a huge amount of permits, so that revenues from selling dispensable permits exceed the mitigation costs in the default allocation, the region even benefits from climate policy.

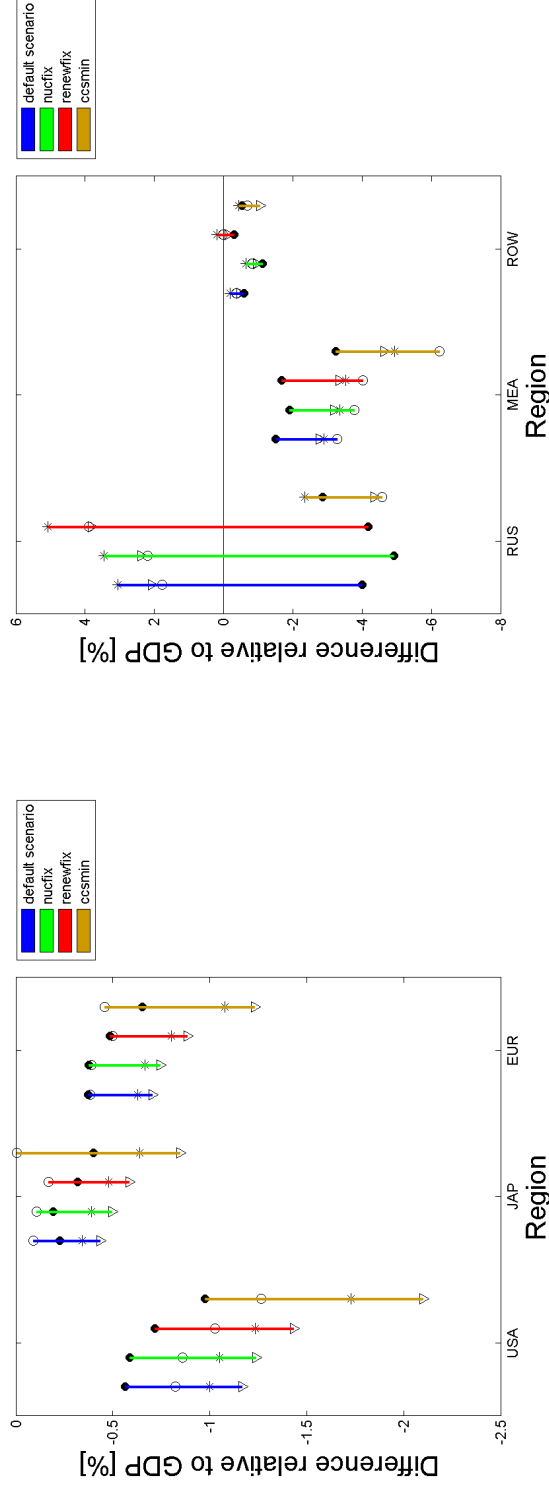
Second, we analyze how the range of redistribution implied by the allocation schemes compares to technology-induced changes in domestic and energy trade effects (as discussed in the previous subsection). The distributive impacts of the allocation exceed the domestic and energy trade effects (represented by the shifts of the markers along the y-axis in Figure 9) except for region ROW. This results of course from the rather high flexibility of the REMIND-R model to compensate restriction on low-carbon technologies at moderate costs.

If low-carbon technologies are not available, consumption differences for industrialized regions are still in the redistribution range of the default technology scenario. Let us discuss an example. Two storylines are comparable from the perspective of industrialized regions: 1. A global cap tax regime (default allocation), and CCS strongly limited. 2. A C&C allocation, and CCS fully available. We will discuss the policy implications of this observation in the Conclusions section.

Some regions benefit in consumption from a reduced technological flexibility due to a reduced regional share in the global emission reduction, as shown in the previous subsection. (Consider the example of JAP, which benefits from a restriction of nuclear energy.) However, this is overcompensated by the permit trade effect: Consumption losses or gains get larger, if low-carbon technologies are reduced. (In the example mentioned before, JAP benefits from a restriction of nuclear energy *only in the default allocation*.) The only exception is region ROW. In other words: Generally, losses from the permit trade effect due to reduced technological flexibility outweigh gains from domestic effects.

