Distributive Impacts of Global Climate Change Mitigation

Effects of Technology, Emission Permit Allocation and Energy Trade

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Für meine Eltern
und
für Valeria

Contents

Summary

This thesis analyzes the impacts of a stringent limitation of global carbon dioxide emissions on the welfare of world regions. A stringent emission target leads to a significant redistribution of welfare among world regions due to a devaluation of resource rents and to the distribution of a climate rent among the participants of a global emission trading system. The redistribution implies different mitigation costs for world regions.

Previous studies have pointed out the central role of three dimensions for regional mitigation costs: The availability of low-carbon technologies in the energy sector, international trade with fossil energy carriers, and the initial allocation of emission allowances in a global emission trading system. However, the relevance of individual factors has so far been discussed only qualitatively.

The novelty of this thesis lies in the approach to analyze the three dimensions of technology, initial allocation of emission allowances and energy trade as well as their interrelations in a comprehensive framework. The thesis uses the method to analyze scenarios in the model REMIND. REMIND describes relevant dynamic processes of the macroeconomy and the energy system that are influenced by a global emission target in a long-term multiregional perspective. Furthermore, a novel decomposition method in applied to quantify different influence factors on regional mitigation costs.

The core result of the thesis are as follows:

The availability of a broad portfolio of low-carbon technologies keeps global CO_2 prices low. It reduces global mitigation costs and - generally - also regional costs of mitigation. However, some regions benefit from restrictions on low-carbon technologies in particular cases. A devaluation of coal and oil endowments contributes to relatively high mitigation costs of major export regions. To the contrary, the exporters of natural gas and uranium profit from a revaluation of their endowments. The determination of trade-related effects on regional mitigation costs is improved substantially by the consideration of trade costs in the model. The trade with emission allowances acts as a pure redistribution among regions - under the assumptions made in this thesis. The negotiable choice of an initial allocation scheme can modify regional costs substantially.

Interrelations among the three dimensions play a crucial role for the distributive impacts of mitigation. A low CO_2-price reduces the monetary equivalents of tradable emission permits, so that a variation of the initial permit allocation scheme has a lower redistributive impact. Furthermore, the availability of low-carbon technologies can alter the preference order of regions for permit allocation schemes and influences the size of energy trade effects. Finally, technologies can take the role to render a new trade flow possible.

The example of an interregional electricity transmission technology shows that additional trade options bear the potential to reduce global and regional mitigation costs.

Important conclusions for climate policy can be drawn from the results. Climate policy could benefit from paying more attention to the relevance of the technology dimension as it provides a chance to ease political negotiations on the distribution of mitigation costs. Furthermore, international negotiations should take regional mitigation costs more than before into account when defining national emission targets, as regional mitigation costs are the key variable that expresses each nation's burden to participate in the global mitigation effort. The results in this thesis might provide helpful advice by allowing to distinguish negotiable and un-negotiable parts of the costs.

Chapter 1

Introduction

1.1 Motivation

In December 2009, the 15th Conference of Parties of the United Nations Framework Convention on Climate Change in Copenhagen acknowledged the political target to limit global warming to 2°C beyond preindustrial level and underlined the necessity for according emission reductions (UNFCCC, 2009a). However, the parties did not achieve a binding decision on a global emission reduction target. Rather, individual countries announced commitments on national emission reductions against a reference pathway or a specific year. These national commitments can be added up to a global reduction effort that leads to a certain temperature increase against pre-industrial conditions. Currently announced national commitments for emission reductions would lead to a temperature increase of more than 3°C (Rogelj et al., 2010) by 2100 and are thus not sufficient to fulfill the 2°C target.

The 2°C target implicitely defines a cumulative global emission budget (Meinshausen et al., 2009). The decision on a binding emission budget as global policy target bears the advantage that the budget allows for flexibility in the timing of emission reductions and might hence be easier to attain in international negotiations. Once a global emission budget is agreed upon, a decision how to distribute the budget among countries is required. Different schemes for the distribution are proposed in the literature (Baer et al., 2008; Chakravarty et al., 2009; Meyer, 2004; WBGU, 2009). The focus in the proposals as well as in political debates is on the physical value of national emission reductions, because the idea predominates that these reductions determine the respective national burden. Less attention is paid to the overall economic costs to attain the reduction, but these costs are in the end relevant for each country.

As the determination of the economic costs to comply with a national emission target is not a straight-forward calculation, the effort to understand and quantify the main processes behind national costs is a central task for science to support future climate negotiations. The national costs of mitigating climate change (denoted as ”mitigation costs” in the following) depend not only on the initial allocation of emission reductions among countries, but on several other factors, of which technological progress and changes in international trade flows under climate policy are of particular importance. In this thesis, a comprehensive analysis of the major drivers determining the mitigation costs of world regions is analyzed within an intertemporal general equlibrium modeling framework.

1.1.1 The Distributive Dimension of Climate Policy

Economic welfare currently depends strongly on the exploitation of fossil fuels which allows for a cheap and reliable availability of energy but is accompanied by the release of carbon dioxide into the atmosphere. Figure 1.1 shows that high national capital stocks coincide with cumulative historic emissions (Edenhofer et al., 2010c; Stern, 2007). Hence, economic wealth relates to the free use of the atmosphere as a disposal space for CO_2 emissions. Given the necessity to reduce global emissions while sustaining economic growth at the same time, the relationship between economic growth and emissions must be decoupled, implying a reduction of energy- and carbon intensity (Kaya, 1990; Stern, 2007). As energy intensity improvements alone cannot be expected to allow for a sufficient emission reduction, a drastic decarbonization of the economy is required (Steckel et al., 2010).[1] Currently, CO_2 emissions from fossil fuel burning contribute 56.6% of all greenhouse gas emissions (IPCC, 2007a). Therefore, the decarbonization of the energy sector is essential (Edenhofer et al., 2010a; Weyant, 2004).

A decarbonization of the energy system requires the application of innovative technologies that allow to shift primary energy usage towards energy carriers with a lower or even zero carbon intensity (in particular towards renewable energy sources), an increase of efficiency on the energy supply side, or the Carbon Capture and Storage technology (denoted as CCS in the following). Many of the technologies involved in these transformations are currently not mature market technologies, but in the stage of development or niche applications. In consequence, the technical and economic feasibility of innovative low-carbon technologies, such as renewable energy and CCS, is required on a large scale (IPCC, 2007a). The availability of a broad portfolio of technology options is beneficial to account for the risk that some technologies might turn out to be infeasible due to technological or economic reasons (IPCC, 2007a).

The global costs of mitigation are estimated to be on the order of 1-2% of gross domestic product (denoted as GDP in the following) over the century for a long-term stabilisation level of 400ppm CO_2eq (Edenhofer et al., 2010a), which is significantly lower than the costs to compensate for damages of unabated climate change of 5-20% (Stern, 2007). In consequence, mitigation clearly pays off in a long-term global perspective. A global commitment to an upper limit of emissions is, however, essential to induce the necessary redirection of investments in the energy sector and the required technological progress (IPCC, 2007a).

A cost-efficient allocation of emission reductions would be of vital interest for most participants, as it would reduce global mitigation costs drastically. Among different political frameworks that allow for a cost-efficient allocation of emission reductions, the global emission trading system receives special attention.[2] An emission trading system

[1] See also Chapter 8 for a further discussion on the potentials of energy efficiency improvements and decarbonization.

[2] A global carbon tax also leads to cost-efficiency. The two approaches of tax and cap-and-trade both have their particular advantages and disadvantages (Kalkuhl and Edenhofer, 2010; Stern, 2007; Weitzman, 1974).

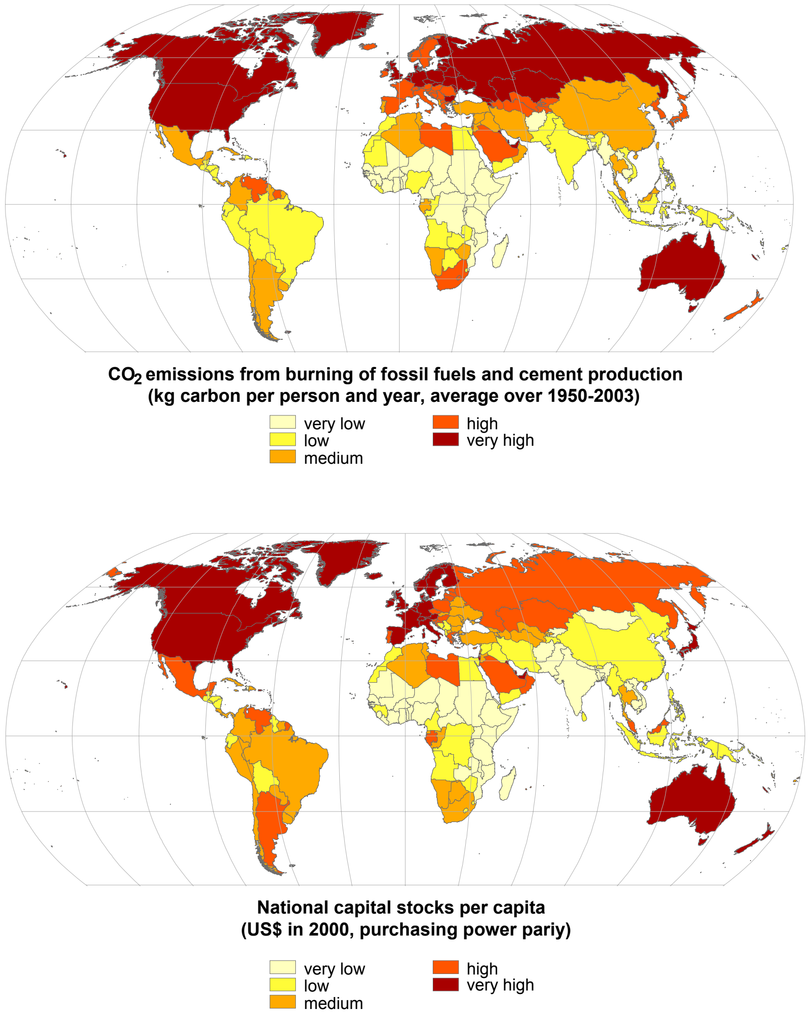

Figure 1.1: National carbon dioxide emissions from fossil fuel burning and cement production per capita, average over the period 1950-2003 (top) and national capital stocks per capita in the year 2000 (bottom) (Füssel, 2010; Edenhofer et al., 2010c)

requires a definition of an initial allocation of tradable emission permits.

Additional drivers influence the mitigation costs of individual world regions. They face different net revenues on the permit market depending on the initial permit allocation (den Elzen and Höhne, 2010; Rose et al., 1998). As high monetary redistributions are expected to result from a global permit market (Luderer et al., 2010b), the definition of an initial permit allocation adds a distributive dimension to climate policy: The definition of an initial permit allocation leads to an extra burden for countries that need to import permits, thereby providing another obstacle in negotiations on the first glance. But on the other side of the coin it provides a chance to address the principle of ”common but differentiated responsibilities" (UNFCCC, 1992) when poorer countries receive permits in excess to their emissions, so that export profits can be used to compensate for climate damages or to support their development (see Chapter 9 and references therein) and thus to increase the acceptance for a climate treaty.

However, regional mitigation costs are not fully determined by net revenues on the permit market. Rather, mitigation will lead to differentiated pressure on the technological and economic developments for each country, depending on the respective marginal costs of CO_2 abatement (Criqui et al., 1999). For example, high potentials of renewable energy sources might allow for replacement of fossil energy carriers at low costs in some countries, while others face the challenge of decarbonization with only limited prospects for the application of low-energy technologies. Another example is related to the impacts of mitigation on the global markets of tradable goods. Exporters of fossil energy carriers benefit nowadays from the global dependence on fossil fuels. A stringent mitigation policy would imply a decreased demand for fossil energy carriers and hence reduced export profits (den Elzen et al., 2008; Luderer et al., 2010a; Leimbach et al., 2010a).

In total, a stringent mitigation policy leads not only to an inevitable global reduction of welfare, but also to a redistribution of welfare among countries. Hence, the mitigation costs of individual countries will deviate significantly from the global average, depending not only on the domestic emission reduction efforts, but also on the available technological options, the impact of climate policy on energy trade and, assuming that a global cap-and-trade system is applied, the initial permit allocation.

This thesis adds to the understanding and the quantification of this distributive dimension of climate policy by analyzing the combined effects on regional mitigation costs with an intertemporal general equilibrium model. The focus is on market interactions of world regions via trade flows, but not via strategic behaviour. The implications of the latter in the context of mitigation policy have been discussed in a different strand of literature. For example, Lessmann et al. (2009) and Lessmann and Edenhofer (2010) discuss the stability of a multi-regional climate coalition.

1.1.2 The Perspective and Method of this Thesis

This thesis focuses on the economic perspective on the distributive challenge of climate change, considering the fact that the assessment of the *monetary* impacts of climate policy becomes more and more important. The focus of this thesis is on the mitigation aspect of climate change. A realistic pathway towards a decarbonized economy needs to be initialized soon and be followed for several decades. Hence, the assessment of model-based scenarios is inevitable to inform policymakers about implications of climate policy on long timescales: Model scenarios and their comparison allow for a formal understanding and quantification of processes that determine mitigation costs and strategies, and enable for a discussion about the role of policy choices and uncertainties (Knopf et al., 2010c). This thesis follows the method to develop and discuss model-based mitigation scenarios over a centennial time horizon. The regional intertemporal general equilibrium model framework REMIND provides the appropriate tool for the analysis. The model and its central features will be further introduced in Section 1.3.

A set of assumptions are made in this thesis, with the most crucial ones being the following:

- Stringent restrictions on global emissions are applied in climate policy scenarios.[3] No other policy instruments (e.g. subsidies for renewables) are implemented. In a "cost-effectiveness" perspective on climate policy, climate change damages and measures of adaptation are not considered. Policy scenarios are compared to "business as usual" scenarios that do not account for any emission reducion target (not even a continuation of the targets defined in the Kyoto Protocol).

- A particular policy framework is considered, namely a cap-and-trade system with immediate global participation and tradability of emission permits in a competitive market.

- World regions are described from a social planner perspective, and a Pareto optimal solution among regions is assumed. The latter implies that all world regions cooperate fully in the maximization of global welfare.

This perspective and the assumptions define limits to the questions that can be answered and set borders to the explanatory power of the results. In particular, additional effects that can arise from strategic behaviour of world regions and economic sectors within regions are not considered.

The assumptions and the scenario-based method imply no normative judgements and preferences. Rather, the consequences associated with certain policy choices are revealed by the comparison of different scenarios. For example, scenarios that assume the removal of CCS from the portfolio of technological options asks for the consequences of an eventual infeasibility of this option but expresses no valuation of the CCS option.

