Energy Policy 39 (2011) 6030–6039

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The role of technological availability for the distributive impacts of climate change mitigation policy

Michael Lüken*, Ottmar Edenhofer, Brigitte Knopf, Marian Leimbach, Gunnar Luderer, Nico Bauer

Potsdam Institute for Climate Impact Research (PIK), Research Domain Sustainable Solutions, PO Box 60 12 03, 14412 Potsdam, Germany

A R T I C L E I N F O

Article history:
Received 13 December 2010
Accepted 1 July 2011
Available online 19 August 2011

Keywords:
Climate policy
Welfare redistribution
Energy–economy–environment model

A B S T R A C T

The impacts of the availability of low-carbon technologies on the regional distribution of mitigation costs are analyzed in a global multi-regional integrated assessment model. Three effects on regional consumption losses are distinguished: domestic measures, trade of fossil energy carriers and trade of emission permits. Key results are: (i) GDP losses and a redirection of investments in the energy system towards capital-intensive technologies are major contributions to regional consumption losses. (ii) A devaluation of tradable fossil energy endowments contributes largely to the mitigation costs of fossil fuel exporters. (iii) In case of reduced availability of low-carbon technologies, the permit market volume and associated monetary redistributions increase. The results suggest that the availability of a broad portfolio of low-carbon technologies could facilitate negotiations on the permit allocation scheme in a global cap-and-trade system.

1. Introduction

Ambitious climate change mitigation policy leads to welfare redistribution among world regions. Several reasons to explain differing regional mitigation costs have been identified in the literature, especially region-specific abatement costs that depend on assumptions on the availability of low-carbon technologies (den Elzen et al., 2008; Luderer et al., 2009), regional endowments with fossil energy carriers (den Elzen et al., 2008; Leimbach et al., 2010a) and specifications of the climate regime, such as different climate targets (Clarke et al., 2009; Edenhofer et al., 2010) or the international burden sharing (den Elzen and Lucas, 2005; Rose et al., 1998). However, the effort to separate and quantify the main effects that determine the distribution of regional mitigation costs in a comprehensive framework to our knowledge has not yet been undertaken in the literature. This paper aims to fill this gap.

The availability of a broad portfolio of low-carbon technologies has been identified as a key influencing factor for reducing mitigation costs on a global scale. Bauer et al. (2009b), Edenhofer et al. (2010) and Weyant (2004) show that restrictions on the deployment of low-carbon technologies lead to higher costs. Several studies emphasize a differentiated impact on the mitigation costs of world regions (Bosetti et al., 2009; Crassous et al., 2006; den Elzen et al., 2008; Leimbach et al., 2010b; Luderer et al., 2009; Richels and Blanford, 2008). Edenhofer et al. (2006), Manne and Richels (2004) and Kypreos (2005) point out that technological learning contributes largely to the efficient application of innovative low-carbon technologies under climate policy.

Special attention has recently been paid to mechanisms that arise from interactions among world regions, especially the trade with energy carriers. Due to the redirection of investments towards low-carbon technologies, the global demand for fossil energy carriers decreases, resulting in a devaluation of fossil energy endowments.

This is proposed as an explanation for relatively high consumption losses for major exporters of fossil fuels (den Elzen et al., 2008; Luderer et al., 2009; Leimbach et al., 2010a,b).

Another strand of literature analyzes the impact of different climate policy regimes on mitigation cost and concludes that more stringent climate targets lead to higher mitigation costs on a global level (Clarke et al., 2009), which affects world regions differently (Bosetti et al., 2009; Crassous et al., 2006; Edenhofer et al., 2010; den Elzen and Höhne, 2010). A delay of climate policy increases global costs (Clarke et al., 2009), but has also a differentiated impact on regional costs according to Luderer et al. (2009). The burden sharing regime constitutes a further key factor on regional mitigation costs: in a global cap-and-trade system, emission permits are allocated to regions based on the outcome of negotiations ('initial allocation') and can be traded to reconcile supply and demand of permits among regions, thereby creating extra regional costs or revenues (den Elzen and Lucas, 2005; Leimbach et al., 2010a; Rose et al., 1998).

As the contributions to regional mitigation costs are either related to trade or to domestic actions within each world region, they can be grouped as follows:

The *domestic effect* covers the reaction of regional energy systems and macroeconomies to climate policy apart from

---

* Corresponding author. Tel.: +49 178 8588126.
E-mail address: bmlueken@web.de (M. Lüken).

0301-4215/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2011.07.002

changed trade flows.[1] If restrictions on low-carbon technologies are assumed, regional abatement strategies and consequently the domestic components change.

The *energy trade effect* quantifies changed profits from the trade with energy carriers under climate policy, which is modified by technology restrictions as well. In particular, this effect covers the devaluation of tradable fossil energy carriers.

The *permit trade effect* accounts for revenues from trade with emission permits in a global cap-and-trade system. The revenues have a purely distributional effect on the regional consumption without affecting their investment decisions, if a free flow of capital as well as an unrestricted permit market without market power is assumed ('separability of efficiency and equity', see Manne and Stephan, 2005 and references there in), so that the efficient market allocation of permits is not influenced by the initial allocation. The permit trade effect comprises the influence of the supply with permits (subject to the initial allocation) as well as the demand for permits and the carbon price (subject to the availability of low-carbon technologies).

Various links exist between the influencing factors on mitigation costs. Luderer et al. (2009) point out that pessimistic assumptions on technologies induce a higher carbon price and therefore higher monetary flows in response to permit trade, so that the distributive impact of different permit allocation schemes is higher. Den Elzen et al. (2008) report regional costs under different assumptions on both the climate target stringency and the initial permit allocation. Leimbach et al. (2010b) emphasize the relevance of the interdependence of international trade and technological development for regional mitigation costs.

The aim of this paper is to quantify the impact of domestic and trade effects on regional mitigation costs, and to analyze how assumptions on the availability of low-carbon technologies and on the initial permit allocation scheme influence the effects. For this purpose, we present an economic decomposition method that allows us to compute differentiated contributions to regional costs. The idea to quantify distinct contributions that add up to a total loss can be traced back to Harberger (1964) and Diewert (1981) in a static framework, and Diewert (1985) in a dynamic one. In the context of global climate policy, similar approaches have been applied using Computable General Equilibrium models, for example Böhringer and Rutherford (2000). The present study uses an intertemporal model that allows for a consistent valuation of domestic and trade effects.

The investigation of model scenarios over a long time horizon is inevitable for understanding effects on regional mitigation costs (Knopf et al., 2010). Suitable models need to describe the integrated dynamics of regional energy systems, represent long-term macroeconomic growth, and account for trade flows and market equilibria under full flexibility in the timing and location of emission reductions. Compared to Computable General Equilibrium models, which are (besides their particular strengths) not intended to cover long-term intertemporal dynamics, the multi-regional integrated assessment model REMIND-R (Leimbach et al., 2010a,b) is well suited for this study.

The paper is structured as follows. Section 2 describes the model REMIND-R. Section 3 introduces the economic decomposition method. Section 4 documents the definition of model scenarios. The results are presented in Section 5. Finally, Section 6 contains a discussion of the results and their implications for future climate negotiations.

2. The model REMIND-R

REMIND-R (Leimbach et al., 2010a,b) is a global multi-regional integrated assessment model that couples a stylized top-down macroeconomic growth module with a detailed bottom-up energy system module.[2] The advantage of the hard-link between the modules is that it guarantees a simultaneous equilibrium of both energy and capital markets (Bauer et al., 2008). The model comprises eleven regions[3] that are represented by individually calibrated macroeconomy and energy system modules and the objective to maximize intertemporally aggregated welfare. In the following, features of the model with particular relevance for this study are introduced in detail.