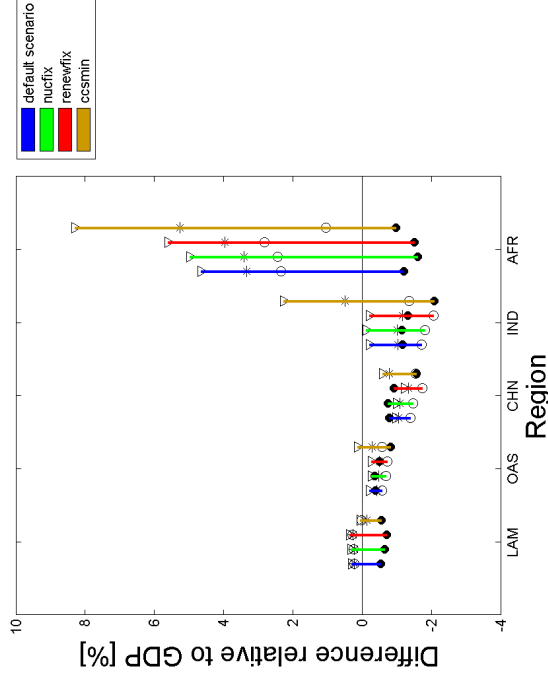
Third, we discuss how reduced technological flexibility affects the range of redistribution. In scenarios *nucfix* and *renewfix*, the range of redistribution grows compared to the default scenario. Higher carbon prices lead to higher redistributive consequences of permit trade. In scenario *ccsmin*, the range grows even further (due to even higher carbon prices) but with the exception of regions RUS and LAM which will be explained later on.

Especially, the benefits of the "winners" of permit trade (regions with total benefits under a certain allocation) are higher, because selling unneeded permits yields higher benefits due to the increased permits price. Consider the



(a) resource-importing industrialized regions

(b) fossil fuel exporting regions



(c) developing and emerging economies

Figure 9: Impact of the permit trade effect on regional consumption losses. (Filled circles: default allocation. Open Circles: Intensity allocation. Stars: C&C allocation. Triangle: equal per capita allocation.) Note the different scalings of the y-axis in the subfigures.

example of AFR: In the default scenario, the consumption would decrease by about 1% under the default allocation, but increase by 5% under an equal per capita allocation. This range of 6% grows to more than 9% in the *ccsmin* scenario. In turn, the losses of other regions are boosted, if low-carbon technologies are restricted, like for the resource-importing industrialized regions.

Fourth, the distributive impacts of scenario *ccsmin* need some further interpretation. The restriction of CCS causes significant changes in the regional shares of the global emission reduction, as shown in Figure 4. RUS and LAM increase their emissions by a factor of five compared to the default scenario, so that their respective *amounts* of permits traded are considerably lower in scenario *ccsmin* compared to the default. This effect outweighs the increased price, leading to a smaller variability of mitigation costs under different allocation schemes. Therefore, the range of redistribution is smaller in this scenario. For RUS, an equal per capita allocation implies huge revenues from permit exports in the default scenario, but actually the necessity to import permits in the *ccsmin* scenario. The same allocation scheme has thus different distributive consequences for RUS depending on technological flexibility.

Finally, we consider the distributive effects in absolute terms of consumption losses in the following rather than the relative values used so far. We define a Carbon Trade Balance as the temporally aggregated product of permit volume traded in each model year and the discounted carbon price of the respective year. As a consequence of the separability of the permit trade effect on the one hand, and the domestic and energy trade effect on the other hand, a linear relation can be expected between the Carbon Trade Balance and the likewise aggregated consumption losses of each region. This is formally shown in the Technical Appendix.

The results are displayed in Figure 10 exemplarily for the default technology scenario. First, we find as expected a linear relation between Carbon Trade Balance and consumption losses, if four different permit allocation schemes are considered. The slopes of the regression lines are close to 1.¹² In consequence, the distributive effects of any other permit allocation scheme could be easily determined.¹³ Furthermore, the results show, that the relative numbers presented before on the order of magnitude of one percent, translates into absolute numbers of up to 1T\$. Especially for USA and EUR, the small percent numbers imply a huge distributive effect in absolute terms.

¹²Numbers are documented in the Technical Appendix.