1.1.3 Distributive Effects of Climate Change Mitigation

This section reveals the effects that are indicated in the existing literature as potential influence factors on regional mitigation costs. Before turning to the effects on regional costs, it is helpful to start with the effects on global costs; the conceptual mechanism is illustrated in Figure 1.2. Three effects influence the global CO_2-price which induces the necessary substitutions in the energy sector in a cost-efficient way.

A broad portfolio of low-carbon technologies is highly desirable to keep mitigation costs low on a global scale. Technological learning-by-doing allows for a future decrease in the investment costs of innovative technologies, so that current niche market options have the potential to become economically feasible on large scales (Edenhofer et al., 2006b; Manne and Richels, 2004; Kypreos, 2005). In turn, restrictions on the deployment of low-carbon technologies or on their learning potential lead to an increase in global mitigation costs (Bauer et al., 2009b; Edenhofer et al., 2010a; Weyant, 2004).

If fossil energy carriers are very abundant, their heavy usage is characteristic for business as usual scenarios, so that the decarbonization of the energy system under climate policy

[3] Different policy targets are used in the subsequent chapters. The results are thus not strictly comparable. In particular, Chapters 4 and 5 apply a target on cumulative emissions in line with the 2°C target.

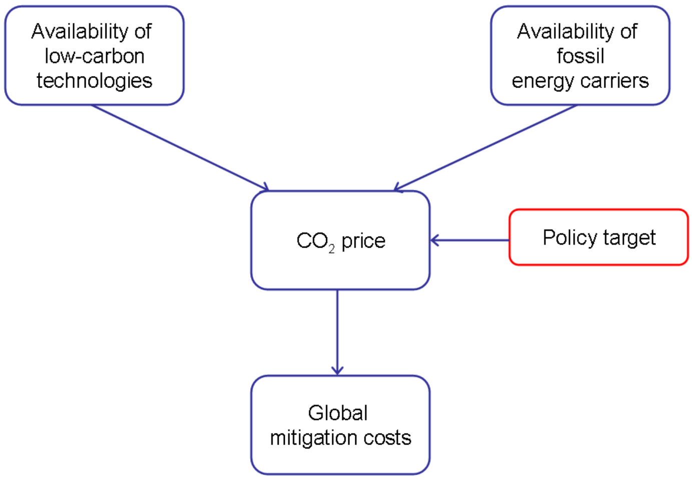

Figure 1.2: Effects of climate change mitigation on *global* mitigation costs. The red box around "Policy target" indicates that this effect is of central relevance to induce a CO_2 price.

becomes more costly. A higher scarcity of fossil energy carriers leads to substitutions towards renewable energy sources even in business as usual scenarios that assume no climate policy. Although this substitution is not sufficient to comply with the required emission reductions, scarce fossil resources generally lead to lower mitigation costs, see Chapter 8. Furthermore, more stringent climate targets as well as a delay of climate policy lead to higher mitigation costs on a global level (Clarke et al., 2009; Luderer et al., 2010a).

Several reasons to explain regional mitigation costs and redistributions among regions have been identified in the literature, but a comprehensive separation and quantification of the main effects has to my knowledge not yet been undertaken. Regional mitigation costs are influenced by the same effects as global costs, but additional mechanisms arise from interactions among world regions, as conceptually illustrated in Figure 1.3.

A growing stream of literature analyzes the impact of the availability of low-carbon technologies on regional mitigation costs, reporting the total effect on regional costs. But the question for the reasons behind is left unanswered except for qualitative reasoning in these studies (Bosetti et al., 2009; Crassous et al., 2006; den Elzen et al., 2008).

While the scarcity of fossil energy carriers impacts the CO_2 price as discussed before, effects of climate policy on energy trade has further consequences on the regional cost distribution. 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.[4] This devaluation has been identified as a candidate for explaning the relatively high mitigation costs for major exporters of fossil energy (den Elzen et al., 2008; Luderer et al., 2010a; Leimbach et al., 2010a). But a quantitative assessment how the devaluation translates into mitigation costs has not been undertaken in previous studies.

[4]On the contrary, tradable energy endowments with a relatively low carbon intensity can be revalued, if climate policy leads to a transitionally or permanently increased demand.

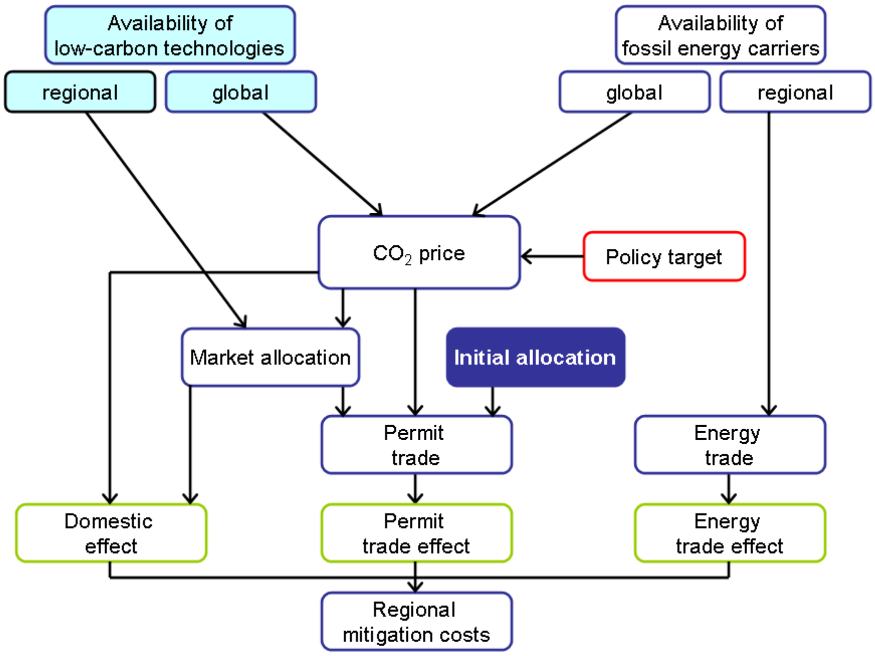

Figure 1.3: Effects of climate change mitigation on *regional* mitigation costs. Compared to the previous figure, additional effects occur in the regional perspective. The red box around "Policy target" indicates that this effect is of central relevance to induce a CO_2 price. Dark and light blue shading indicates assumptions whose influence is analysed in depth in the thesis. Green boxes denote a separation of regional costs into three components.

A further aspect of energy trade has not yet received attention in the economic literature on regional mitigation costs: A higher global demand for renewable energy carriers, in particular for the huge solar potentials located in some world regions, could lead to additional trade revenues. As solar energy by itself is not a tradable good, its transformation into a tradable one is required. Hence, the *tradability* of an energy carrier plays a crucial role.

A higher CO_2 price as the consequence of more stringent climate targets or a delay of participation leads not only to higher global costs, but also affects world regions differently (Bosetti et al., 2009; Crassous et al., 2006; Edenhofer et al., 2010a; Luderer et al., 2010a).[5]

In a global cap-and-trade system, emission permits are allocated to regions. Trade in permits occurs in case of a mismatch of supply and demand for emission permits. The initial permit allocation scheme hence leads to extra regional net revenues (den Elzen and Lucas, 2005; Leimbach et al., 2010a; Rose et al., 1998). Under the assumption of a free flow of tradable goods on all markets (in particular, without regions exerting market power), the demand for permits is independent from the supply with permits that is defined by the initial allocation scheme. In consequence, the choice of an initial allocation scheme

[5]The effect of more stringent temperature-based policy targets on regional costs generally works into the same direction as the effect of higher climate sensitivity. Leimbach et al. (2010a) shows a result for regional costs if a higher climate sensitivity is assumed.

leads only to a redistribution of mitigation costs among regions. The global mitigation costs as well as all investment decisions are not affected. Manne and Stephan (2005) denote this feature of a cap-and-trade system as the ”separability of efficiency and equity”.

First considerations of interrelations between the influence of technologies and trade flows on regional mitigation costs can be found in the existing literature (den Elzen et al., 2008; Luderer et al., 2010a,b). A comprehensive analysis of these interrelations has not been conducted so far.

I distinguish three effects on regional mitigation in the following:

1. The domestic effect covers the response of regional energy systems and macroeconomies to climate policy besides changed trade flows.

2. The energy trade effect sums the changed profits and costs from the trade with energy carriers under climate policy. In particular, this effect covers the devaluation (or revaluation) of endowments with tradable energy carriers which is influenced by technology restrictions as well. The energy trade effect also considers prospects to allow for a revaluation of endowments with renewable energy carriers that are not tradable but can be transformed into tradable secondary energy carriers.

3. The permit trade effect covers profits and costs on the global market for permits. Assumptions on the availability of low-carbon technologies influence the global carbon price (global reaction) and the demand for permits (region-specific reaction). This is included in the definition of the permit trade effect.

These definitions provide helpful guidance for the subsequent analyses. Before turning to the definition of research objectives, it is beneficial to relate the trade effects of mitigation to the concept of rent income of scarce production factors.

1.1.4 Trade Effects as a Distribution of Rents

In this Section, I introduce the concept of an economic rent and attribute it to the distributive dimension of climate change mitigation.

In the economic literature, the concept of an economic rent can be traced back to George (1879) where it is defined as the part of the produce that accrues to the owners of land (or other natural capabilities) by virtue of ownership, in particular the share of wealth given to landowners because they have an exclusive right to the use of those natural capabilities.

In the context of climate change mitigation, rents are created from the exploitation of non-renewable endowments (Kalkuhl and Edenhofer, 2010). This can be applied to fossil energy carriers (resource rent) and the limited disposal space of the atmosphere for anthropogenic emissions (climate rent).

The resource rent denotes the Hotelling rent or scarcity rent which is obtained by the owner of a stock resource while exploiting the resource under the objective to maximize own welfare (Hotelling, 1931; Gray, 1914). Fossil energy resources are non-renewable, hence their exploitation leads to scarcity, and tradable fossil energy resources represent factor endowments, whose prices include a scarcity rent. The scarcity rent is to be distinguished from other rents, e.g., from the exertion of market power. Fossil endowments are subject to natural conditions, but their value is subject to technological developments that influence the demand as discussed before.

If a global emission limit is implemented, emission permits become a scarce good, and a climate rent is created. If the permits are tradable, their allocation to countries as market participants implies the distribution of the climate rent among countries. As long as the storage volume of the atmsophere is considered as infinite (in the absence of climate policy), the climate rent is zero. In a cap-and-trade system, the endowments with permits are subject to political negotiations.

Under climate policy, the demand for fossil energy carriers declines, the associated export revenues and rents decrease, so that fossil endowments are devalued. However, if coal, natural gas and oil are distinguished, substitution to fossil energy carriers with lower carbon intensity could lead to a revaluation of the respective resources.

From a global perspective, the resource rent is reduced and a new climate rent is created due to climate change mitigation (Kalkuhl and Edenhofer, 2010). Considering the rents earned by individual regions, mitigation leads not only to global costs, but also to a redistribution of rents among regions which is mirrored by the trade effects as defined in the previous section.

1.2 Objectives and Research Questions

Regional mitigation costs deviate from the global average, indicating high monetary redistributions under climate policy. The distributive challenge of climate policy is characterized by a multiplicity of effects on regional mitigation costs.

The aim of this thesis is to understand and quantify the effects on regional mitigation costs as introduced in Section 1.1.3. Previous studies have discussed several aspects, but the novelty in this thesis is a) to analyze all effects in a comprehensive framework, and b) to formally separate and quantify the mechanisms behind the redistributions. Particular attention is paid to the role of low-carbon technologies on all effects, and the influence of initial allocation schemes for emission permits. The thesis objectives consider (A) a thematic dimension with regard to climate policy and (B) a methodologic dimension.

1.2.1 Objective with Regard to Climate Policy (Objective A)

International trade has been discussed as a major effect on regional costs in the literature, covering trade in fossil energy carriers and permits. This leads to the question: How does the endowment with tradable factors influence mitigation costs and associated redistributions among regions? Tradable factors that are taken into account are emission permits, whose initial allocation is subject to negotiations, the tradable primary energy carriers coal, natural gas, oil and uranium, whose initial allocation is subject to natural conditions, and electricity. Electricity by itself is not a factor endowment, but a secondary energy carrier being produced from primary energy by a specific capital stock representing the transformation technology.

Besides the availability of an endowment, its *tradability* plays a role. In case of electricity trade, the flexibility of the energy system allows for the use of different primary energy carriers. In particular, it is possible to generate electricity from solar energy that cannot be traded as such. Rather, a specific combination of innovative technologies is required to transform the solar potential as a non-tradable factor endowment into a tradable good (electricity generation) and then to trade it (electricity transmission).

The availability of low-carbon technologies has been shown to influence global and regional mitigation costs. In particular, the costs and benefits from trade of each endowment depends on the market price. The availability of technologies has an impact on global demand and supply and hence on redistributions of welfare among regions. This leads to the next question: What is the role of technology on redistributions? As discussed in Section 1.1.3, the availability of low-carbon technologies influences regional costs via different mechanisms. In the particular case of electricity trade, significant investments into a bilateral transmission infrastructure are needed, so the additional role of technology is to render the novel trade flow possible.

Based on these considerations, the following thematic research questions are defined:

A.1. What is the impact of the availability of low-carbon technologies on global and regional mitigation costs?

A.2. What is the role of fossil energy carrier trade on regional mitigation costs, and how does it interact with the availability of low-carbon technologies?

A.3. What are the distributive effects of permit allocation schemes, and how do they interact with the availability of low-carbon technologies?

A.4. What is the role of bilateral electricity transmission for regional mitigation costs?

1.2.2 Objective with Regard to Methodology (Objective B)

Particular methodologic challenges need to be solved in order to answer the thematic research questions. Most fundamentally, an intertemporally general equilibrium model that hard-links a long-term macroeconomic growth model and a detailed energy system model in a multi-regional structure is a prerequisite for the subsequent analyses. In the preparation of this thesis, contributions have been made to the development of REMIND-R. The model and its particular features are explained further in Section 1.3. Particular model extensions and analysis tools are developed as described in the following.

B.1. How to quantify different contributions to regional mitigation costs?

The various effects that influence regional mitigation costs epxress themselves in changes in endogenous variables. Hence, a method is needed that allows to define and calculate their contributions to regional mitigation costs. For this purpose, a novel economic decomposition method is developed in this thesis. Thereby, intertemporally aggregated consumption differences between a pair of scenarios can be explained by the sum of particular domestic and trade-related effects. Quantitative decomposition methods are a common tool to analyse the results generated by Computable General Equilibrium models (Böhringer and Rutherford, 1999, 2000; Harrison et al., 2000), but these methods are not applicable for the analysis of mitigation costs in a long-term intertemporal model approach, as they relate to the static or recursive-dynamic approach in Computable General Equilibrium models.