The first important model feature comprises technological flexibility. The energy system module contains a variety of existing and future energy transformation technologies, described by detailed techno-economic parameters and specific CO_2 emissions. The model is flexible in its choice of energy conversion technologies. However, the deployment of a technology requires investments into capacities that must be used until the end of their technical lifetimes, as well as availability of the respective primary energy carrier.

Reserves of exhaustible energy carriers (coal, natural gas, oil, uranium) are highly unevenly distributed among regions as depicted in Fig. 1; a mismatch of their regional demand and supply induces trade flows. Renewable energy carriers (wind, solar, hydro and geothermal energy) and biomass are limited by region-specific potential constraints and cannot be traded.

Various low-carbon technologies are available in REMIND-R: renewable energy, thermal nuclear reactor and fossil- or biomass-based technologies with Carbon Capture and Storage (CCS).[4] Together with the options to increase energy efficiency or to decelerate economic growth, these technologies allow for a flexible response to a climate policy target with respect to welfare maximization.[5] The relevance of certain technologies for the costs of climate policy can be assessed in scenarios with constraints on their respective deployment.

The second important model feature is the role of initial allocation and trade of emission permits. In climate policy scenarios, a global cap-and-trade-system is assumed in REMIND-R. Tradable emission permits are initially allocated to model regions as their national emission budget. Domestic emissions of a region must be covered by permits, so a mismatch of demand for permits (the market allocation) and supply of permits (the initial allocation) induces trade flows. The model assumes efficient global markets and, therefore, a free flow of capital between regions. Under this assumption, optimal investment decisions and hence also the market allocation of permits are

---

[1] Please note that our definition is different than the common use of the term in studies working with Computable General Equilibrium models. (E.g. Böhringer and Rutherford (1999) distinguish a 'domestic market effect' at constant prices from a purely price-induced effect.) The domestic effect as it is defined here covers also the indirect impact of climate policy on regional energy systems and macroeconomies by terms of trade effects.

[2] On 〈http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/models/remind/remind-code〉 the technical description of REMIND-R is available. REMIND-R is programmed in GAMS. The code is available from the authors on request. The version we use in this study (REMIND-R1.2) corresponds to the version in Leimbach et al. (2010b) except for minor adjustments in calibration.

[3] USA—United States of America, EUR—European Union (27 countries), JPN—Japan, CHN—China, IND—India, RUS—Russia, AFR—Sub-Saharan Africa (excluding Republic of South Africa), MEA—Middle East and North Africa, OAS—Other Asia, LAM—Latin America, ROW—Rest of the World (Canada, Australia, Republic of South Africa, Rest of Europe).

[4] Biomass-based technologies with CCS are assumed to result in negative emissions.

[5] Unrealistic capacity additions into thermal nuclear reactors are avoided by imposing adjustment costs, as described in Bauer et al. (2010).

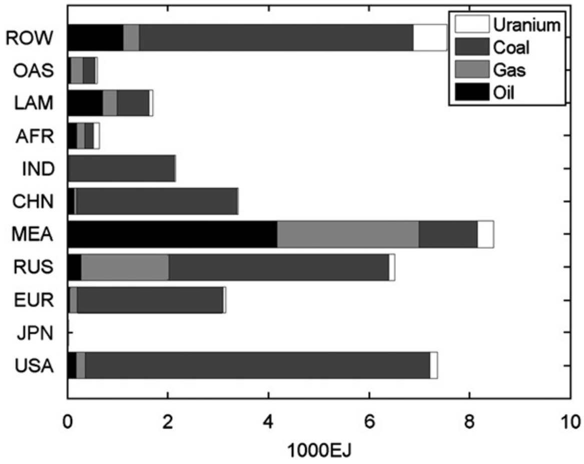

Fig. 1. Reserve endowments of exhaustible primary energy carriers, based on Enerdata. Most recent data is available on http://www.enerdata.fr/enerdatauk/index.html.

independent from the initial allocation of permits, so that revenues from permit trade have a purely distributional effect on regional consumption. Global consumption losses are not influenced by redistributions among regions and are thus not influenced by the initial allocation as well.

Third, the model approach to trade in general is crucial for this study. Model regions interact via world trade of exhaustible energy carriers (coal, oil, natural gas, uranium), an aggregate macroeconomic good (measured in monetary units) and emission permits. Trade balances require that exports equal imports of each tradable good in every time step. Global prices are derived endogenously from shadow prices of these balance equations. Tradable primary energy carriers constitute endowments of exporting regions, hence trade implies an exchange of ownership in REMIND-R. Increasing extraction costs are anticipated by exporters, so trade prices account for scarcity rents. The allocation of emission permits can be regarded as distribution of an additional endowment among regions. While endowments with energy carriers are subject to natural conditions, the initial permit allocation can be designed due to political or normative considerations.

For each region *r*, monetary equivalents of trade flows need to be balanced over the entire time horizon. 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,[6] the intertemporal trade balance reads

$$\sum_t \left(\sum_i p_{E,i}(t)X_{E,i}(t,r) + p_p(t)X_p(t,r) + p_G(t)X_G(t,r) \right) = 0 \quad \forall r \qquad (1)$$

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 (Manne and Rutherford, 1994; Leimbach and Toth, 2003). The model calculates a Pareto solution between regions, corresponding to the general market equilibrium in the absence of externalities. Climate policy implies a redirection of trade flows due to lower demand for relatively carbon-intense energy carriers and additional demand for emission permits, adjusted by accordingly redirected flows of aggregate good trade.

The fourth important aspect is the calculation of regional consumption in the macroeconomic module of REMIND-R, as we follow the approach to measure mitigation costs in terms of discounted consumption losses. A pure rate of time preference of 3% is assumed. An aggregate good is produced by combining capital, labor and various final energy types, described by a nested CES production function. A macroeconomic 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}:

$$Y(t,r) - X_G(t,r) = C(t,r) + I(t,r) + G_{ESM}(t,r) \quad \forall t,r \qquad (2)$$

Climate policy constraints affect consumption along two lines. On the one hand, costs for the domestic energy system G_{ESM} as well as investments into the macroeconomic capital stock *I* are modified. On the other hand, redirected trade flows imply a changed contribution of good trade X_G in the macroeconomic budget. Consequently, by considering differences between scenarios with and without climate policy in Eqs. (1) and (2), consumption losses can be traced back to domestic and trade-related contributions, as will be shown in the next section.

3. Economic decomposition method

The economic decomposition method allows us to decompose regional consumption losses between a *business as usual* scenario and a climate policy scenario into domestic and trade-related components.[7] Decomposition methods are frequently used for the analysis of results generated by Computable General Equilibrium models, but existing methods, e.g. as developed by Böhringer and Rutherford (1999, 2000) and Harrison et al. (2000), are not appropriate for the analysis of mitigation costs in an intertemporal perspective.