¹³Please remember our assumption that the global sum of permits equals the intertemporally optimal global emission time path.

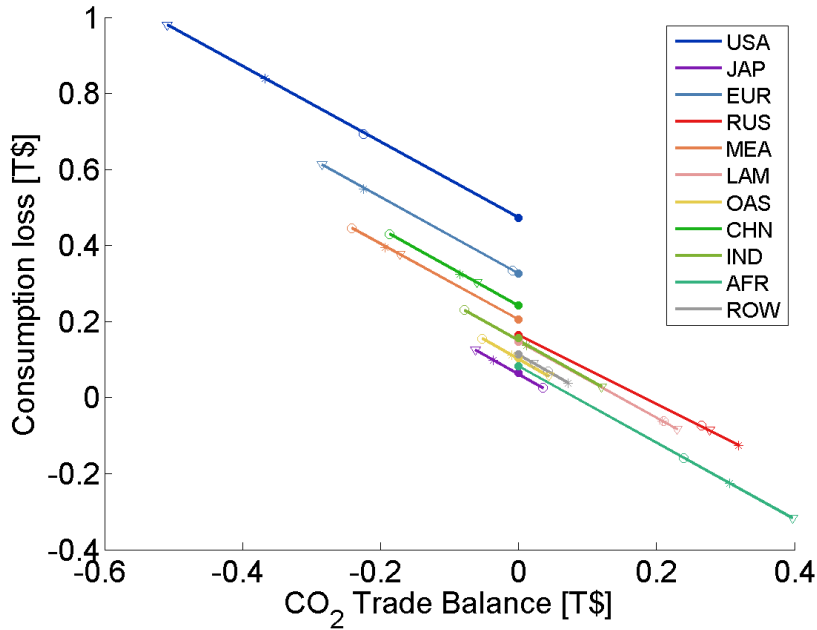


Figure 10: Regional consumption losses as a function of the Carbon Trade Balance in the default technology scenario. Both consumption losses and Carbon Trade Balance are expressed in absolute terms. (Filled circles: default allocation. Open Circles: Intensity allocation. Stars: C&C allocation. Triangle: equal per capita allocation.)

5 Discussion and Conclusions

We applied the global multi-regional hybrid model REMIND-R to analyze distributive impacts of climate policy by considering four scenarios about the availability of low-carbon technologies and - within each technology scenario - four initial allocation schemes for emission permits. We developed a method to decompose regional consumption losses into contributions from domestic effects, energy trade effects, and emission permit trading effects. Furthermore, we discussed the impact of technological flexibility on the different effects.

We found three key results:

- Excluding low-carbon technologies from the portfolio of mitigation options leads to a higher carbon price, implying higher costs and revenues from permit trade, and hence in general higher distributive consequences if the allocation scheme is varied. Exceptions are lower distributive ranges for RUS and LAM if CCS is strongly restricted. The adoption of an initial permit allocation scheme implies welfare redistributions in the same order of magnitude as domestic and energy trade effects.

As expected, we found that costs and revenues from emission permit trade can be separated from other effects. A linear one-to-one relation holds between the Carbon Trade Balance, defined as the aggregated discounted monetary permit trade volume of a region, and the likewise aggregated absolute consumption losses.

However, this result depends on specific features of the model used in this study, REMIND-R, so that analyses with other models could lead to different results, especially with regard to the separability of the permit trade effect and the one-to-one relationship between Carbon Trade Balance and consumption losses. Furthermore, the size of the welfare redistributions implied by the choice of an initial allocation scheme is a consequence of relatively moderate carbon prices in the model REMIND-R.