B.2. How to improve the representation of fossil energy trade flows in the model?

Trade flows are not subject to initial calibration in REMIND-R. Model results for fossil energy trade show unsatisfactory high volumes of primary energy carriers and an initial trade pattern that deviates strongly from empirical data. Accordingly, model regions exhibit strong specialization. This is contrary to the preference of domestic sources over trade found empirically, the so-called ”home-bias” (Obstfeld and Rogoff, 2000). In order to increase the reliability of the results on the energy trade effects, it is essential to improve the dynamics of fossil energy trade in REMIND-R.

B.3. How to include trade in secondary energy carriers in the model?

The default model structure describes trade by a global market approach without representation of the required trade infrastructure, as investments into the trade infrastructure are considered negligible compared to the value of the traded goods. By contrast, the assessment of electricity trade requires the explicit representation of investments into a transmission technology for a bilateral trade flow.

1.3 The Modeling Framework REMIND

The integrated assessment model framework REMIND[6] (Bauer et al., 2010; Leimbach et al., 2010a) serves as the tool for computing scenarios in the thesis. REMIND is developed at the Potsdam Institute for Climate Impact Research. It is applied for the development and assessment of scenarios on global and regional mitigation costs and strategies over the 21st century, e.g. Bauer et al. (2009b), and participated in model comparison studies (Edenhofer et al., 2010a; Luderer et al., 2010a).[7]

A single-region version (REMIND-G) which represents the whole world as a one-region aggregate, is applied in Chapters 2 and 8. While regional differentiation and the consideration of trade effects is not possible in the single-region version, its value lies in the fact that it allows for an assessment of the role of low-carbon technologies under reduced model complexity. In the other Chapters, a multi-region version (REMIND-R1.2) is applied. REMIND-R represents the world by eleven aggregated regions of similar economic and energetic characteristics.

Central features of REMIND that the reader should bear in mind are characterized in the following.

[6]Refined Model of Investment and Technological Development.

[7]A technical documentation of REMIND is found in the Appendix of the thesis. The model is programmed in GAMS.

- Macroeconomic Module: The representation of long-term economic growth in an intertemporal optimization framework in the tradition of Ramsey (1928) allows to consider macroeconomic effects of policies, in particular their impacts on consumption. First applications of this framework to climate change mitigation were studies by Nordhaus (1991) in a cost-benefit mode with stylized mitigation cost functions. Since then, Ramsey-type growth models have been widely used for integrated assessments of mitigation policies in an intertemporal long-term perspective. A social planner with perfect foresight over the whole time horizon is assumed.

- Energy System Module: A detailed representation of energy transformation technologies, especially low-carbon technologies, is inevitable for the analysis of their role on regional costs. Endogenous learning-by-doing is included for selected innovative technologies. Furthermore, an endogenous price formation of exhaustible energy carriers subject to extraction costs curves is central for the analysis of resource rents and the associated energy trade effects.

- The hybrid approach to couple a macroeconomic module and an energy system module in a hard-link mode has the strength to allow for simultaneous equilibria on all capital and energy markets (Bauer et al., 2008). The hybrid approach follows the tradition of Manne et al. (1995) to represent the energy sector explicitely in the context of a macroeconomic model.

- Based on experiences with multi-regional intertemporal macroeconomic growth models (Nordhaus and Yang, 1996; Nordhaus and Boyer, 2003), multi-regional intertemporal energy-economy models incorporate a stylized representation of international trade. They provide an adequate framework to analyze the long-term intertemporal dynamics within the regionalized energy system and the macroeconomy in simultaneous equilibrium of all markets. Besides REMIND, other models follow the same approach, e.g. the WITCH model (Bosetti et al., 2006).

- Trade is represented by an exchange of ownership. This approach is fundamental for the determination of associated rents and effects on regional consumption. An equilibrium solution for trade flows is obtained by applying the Negishi-approach (Leimbach and Toth, 2003; Manne and Rutherford, 1994). The model calculates a Pareto optimal solution between regions, corresponding to the general market equilibrium in the absence of externalities. An intertemporal balance of payment requires for each region, that the intertemporally aggregated monetary equivalents of all imports and exports level out.

- The model is solved in a cost-efficiency-mode: Climate policy is described by an exogenous policy target, taking the socially optimal level of emissions for granted. This differs from a cost-benefit-mode that comprises the application of a climate damage function in order to determine the socially optimal level of emissions.

- In policy scenarios, immediate global participation on a global policy target is assumed. An optimal market allocation of emissions is attained through a global cap-and-trade system which allows for a free trade of emission permits.

Objectives	with regard to Climate Policy				with regard to Methodology		
Chapter	A.1 technology	A.2 fossil trade	A.3 emission permits	A.4 electricity trade	B.1 decom-position	B.2 home bias	B.3 electricity trade
2	X						
3	X	X	X				
4	X	X	X		X		
5		X				X	
6				X	X		X
8	(X)	(X)					
9			(X)				

Table 1.1: Mapping of Chapters to research questions. X = The chapter provides a major contribution to answering the question. (X) = The chapter provides a minor contribution to answering the question.

- A free flow of capital as well as an unrestricted permit market without market power is assumed, so that the "separability of efficiency and equity" holds (Manne and Stephan, 2005), see Section 1.1.3.

1.4 Outline of the Thesis

The research questions are answered in a series of articles which are reproduced in Chapter 2 to 6. The summary and discussion of the results with respect to the overall research objective of the thesis are assembled in Chapter 7. Two articles that contribute supplementary aspects are found in the appendix (Chapters 8 and 9). This section contains a guideline through the following chapters by showing how the chapters are mapped to the research questions. Table 1.1 provides an overview.

Low-Carbon Technologies and Global Mitigation Costs (Chapter 2)

Chapter 2 introduces the single-region model REMIND-G and analyzes the role of low-carbon technologies for global mitigation costs and strategies under two different policy approaches (climate policy target versus technology policy target). The costs and strategies to fulfill a climate policy are assessed first in a reference scenario that contains the full portfolio of low-carbon technologies. Then, further scenarios assume the removal of particular technologies. The energy mixes as well as consumption and GDP losses are compared to reveal the contribution of the respective technology option to the fulfillment of the climate policy target. The Chapter contributes to question A.1 by exploring the role of low-carbon technologies for the strategies and costs of mitigation in an globally aggregated perspective.

Further issues are addressed in this chapter: Scenarios with prescribed climate policy target are compared to scenarios where a technology policy is assumed by prescription of a lower market share of particular low-carbon technologies. In the technology policy scenarios, rebound effects lead to a failure to fulfill a global temperature target.

The chapter has been published as a conference paper.[8]

Low-Carbon Technologies, Trade and Regional Mitigation Costs (Chapter 3)

The paper introduces the multi-regional model REMIND-R1.2.[9] The paper analyzes the technical and economic feasibility of stringent climate policy scenarios with a 400ppm concentration target. It pays particular attention to regional mitigation costs. Besides a scenario without restrictions on low-carbon technologies, the effect of seven scenarios with such restrictions on regional mitigation costs is assessed, thereby contributing to question A.1 in a multi-regional perspective.

The chapter lays special attention on interactions between international trade and technological development by evaluating trade flows in emission permits, fossil energy carriers and the aggregate macroeconomic good as well as the development of the respective prices. Changes in trade patterns between policy scenarios and the business as usual scenario are discussed, in order to interpret the resulting discrepancies of mitigation costs among world regions qualitatively. This analysis provides first results for answering questions A.2 and A.3.

The chapter has been published in the *Energy Journal* Special Edition on The Economics of Low Stabilization.[10]

The Role of Technological Availability for the Distributive Impacts of Climate Change Mitigation Policy (Chapter 4)

The chapter analyzes the interrelations among the availability of low-carbon technologies and international trade in primary energy carriers and emission permits in order to understand and quantify the distributive impacts of mitigation. A survey of previous literature on the mechanisms that influence regional mitigation costs reveals that a formal quantification of separate effects in a comprehensive study is still missing. By a series of model scenarios and a formal economic decomposition method, the chapter fills this gap. The policy scenarios assume a cumulative emission budget as a policy target and assess the impact of restricting the usage of the three major low-carbon options (CCS, nuclear energy, renewable energy) to respective values in the business as usual scenario. Four different schemes for the initial allocation of emission permits are considered. The novel economic decomposition method allows to differentiate domestic contributions and trade-related contributions to regional costs, thereby solving the methodological question B.1.[11]

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[8]Bauer, N.; Edenhofer, O.; Haller, M.; Klein, D.; Lorenz, A.; Luderer, G.; Ludig, S.; Lüken, M.; Pietzcker, P. (2010): Technologies, Policies and Economics of Global Reductions of Energy Related CO_2 Emissions. An Analysis with ReMIND. Paper presented at the International Energy Workshop. June 21-23, 2010, Stockholm, Sweden.

[9]The model has first been published in an earlier journal publication (Leimbach et al., 2010a). Chapter 3 introduces a new version of REMIND-R which is also used for the further chapters. The new version contains an upgraded definition of the world regions and revisions in the calibration.

[10]Leimbach, M.; Bauer, N.; Baumstark, L.; Lüken, M.; Edenhofer, O. (2010.): Technological Change and International Trade-Insights from REMIND-R. Energy Journal 31, Special Issue "The Economics of Low Stabilization", 161-188.

[11]The decomposition method builds on an earlier preliminary approach that is presented in Chapter 6.

The results allow to discuss the relevance of domestic measures on regional mitigation costs under different technology scenarios, which adds further details to solving question A.1. Question A.2 is tackled by the quantification of regional costs and profits on the fossil energy markets in different technology scenarios. A fundamental contribution to question A.3 is attained by the analysis of welfare redistributions due to permit trade under different technology scenarios. In particular, the interactions between the availability of technologies and revenues on the permit market are discussed.

The chapter is accepted for publication in *Energy Policy*.[12]

The Impact of Trade Costs on Fossil Energy Carrier Trade and Implications for Mitigation Costs (Chapter 5)

Special attention on fossil energy trade is paid in this Chapter. The impact of the costs for international fossil energy trade on regional mitigation costs are analyzed in this paper. Initially, existing literature on different approaches to the representation of fossil energy trade in long-term mitigation scenarios is discussed. While intertemporal energy-economy models are an appropriate tool for the analysis of long-term mitigation scenarios, they tend to produce trade flows that exceed observed numbers by far. In order to solve the methodological question B.2, an approach is chosen in REMIND-R to explicitely account for the costs of international trade. An improved representation of trade flows is attained, and the analysis of trade effects on mitigation costs can be improved substantially.

Based on policy scenarios with the same cumulative emission budget as in Chapter 4, the contribution of energy trade effects on regional mitigation costs is discussed. The subsequent analysis adds a more detailed answer to question A.2: The role of energy trade effects on regional mitigation costs is quantified by the analysis of changes in trade flows, price markups and resource rents under climate policy.

The chapter is an article in preparation.[13]

Electricity Trade among World Regions (Chapter 6)

This chapters intends to answer question A.4 by turning to the consideration of bilateral infrastructure-based electricity transmission between the two model regions MEA and EUR.[14] The model structure is extended by infrastructure investments that render possible electricity trade among two regions which solves the methodological question B.3.

Simulation results with REMIND-R consider policy scenarios with and without availability of the electricity trade option. The impact of electricity generation on mitigation costs of the participating regions as well as third party regions is revealed by a preliminary version of the formal economic decomposition method.

[12] Lüken, M.; Edenhofer, O.; Knopf, B.; Leimbach, M.; Luderer, G.; Bauer, N. (2010): The Role of Technological Availability for the Distributive Impacts of Climate Change Mitigation Policy. Energy Policy, in press.

[13] Lüken, M.; Bauer, N.; Leimbach, M.; Edenhofer, O. (2011): Fossil Energy Trade and Regional Mitigation Costs: The Effect of Trade Costs. In preparation.

[14] MEA: Middle East and North Africa, EUR: European Union (27 countries).

The results are compared to insights from a conceptual neo-classical trade model. Furthermore, potential barriers based on the interpretation of results from a sectoral perspective are discussed. Both aspects do not address the main focus of the thesis.

The chapter has been published as a conference paper.[15]

Robust Options for Decarbonisation (Appendix Chapter 8)

Additional results for an extended discussion of question A.1 is provided in this paper: In policy scenarios under a 450ppm concentration target, a variation of the global resource base for coal, natural gas and oil allows to assess the role of fossil scarcity on global mitigation costs and the relevance of low-carbon technologies. Although the global perspective in this paper does not account for energy trade, the results on fossil scarcity provides additional insights into the devaluation of fossil energy endowments which adds to the answering of question A.2.

Several further aspects of global mitigation strategies are covered in this Chapter: The technological challenge implied by a decarbonization of the energy system and limitations of energy efficiency improvements are discussed. Additional model scenarios reveal the influence of the social rate of time preference on mitigation costs and the timing of mitigation measures.

The chapter has been published as a book chapter by *Cambridge University Press*.[16]

A Global Carbon Market and the Allocation of Emission Rights (Appendix Chapter 9)

A deeper analysis of the impact of permit allocation on regional costs with regard to discussions about ethical presumptions in terms of justice is provided by this Chapter. The influence of a wide number of permit allocation schemes on regional mitigation scenarios is assessed with REMIND-R, contributing supplementary information to question A.3. Normative aspects of the discussion on the fairness of allocation schemes exceed the perspective of this thesis.

The chapter is submitted for publication as a book chapter by *Springer*.[17]

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[15] Bauer, N.; Edenhofer, O.; Jakob, M.; Ludig, S.; Lüken, M. (2009): Electricity Trade among World Regions. Trade Theoretic Foundation of Energy-Economy Models. Paper presented at the NCCR Conference on the International Dimensions of climate Policy. January 21-23, 2009, Bern, Switzerland.
Please note that the layout of the manuscript has been changed compared to the published version, without modification of the content.

[16] Bruckner, T.; Edenhofer, O.; Held, H.; Haller, M.; Lüken, M.; Bauer, N.; Nakicenovic, N. (2010): Robust options for decarbonisation. In: Schellnhuber, H. J.; Molina, M.; Stern, N.; Huber, V.; Kadner, S. (eds.), Global Sustainability-A Nobel Cause. Cambridge University Press, Cambridge, United Kingdom and New York, USA, p. 189-204.

[17] Knopf, B.; Kowarsch, M.; Lüken, M.; Edenhofer, O.; Luderer, G. (2010): A global carbon market and the allocation of emission rights. In: Edenhofer, O.; Wallacher, J.; Lotze-Campen, H.; Reder, M.; Knopf, B.; Müller, J. (ed.), Overcoming Injustice in Climate Change - Linking Climate and Development Policy. Berlin, Germany, Springer. Submitted.