We use the macroeconomic budget, Eq. (2), to explain the intertemporally aggregated consumption differences as the sum of domestic components plus differences in revenues from trade in the final good. In order to integrate revenues from energy and permit trade, we consider the intertemporal trade balance, Eq. (1), which requires a conversion of the macroeconomic budget to present value prices and summation over time. For a comparison of the *business as usual* scenario and a climate policy scenario, it is crucial to apply a common time path of good prices for discounting. The details of the formal derivation can be found in the appendix. Finally, regional cumulative consumption differences between *business as usual* scenario and climate policy scenario can be expressed as the sum of six components:

$$\Delta C(r) = \left(\Delta Y(r) - \Delta I(r) - \Delta G_{inv}(r) - \Delta G_{fuel}(r) \right) + \sum_i \Delta X_{E,i}(r) + \Delta X_p(r) \quad \forall r \qquad (3)$$

The first four components (differences in GDP generation ΔY, investments into the macroeconomic capital stock ΔI, investment costs in the energy system including O&M costs ΔG_{inv} and fuel costs ΔG_{fuel}) can be attributed to the domestic effect, defined as the reaction of regional energy systems and macroeconomies apart from changed trade flows. The fifth component measures the net trade effect of primary energy carriers *i*, $\Sigma_i \Delta X_{E,i}$, and the sixth component quantifies the permit trade effect ΔX_p. Trade effects relate to profits and costs from trade and hence cover price effects as well as volume effects.

---

[6] Present value prices account for the endogenous discounting of future prices.

[7] A preliminary version of the method has already been applied by Bauer et al. (2009a). In this paper, we contribute a higher degree of disaggregation of effects and the formal derivation of the method. A similar method to separate revenues on the permit market from other effects has been developed by Luderer et al. (2009).

4. Scenarios

This section explains our representation of climate policy by a target on CO_2 emissions from the energy sector and defines a series of scenarios with different assumptions on the portfolio of technologies and the permit allocation scheme. A *business as usual* scenario without any climate policy target or technology restriction acts as common base case for all climate policy scenarios. In climate policy scenarios, we assume a budget target for CO_2 emissions from the energy sector that restricts cumulative emissions in the period 2005–2100 to 400 GtC. The timing of emission reductions is not regulated.

The use of a carbon budget is inspired by Meinshausen et al. (2009), who find that cumulative CO_2 emissions in 2000–2050 are a robust indicator of the probability to limit global temperature increase to 2 °C relative to pre-industrial. A probability of 50% can be obtained by limiting CO_2 emissions from all sectors until 2050 below 1437 $GtCO_2$, equivalent to 392 GtC (Meinshausen et al., 2009). In order to define a CO_2 budget of energy-related emissions for the analyzed time horizon, additional assumptions are needed: 92 GtC are subtracted to account for emissions before 2005 and land use-related CO_2 emissions until 2050, and an estimate of 100 GtC for emissions in 2050–2100 is added.[8]

From the perspective of this study, budget targets bear two advantages over climate policy targets referring to concentrations, radiative forcings, or temperature. First, the same budget can be applied in different technology scenarios, allowing for a comparison of monetary effects; in contrast, e.g. a temperature target would imply different emission budgets in different technology scenarios. Second, uncertainties within the climate system are not relevant in the analysis.

The following four climate policy scenarios with different assumptions on the availability of technologies are performed:

- *allTech*: the full portfolio of technologies is available.
- *nucfx*: the use of nuclear power is restricted to the level in the *business as usual* scenario.
- *renewfx*: the use of renewable energy sources is restricted to respective levels in the *business as usual* scenario. Biomass use is not restricted.
- *ccsoff*: CCS technologies are not available.

We consider the following schemes for the initial allocation of emission permits among regions:

- Reference: the initial allocation is chosen to match the demand for permits in each region. Hence, no trade in emission permits occurs, and permit trade effects on regional consumption losses are zero.[9]
- C&C: contraction and convergence allocation scheme (Meyer, 2004). As of 2050, the same per capita emission rights are allocated. Between 2010 and 2050, there is a smooth transition of the regional shares between grandfathering and equal per capita emissions. 2000 is assumed as the reference year for grandfathering.
- Intensity: allocation in proportion to regional GDP from the beginning over the entire time horizon.
- Equal per capita: allocation in proportion to regional population from the beginning over the entire time horizon.

5. Results

The results will be presented in three steps. The first subsection characterizes the global emission reduction effort and its regional market allocation in the four technology scenarios. The second subsection discusses the domestic and energy trade effect on regional consumption losses obtained by the decomposition method. Up to this point, we restrict the analysis to the reference permit allocation scheme. The third subsection analyzes the distributive consequences of permit allocation schemes and how they interfere with the availability of low-carbon technologies.

5.1. Characteristics of the technology scenarios

In the *business as usual* scenario, energy-related CO_2 emissions accumulate to 1725 GtC until 2100. Compliance to the budget target of 400 GtC induces a strong reduction of emissions, as illustrated in Fig. 2. A peak of emissions in 2015 is followed by a continuous decrease of annual emissions to −1.7 GtC/a in 2100. (See Knopf et al. (2010) for a similar result in a 400 ppm scenario.) Negative emissions imply a net removal of CO_2 from the atmosphere by deployment of biomass with CCS, so consequently in the *ccsoff* scenario negative emissions are not possible. Rather, emission reductions need to begin immediately, and emissions amount to 0.8 GtC/a in 2100. The emission target is mirrored by a carbon price that increases from 5 to 920 \$/tCO_2 in 2100 in the *allTech* scenario. Restrictions on low-carbon technologies cause higher prices, starting at 6 \$/tCO_2 (*nucfx*), 8 \$/tCO_2 (*renewfx*) and 11 \$/tCO_2 (*ccsoff*) in 2005.[10]

In the *business as usual* scenario, the energy system is predominantly based on fossil fuels with a growing share of coal. In the *allTech* policy scenario, the emission target leads to a reduction of total primary energy consumption as well as a substitution towards low-carbon technologies. A strong reduction of coal consumption is most prominent, partly compensated by higher consumption of renewable energy carriers, biomass and uranium. Natural gas is consumed as a transitional option to reduce specific emissions as compared to coal. The option to generate negative emissions using biomass with CCS allows for a continued use of crude oil under climate policy; as oil is more costly to substitute than coal, the decline of oil consumption is rather modest. Changed consumption of tradable energy carriers implies a redirection of respective trade flows, e.g. the volume of coal trade is strongly reduced (Leimbach et al., 2010a). Increased deployment of renewable energy leads to higher investment and lower fuel costs.

In the scenarios *nucfx*, *renewfx* and *ccsoff*, the unrestricted technologies take up a higher share of total primary energy consumption. For example, the consumption of uranium almost doubles in 2100 in the *renewfx* scenario, and extended application of CCS leads to a transitionary increase of coal demand. The reduction of crude oil consumption is strongest in the *ccsoff* scenario.

In a global cap-and-trade system, the levelling of carbon prices among regions ensures a welfare-maximizing regional market allocation of the global emission reduction. Regions with reduction

---

[8] Models following an intertemporal welfare optimization approach typically exhibit distortionary terminal period effects which are insignificant for the results in earlier time steps. Hence, it is common practice to run intertemporal optimization models for an extended time horizon and to omit its later part for the analysis. The model time horizon covers the period from 2005 to 2150 with an additional carbon budget of 10 GtC for the period from 2105 to 2150 in climate policy scenarios.

[9] In the absence of uncertainty, this setting is equal to a global tax regime with regional revenue recycling.

[10] The carbon price in REMIND-R is rather low compared to other models, see Clarke et al. (2009) and Edenhofer et al. (2010).