- The devaluation of coal and oil endowments constitutes a major reason for the relatively high consumption losses of fossil energy exporting regions. Natural gas endowments are revalued by climate policy if the CCS option is fully available. These findings have to be considered with some caution, as the extraction cost curve approach used in the model should be regarded as an upper limit of cost estimates. We find almost the same devaluation of oil and coal endowments in all technology scenarios. This does not contradict the conclusion in [15] that mitigation costs of fossil exporting regions are strongly influenced by the availability of low-carbon technologies under a C&C allocation scheme. In a C&C allocation scheme, increased expenditures for emission permits influence the mitigation costs.
- Assumptions on the availability of low-carbon technologies clearly influence regional consumption losses via domestic effects. When the potential of low-carbon technologies is reduced, carbon prices reach a higher level, and GDP is generally lower. The effect is more pronounced for a limitation of CCS to an accumulated injection of 100 GtC (scenario *ccsmin*) than for restrictions of nuclear energy or renewable energy, resp., to baseline levels (scenarios *nucfix* and *renewfix*). However, the domestic component reduces consumption losses for particular regions, if the availability of certain technologies is restricted (e.g., RUS in the *ccsmin* scenario). The main reason is a reduction of the shares that these regions contribute to the global emission reduction due to their limited potential to employ alternative low-carbon technologies, because a welfare-maximizing sharing of the global mitigation efforts is guaranteed in REMIND.

In summary, our results allow for a separation of the multiple effects that constitute the regional distribution of mitigation costs, and for a discussion on how the availability of low-carbon technologies and the agreement about an initial emission permit scheme affects them. We conclude that technolog-

ical flexibility influences the distributive consequences of climate policy via domestic, energy trade, and permit trade effects. Our results underline the findings of previous studies that technological flexibility, trade-related effects and their feedbacks on investment dynamics are crucial factors for regional mitigation strategies and the associated consumption losses (e.g., [2], [14], [15]).

While the availability of technological options is primarily (but not exclusively) subject to uncertain technological developments, the initial permit allocation scheme is subject to international negotiations. Allocation schemes can thus be designed to modify regional mitigation costs within certain boundaries according to considerations of equity or political acceptance.

Our results thus lead to implications for climate policy: The higher the technological flexibility, the lower is generally the welfare redistribution associated to the choice of a permit allocation scheme. Our results indicate strong incentives for industrialized regions to promote the feasibility of low-carbon technologies (e.g., by financing CCS demonstration projects) to reduce their mitigation costs. This argument applies especially under allocation schemes that generate particularly high redistributions (e.g., equal per capita or C&C) and are hence more acceptable for poorer world regions. If CCS is fully available, and a C&C allocation is globally accepted, consumption losses for industrialized regions are not higher than in a global tax regime but with CCS strongly limited.

A broad portfolio of low-carbon technologies could thus help to facilitate negotiations on a permit allocation scheme, thereby increasing the chances to attain an international agreement on a stringent global climate policy.

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Technical Appendix

Decomposition of Consumption for One Scenario

For each time step and region, the **macroeconomic budget** balances the macroeconomic output Y , reduced by net exports X_G of the final good, with consumption C , investments into the macroeconomic capital stock I , and the total energy system costs G_{ESM} (fuel, investment, and O&M costs):¹⁴

$$Y(t, r) - X_G(t, r) = C(t, r) + I(t, r) + G_{\text{ESM}}(t, r) \quad \forall t, r \quad (3)$$

The macroeconomic budget accounts for good trade in terms of current value prices. (Current value prices denote prices *relative to the price of the final good*, so the current value price of the final good is clearly 1 in each time step.)

The **intertemporal trade balance** ensures, that the discounted monetary values of each region's imports and exports of all tradable goods yields zero over the whole time horizon.¹⁵ (We can assume that the trade deficit that remains at the end of a finite number of steps in the Negishi algorithm is sufficiently small.) With $X_{E,i}$ as the net export of energy carrier i (coal, natural gas, oil, and uranium), X_p as the net export of emission permits, X_G as the net export of the final good, and $p_{E,i}$, p_p and p_G as the respective present value prices, the intertemporal trade balance reads

$$\sum_t \left(\sum_i p_{E,i}(t) X_{E,i}(t, r) + p_p(t) X_p(t, r) + p_G(t) X_G(t, r) \right) = 0 \quad \forall r \quad (4)$$

In order to combine the macro budget (3) and the trade balance (4) to display contributions of different tradable goods, we need thus to convert both equations to the same definition of prices. We multiply (3) by $p_G(t)$ (Note that this factor is different in every time step):

$$\begin{aligned} p_G(t) \cdot Y(t, r) - p_G(t) \cdot X_G(t, r) \\ = p_G(t) \cdot C(t, r) + p_G(t) \cdot I(t, r) + p_G(t) \cdot G_{\text{ESM}}(t, r) \quad \forall t, r \end{aligned} \quad (5)$$

This holds for every time step, it is also true if we sum the equation over time. We define the *intertemporally aggregated GDP with respect to present vale prices*

$$\bar{Y}(r) := \sum_t p_G(t) \cdot Y(t, r) \quad (6)$$

¹⁴See REMIND equation 'budget' in the technical documentation of REMIND-R, available on <http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/remind-code-1>.