Chapter 2

Low-Carbon Technologies and Global Mitigation Costs*

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*published as Bauer, N.; Edenhofer, O.; Haller, M.; Klein, D.; Lorenz, A.; Luderer, G.; Ludig, S.; Lüken, M.; Pietzcker, P. (2010): Technologies, Policies and Economics of Global Reductions of Energy Related CO2 Emissions. An Analysis with ReMIND. Paper presented at the International Energy Workshop. June 21-23, 2010, Stockholm, Sweden.

Technologies, Policies and Economics of Global Reductions of Energy Related CO_2 Emissions

An Analysis with ReMIND

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Abstract

The present study analyzes the deployment of technologies to reduce CO_2 emission in the global energy sector and the implied costs using the energy-economy-climate model ReMIND. The results depend on the policy chosen for inducing changes of investments. Climate policies price emissions and therefore induce changes of investments. The mitigation costs for not exceeding a 2°C increase of global mean temperature are less than 1% of GDP. Targeted technology policies enforce investments for subsets of technologies but do not implement emission pricing. Deployment of low-carbon technologies is not sufficient for reducing emission because utilization of low cost coal remains competitive, which is termed emission rebound effect. Technologies differ with respect to mitigation costs and environmental effectiveness depending on the policies that are imposed. The energy-economy system represented in REMIND is highly flexible, which suggests generally low mitigation costs and high rebound effects. The validity of this rule is confirmed for renewables and nuclear, but not for fossils and biomass with carbon capture and sequestration due to specific techno-economic properties.

Key words: *climate policy, technology policy, emission mitigation, energy-economy-climate modeling, rebound effect*.

JEL classification: Q42, Q54

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1. Introduction

The energy sector contributes about 65% to the total emissions of greenhouse gases (GHG), which have been identified as the main cause of climate change. Energy demand is increasing with economic growth and can be met in very different ways. Fossil fuel reserves and resources are sufficiently plentiful to satisfy the bulk of this demand over the 21st century, but if the generated CO_2 is emitted into the atmosphere, large-scale effects on the climate system are to be expected. Climate change in such a scenario is considered to negatively affect eco-systems, economic activity and human well being; see Lenton et al. (2008) and Smith et al (2009). Several emission mitigation options regarding the energy sector have been identified to supply growing energy demand with less emissions; see IPCC WG3 (2007). These include renewables, nuclear, coal to gas substitution, biomass and fossil fuels with carbon capture and sequestration (CCS) as well as increasing energy efficiency.

The deployment of such mitigation options requires policies to alter investment behavior towards low-carbon technologies and energy efficiency. The reduction of CO_2 emissions also requires that investments into technologies that utilize fossil fuels without emission controls are reduced.

Two main types of policies can be distinguished that aim at inducing such re-allocation of investments: climate and technology policies. The former type of policies originates in environmental economics. It starts at the emissions and puts a penalty on the undesired joint product of energy conversion processes by either taxing emissions or imposing a cap-and-trade system. This leads to changes of relative primary energy prices, which in turn changes the competitiveness of alternative energy conversion technologies. The prices of final energy carriers may also increase, which leads to substitution of energy for other production factors or the reduction of economic activity. Climate policies target CO_2 emissions directly; the deployment of low-carbon technologies is indirectly induced.

Technology policies start at the deployment of low-carbon technologies and offer incentives to undertake such investments. Increasing deployment of low-carbon energy technologies affects indirectly CO_2 emissions from fossil fuels in various ways. Non-fossil energy technologies – like renewables and nuclear – increase the supply of final energy and, hence, reduce the competitiveness of conventional fossil technologies. The decreasing fossil fuel price, however, improves the competitiveness of alternative uses of fossil fuels like coal liquefaction for transport. Different to that, deployment of fossil fuels with CCS does not lead to decreasing fossil fuel prices by reducing its demand. Technology policies target the deployment of low-carbon technologies directly; carbon emissions are only affected indirectly.

After the Conference of the Parties in Copenhagen we are faced with a situation, in which the importance of long-term emission reductions is accepted by international policy makers, but no global climate policy is implemented. At the same time national policies incentivize the deployment of low-carbon technologies, especially renewables, but also emissions are growing at unprecedented rates. This leads to the following questions:

1. What is the contribution of mitigation options to emission reductions in a climate policy framework and what is the importance of having various options available?
2. What emission reductions – net of the emission rebound effect – can these mitigation options achieve in a technology policy framework and what are the economic impacts?

The present study applies the energy-economy-climate model ReMIND to assess the two policy strategies regarding the various energy sector mitigation options by quantifying and comparing emission reductions and economic impacts. For this purpose a set of scenarios is designed and analyzed with ReMIND.

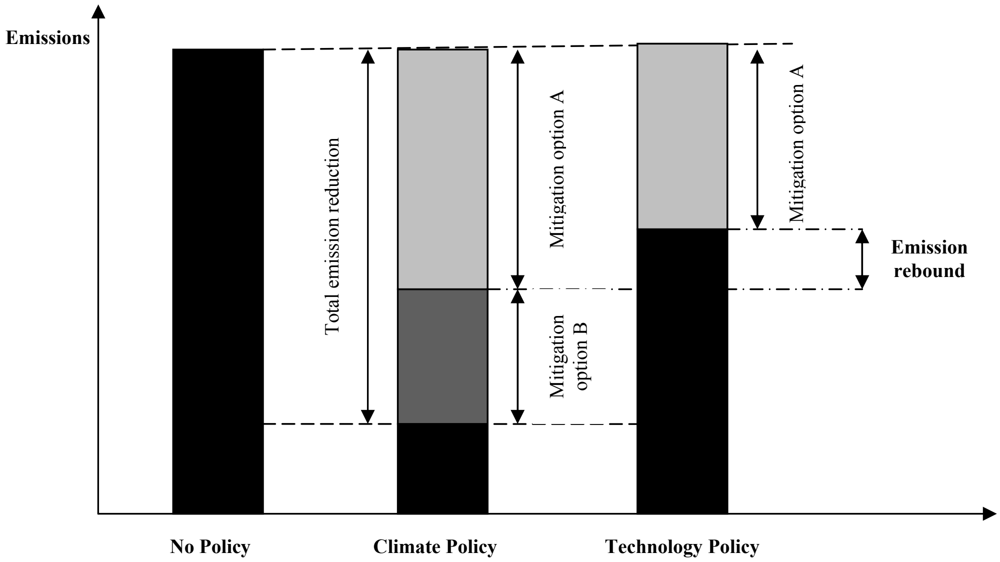

Figure 1: Illustration of the emission rebound effect for comparing the emission reduction effect of mitigation option A. Here the absolute emission rebound effect is given as the difference of the emission reduction realized from the same technology deployment from mitigation option A in the two policy frameworks. In the two policy frameworks technology deployment related to mitigation option A is the same by definition (e.g. number of wind turbines); deployment of all other technologies may differ.

The concept of *emission rebound effect* is introduced in this study to evaluate the emission related performance of a mitigation option in the technology policy framework compared with the climate policy case. Figure 1 illustrates the concept. The emission rebound effect relates the emission reduction of a particular mitigation option realized in the climate policy framework to the emission reductions realized in the technology policy framework given that the technology investments of the option under study are the same (e.g. installed number of wind turbines), but all other investments are unconstrained and CO_2 emissions are not targeted by policy. The economic impact in the technology policy cases are quantified by comparing GDP and consumption differences relative to the no-policy case. The economic importance of mitigation options in the climate policy framework are quantified by limiting investments of a mitigation option to the no-policy case and re-run the scenario subject to the limited technology portfolio.

The two policy approaches have been addressed in only few scientific contributions although the significance is identified; see Sorrell and Sijm (2004) and Knopf et al. (2010). Kverndokk and Rosendahl (2007) studied the first best and second best policy mix for achieving a given emission target in a generic electricity sector model with low-carbon technologies, where learning-by-doing is a spill-over that needs to be internalized; see also Kverndokk et al. (2004). The interrelationship between climate and R&D policies has attracted more attention and is better understood; see e.g. Gerlagh et al. (2009). Recently a number of studies addressed the significance of having available mitigation options in global energy-economy models to achieve stringent mitigation targets within a climate policy framework; see Bauer et al. (2009), Luderer et al. (2009) and Edenhofer et al. (2010). The technology policy framework for mitigation purposes has not received as much attention in modeling studies so far. It has been mainly put forward by technology analysts asking for the need to apply low-carbon technologies to replace conventional fossil fuel technologies; see Hoffert et al. (2002) and Pacala and Socolow (2003). These contributions do not focus on the significance of climate policies and neglect the emission rebound effect. The analysis of additional costs of inefficient technology policies compared with climate policies to achieve equal emission reductions is a notable exception; see e.g. Rafaij (2005, Ch. 7). Recently, Sinn (2008) highlighted the fossil energy supply side of the climate change mitigation problem that is closely related to the emission rebound effect.

The emission rebound effect, introduced in this study, extends the classical rebound effect that originates in the field of end-use energy efficiency improvements, which says that the technical improvements reduce energy demand, but these improvements make energy using activities more attractive and more energy is used for other activities. The rebound effect measures the negative second-order effects relative to the energy saving effect due to technical improvements. Empirical estimates in the US residential sector suggest an energy efficiency rebound effect of 0-50% for 100% increase of end-use efficiency; see Greening et al. (2000). Frondel et al (2007) found rebound effect for the German private use of cars of up to 67%.

In general, the higher the flexibility of the economy to find alternative ends for using the energy that is originally saved, the smaller is the economy-wide energy demand reduction; see Birol and Keppler (2000).[2] The emission rebound effect focuses on emissions from the energy conversion sector rather than on final energy demand in the energy using sectors. The flexibility argument remains valid, which is represented in the REMIND model by price responsiveness of both, primary energy supply and final energy demand, as well as a detailed energy system model that covers various energy conversion possibilities.

The present study contributes to the existing literature by assessing climate change mitigation of the energy sector in two different policy frameworks and comparing their environmental and economic performance quantitatively. The REMIND model can be applied for this challenge because it integrates long-term developments of energy, economy and climate and renders possible the analysis of the two policy approaches. The analysis in here is not analyzing the

[2] Acemoglu (2002) provides basically the same arguments.

optimal mix of climate and technology policy instruments as has been discussed in Kverndokk and Rosendahl (2007). This is an important field of future research for the analysis of detailed energy-economy models.

The remainder of this paper is organized as follows. In Section 2 the model framework ReMIND is introduced. Results are presented in Section 3. The study concludes in Section 4 with a discussion and gives hints to future research.

2. The ReMIND Model

The Refined Model of Investment and Technological Development (REMIND)[3] is an extension of the MIND model; see Bauer (2005) and Edenhofer et al. (2005). It was improved in all parts, though the basic structure is maintained. Bauer et al. (2009) and Leimbach et al. (2009) already introduced the model at a more general and less technical level. This section first provides a general overview of the ReMIND model framework, the macroeconomic growth model (MGM), and the energy system model (ESM). The climate system model (CSM) is not discussed in detail here. Appendix A and B provide detailed information on technical issues.

2.1. Overview

The ReMIND model is an integrative framework that embeds a detailed energy system model into a macro-economic growth model and a climate system model that computes the effect of GHG emissions. Figure 2 provides an overview of the model structure. The ReMIND model is

[3] See: http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/remind-code-1 for the technical documentation of the code.

completely hard-linked and solves the three integrated models simultaneously considering all interactions with perfect foresight over the model's time horizon from 2005 to 2150. The present study uses a global single region version, which is equivalent to a multi-regional model with completely integrated world markets. The single region model is sufficient because this study is not supposed to analyze trade related effects.

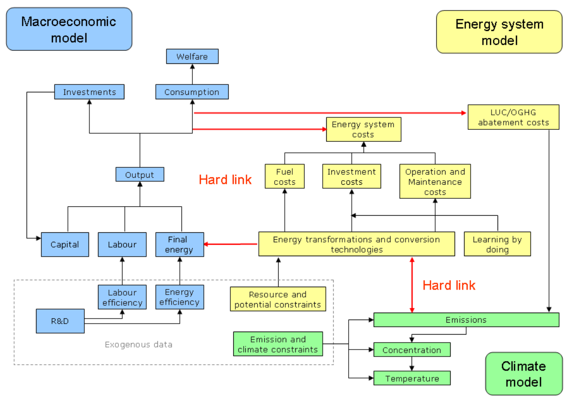

Figure 2: Overview of the ReMIND model framework. Blue boxes on the left are related to the macroeconomic growth model (MGM), yellow boxes on the right denote elements of the energy system model (ESM), and green boxes indicate elements of the climate system model (CSM). The red arrows highlight the hard-links between models.

The MGM of the Ramsey-type is the backbone of the ReMIND model. It solves a general equilibrium problem by maximizing inter-temporal social welfare of the household sector with perfect foresight subject to constraints of the macroeconomic, the energy and the climate system. This approach is well-established in the literature on climate change mitigation; see e.g. Manne et al. (1995), Edenhofer et al. (2005) and Nordhaus (2008).

The household sector owns all production factors – labor, resources, capital stocks and emission permits – that are supplied to the other sectors, which in turn pay factor prices that make up the income of households that they allocate to consumption and saving. The macroeconomic production sector demands aggregate capital, labor and various types of final energy to produce an aggregate economic good. The value of this aggregate good is completely exhausted to pay the household sector for the production factors. For the purpose of the present study the macro-economic production function is important because it implies that final energy demands are price elastic depending on the elasticities of substitution.

In the ESM, the energy sector demands financial means for investments, operation and maintenance, and primary energy in order to produce final energy carriers that are supplied to the macroeconomic production sector. The energy sector comprises a large number of energy conversion technologies – i.e. a heterogeneous capital stock – that convert scarce primary energy carriers into final energy carriers that are supplied to the macro-economy. Some low-carbon technologies improve endogenously from accumulating experience known as learning by doing. The emission reductions of other GHG and land-use related CO_2 emissions are integrated into the model structure via marginal abatement cost functions; see Lucas et al. (2008). For the present study it is essential that the supply of primary energy is price elastic and various alternative energy conversion routes are available. The latter point is important with respect to alternative ways to use biomass as well as coal with and without CCS.

The macro-economy and the energy sector interact via energy and capital markets. The supply of final energy by the energy sector is remunerated by the macro-economy. The supply of primary energy is remunerated by the energy sector. The supply of capital from the households is remunerated by the energy sector. The hard-link between the ESM and the MGM solves for a social optimum that establishes a simultaneous equilibrium on the capital and energy markets as has been shown in Bauer et al. (2008). Hence, the ReMIND model considers all interactions between the various markets and investments change accordingly.

For the CSM the ACC2 model has been used; see Tanaka and Kriegler (2007). It considers the accumulation of CO_2 and other GHG and computes the global mean temperature (GMT). ACC2 is computationally efficient and reproduces sophisticated carbon-cycle and atmosphere-ocean general circulation models very well.