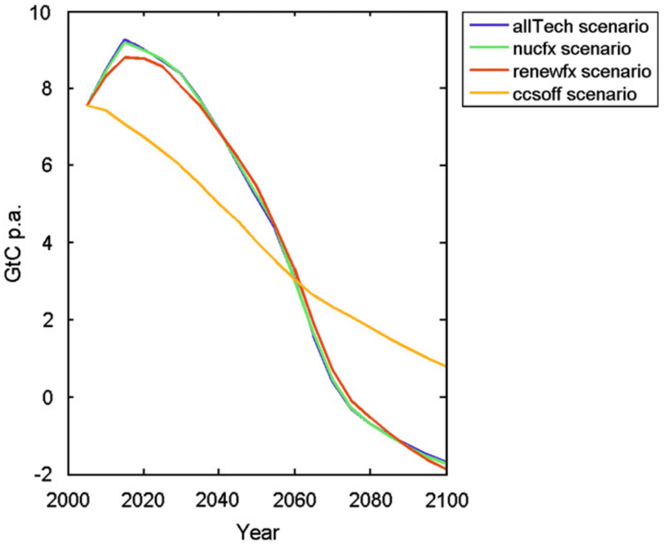

Fig. 2. Global energy-related emissions of CO_2 in 2005–2100 in GtC per year.

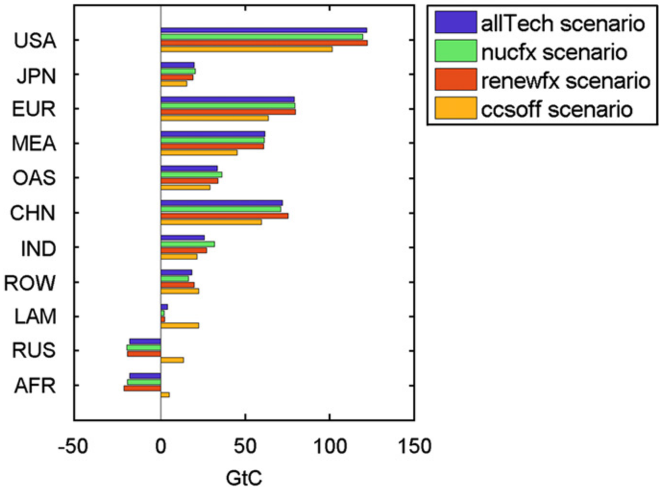

Fig. 3. Cumulative regional emissions of CO_2 from the energy system in the period 2005–2100 for the technology scenarios in GtC.

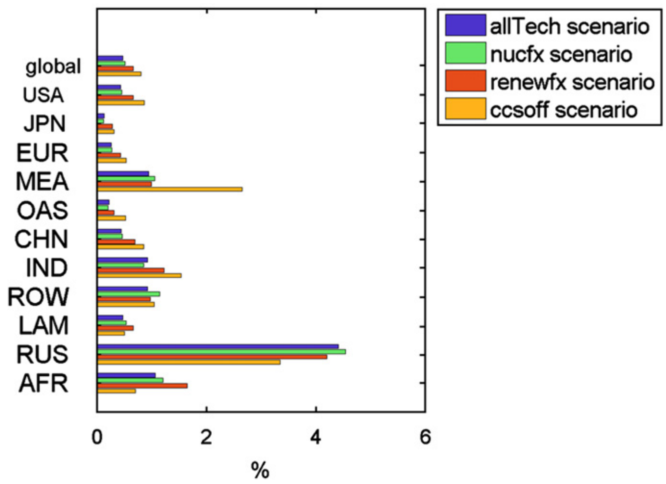

Fig. 4. Global and regional consumption losses for the technology scenarios in the reference permit allocation, in % of the GDP in the *business as usual* scenario.

possibilities at relatively low abatement costs bear high reductions. In the RUS and AFR regions, huge biomass potentials as well as Carbon Storage potentials and the exploitation of both potentials by biomass-based CCS technologies allow for significant negative emissions in the second half of the century. This outweighs positive emissions from other technologies, in particular in the time period before biomass with CCS becomes competitive. Hence, the cumulative emissions in RUS and AFR are negative (see Fig. 3). If low-carbon technologies are restricted, cumulative emissions are relocated between regions according to changed regional abatement costs. This is most significant for RUS, AFR and LAM in the *ccsoff* scenario. The global sum of cumulative emissions is by definition the same in all scenarios.

Global consumption losses amount to 0.6% of GDP in the *allTech* scenario.[11] Regional losses deviate from the global value with RUS displaying the highest losses of 4.4% of GDP (see Fig. 4). Limitations of low-carbon technologies lead to higher consumption losses in most regions, in particular the unavailability of CCS, which implies more than a doubling of losses in MEA.

The economic decomposition method allows us to investigate regional consumption losses in detail. The results reported so far indicate that redirected abatement obligations, modified trade flows and a shift from fuel to investment costs contribute strongly to regional consumption losses.

5.2. *Domestic and energy trade effects on regional consumption losses*

The economic decomposition method allows for a quantification of domestic and trade-related effects on regional consumption losses. This section considers the reference permit allocation, so that the permit trade effect is zero.

Let us start with analyzing domestic effects, of which reductions in economic output (GDP loss) constitutes the major contribution. The GDP loss is partly counterbalanced by other components and thus exceeds the consumption loss in most regions. Restrictions on low-carbon technologies lead to a further reduction in GDP in most cases. However, some regions benefit from a reduced availability of certain technologies, in particular RUS and AFR in the *ccsoff* scenario. We will discuss this point in detail later.

Reduced macroeconomic growth goes along with lower investment into the macroeconomic capital stock, thereby partly counterbalancing the GDP loss. In the energy system, a shift from fossil fuel-intense technologies towards capital-intense low-carbon technologies leads to positive contributions from saved fuel expenditures and negative contributions from increased energy system investments. Due to restrictions on capital-intense technologies in the *renewfx* scenario, the energy system investment component is reduced and even changes sign in some regions.

Now we turn to the energy-trade effects.[12] The contribution of energy trade to consumption loss is rather low compared to domestic effects, except for RUS, where reduced coal export profits (−2.2% of GDP) are the largest contribution to consumption losses (−4.4% of GDP) in the *allTech* scenario. Trade components change once restrictions on low-carbon technologies apply,

---

[11] The measure for consumption losses is the difference between the intertemporally aggregated consumption in present value terms in a policy scenario and the respective number in the business as usual scenario. Numbers are expressed in units of % of GDP.

[12] Please note that increased export profits or reduced import costs appear as positive components, and reduced export profits or increased import costs as negative components. Results for the direction of trade flows allow us to distinguish the cases; see Leimbach et al. (2010b).

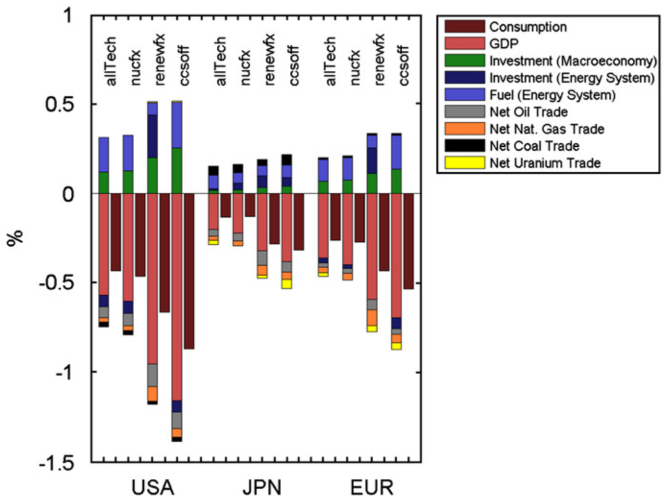

Fig. 5. Decomposition of cumulative consumption losses for resource-importing industrialized regions (USA, JPN and EUR) in % of GDP. For each region and technology scenario, the brown bar shows the consumption loss, and the stacked bar left to it shows the components. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