¹⁵See Chapter 5 in the technical documentation of REMIND-R.

and, analogously, $\bar{X}_G(r)$, $\bar{C}(r)$, $\bar{I}(r)$ and $\bar{G}_{\text{ESM}}(r)$. With these definitions, the intertemporally aggregated macro budget reads

$$\bar{Y}(r) - \bar{X}_G(r) = \bar{C}(r) + \bar{I}(r) + \bar{G}_{\text{ESM}}(r) \quad \forall r \quad (7)$$

Now we can combine (7) and (4), as both are expressed with respect to present value prices $p_i(t)$:

$$\begin{aligned} \bar{Y}(r) + \sum_{t,i} p_{E,i}(t) \cdot X_{E,i}(t,r) + \sum_t p_p(t) \cdot X_p(t,r) \\ = \bar{C}(r) + \bar{I}(r) + \bar{G}_{\text{ESM}}(r) \quad \forall r \end{aligned} \quad (8)$$

Finally, we normalize the equation by the initial price of the final good, $p_G(t_0)$.

Decomposition of Consumption Differences for a Pair of Scenarios

In order to analyze differences between a reference scenario and a climate policy scenario, it is useful to **use the same discounting factor $p_G(t)$ in both experiments**. We choose w.l.o.g. the reference case good price, $p_G^R(t)$, and apply it to eq. (5) for both experiments:

$$\begin{aligned} p_G^R \cdot Y^R - p_G^R \cdot X_G^R \\ = p_G^R \cdot C^R + p_G^R \cdot I^R + p_G^R \cdot G_{\text{ESM}}^R \quad \forall t, r \end{aligned} \quad (9)$$

$$\begin{aligned} p_G^R \cdot Y^{\text{POL}} - p_G^R \cdot X_G^{\text{POL}} \\ = p_G^R \cdot C^{\text{POL}} + p_G^R \cdot I^{\text{POL}} + p_G^R \cdot G_{\text{ESM}}^{\text{POL}} \quad \forall t, r \end{aligned} \quad (10)$$

In the intertemporal trade balance, however, we have to use the good price of the respective scenario, and thus different good prices for the reference and the climate policy scenario. In the reference scenario, the permit trade is zero, so eq. (4) reads for the pair of experiments:

$$\sum_t \left(\sum_i p_{E,i}^R(t) X_{E,i}^R(t,r) + p_G^R(t) X_G^R(t,r) \right) = 0 \quad \forall r \quad (11)$$

$$\begin{aligned} \sum_t \left(\sum_i p_{E,i}^{\text{POL}}(t) X_{E,i}^{\text{POL}}(t,r) + p_p^{\text{POL}} X_p^{\text{POL}} \right. \\ \left. + p_G^{\text{POL}}(t) X_G^{\text{POL}}(t,r) \right) = 0 \quad \forall r \end{aligned} \quad (12)$$

For the reference experiment, we can easily combine (9) and (11):

$$\bar{Y}^R(r) + \sum_{t,i} p_{E,i}^R(t) \cdot X_{E,i}^R(t) = \bar{C}^R(r) + \bar{I}^R(r) + \bar{G}_{\text{ESM}}^R(r) \quad \forall r \quad (13)$$

But for the policy experiment, eq.s (10) and (12) contain different price vectors for the good trade component. To bypass this problem by an appropriate approximation, we rewrite the left hand side of eq. (10):

$$p_G^R(t) \cdot Y^{\text{POL}}(t, r) - p_G^{\text{POL}}(t) \frac{p_G^R(t)}{p_G^{\text{POL}}(t)} \cdot X_G^{\text{POL}}(t, r) = \dots \quad \forall t, r \quad (14)$$