Climate policies are analyzed by limiting the increase of GMT to a certain level. The model then computes the first-best cost-minimal solution for keeping the climate system within this limit regarding the emission pathway in general and the investments in particular. *Technology policies* are introduced into the model by fixing investments of a particular subset of technologies related to a mitigation option and skipping the climate change mitigation target.

2.2. The Macroeconomic Growth Model

The MGM consists mainly of the household sector and firm sector that produces an aggregate good. Both sectors are interrelated by the demand and supply of goods and factor payments.

The inter-temporal social welfare function is the sum of discounted utility of the world population that depends on the per-capita consumption of an aggregate good. The utility function in each period is logarithmic, which implies an inter-temporal elasticity equal to one. The pure rate of time preference is set to 3% p.a. The time horizon spans from 2005 to 2150 in five year time steps.

The household sector's budget equation balances in each period the macroeconomic income, which equals world gross domestic product (GDP), and the sum of consumption, savings that equal investments in all capital stocks for the macroeconomy and the energy sector, and other energy related expenditures.

The firm sector's macroeconomic production function applies the concept of nested CES (constant elasticity of substitution) production functions. The nesting structure applied in the

ReMIND model is given in Figure 3. Outputs of all CES aggregations are measured in monetary terms; i.e. also the intermediates (blue boxes). The primary production factors (yellow boxes) are measured in various units: labor in the number of workers, macroeconomic capital in monetary units and energy in physical units. At the top-level the overall GDP is generated. The sub-nest of the energy intermediate is quite elaborate and aims at reproducing the sectoral differentiation of the economy in industry, services&residential and transportation. The differentiation between the various final energy carriers is located at lower levels of the nesting structure.

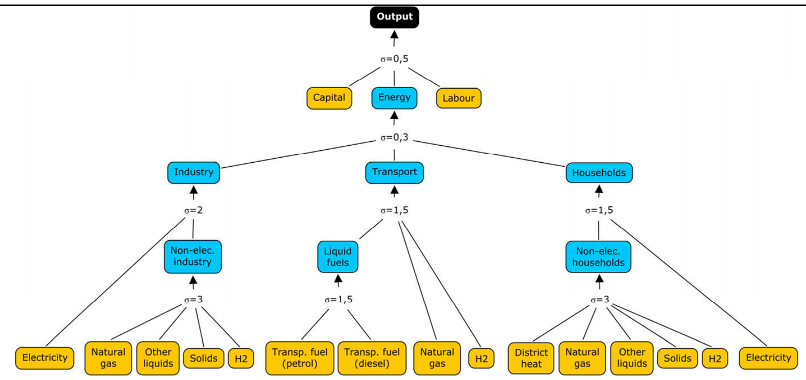

Figure 3: Nested CES structure of the macroeconomic production function. Yellow boxes indicate primary production factors; blue ones intermediate products and the black box is the final output. The parameters σ denote the elasticities of substitution for the corresponding nests.

This is a point of departure with respect to other energy-economy models using nested CES structures. MERGE and WITCH do not represent the sectoral differentiation and only aggregate different final energy carriers; see Manne et al. (1995) and Bosetti et al. (2006). ReMIND pays particular attention to the different services fueled by final energy carriers and therefore the prominence of the transport sector is highlighted: its services are hard to substitute and transportation fuels are difficult to de-carbonize. Note that the demand of final energy carriers arising from the macro-economic production function means that there is no bottom-up representation of downstream technologies like cars, trucks, domestic heating systems, etc. The macroeconomic production function is essential for the policy assessment of this study because it implies endogenous energy demand that is in turn related to the generation of GDP.

2.3. The Energy System Model

The energy sector is represented by a detailed model of technologies and energy carriers that are characterized by their techno-economic attributes. The demand of primary energy carriers and the emissions of CO_2 are determined by the structure and size of the heterogeneous capital stock that is made up of the composition of technologies. The future development of the energy sector's capital stock depends on investment decisions that in turn depend on the development of primary energy and CO_2 prices, technological improvements, energy demand and the interest rate of the economy.

The most notable part of the energy system model is the conversion of primary energy into secondary energy by applying specific technologies. The alternative conversion routes and the availability of alternative technologies is an important channel for the emission rebound effect in the energy conversion sector because it represents the flexibility to use fossil fuels with different technologies to generate a variety of valuable energy carriers. Table 1 provides an overview of all technologies that convert primary into secondary energy carriers.

Primary energy carriers are supplied price elastically. They are distinguished into renewable and exhaustible energy carriers. Exhaustible energy carriers are subject to extraction costs that increase with cumulative extraction. The concept of extraction cost curves reconciles the idea that low cost deposits are exhausted first and higher cost deposits are used later in a rational sequence; see e.g. Herfindahl (1967).

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Table 1: Overview of primary energy carriers, secondary energy carriers and the technologies for conversion.

	Primary energy carriers						
	Exhaustible				Renewable		
Secondary energy carriers	Coal	Oil	Gas	Uranium	Solar, Wind, Hydro	Geo-thermal	Biomass
Electricity	PC*, IGCC*, CoalCHP	DOT	GT, NGCC*, GasCHP	TNR, FNR	SPV, WT, Hydro	HDR	BioCHP, BIGCC*
H2	C2H2		SMR*				B2H2*
Gases	C2G		GasTR				B2G
Heat	CoalHP, CoalCHP		GasHP, GasCHP			GeoHP	BioHP, BioCHP
Liquid fuels	C2L*	Refin.					B2L*, BioEthanol
Other Liquids		Refin.					
Solids	CoalTR						BioTR

Abbreviations: PC = conventional coal power plant, IGCC = integrated coal gasification combined cycle, CoalCHP = coal combined heat power, C2H2 = coal to H2, C2G = coal to gas, CoalHP = coal heating plant, C2L = coal to liquids, CoalTR = coal transformation, DOT = diesel oil turbine, Refin. = Refinery, GT = gas turbine, NGCC = natural gas combined cycle, GasCHP = Gas combined heat power, SMR = steam methan reforming, GasTR = gas transformation, GasHP= gas heating plant, TNR = thermal nuclear reactor, FNR = Fast nuclear reactor, SPV = solar photovoltaic, WT = wind turbine, Hydro = hydro power, HDR = hot-dry-rock, GeoHP = heating pump, BioCHP = biomass combined heat and power, BIGCC = Biomass IGCC, B2H2 = biomass to H2, B2G = biogas, BioHP = biomass heating plant, B2L = biomass to liquids, BioEthanol = biomass to ethanol, BioTR = biomass transformation

* These technologies are also available with carbon capture.

Renewable energy carriers are subject to constraints on the potential output per year that is differentiated by various grades. For solar, wind, hydro and geothermal energy the grades differ in the maximum output and the capital utilization factor due to the fact that highly attractive locations are relatively scarce. Fluctuating renewable sources for electricity production require storage to guarantee stable supply of electricity; see Pietzcker et al. (2009). Regarding biomass the model only takes into account purpose grown ligno-cellulosic biomass. Hence, land competition for food production is not as severe as for first generation biofuels and the direct greenhouse gas emissions from fertilization need not be modeled explicitly because the co-emissions are relatively small; see e.g. Farrell et al. (2006).

Secondary energy carriers are distinguished into modern (electricity, hydrogen, district heat), de-central (gases, transportation fuels, other liquids) and traditional (solids). The technologies for producing secondary energy carriers will be introduced next.

Coal, natural gas and biomass are highly flexible because a various secondary energy carriers can be produced using alternative technologies, some with and without CCS. Renewables are especially important for the production of electricity. The choice between different conversion routes is essential for the study at hand. E.g. the flexible use of biomass and coal is important for the emission rebound effect that will be studied below.

3. Scenarios and Results

For studying the issues raised above with the ReMIND framework three types of scenarios are computed:

1. Business-as-Usual (BAU): this scenario describes the optimal growth path if none of the policies discussed above are implemented. It serves as a reference point for the policy scenarios.
2. Climate Policy Scenario (CPS): the GMT is constrained to stay below 2°C compared with the pre-industrial level until 2150 with a 50% probability. Consequently, the socially optimal solution for the scale and timing of mitigation measures is computed. In additional experiments, the deployment of mitigation options in the energy conversion sector fossil CCS, biomass CCS (BCCS), biomass (BIO), renewables (RES) and nuclear (NUC) are constrained to the solution of the BAU scenario; this is indicated by sub-scripts to CPS.
3. Technology Policy Scenarios (TPS): evaluates policies that enforce deployment of technologies related to the five mitigation options in the energy conversion sector. The

technology investments related to a mitigation option are fixed to the levels of the CPS, but all other investments and emissions are unconstrained. Hence, five TPSs are computed that are indicated by sub-scripts. It would also be possible to use other time paths for the technology policies, but choosing the particular ones from the CPS enables the computation of the rebound effects because the deployment of the technology of interest is equal for two different policy approaches.

The CPS with full availability of all technologies is characterized by heavy reliance on solar energy. This standard case is augmented by switching off solar technologies leading to a high use of fossil CCS. There are two reasons for doing so. First, the optimistic potential for technology improvements may either turn out to be flawed or technology policies to develop the particular technology may not be successful. Second, the solution with high fossil CCS deployment is the basis for assessing the corresponding rebound effect of the fossil CCS option. We indicate with the super-scripts "S" and "C" for the CPS and the TPS which solution is the reference.

The emission reductions of the mitigation options in the CPS cases are derived from the optimal solution by comparing technology deployment in the CPS case and the BAU scenario. The general idea is that the application of low-carbon technologies replaces more carbon intensive technologies and reduction of final energy supply reduces emissions. In each time step emission reductions can be attributed to technologies and end-use energy efficiency. The sum of all of these components equals the overall emission reduction, which is the difference between total emissions in the BAU and the CPS case. The emission reductions related to a mitigation options – termed "mitigation wedges" – are summations over components; see Appendix C for details. The derivation of emission reductions achieved by a mitigation option in the TPS case is simply the difference between the emissions in the BAU case and the total emissions in the TPS case.

3.1. The Business-as-Usual Scenario

The BAU scenario is characterized by an annual GDP growth of 2.3% achieving 418tril.$US in 2100. The annual primary energy demand shown in the left panel of Figure 4 increases to 907EJ and 1266EJ in 2050 and 2100, respectively. Coal is the most prominent primary energy source, accompanied by biomass that is already used up to its maximum potential in the BAU scenario. The price of coal is doubling as shown in the right panel of Figure 4. The use of hydrocarbons remains roughly constant though the price of oil is also doubling and natural gas prices only increase by a third. Renewables only contribute little and no new nuclear capacities are added. The penetration of wind conserves some coal in order to fuel growing final energy demand; see Amigues et al. (1998) for an analytical treatment of this result.

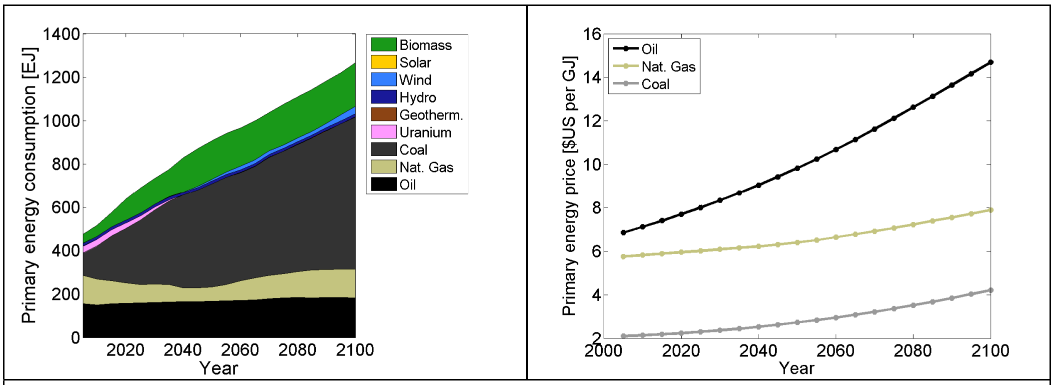

Figure 4: Primary energy consumption (left panel) and fossil fuel prices (right panel) in the BAU scenario. Primary energy inputs are accounted in line with the physical energy content method.

The high growth of electricity demand – shown in the left hand panel of Figure 5 –is mainly fuelled with coal. The production of transportation fuels is also increasing, though the consumption of crude oil remains stable. This is feasible because less other liquids are produced from oil. Additionally, biomass is increasingly used to supply the growing demand, especially during the second half of the 21st century. The demand for gases is decreasing after 2005 in the short term due to the high supply price of natural gas but demand growth recovers quickly. The growing demand is satisfied by synthetic natural gas from biomass that peaks around the middle of the century. Finally, the production of solid energy carriers decreases because of relatively low demand. The right hand panel of Figure 5 shows the comparison of historic income elasticities[4] of final energy carriers and those implied by the model until 2050; note that these estimates do not account for price changes. The scenario exhibits an accelerated modernization of the energy system: the income elasticity of electricity is highest and the scenario value is higher than the historic. For gases and transportation fuels ReMIND matches well with historic data. Solids, other liquids and heat exhibit relatively low – and even negative – income elasticities for the scenario.

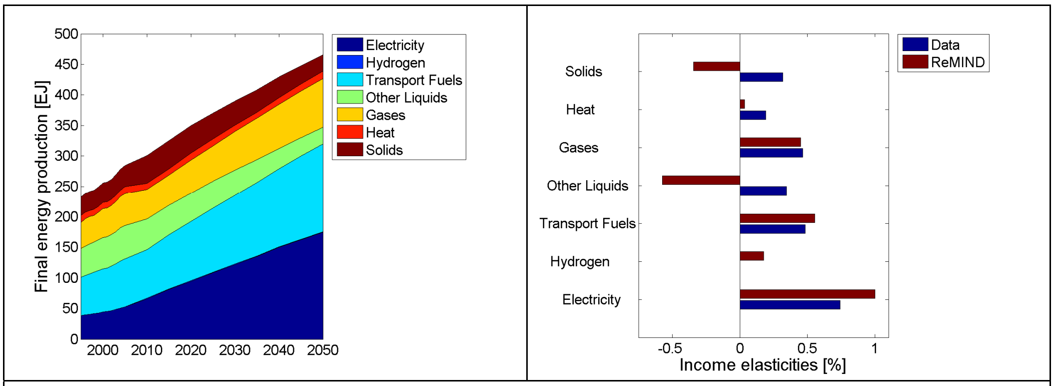

Figure 5: Comparison of history (1995-2005) and BAU scenario (2005-2050) regarding final energy production (left panel) and income elasticities (right panel). Historic data from IEA (2007) and PWT6.2.

[4] The income elasticity is the percentage change of final energy consumption for a one percent increase of income.