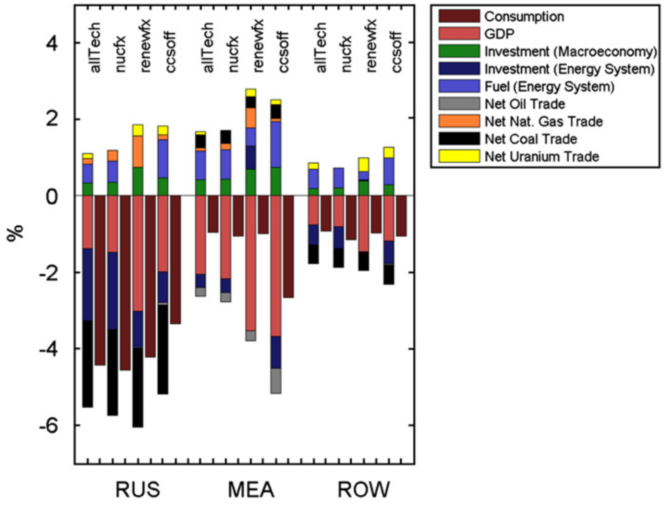

Fig. 6. Decomposition of cumulative consumption losses for the major fossil fuel exporting regions (RUS, MEA and ROW) in % of GDP. For each region and technology scenario, the brown bar shows the consumption loss, and the stacked bar left to it shows the components. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for example, the role of natural gas as a transitional emission reduction option increases in the *renewfx* scenario compared to the *allTech* scenario. This results in higher import costs (for importers USA, JPN, EUR) and higher export profits (for exporters RUS, MEA).

Next, we focus on specific results for three groups of regions, starting with resource-importing industrialized regions (USA, JPN, EUR), see Fig. 5. This group can be characterized by relatively modest consumption losses and extra costs for the import of uranium and natural gas to cover higher usage of these energy carriers under climate policy. However, trade components play only a minor role compared to GDP losses.

The energy trade effect is more relevant for major fossil fuel exporting regions (RUS, MEA, ROW), see Fig. 6. Profits from coal export (RUS, ROW) and oil export (MEA, RUS to a very small extent) are reduced due to decreasing demand and lower prices under climate policy. This implies a devaluation of the exporters' coal and oil endowments.[13] A transitional increase in the demand for natural gas leads to a revaluation of natural gas endowments in RUS and MEA, which partially compensates for the devaluation of oil and coal endowments. Furthermore, RUS, MEA and ROW receive higher profits from uranium exports. The availability of low-carbon technologies clearly impacts the energy trade components; reduced oil demand in the *ccsoff* scenario leads to a stronger devaluation of oil endowments. On the contrary, a limitation of renewable energy raises natural gas demand, resulting in a stronger revaluation of natural gas endowments in the *renewfx* scenario.

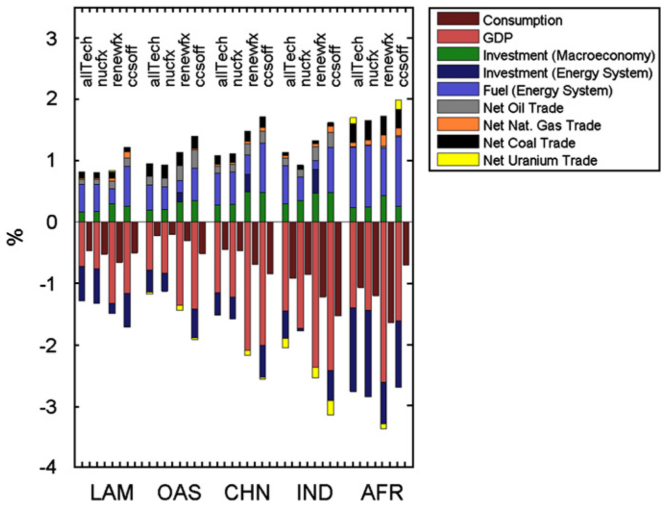

Fig. 7. Decomposition of cumulative consumption losses for developing and emerging economies (LAM, OAS, CHN, IND and AFR) in % of GDP. For each region and technology scenario, the brown bar shows the consumption loss, and the stacked bar left to it shows the components. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

RUS bears the highest consumption loss of all regions that even exceeds the GDP loss. This can be attributed to the coincidence of two strong negative components—the devaluation of coal endowments and strong investments into CCS technologies using biomass. den Elzen et al. (2008) similarly find that both a devaluation of fossil endowments and high domestic abatement costs contribute to high mitigation costs in their model region Former Soviet Union.

For RUS, we find a lower GDP loss and consumption loss in the *ccsoff* scenario compared to the *allTech* scenario. Large deployment of biomass with CCS in RUS is not possible in the *ccsoff* scenario, so emission reductions are shifted to other regions as explained in Section 5.1. Higher emissions in RUS allow for a higher total energy consumption and hence a reduced GDP loss. In total, RUS profits from the modified market allocation of the global emission reduction in the *ccsoff* scenario.[14]

Finally, we discuss specific results for emerging and developing economies LAM, OAS, CHN, IND and AFR (see Fig. 7). Consumption losses of emerging and transition economies are mainly determined by domestic effects. Regarding energy trade components, all

---

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

[14] Please note that the total effect on regional consumption is modulated by the permit trade effect in the case of other permit allocation schemes different from the reference scheme.

regions profit from reduced coal import costs under climate policy, AFR also benefits from extra natural gas and uranium export profits, whereas IND spends more for uranium imports. High biomass potentials in LAM and AFR are used with CCS technologies. We observe similar effects as in RUS; high investments into CCS explain the large investment cost component in LAM and AFR in the *allTech* scenario. In the *ccsoff* scenario, emissions in LAM and AFR increase; GDP loss and consumption loss are reduced accordingly.

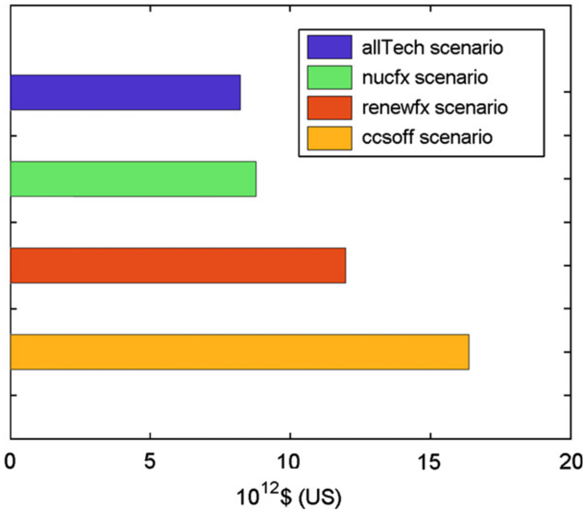

Fig. 8. Global discounted value of permits in $10^{12}$$ (US).

5.3. Permit trade effects on regional consumption losses

Profits on the global market for emission permits constitute another component of regional consumption losses. First, we calculate the cumulative *global* discounted value of permits that are distributed by the initial permit allocation. Then we analyze the redistribution of regional consumption implied by different allocation schemes in the *allTech* technology scenario. Finally, we take the interference of technology scenarios and allocation schemes into account.

Fig. 8 displays the global discounted value of permits for each technology scenario, defined as the cumulative product of global emissions and discounted carbon price. While cumulative global emissions are the same in all technology scenarios, restrictions on low-carbon technologies lead to higher carbon prices and consequently to a higher discounted value of permits, implying larger redistributions among regions.

If CCS is not available, the value doubles from $8.2\times10^{12}$$ (US) to $16.4\times10^{12}$$ (US). The initial permit allocation scheme determines the direction and size of permit trade flows and hence the regional shares of the discounted permit value. Resulting permit trade profits add to the domestic and energy trade components.