Suming over time leads to

$$\bar{Y}^{\text{POL}}(r) - \sum_t p_G^{\text{POL}}(t) \frac{p_G^R(t)}{p_G^{\text{POL}}(t)} \cdot X_G^{\text{POL}}(t) = \dots \quad \forall r \quad (15)$$

Replacing $\frac{p_G^R(t)}{p_G^{\text{POL}}(t)}$ by the time-independent temporal average

$$\left\langle \frac{p_G^R}{p_G^{\text{POL}}} \right\rangle := 1/t \cdot \sum_t \frac{p_G^R(t)}{p_G^{\text{POL}}(t)}$$

yields the approximation

$$\bar{Y}^{\text{POL}}(r) - \left\langle \frac{p_G^R}{p_G^{\text{POL}}} \right\rangle \cdot \sum_t p_G^{\text{POL}}(t) \cdot X_G^{\text{POL}}(t) = \dots \quad \forall r \quad (16)$$

Now we can combine macro budget (16) and trade balance (12) for the climate policy scenario:

$$\begin{aligned} & \bar{Y}^{\text{POL}}(r) + \left\langle \frac{p_G^R}{p_G^{\text{POL}}} \right\rangle \\ & \cdot \left(\sum_{t,i} p_{E,i}^{\text{POL}}(t) \cdot X_{E,i}^{\text{POL}}(t) + \sum_t p_p(t) \cdot X_p(t, r) \right) \\ & = \bar{C}^{\text{POL}}(r) + \bar{I}^{\text{POL}}(r) + \bar{G}_{\text{ESM}}^{\text{POL}}(r) \quad \forall r \end{aligned} \quad (17)$$

From (17) and its business as usual counterpart (13) we determine the differences of the components in absolute terms:

$$\begin{aligned} \text{Del}Y(r) &= \bar{Y}^{\text{POL}}(r) - \bar{Y}^R(r) \quad \forall r \\ \text{Del}C(r) &= \bar{C}^{\text{POL}}(r) - \bar{C}^R(r) \quad \forall r \end{aligned} \quad (18)$$

and equivalent for $\text{Del}I$ and $\text{Del}G_{\text{ESM}}$,

$$\text{Del}X_{E,i}(r) = \left\langle \frac{p_G^R}{p_G^{\text{POL}}} \right\rangle \cdot \sum_t p_{E,i}^{\text{POL}} \cdot X_{E,i}^{\text{POL}} - \sum_t p_{E,i}^R \cdot X_{E,i}^R \quad \forall r \quad (19)$$

$$\text{Del}X_P(r) = \left\langle \frac{p_G^R}{p_G^{\text{POL}}} \right\rangle \cdot \sum_t p_P^{\text{POL}} \cdot X_P^{\text{POL}} \quad \forall r \quad (20)$$

Relative differences $\text{del}Y(r)$, $\text{del}X_{E,i}(r)$ and so on are the absolute differences divided by the reference case GDP, $\bar{Y}^R(r)$.

Clearly, it follows from eq.s (17) and (13) that the absolute and relative differences also add up:

$$\begin{aligned} & \text{Del}Y(r) + \text{Del}X_{E,i}(r) + \text{Del}X_P(r) \\ &= \text{Del}C(r) + \text{Del}I(r) + \text{Del}G_{\text{ESM}}(r) \quad \forall r \end{aligned} \quad (21)$$

$$\begin{aligned} & \text{del}Y(r) + \text{del}X_{E,i}(r) + \text{del}X_P(r) \\ &= \text{del}C(r) + \text{del}I(r) + \text{del}G_{\text{ESM}}(r) \quad \forall r \end{aligned} \quad (22)$$

Numerical Results

The accuracy of the approximation between equations (15) and (16) leads to a mismatch between the good trade component and the sum of energy and permit trade components in the policy experiment. This leads also to a mismatch between $\text{del}C$ and the sum of the other relative differences in eq. (22). Table 2 lists regional numbers of $\text{del}C$ and the sum of the other relative differences exemplarily for the emiopt scenario. No mismatch occurs in the global aggregate, because the approximation regards only trade flows, which cancel out in the global aggregate.