Consequently, CO_2 emissions from the energy sector increase to 24.0GtC p.a. in 2100, which leads to an atmospheric CO_2 concentration of 803ppm in 2100. In combination with the other GHGs the total radiative forcing increases to 6.3W/m² that implies a GMT increase until 2100 by 3.8°C above pre-industrial levels.

3.2. Policy Scenarios

As noted above we present results for two main families of climate policy scenarios: one with high reliance on solar energy CPS^S and one without solar energy, but high reliance on fossil CCS named CPS^C. The primary energy mixes are shown in Figure 6. The left panel shows the solution with heavy reliance on SPV. The right panel shows the case for high deployment of CCS for electricity production.

There are only small differences between both scenarios until 2030. Both scenarios use considerable amounts of biomass with CCS for producing liquid fuels and electricity starting in 2020. Biomass to liquids with CCS is peaking in 2060 and at the end of the 21st century biomass is nearly completely allocated to biomass IGCC with CCS. Also nuclear, wind and hydro and are considerably extended; the increase is higher in the CPS^C. For the CPS^S scenario investments into solar technologies start in 2020 and become significant in 2030. In the case with high CCS deployment the investments into coal IGCC with CCS start in 2030 and take off in 2060. The investments in NGCC with CCS start in 2050, but decrease after two decades. In both cases the electricity sector is nearly completely de-carbonized. Most significant is the reduction of coal consumption: 28ZJ in CPS^C and 36ZJ in CPS^S. The cumulative use of oil compared to the BAU scenario is reduced by 1070EJ and 1230EJ in CPS^S and CPS^C, respectively. Natural gas demand remains roughly constant in the CPS^S case, but increases in the CPS^C scenario by 2310EJ compared to the BAU scenario over the 21st century. The increased use of natural gas after 2030 in both scenarios is due to fossil fuel switching in the electricity sector by the deployment of NGCC power plants. Maintaining the use of hydrocarbons without CCS is rendered possible by the use of biomass with CCS because it allows for positive gross emissions.

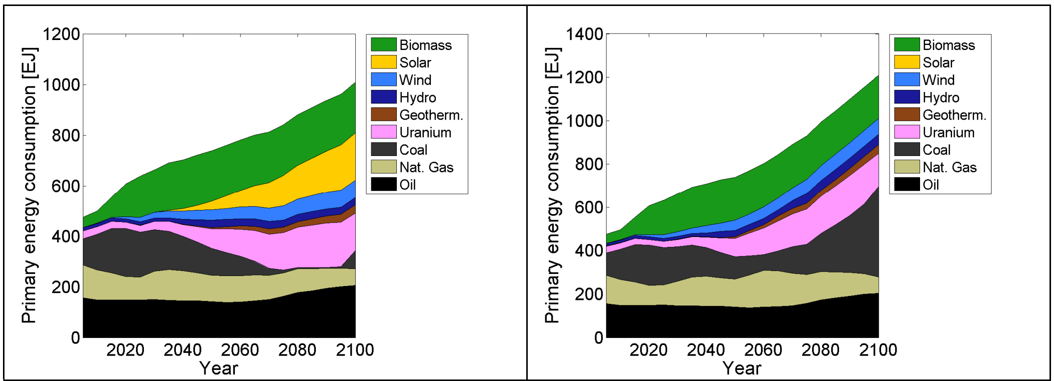

Figure 6: Primary energy mix for the two CPS scenarios. Left panel shows the solution with heavy use of solar; the right panel shows the solution without solar but high penetration of CCS. Primary energy inputs are accounted in line with the physical energy content method.

Figure 7 shows the mitigation wedges for the two scenarios CPS^S and CPS^C. The upper boundary shows the emissions in the BAU scenario. The lower boundary is the emissions in the CPS scenario net of the carbon removed from the atmosphere by biomass with CCS. The optimal emissions paths in both CPS cases are approximately the same. The emissions in both policy solutions increase until 2020 up to about 9.2GtC, but they deviate from the BAU case from the very beginning. Afterwards, the emissions decrease sharply, reach a nearly constant level of 1.2GtC p.a. in 2075 and keep on decreasing slowly to 0.9GtC p.a. in 2100. Other GHG emissions are significantly reduced according to the marginal abatement cost functions, but this is not discussed here.

The differently colored patches are the mitigation wedges; i.e. the emission reductions attributed to mitigation options. In the near term the efficiency wedge is most prominent, but it remains relatively small over the mid- to long-term. The other mitigation options kick in one after the other. The huge mitigation wedges for the conversion sector in both cases reflect the significance of de-carbonizing the electricity sector that makes the deep emission reduction possible. Biomass makes only a little contribution because it is already heavily deployed in the BAU scenario, hence, it does not contribute to additional emission reductions. However, the application of CCS with biomass makes a critical contribution and compensates for the emissions from using oil and natural gas derived products in de-central facilities like transportation vehicles. The use of energy is valued sufficiently high and changes in the conversion sector are competitive so that reductions in energy demand are not very emphasized.

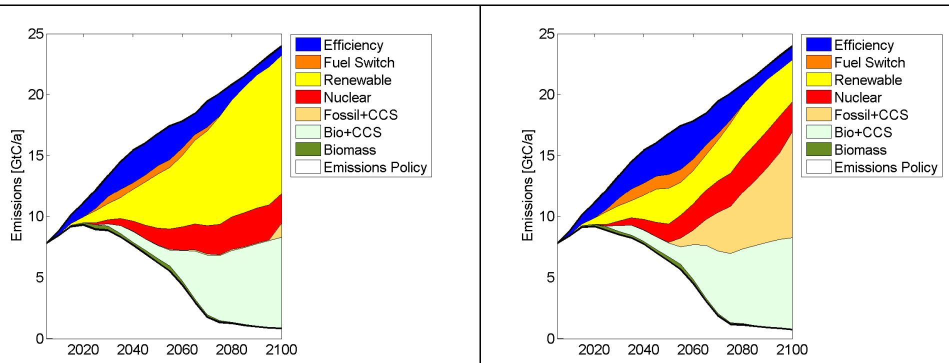

Figure 7: Mitigation wedges in the CSP scenarios. The left panel shows the solution with high share of solar CPS^S and the right hand panel the solution with carbon capture and sequestration CPS^C.

Next, the results of the technology policy scenarios TPS are introduced. The left hand panel of Figure 8 highlights the primary energy mixes of a selected technology policy scenario: TPS^S_{Ren} takes the high renewable contribution from CPS^S as a constraint. It shows that coal is heavily used and not locked out of the system. Coal is also used for various purposes that were not competitive in the BAU scenario like coal-to-gas and coal-to-liquid. However the main reason is that coal is fuelling electricity production in addition to the renewable electricity production. Cumulative electricity production increases for the TPS^{S}_{Res} scenario by 4.4% above the BAU scenario over the entire century. However, in the corresponding CPS^{S} scenario cumulative electricity production has been reduced by 6.5%. This pattern holds for the two sets of policy scenarios in general.

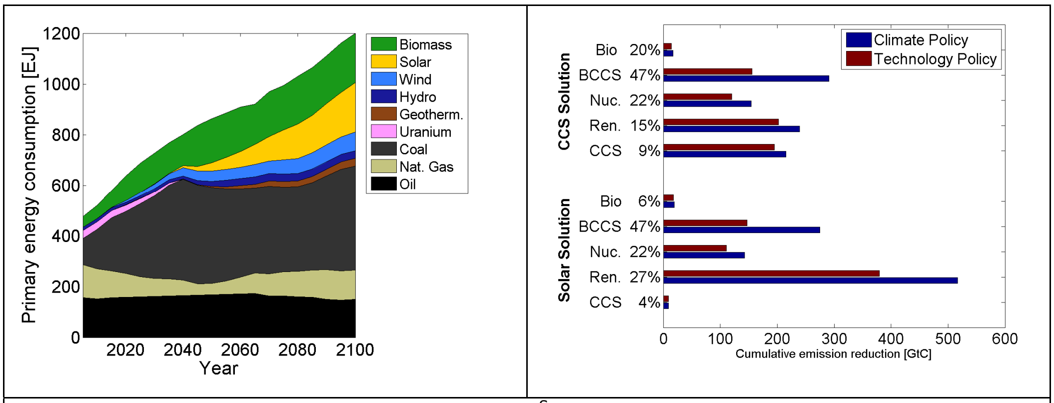

Figure 8: Primary energy mix in the scenarios TPS^{S}_{RES} (left panel). The right hand panel compares the cumulative emission reduction contributions for the 21st century of the various options for the two sets of policy scenarios. For the climate policy scenarios the bars correspond with the integral of the mitigation wedges. The numbers on the y-axis indicate the relative emission rebound effect. Primary energy inputs are accounted in line with the physical energy content method.

The rebound effect is shown in the right hand panel of Figure 8. It compares the cumulative emission reductions of the energy mitigation options for the two policy approaches and computes the relative rebound effect as given by the percentage numbers on the y-axis. The emission reduction achieved by the application of biomass is very small, hence, this option is not discussed any further. The combination of biomass with CCS has a high emission reduction potential but also a high rebound effect of nearly 50%. The reason is due to the maximum biomass potential of 200EJ p.a. Fixing the multi-purpose energy carrier biomass that is limited in its potential to a particular conversion route attracts fossil energy carriers for the alternative purposes that were biomass fuelled in the BAU scenario. The rebound effect for nuclear power is 22% in both TPS cases. For renewables the rebound effect in the TPS^C is only 15% and the effect increases to 27% for the TPS^S case with the huge deployment of solar PV. The rebound effect of CCS in the TPS^C scenario is 9% and therefore much lower than for the case with high solar PV deployment. The positive rebound effect is due to the additional application of CCS from NGCC plants, which were not applied in the BAU scenario.

The rebound arguments put forward by Sinn (2008) suggest that the rebound is particularly high for renewables and much less for fossils with CCS. Though the suggested ranking of both options is confirmed, the relative differences are not as dramatic as Sinn suggested. The rebound effect is not negligible for CCS. It is significantly higher for renewables and nuclear. However, the rebound effect is high for the CCS from biomass option because related technology policies increase the use of oil and coal.

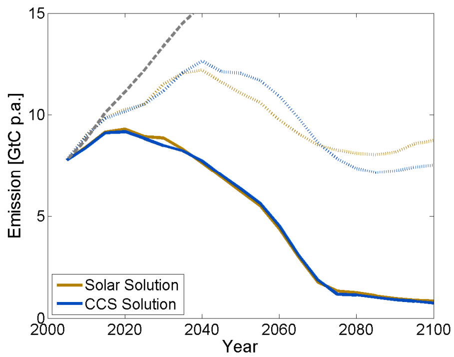

Figure 9: Emissions in the scenarios BAU, CPS^S, CPS^C, TPS^S_{All} and TPS^C_{All}.

For TPS scenarios that apply all mitigation options of the energy conversion sector simultaneously – shown in Figure 9 – the rebound effect implies that emissions increase to 12GtC p.a. until 2040 and never fall below 7GtC p.a. thereafter. This would significantly overshoot the original climate change mitigation target. The overall emission rebound effect in both cases is 27%.

Finally, we turn to the economic implications of the policy scenarios. Table 2 shows the results for the CPS cases. The rows in gray show the results for the GDP indicator and those without background color the consumption losses that are a more appropriate welfare measure.[5] Finally, the implications for the solar and the CCS case are separately shown. The first column shows the mitigation costs, in case that all technologies are fully available. The remaining five columns show the mitigation option if an option is not.

The mitigation costs in the two main CPS scenarios are 0.55% for the solar solution and 0.75% for the fossil CCS solution. Hence, the availability of solar PV can significantly reduce the overall costs of an emission pricing policy.

Removing options from the mitigation portfolio in the CPS scenarios increases the mitigation costs because the flexibility of the energy-economy system is reduced. The high value for biomass with CCS is notable for both CPS scenarios. Comparing this with the low value for fossil CCS in the scenario CPS^{C}_{CCS} is surprising. This is due to the flexibility regarding mitigation options in the electricity sector that substitute the missing fossil CCS option in relatively late periods. Non-availability of biomass with CCS has more severe consequences, because less hydrocarbons can be used, the deployment of fossil CCS has to be reduced and hence electricity production as whole decreases more significantly. This leads to a significant change of the optimal CO_2 emission path: it is optimal to reduce emissions strongly in the near term, which increases the mitigation costs. The cost increase for renewables in the CPS^{S}_{REN} scenario is high, because the large and early contribution of solar PV is difficult to substitute by other mitigation technologies. The relatively high value in the CPS^{C}_{REN} is due to the fact

[5] The reason is that welfare depends on consumption and not on GDP. We report figures on GDP because it is an indicator for the overall economic activity.

that wind and hydro are low cost options, and it is costly to replace them. The small value of nuclear indicates that the emission reduction contribution can be substituted more easily.

Table 2: Cost implications of the climate policy scenarios. Numbers indicate relative differences of cumulative discounted values 2005 – 2100 using a discount rate of 3%.

Indicator	Solution	All Options available	Cost increase from removing options				
			CCS	Ren.	Nuc.	BCCS	Bio.
Cons. Losses	Solar	0.55	0.00	0.37	0.03	0.37	0.01
	CCS	0.75	0.07	0.19	0.04	0.46	0.01
GDP Losses	Solar	0.66	0.00	0.41	0.04	0.62	0.01
	CCS	0.86	0.12	0.22	0.07	0.69	0.01

The results of economic impacts of the TPS scenarios are shown in Table 3. The numbers indicate relative differences of discounted values of GDP and consumption. The first finding is that the figures are quite small. Regarding the specific mitigation options the consumption losses are higher, if one of the two CCS options receives support compared with the renewable and nuclear options. The two CCS options are reasonable to reduce emissions but the energy penalty and the distorted allocation within the energy conversion sector incur costs to the economy. The allocation effect is particularly important for the biomass with CCS option, because the biomass devoted to produce electricity with CCS is not available anymore for substituting hydrocarbons. Within the technology policy framework the renewable and nuclear options are not distorting the allocation in the energy conversion sector by deviating resource from uses that were optimal in the BAU case. Both options simply add to the electricity production. The differences in the allocation effects explain why the renewable and the nuclear option imply higher GDP than in the BAU scenario. The effect on consumption that is determining welfare, however, is negative for all TPS cases.

Table 3: Cost implications of the climate policy scenarios. Numbers indicate relative differences of cumulative discounted values 2005 – 2100 using a discount rate of 3%.