Fig. 9 shows the cumulative regional consumption losses per GDP in all technology scenarios, taking the permit trade component into account. For the reference allocation scheme consumption differences are identical to those discussed in the previous subsection. Other allocation schemes lead to redistributions of consumption among regions. 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 takes a position in between. The colored

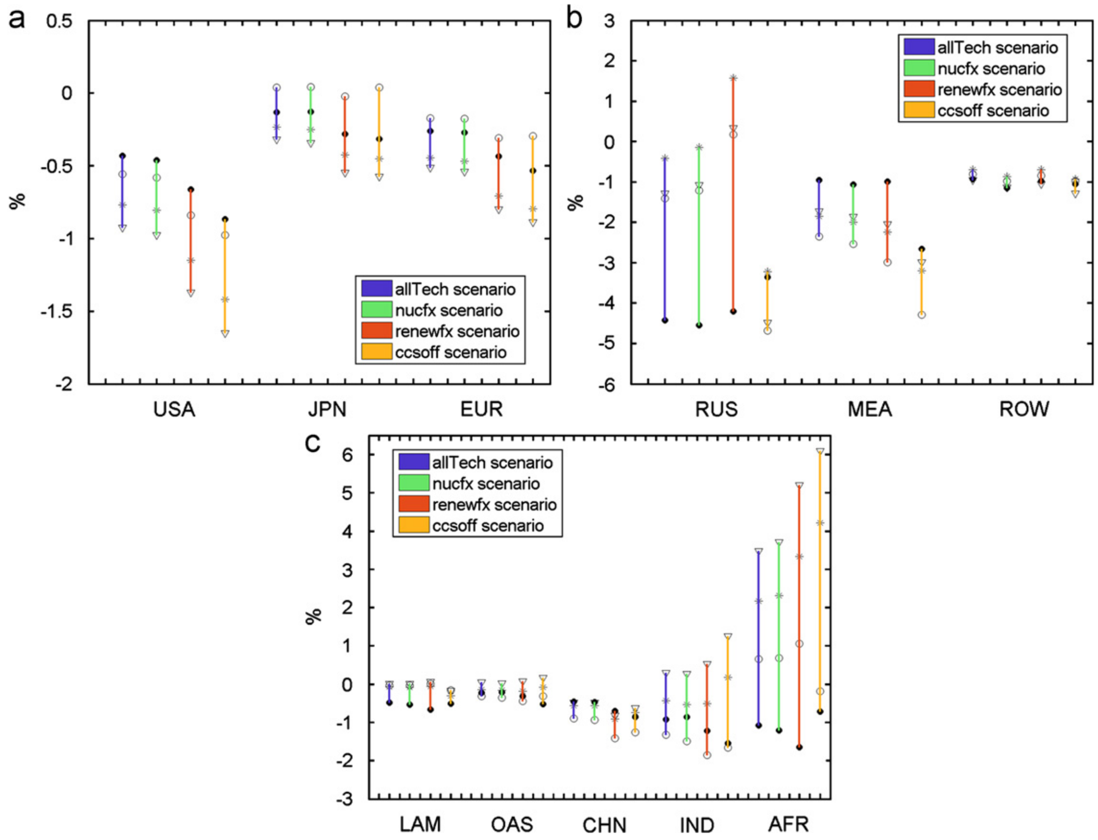

Fig. 9. Impact of the permit trade effect on regional consumption losses in % of GDP. Filled circles: reference allocation. Open circles: intensity allocation. Stars: C&C allocation. Triangle: equal per capita allocation. Notice the different scaling of the *y*-axis in the subfigures. (a) Resource-importing industrialized regions; (b) major fossil fuel exporting regions; (c) developing and emerging economies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bars in the figure indicate the size of redistribution given the range of allocation schemes in this study.

A comparison of technology scenarios reveals that the range of redistribution grows if restrictions on low-carbon technologies apply, except for the regions RUS and LAM in the *ccsoff* scenario: in the *allTech* scenario, the consumption in USA would decrease by about 0.4% under the reference allocation and by 0.9% under an equal per capita allocation. This range of 0.5% grows to 0.9% in the *ccsoff* scenario. For AFR, the range between reference allocation and equal per capita allocation grows from 4.5% in the *allTech* scenario to more than 6% in the *ccsoff* scenario. Hence, the availability of low-carbon technologies is advantageous for permit importers to keep carbon prices and ranges of redistribution low; the opposite holds for permit exporters.

A reduced availability of technologies has a smaller impact on regional consumption losses than a variation of the allocation scheme, except for ROW (all technology scenarios), RUS and LAM (*ccsoff* scenario). Hence, if selected low-carbon technologies are restricted, consumption differences for industrialized regions are still within the redistribution range of the *allTech* technology scenario. For example, the reference allocation in the *ccsoff* scenario leads to about the same consumption losses as the C&C allocation when CCS is available for USA, JPN and EUR.

In the *ccsoff* scenario, significant changes in the market allocation of the global emission reduction provide an explanation for the relatively low relevance of the initial permit allocation for RUS and LAM in this scenario: regional emissions increase strongly, so that the permit export under all allocation schemes is considerably lower as compared to the *allTech* scenario.

6. Discussion and conclusions

International climate policy negotiations can benefit from a deeper understanding how the design options of climate policy influence welfare redistributions among world regions. Previous studies have focused on particular effects without a comprehensive quantification of their contributions to regional consumption losses. This paper analyzes regional consumption losses in a framework that allows for a complete decomposition into domestic, energy trade and emission permit trade effects. The influence of technological availability and its interference with permit allocation schemes on the effects is discussed, based on a series of scenarios in the global multi-regional hybrid model REMIND-R. While the analysis of the permit trade effect assumes a global cap-and-trade system, the results on the domestic and energy trade effect require global participation, but not necessarily a cap-and-trade regime.

Our first key result states that domestic effects are the major contribution to regional consumption losses in most regions and scenarios. In particular, GDP losses, higher expenditures for investments into energy transformation technologies and reduced spending for fuels play a dominant role. When restrictions on certain technologies apply, regional economies generally react by increased GDP losses, particularly in a scenario without CCS. A welfare-maximizing market allocation of global mitigation efforts in REMIND-R leads to exceptions for some regions. If CCS is not available, the regions RUS and LAM have a limited potential to employ alternative low-carbon technologies and consequently reduce their contribution to the global abatement effort. In consequence, their GDP losses are smaller than in the scenario without technology restrictions.

Our second key result is the quantification of the energy-trade effect. The substitution from coal and oil to natural gas and uranium changes trade profits and costs for both importers and exporters. The coal-trade effect is more prominent than the oil-trade effect due to higher costs to substitute oil under climate policy. As the devaluation of coal and oil endowments constitutes a major reason for the relatively high consumption losses of fossil energy exporting regions, the effect is more pronounced for exporters. If CCS is not available, the impossibility to compensate emissions from oil use by biomass technologies with CCS leads to a significant increase in the devaluation of oil endowments. On the contrary, natural gas endowments are revalued by climate policy, especially in scenarios where the usage of renewable energy is restricted. The relevance of energy trade-related effects on consumption losses supports and specifies respective conclusions by den Elzen et al. (2008) and Leimbach et al. (2010b). The devaluation of fossil endowments reported in this study should be regarded as a lower limit, because it depends on the extraction cost curve approach used in the model which constitutes rather an upper limit of cost estimates.

The third key result can be drawn from the consideration of the permit trade effect: excluding low-carbon technologies from the portfolio of mitigation options leads to a higher monetary value of the emission budget. Consequently, the range of redistribution implied by different permit allocation schemes grows for most regions, in good agreement with Luderer et al. (2009), and even exceeds the range of consumption losses that occur from a comparison of technology scenarios. In a more general perspective, it can be assumed that other measures that elevate the global carbon price (for example stricter climate targets or a delay of action) lead to a higher global permit value.