Linear Relation of Carbon Trade Balance and Consumption Differences

From eq. (21) follows a linear relation between $\text{Del}X_P$ and $\text{Del}C$ with a slope of 1:

$$\text{Del}C(r) = 1 \cdot \text{Del}X_P(r) + \text{Del}C_0(r) \quad (23)$$

where

$$\text{Del}C_0(r) = \text{Del}Y(r) + \text{Del}X_{E,i}(r) - \text{Del}I(r) - \text{Del}G_{\text{ESM}}(r) \quad \forall r$$

is the aggregate consumption difference in a situation without permit trade.

region	delC	decomposition sum
USA	-0.56	-0.46
JAP	-0.23	-0.13
EUR	-0.37	-0.29
RUS	-4.00	-4.52
MEA	-1.51	-1.72
LAM	-0.55	-0.62
OAS	-0.39	-0.54
CHN	-0.78	-0.94
IND	-1.18	-1.36
AFR	-1.21	-1.27
ROW	-0.59	-0.60

Table 2: Numerical results for delC (in %) and the sum of components in the decomposition (in %), default technology scenario.

scenario	mean value over regions	standard deviation
default	1.00	0.03
nucfix	1.01	0.02
renewfix	1.01	0.02
ccsmin	1.02	0.04

Table 3: Numerical results for the slope in the linear relation between $\text{Del}X_P$ and $\text{Del}C$.

In subsection 4.4 we use the **Carbon Trade Balance** according to the definition in eq. (20) as the aggregated permit trade revenues with respect to present values prices corrected by the change of present value good price. Instead of the Consumption differences according to eq. (18), we use the more intuitive **Consumption losses** $\bar{C}^R(r) - \bar{C}^{\text{POL}}(r)$, so the slope of the linear function becomes -1 . This means: One additional monetary value of permit export in the Carbon Trade Balance *decreases* the Consumption losses by exactly the same monetary amount.

This relation is also subject to the approximation used in the decomposition analysis as described above.

Numerical Results

In the model results, the slope in the linear relation between $\text{Del}X_P$ and $\text{Del}C$ (see figure 10) is close to 1 for all regions. Table 3 lists mean values and standard deviations for each scenarios.

Net Energy Trade Revenues

So far, we have considered the total revenues for the export of energy carriers. However, lower revenues by a reduced export volume are partly counterbalanced by saved extraction costs, yielding the net revenues for the export of energy carriers. In the model, extraction costs are computed as a function of fuel extraction F_i for energy carrier i .¹⁶ The extracted fuel amount, F_i , is then used either for domestic primary energy production P_i or for export.¹⁷ This means that **extraction costs cover domestic fuel demand as well as extraction for the purpose of export**. We thus break up energy system costs G_{ESM} into three components:

- G_I^d : investment costs G_I (including O&M costs G_O); they are completely due to domestic energy usage,
- $G_{F,i}^d$: the share of fuel costs $G_{F,i}$ which can be attributed to domestic primary energy production P_i , and
- $G_{F,i}^e$: the share of fuel costs $G_{F,i}$ which can be attributed to export $X_{E,i}$ of energy carrier i .

We attribute fuel costs to domestic usage and export, resp., according to their respective contribution to the usage of fuel:

$$G_{F,i}^d(t, r) = G_{F,i}(t, r) \cdot \frac{P_i(t, r)}{F_i(t, r)} \quad \forall t, r, i$$

$$G_{F,i}^e(t, r) = G_{F,i}(t, r) \cdot \frac{X_{E,i}(t, r)}{F_i(t, r)} \quad \forall t, r, i$$

So we replace G_{ESM} in our decomposition analysis by G_I^d , the sum of $G_{F,i}^d$ for all energy carriers i , and export related terms $G_{F,i}^e$. Then we replace total export revenues and export related extraction costs by the **net revenues from extracting and exporting energy carriers**:

$$\sum_{t,i} p_{E,i}(t) \cdot X_{E,i}(t, r) - \bar{G}_{F,i}^e(r) \quad \forall r, i$$

After following the further steps in the previous subsections, we can report differences of domestic-related energy system costs and differences of net energy export revenues between reference and climate policy scenarios in our decomposition analysis.

¹⁶See REMIND equation 'ccostfu'.

¹⁷See REMIND equation 'fuelconst2'.