Indicator	Solution	Mitigation Option				
		CCS	Ren.	Nuc.	BCCS	Bio.
Cons. Losses	Solar	0.02	0.01	0.02	0.14	0.04
	CCS	0.18	0.02	0.03	0.15	0.04
GDP Losses	Solar	0.00	-0.15	-0.02	0.02	0.01
	CCS	0.02	-0.06	-0.02	0.02	0.01

4. Discussion and Further Research

The analysis in this study assesses technological options for climate change mitigation in two different policy frameworks using the integrated energy-economy-climate model ReMIND. The study contributes to the debate about two policy approaches that aim at reducing CO_2 emissions from the energy sector. Climate policies address emission reductions by pricing emissions. This is effective in order to achieve a certain climate protection target like the 2°C target with 50% probability. Technology policies targeting at direct deployment of technologies through specific support measures would be cheaper than the climate policy, but it suffers from considerable emission rebound effects. Hence, it fails to achieve the climate protection target. The lower costs are due to the high use of fossil fuels – in particular coal – that are not locked out effectively. The continued use of coal increases the production of final energy – especially electricity – and therefore energy prices decrease and economic costs are lower. Hence, deployment of low-carbon technologies only does not effectively lock out carbon emitting technologies from the energy conversion sector. Climate policies effectively lock out the carbon emitting technologies but this also reduces the production of final energies, which increases energy prices and therefore mitigation costs.

The performance in terms of emission mitigation and costs varies significantly between the mitigation options and heavily depends on the policy approach. The contribution to emission reductions of nuclear and renewables would be reduced by the rebound effect in the technology policy case, though the costs would be low. The renewables option has a high option value in the climate policy framework, because mitigation costs would increase significantly, if it is not available. In particular the solar PV technology is essential for achieving the climate protection target at low costs, but the initially high investment costs need to be decreased by technology support that induces early learning investments. However, the emission rebound effect of renewables nearly doubles adding the huge contribution of solar energy. Fossil CCS could replace the contribution of solar PV, but the costs would increase significantly. The support of fossil CCS within a technology policy framework would have higher costs than the renewable option, but it leads to much lower rebound effects. Biomass CCS is indeed a mitigation option that only makes sense within a climate policy framework. It is very valuable in producing final energy carriers and taking up CO_2 from the atmosphere, which allows for the continued use of hydrocarbons. In a technology policy framework the costs would be high and half of the emission reduction would be offset by the rebound effect. Biomass without CCS would not lead to notable additional emission reductions because it is already heavily used in the scenario without any policy addressing climate change.

The high flexibility of the ReMIND model suggests a relationship between the low mitigation costs in the climate policy case and the high rebound effects in the technology policy scenarios. The flexibility of reallocating investments within a broad portfolio of technologies and adjusting demand to price changes is the general reason for the low mitigation costs. The rebound effects are so significant because the energy sector offers many alternatives to use coal that is substituted by the deployment of low carbon technologies. Thus coal is not replaced, if low-carbon technologies only add to the supply of energy. These findings highlight the need to analyze technologies and policies in an integrative way taking into account the economic dynamics that are induced.

The findings of this study have an important implication for the debate about the economics of climate change mitigation. High rebound effects are consistent with little costs for reducing emissions by climate policies. If the rebound effect was found to be negligible, technology support policies would be effective in reducing emissions, but constraining emissions by climate policies would lead to high costs.

Building on the work of this study we see four promising fields for future research. First, the current political situation of a missing global climate policy and ambitious national technology support programs may change in the future. Climate policies may be implemented in ten or twenty years from now, but then it is important to know today whether early technology policy would reduce the enormous costs of delayed climate policies; see Clarke et al. (2009). Second, economic significance of coordinating instruments of technology policies and climate policies in an integrated framework should be studied intensively; see e.g. Kverndokk and Rosendahl (2007). The available studies only used idealized models of the energy sector and did not consider the fossil energy supply side of the climate problem; see Sinn (2008). Conceptual research is needed to develop approaches that allow studying second best coordination of climate and technology policies in a perfect foresight framework like ReMIND. Then we could ask for the significance of coordinating policies and whether ill-defined technology support may do more harm than good. Third, the present study only focused on the two policy approaches for reducing CO_2 emissions from the energy sector. However, the same question is worth to be explored regarding other sources of GHGs. In particular, the land use sector, which is the second most important emitter of GHGs, is different in many respects compared to the energy sector because the latter today is fuelled from fossil stock resources but land-use change decisions are annually revised. Moreover, the quest for diet behavior (meat demand, etc.) could turn out as a field that is subject to little rebound effects. Finally, the flexibility of the energy sector can be measured by the elasticity of substitution between the production factors carbon emissions and capital; see Birol and Keppler (2000). The numerical model should be analyzed to estimate the elasticity of substitution subject to technology availability, techno-economic parameters and availability of policy instruments. Such analysis would improve our understanding of the costs of climate change mitigation and could also be applied to other models.

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Appendix A: The Macro-economic Growth Model

In the initial year the overall nested CES production function is calibrated to convert the production factors into GDP, which is 47.1tril.$US. For labor the number of workers is equaled to world population. In the context of the present study this assumption is justified because labor is supplied inelastically with respect to the wage rate and the work force is assumed to grow proportional to population. The macroeconomic capital stock in 2005 is estimated at 104tril.$US. The elasticities of substitution σ are reported in Figure 3 above. The choice of the values is based on a literature review; see Bauer (2005, p. 103), Jones (1996) and Urga and

Walters (2003). The process of capital accumulation in the macroeconomic sector follows the perpetual inventory assuming exponential depreciation with an assumed rate of 5%.

The growth engine comprises exogenous scenarios of population and development of efficiency parameters. For population we assume a medium scenario in which population reaches 8778 million people in 2050 and 9776 million people in 2100. For the efficiency parameters scenarios are assumed that generate a GDP growth that leads to a 3.3-fold increase until 2050 and a 8.8-fold increase until 2100. For energy demand efficiency parameters are chosen in order to reproduce income elasticities that are consistent with historical data. Since efficiency parameters are dimensionless numbers this point will be revisited in Sec. 4.1, in which the BAU scenario is presented.

Appendix B: The Energy Sector Model

Figure 9 presents the fossil fuel extraction cost curves that are used for the present study. The data was mainly based on the study by Rogner (1997). The original costs reported in Rogner started at about 2.5$US per GJ for oil and gas and 1.5$US per GJ for coal, which are much lower than market prices in 2005. The initial extraction costs were corrected up-wards to meet current market prices. Brecha (2008) provides a rationale why the strict sequence of extracting the deposits should indeed be corrected upwards.

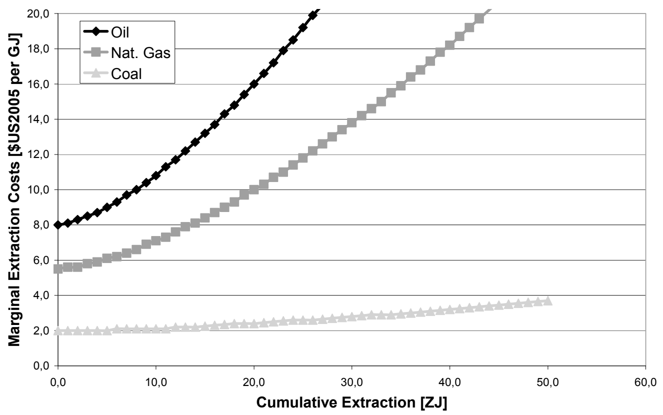

Figure 9: Extraction cost curves for the fossil energy carriers.

Extraction costs for uranium are based on NEA (2003). Uranium extraction costs increase from initially 30$/kgU to 300$/kgU at a cumulated extraction of 15.8MtU.

The left hand panel of Figure 10 presents the renewable energy potentials. For geo-thermal Hot Dry Rock only a small potential of 1EJ p.a. is assumed; Turkenburg (2001) reported a maximum electricity production potential of 43EJ p.a., but a final assessment is difficult to make because HDR is highly site dependent. The right hand panel of Figure 10 presents the biomass production costs that also change with time until 2050.

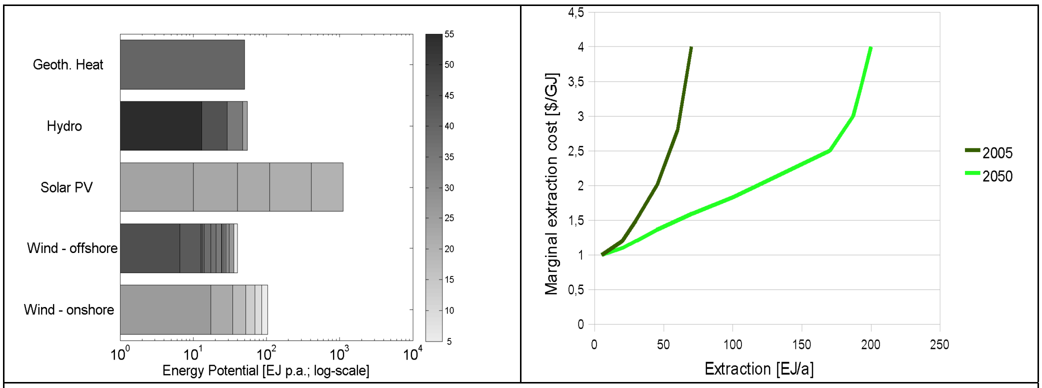

Figure 10: Availability of renewable energy carriers. Left panel: energy production potentials differentiated by technologies and grades. The gray color indicates the capacity factor as the fraction per year a technology is available. Right panel: biomass harvesting costs at different points in time. Sources: ENERDATA (2006), Trieb et al. (2009), Hoogwijk (2004), Sims et al.

(2007).

The additional indirect GHG emissions due to bioenergy production of nitrous oxide (N_2O) from overall land use intensification over the 21st century that result from the production of 200EJ p.a. lingo-cellulosic bio-energy by 2050 are 6% of the carbon contained in the biomass; see Popp et al. (2009).

Table 4: Techno-economic characteristics of technologies based on exhaustible energy sources and biomass (cf. Iwasaki (2003), Hamelinck (2004), Bauer (2005), MIT (2007), Ragettli, (2007), Rubin et al. (2007), Schulz et al. (2007), Uddin and Barreto (2007), Takeshita and Yaaij (2008); Gül et al. (2008), Brown et al. (2009), Chen and Rubin (2009), Klimantos et al. (2009). All $US values refer to 2005 values. Original literature values are normalized to this value taking into account general inflation, the CERA (2009) power plant price index and – if necessary – exchange rates.

		Techno-economic Parameters							
		Life-time	Investment costs		O&M costs		Conversion efficiency		Capture rate
		years	$US/kW		$US/GJ		%		%
			No CCS	With CCS	No CCS	With CCS	No CCS	With CCS	With CCS
Coal	PC	55	1400	2400	2.57	5.04	45	36	90
	Oxyfuel	55		2150		4.32		37	99
	IGCC	45	1650	2050	3.09	4.20	43	38	90
	C2H2*	45	1264	1430	1.65	1.87	59	57	90
	C2L*	45	1000	1040	1.99	2.27	40	40	70
	C2G	45	900		0.95		60		
Gas	NGCC	40	650	1100	0.95	1.62	56	48	90
	SMR	40	498	552	0.58	0.67	73	70	90
Biomass	BIGCC*	40	1860	2560	3.95	5.66	42	31	90
	BioCHP	40	1700		5.06		43.3		
	B2H2*	40	1400	1700	5.27	6.32	61	55	90
	B2L*	40	2500	3000	3.48	4.51	40	41	50
	B2G	40	1000		1.56		55		
Nuclear	TNR	35	3000		5.04		33~		

*) these technologies represent joint processes
~) thermal efficiency
Abbreviations: PC – conventional coal power plant, Oxyfuel – coal power plant with oxyfuel capture, IGCC – integrated coal gasification combined cycle power plant, C2H2 – coal to hydrogen, C2L – coal to liquids, NGCC – Natural gas combined cycle power plant, SMR – steam methane reforming, B2H2 – biomass to hydrogen, B2G – biogas plant, B2L – biomass to liquid, TNR – thermal nuclear reactor, SPV – solar photovoltaic, WT – wind turbine, Hydro – hydroelectric power plant.
Note: technologies marked with a * are joint production processes; for these technologies, capturing does not necessarily result in higher investment costs and lower efficiency in producing the main product.

Techno-economic details for most exhaustible and biomass fueled conversion technologies are provided in Table 4. Over the last few years the more pessimistic assessment of coal fired IGCC plants was the most important shift. The assumptions take this more careful interpretation into account: without CCS investment costs for IGCC are lower than for conventional pulverized coal (PC) plants, and the advantage in the case with CCS is greatly reduced. The general assessment to be found in the literature about electricity plants fueled with gas did not change that much over the last few years. The assumptions used here are generally in line with the literature. For biomass IGCC with and without CCS the parameters are chosen based on a broad literature review for a plant size of 100MW electrical output. Less optimistic assessments about the investment costs than those applied in the present study are provided by Faaij (2006) and IEA (2008a).

Coal and biomass can also be converted into gases, liquids and hydrogen based on gasification. The conversion of coal, gas and biomass into liquid fuels and hydrogen can be augmented by carbon capture. The values for biomass technologies are at the pessimistic end of the range to be found in the literature. Those for coal and gas are in the medium range.

Table 5: Techno-economic characteristics of technologies based on renewable energy sources and biomass. For details see Neij (2003), Nitsch et al. (2004), IEA (2008a), Junginger et al. (2008), Lemming et al. (2008).

	Lifetime	**Investment costs**	**Floor costs**	**Learning Rate**	**Cumulative capacity 2005**	**O&M costs**
	Years	$US/kW	$US/kW	%	GW	$US/GJ
Hydro	95	3000	-	-	-	3.46
Geo HDR	35	3000	-	-	-	4.2
Wind onshore	35	1200	883	12	60	2.9
Wind offshore	35	2200	1372	8	1	4.7
SPV	35	4900	600	20	5	10.33

The techno-economic parameters for renewable technologies producing electricity are given in Table 5. Hydro power has investment costs of 3000$US per kW. The exact number is highly site-dependent; see IEA (2008a). For wind power stations we distinguish on- and off-shore locations separately because both technologies are very different with respect to costs and other technological features. The floor costs are derived from cost projections for the year 2050.

Table 6: Techno-economic parameters of storage technologies; based on Chen et al. (2009) and expert interviews.

	Units	**Daily variation**	**Weekly variation**	**Seasonal variation**
Technology		Redox-Flow-batteries	H2 electrolysis + combined cycle gas turbine	Capacity penalty to secure supply
Efficiency	%	80	40	
Storage capacity	Hours	12	160	
Investment costs	$US/kW	4000	6000	
Floor costs	$US/kW	1000	3000	
Learning rate	%	10	10	
Cumulative capacity in 2005	TW	0.7	0.7	
Life time	Years	15	15	
Cheaper technologies but not included due to limited potential		Pump-storage hydro & compressed air storage	Pump-storage hydro & compressed air storage	

The approach for balancing fluctuations of renewable energy technologies wind and solar PV implemented into the ReMIND model distinguishes between variations on the daily, weekly and seasonal time scale. Increasing market shares of fluctuating energy sources increase the need for storage to guarantee stable electricity supply. The superposition of variations on the three time scales is completely represented. Daily and weekly variations are compensated by installation of storage plants; see Table 6. Seasonal variations imply a capacity penalty.