The decomposition method presented in this study allows for the analysis of contributions to regional consumption differences in a cumulative perspective. The development of contributions over time can be assessed by an extension of the method in future studies.

From the perspective of design options for an international climate agreement, the results allow to identify *negotiable* contributions to regional mitigation costs. The availability of technological options is primarily subject to technological developments; however, programs to enhance the global feasibility of low-carbon technologies as part of an international agreement could lower mitigation costs for most world regions, as indicated by reduced consumption losses in the scenario with all technologies available. On the contrary, the initial permit allocation scheme is fully subject to international negotiations. For this reason, allocation schemes can be designed to partially compensate regional mitigation costs – within certain boundaries – according to considerations of equity or political acceptability. The limits of this negotiable component in regional mitigation costs are subject to the permit market volume and accordingly to the availability of low-carbon technologies.

The results indicate strong incentives for industrialized regions to promote the feasibility of low-carbon technologies for reducing their mitigation costs. This argument applies in particular under allocation schemes that generate particularly high redistributions (e.g. equal per capita or C&C) and are therefore more acceptable for poorer world regions. For example, if CCS is available and a C&C allocation is globally accepted, consumption losses for industrialized regions are not higher than in the reference allocation but without feasibility of CCS. A broad portfolio of low-carbon technologies could thus help to facilitate international negotiations on a permit allocation scheme, thereby increasing the chances to attain a global agreement on a stringent global climate policy. More awareness about the importance of technology for the distributive consequences of climate policy could be beneficial for the success of negotiations.

Some of the results depend on specific features of the REMIND-R model. The range of redistributions in this study is limited by relatively moderate carbon prices in REMIND-R (Clarke et al., 2009; Edenhofer et al., 2010), and the separability of allocation-induced redistributions from other effects is based on the model assumption of free flows of capital and permits. Similar analyses with other integrated assessment models would hence be beneficial to assess the robustness of the results.

The choice of assumptions and scenario definitions in this study is motivated to explore the policy space and to compare different alternatives rather than to assess the consequences of politically feasible strategies. In particular, the *ccsoff* scenario bears several reservations. If CCS – in particular if fueled by bioenergy – is not available, then the optimal trajectory is to reduce emissions very quickly, if a strict carbon budget shall be achieved. If we also assume that the emissions keep on growing in the short term the costs of mitigation would increase. Furthermore, we follow a first-best approach of an immediate global cap-and-trade system. International negotiations have failed so far to establish such a system, and current emission trends point upwards. Accordingly, recent studies analyze the effect of delaying the implementation of a global stringent climate target on mitigation strategies and costs (e.g. Clarke et al. 2009; Jakob et al., in press). Increased global mitigation costs from delayed action are a major result of these studies. Likewise, regional costs (and their dependence on the availability of technologies) are modified by delayed action. We defer this important analysis to future research.

Appendix

We use an economic decomposition method to quantify contributions of domestic and trade-related effects on regional consumption differences between a *business as usual* scenario (*BAU*) and climate policy scenarios.

The macroeconomic budget balances the macroeconomic output Y, reduced by net exports X_G of the aggregate good, with consumption C, investments into the macroeconomic capital stock I, fuel costs G_{fuel} and energy system investment costs including O&M costs G_{inv}. For both the *BAU* and the policy scenario, we convert the equation to present value prices by multiplying Eq. (2) with the good price in the *BAU* scenario, $p_G^{BAU}(t)$. We use the same price vector for both scenarios, because the same discounting is needed for a comparison. Then, we sum the discounted macroeconomic budget over time. We use the following definitions to simplify notation (analogous definitions apply to the right hand side terms in Eq. (5)):

$$\overline{Y}(r) := \sum_t p_G(t)\cdot Y(t,r), \quad \overline{X}_{E,i}(r) := \sum_t p_{E,i}(t)\cdot X_{E,i}(t,r) \tag{4}$$

For the *BAU* scenario, we can now include the intertemporal trade balance and replace revenues from good trade by revenues from energy trade:

$$\overline{Y}^{BAU}(r)+\sum_i \overline{X}_{E,i}^{BAU}(r) = \overline{C}^{BAU}(r)+\overline{I}^{BAU}(r)+\overline{G}_{fuel}^{BAU}(r)+\overline{G}_{inv}^{BAU}(r) \quad \forall r \tag{5}$$

For the policy scenario, we have multiplied the macroeconomic budget by the *BAU* scenario good price, whereas the intertemporal trade balance contains the policy scenario good price. Hence we extend the good trade component in the macroeconomic budget and rewrite the term to separate the good trade component in terms of the policy scenario good price:

$$\begin{aligned}
&\overline{Y}^{POL}(r) - \frac{\Sigma_t p_G^{POL} X_G^{POL}}{\Sigma_t p_G^{POL} X_G^{POL}} \sum_t p_G^{BAU} X_G^{POL} \\
&= \overline{Y}^{POL}(r) - \frac{\Sigma_t p_G^{BAU} X_G^{POL}}{\Sigma_t p_G^{POL} X_G^{POL}} \sum_t p_G^{POL} X_G^{POL} \\
&= \overline{C}^{POL}(r)+\overline{I}^{POL}(r)+\overline{G}_{fuel}^{POL}(r)+\overline{G}_{inv}^{POL}(r) \quad \forall r
\end{aligned} \tag{6}$$

Now we can include the intertemporal trade balance for the policy scenario:

$$\begin{aligned}
&\overline{Y}^{POL}(r)+\gamma(r)\sum_i \overline{X}_{E,i}^{POL}(r)+\gamma(r)\overline{X}_p^{POL}(r) \\
&= \overline{C}^{POL}(r)+\overline{I}^{POL}(r)+\overline{G}_{fuel}^{POL}(r)+\overline{G}_{inv}^{POL}(r) \quad \forall r
\end{aligned} \tag{7}$$

In Eq. (7), we introduce a region-specific factor $\gamma(r)$, defined as

$$\gamma(r) = \frac{\Sigma_t p_G^{BAU} X_G^{POL}}{\Sigma_t p_G^{POL} X_G^{POL}} \tag{8}$$

The factor $\gamma(r)$ revalues trade revenues in the policy scenario with respect to present value prices of the *BAU* scenario. (Please note that $\gamma(r)$ is not defined if $\Sigma_t p_G^{POL} X_G^{POL}$ equals zero.)

From Eq. (7) and its business as usual counterpart, Eq. (5), we determine absolute differences of the components. Dividing by GDP in the *BAU* scenario, $\overline{Y}^{BAU}(r)$, yields relative differences. Eqs. (5) and (7) imply that consumption differences can be explained as the sum of all other components:

$$\begin{aligned}
\Delta C(r) &= \Delta Y(r) - \Delta I(r) - \Delta G_{inv}(r) - \Delta G_{fuel}(r) \\
&+ \gamma(r)\left(\sum_i \overline{X}_{E,i}^{POL}(r) - \sum_i \overline{X}_{E,i}^{BAU}(r) + \overline{X}_p^{POL}(r)\right) \quad \forall r
\end{aligned} \tag{9}$$

We calculate the *net* energy trade effect by subtracting the share of $\Delta G_{fuel}(r)$ that can be attributed to fuel export from of $\Delta X_{E,i}(r)$. Remaining extraction costs cover domestic fuel use. With the definitions $\Delta X_{E,i}(r) = \gamma(r)(\overline{X}_{E,i}^{POL}(r) - \overline{X}_{E,i}^{BAU}(r))$ and $\Delta X_p(r) = \gamma(r)\overline{X}_p^{POL}(r)$, this leads to Eq. (3) in Section 3.

The choice of an initial permit allocation scheme has two implications for the components in Eq. (9): First, permit trade revenues are covered in $\overline{X}_p^{POL}(r)$. The initial allocation does not influence regional investment decisions, so the components $\Delta Y(r)$, $\Delta I(r)$, $\Delta G_{fuel}(r)$ and $\Delta G_{inv}(r)$ but also physical trade flows $\overline{X}_{E,i}(r)$ are constant if the initial allocation changes. Second, a modified initial permit allocation affects good trade revenues according to Eq. (1), so that values of $\gamma(r)$ change. In consequence, the evaluation of trade-related components is subject to the initial allocation, even if the physical trade flows are not. But we find that the revaluation of energy trade revenues is a small effect compared to redistributions from permit trade.

References

Bauer, N., Edenhofer, O., Haller, M., Klein, D., Lorenz, A., Luderer, G., Ludig, S., Lueken, M., Pietzcker, R., 2010. Technologies, policies and economics of global reductions of energy related CO_2 emissions. An analysis with ReMIND. Paper Presented at the Fourth World Congress of Environmental and Resource Economists. 28 June–2 July, 2010, Montreal, Canada.

Bauer, N., Edenhofer, O., Jakob, M., Ludig, S., Lueken, M., 2009a. Electricity trade among world regions—trade theoretic foundation of energy–economy models. Paper Presented at the NCCR Conference on International Dimensions of Climate Policies. 21–23 January, 2009, Bern, Switzerland. 〈http://www.nccr-climate.unibe.ch/conferences/climate_policies/working_papers/Bauer.pdf〉.

Bauer, N., Edenhofer, O., Kypreos, S., 2008. Linking energy system and macroeconomic growth models. Journal of Computational Management Science 5, 95–117.

Bauer, N., Edenhofer, O., Leimbach, M., 2009b. Low-stabilisation scenarios and technologies for carbon capture and sequestration. Energy Procedia 1, 4031–4038.

Böhringer, C., Rutherford, T.F., 1999. Decomposing General Equilibrium Effects of Policy Intervention in Multi-Regional Trade Models. Method and Sample Application. ZEW Discussion Paper 99-36.

Böhringer, C., Rutherford, T.F., 2000. Decomposing the Costs of Kyoto. A Global CGE Analysis of Multilateral Policy Impacts. ZEW Discussion Paper 00-11.

Bosetti, V., Carraro, C., Massetti, E., Sgobbi, A., Tavoni, M., 2009. Optimal energy investment and R&D strategies to stabilize atmospheric greenhouse gas concentrations. Resource and Energy Economics 31, 123–137.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M., 2009. International climate policy architectures: overview of the EMF 22 international scenarios. Energy Economics 31, S64–S81.

Crassous, R., Hourcade, J.C., Sassi, O., 2006. Endogenous structural change and climate targets. Modeling experiments with Imaclim-R. The Energy Journal

Special Issue, Endogenous Technological Change and the Economics of Atmospheric Stabilization 93, 161–178.

Diewert, E.W., 1981. The measurement of deadweight loss revisited. Econometrica 49, 1225–1244.

Diewert, E.W., 1985. A dynamic approach to the measurement of waste in an open economy. Journal of International Economics 19, 213–240.

den Elzen, M., Höhne, N., 2010. Sharing the reduction effort to limit global warming to 2 °C. Climate Policy 10, 247–260.

den Elzen, M., Lucas, P., 2005. The FAIR model: a tool to analyse environmental and costs implications of regimes of future commitments. Environmental Modeling and Assessment 10, 115–134.

den Elzen, M., Lucas, P., van Vuuren, D., 2008. Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO_2-equivalent concentrations. Climatic Change 90, 243–268.

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Château, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magné, B., Scrieciu, S., Turton, H., van Vuuren, D.P., 2010. The economics of low stabilization: model comparison of mitigation strategies and costs. The Energy Journal Special Issue, The Economics of Low Stabilization 31, 11–48.

Edenhofer, O., Lessmann, K., Kemfert, C., Grubb, M., Koehler, J., 2006. Technological change: exploring its implications for the economics of atmospheric stabilization. The Energy Journal Special Issue, Endogenous Technological Change and the Economics of Atmospheric Stabilization 93, 56–106.

Harberger, A.C., 1964. The measurement of waste. The American Economic Review 54, 58–76.

Harrison, W.J., Horridge, J.M., Pearson, K.R., 2000. Decomposing simulation results with respect to exogenous shocks. Computational Economics 15, 227–249.

Jakob, M., Luderer, G., Steckel, J., Tavoni, M., Monjon, S. Time to act now? Assessing the costs of delaying climate measures and benefits of early action. Climatic Change, in press. doi:10.1007/s10584-011-0128-3.

Knopf, B., Edenhofer, O., Flachsland, C., Kok, M.T.J., Lotze-Campen, H., Luderer, G., Popp, A., van Vuuren, D., 2010. Managing the low-carbon transition—from model results to policies. The Energy Journal Special Issue, The Economics of Low Stabilization 31, 223–245.

Kypreos, S., 2005. Modeling experience curves in MERGE (model for evaluating regional and global effects). Energy 30, 2721–2737.

Leimbach, M., Bauer, N., Baumstark, L., Edenhofer, O., 2010a. Mitigation costs in a globalized world: climate policy analysis with REMIND-R. Environmental Modeling and Assessment 15, 155–173.

Leimbach, M., Bauer, N., Baumstark, L., Lueken, M., Edenhofer, O., 2010b. International trade and technologcial change—insights from REMIND-R. The Energy Journal Special Issue, The Economics of Low Stabilization 31, 161–188.

Leimbach, M., Toth, F., 2003. Economic development and emission control over the long term: the ICLIPS aggregated economic mode. Climatic Change 56, 139–165.

Luderer, G., Bosetti, V., Steckel, J., Waisman, H., Bauer, N., Decian, E., Leimbach, M., Sassi, O., Tavoni, M., 2009. The Economics of Decarbonization—Results from the RECIPE Model Intercomparison. RECIPE Background Paper. 〈http://www.pik-potsdam.de/members/luderer/recipe-1/wp-model-results〉.

Manne, A., Richels, R., 2004. The impact of learning-by-doing on the timing and costs of CO_2 abatement. Energy Economics, EMF 19 Alternative Technology Strategies for Climate Change Policy 26, 603–619.

Manne, A.S., Rutherford, T., 1994. International trade, capital flows and sectoral analysis: formulation and solution of intertemporal equilibrium models. In: Cooper, W.W., Whinston, A.B. (Eds.), New Directions in Computational Economics. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 191–205.

Manne, A.S., Stephan, G., 2005. Global climate change and the equity-efficiency puzzle. Energy 30, 2525–2536.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., Allen, M.R., 2009. Greenhouse-gas emission targets for limiting global warming to 2 °C. Nature 458, 1158–1163.

Meyer, A., 2004. GCI briefing: contraction and convergence. Engineering Sustainability 157, 189–192.

Richels, R.G., Blanford, G.J., 2008. The value of technological advance in decarbonizing the U.S. economy. Energy Economics 30, 2930–2946 (technological change and the environment).

Rose, A., Stevens, B., Edmonds, J., Wise, M., 1998. International equity and differentiation in global warming policy. An application to tradeable emission permits. Environmental and Resource Economics 12, 25–51.

Weyant, J.P., 2004. Introduction and overview. Energy Economics, EMF 19 Alternative Technology Strategies for Climate Change Policy 26, 501–515.