The sequestration part of CCS requires equipment and energy for transportation and injection. The investment costs for having available the equipment for injecting one GtC per year are 175 bil.$US; see Broek et al. (2008) and Kjärstad and Johnsson (2009). The upper limit for cumulative sequestration is 2775GtC; see Benson and Cook (2005) and IEA (2008b). The model does not consider leakage of injected CO_2.

ReMIND uses adjustment costs for thermal nuclear reactors. For this technology it is assumed that in 2005 a maximum of 5GW could be installed increasing by 1GW p.a. Each percent investment beyond this limit increases the investment costs by 0.5%.

Appendix C: Decomposition of Emissions Reduction in the CPS Scenarios – "Mitigation Wedges"

Mitigation wedges are the contributions of mitigation option to achieve a total emission reduction. They are usually derived by comparing the deployment of two technologies, like coal power plants with and without CCS, and account for the emission reductions. Different to that, in the following we develop an approach to compute mitigation wedges by comparing a CPS scenario with the BAU scenario. The methodology for computing wedges is of particular interest for the present study because wedges serve as the basis for the computation of the rebound effect.

In the present study we distinguish six emission reduction options:

1. Renewables excluding biomass,
2. Fossil CCS,
3. Nuclear,
4. Biomass without CCS,
5. Biomass with CCS,
6. Fossil fuel switching,
7. Efficiency.

Mitigation wedges M_i measure the contribution of mitigation option $i=1,\ldots,l$, to the overall emission reduction ΔE to be achieved in the climate policy scenario compared with the BAU scenario. Hence, mitigation wedges can be understood as the additive terms of a decomposition:

$$\Delta E = \sum_{i=1}^{n} M_i .$$

The energy conversion related mitigation options 1.-6. and the efficiency option 7. are treated in different ways. The emission mitigation M_{jk} – so-called micro-wedges – of technology j that produces the k-th secondary energy carrier S_{jk} are computed as follows:

$$M_{jk} = \left(S_{jk}^{BAU} - S_{jk}^{CPS}\right)\left(\phi_j - \varepsilon_{jk}\right) = \Delta S_k \left(\phi_j - \varepsilon_{jk}\right).$$

Similarly, the emission mitigation related to demand-side efficiency improvements in consumption of secondary energy carrier k is given by:

$$M_k^{Eff} = \left(S_k^{BAU} - S_k^{CPS}\right)\phi_k = \Delta S_k \phi_k .$$

The parameters ε_{jk} and ϕ_j are the carbon intensity of producing secondary energy carrier k with technology j and the baseline carbon intensity of all technologies producing the k-th secondary energy carrier that are replaced in the climate policy scenario, respectively; i.e. with $\Delta S_{jk}<0$. More formally:

$$\varepsilon_{jk} = \frac{E_{jk}}{S_{jk}} \qquad and \qquad \phi_k = \frac{\sum_j \varepsilon_{jk} \Delta S_{jk} \Big|_{\Delta S_{jk}<0}}{\sum_j \Delta S_{jk} \Big|_{\Delta S_{jk}<0}} .$$

By substituting and rearranging terms it can be shown that the following relationship holds:

$$\Delta E = \sum_k M_k^{Eff} + \sum_{j,k} M_{jk} .$$

Thus, this verifies the decomposition of the total emission reduction into single terms at the lowest possible level of the energy system model. By defining sets of technologies the energy conversion sector related mitigation wedges M_i, i=1,…,6, can be appropriately defined. The efficiency related mitigation wedge is simply the sum of all M_k^{Eff} over all secondary energy types as given in the first term on the right hand side.

Chapter 3

Low-Carbon Technologies, Trade and Regional Mitigation Costs*

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Technological Change and International Trade – Insights from REMIND-R

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Within this paper, we explore the technical and economic feasibility of very low stabilization of atmospheric GHG concentration based on the hybrid model REMIND-R. The Fourth Assessment Report *of the IPCC and the scientific literature have analyzed some low stabilization scenarios but with as yet little attention being given to the regional distribution of the global mitigation costs. Our study helps to fill this gap. While we examine how technological development and international trade affect mitigation costs, this paper is novel in addressing the interaction between both. Simulation results show for instance that reduced revenues from fossil fuel exports in a low stabilization scenario tend to increase mitigation costs borne by the exporting countries, but this impact varies with the technology options available. Furthermore it turns out that the use of biomass in combination with carbon capturing and sequestration is key in order to achieve ambitious CO_2 reduction targets. Regions with high biomass potential can clearly benefit from the implementation of low stabilization scenarios due to advantages on the carbon market. This may even hold if a reduced biomass potential is assumed.*

1. INTRODUCTION

A number of findings (e.g., Meinshausen et al., 2009) indicate the need for a sustained reduction of greenhouse gas emissions and stabilization of their concentration at a very low level. Yet, as discussed in Edenhofer et al. (2009, *this issue*), only a few mitigation-policy studies have analyzed the feasibility and costs of very low stabilization scenarios. We add to these few analyses and extend the scope of mitigation-cost assessments by focusing on the joint impact of technological change in the energy sector and international trade. Based on the very low climate stabilization target (400ppm CO_2eq) adopted by the ADAM

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model comparison, this paper aims to identify the magnitude of the aggregate mitigation costs of attaining such a target and to answer the question on how costs vary by technology and region.

A majority of climate policy studies consider the energy sector as the key sector for mitigation strategies. Indeed, the transformation of the global energy system appears to be a promising and effective way of reducing greenhouse gas emissions. Having a portfolio of different technology options is crucial for transforming the energy system, and such options are well represented in bottom-up models. However, technological change in the energy sector is embedded in a microeconomic and macroeconomic environment (as represented by top-down models) where, directed by relative-price, profit, and scale-of-market expectations, investment decisions are made. Few models formally integrate macroeconomic-system and detailed energy-system modules. Hybrid models bridge the gap between conventional top-down and bottom-up modeling approaches (Hourcade et al., 2006), making them the preferred tool for mitigation policy assessments. We discuss the contribution of technological options in containing the costs of climate change mitigation based on such a model - REMIND-R.

The dynamic energy-economy-environment model REMIND-R links technological development of the energy system to the domestic capital market and to international markets. This makes mitigation costs a function of international trade decisions, a dependence that has been neglected in the literature including the *Fourth Assessment Report* of the IPCC (2007). Moreover, the IPCC Report and most studies of low stabilization scenarios (*e.g.*, Azar et al., 2006; den Elzen et al., 2007; Edenhofer et al., 2006; van Vuuren et al., 2007) consider global mitigation costs only. This paper helps to fill this gap by providing estimates of the regional distribution of mitigation costs in a world economy where regions are linked by global markets for emission permits, goods, and energy resources. In many energy-economy-climate models, trade in emission permits is the only recognized element of international trade. Such models do not lend themselves to discovering opportunities for improving welfare through reallocation of capital or of mitigation efforts over regions and time. In contrast to such a model design, REMIND-R derives a benchmark for a first-best intertemporal optimum in all markets.

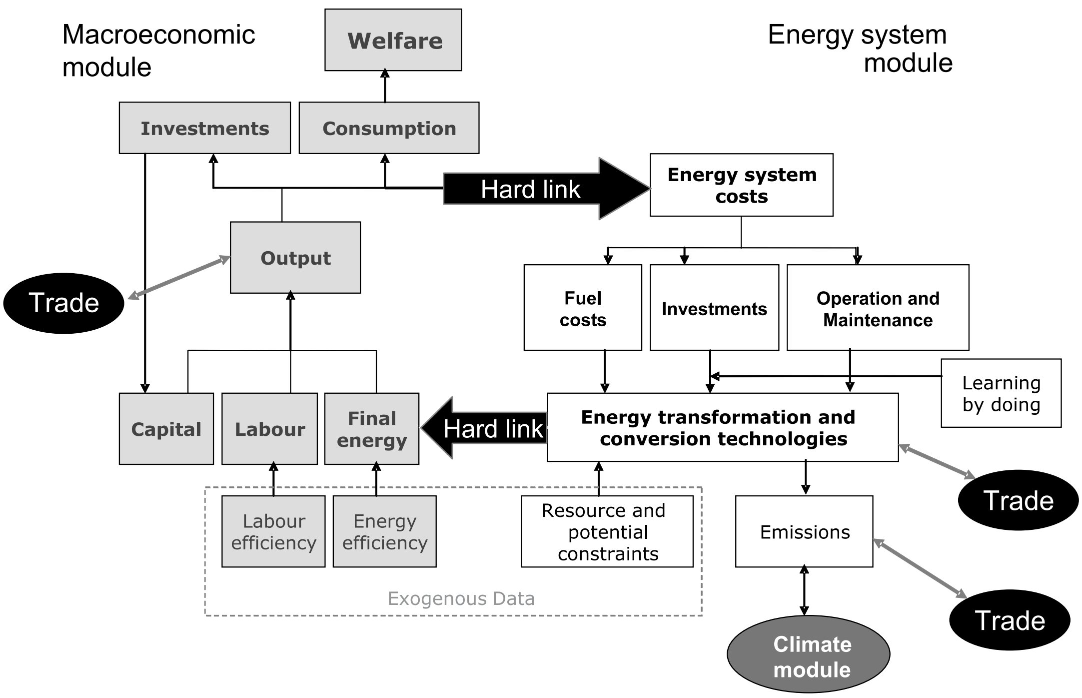
From simulation results, it transpires firstly that deep cuts in emissions - and even negative global emissions from 2075 on - are possible. Second, the loss of consumption need not exceed 2% globally in any period if a broad portfolio of technological options is available; this result is conditional on the assumption of a constant relationship between efficiency improvements in the production factors labor and final energy. Third, carbon capturing and sequestration (CCS) will play a major role in combination with both fossil fuels and biomass; when biomass has a limited potential to contribute to negative emissions, costs will be very much higher. Fourth, regional mitigation costs differ significantly as terms-of-trade effects have a major impact; through a decrease in demand for coal and oil, exporting regions such as Middle East and Russia will suffer from reduced trade revenues. Fifth, by cap, trade and convergence, Africa and Russia can make substantial gains from emissions trading; trade effects on the energy and carbon market vary with the availability of technological options.

This paper is structured as follows: Section 2 presents some details of the model REMIND-R, including important assumptions and empirical foundations. Results from REMIND-R simulations for a reference business-as-usual scenario and a reference climate policy scenario are given in Section 3. The analysis of technology scenarios in Section 4 provides insights into the energy-system dynamics that set the basis for the cost estimates. Cost-relevant changes in trade patterns and the interlinked impact of technology options and trade are highlighted in Section 5, and Section 6 concludes on the results.

2. MODEL DESCRIPTION REMIND-R

As described in Leimbach et al. (2009), REMIND-R is a multi-regional hybrid model which couples an economic-growth with a detailed energy-system model and a simple climate model (see Figure 1). Specification of the hard link between the energy system and the macroeconomic system follows the method given in Bauer et al. (2008).

Figure 1. Structure of REMIND-R



REMIND-R provides for intertemporal maximization of global welfare subject to market clearing. The model's Pareto-optimal solution, obtained with the Negishi algorithm, corresponds to the general market equilibrium in the absence of externalities. In this respect, REMIND-R resembles well-known energy-economy-climate models like RICE (Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000) and MERGE (Manne et al., 1995; Kypreos and Bahn, 2003). REMIND-R is distinguished from these models and from other hybrid models like WITCH (Bossetti et al., 2006) and IMACLIM (Crassous et al., 2006) by a high technological resolution of the energy system and by incorporating intertemporal trade relations between regions.

The current model version – REMIND-R 1.1 – differs from that in Leimbach et al. (2009) by offering a more detailed regional breakdown into 11 groupings:

1. USA – United States of America
2. EUR – European Union (27 countries)
3. JAP – Japan
4. CHN – China
5. IND – India
6. RUS – Russia
7. AFR – Sub–Saharan Africa (excluding the 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, South Africa, Rest of Europe).

All other differences arising in comparison with the earlier study relate to the adoption of the common baseline assumptions of the ADAM model comparison (see Edenhofer et al., 2009, *this issue*). These include population and efficiency growth, higher initial fossil fuel extraction costs, and lower baseline emissions. Likewise, land-use change emissions and non-CO_2 emissions follow an exogenous scenario (cf. van Vuuren et al., 2007). Their abatement costs are not subject to optimization and will not be reported in the analyses below. As in all other models from the ADAM model comparison, we implemented a mitigation scenario by imposing an emission cap. Therefore, feedbacks from the carbon cycle and the atmospheric chemistry had not been taken into account and shall not be discussed here.

2.1 Macro-economy Module

There is room here for only a brief conceptual overview of the main features of REMIND-R; the detailed documentation of this model is available on our website[1]. World-economy dynamics are simulated over the time horizon 2005 to 2100 in five-year steps ($\Delta t = 5$). A utility function $U(r)$ is assigned to the representative agent in each region r:

$$U(r) = \sum_{t=t_0}^{T} \left(\Delta t \cdot e^{-\zeta(t-t_0)} L(t,r) \cdot \ln\left(\frac{C(t,r)}{L(t,r)}\right)\right) \quad \forall r \tag{1}$$

$C(t,r)$ represents non-energy consumption in year t and region r, $L(t,r)$ represents labor (equivalent to population) and ζ the pure rate of time preference[2]. A global welfare function, which is maximized by a social planner, is formed as a weighted sum of the regional utility functions.

For climate-policy simulations, a climate policy target is entered into the model as an additional constraint, and REMIND-R is then run to determine the most cost-effective mode of achieving that target.

Macroeconomic output, i.e. gross domestic product (GDP), is determined by a “constant elasticity of substitution” (CES) function of the production factors labor, capital and final energy. The substitution elasticity assumed between these factors is 0.5. The final energy of the upper production level is calculated with an aggregator function comprising transportation energy and stationary-use energy. Both are connected by a substitution elasticity of 0.3. These two energy types in turn are determined by means of nested CES functions of more specific final energy types. Substitution elasticities between 2.5 and 3 hold for the lower levels of the CES nest. An efficiency parameter is assigned to each production factor in the various macroeconomic CES functions. Changes in the efficiency of the individual production factors are given by exogenous scenarios. While we assume a constant efficiency of capital, labor productivity growth is adjusted to reproduce the regional GDP baselines as harmonized within the ADAM model comparison. Efficiency growth of the different final energy types is in type-specific constant relation to changes of labor productivity.

GDP, denoted $Y(t,r)$, is used for private and government non-energy consumption $C(t,r)$, non-energy gross investments $I(t,r)$, all expenditures in the energy system, and export of the composite good $X_G(t,r)$. Non-energy gross investments enter a conventional capital stock accumulation equation. Energy system costs consist of fuel costs $G_F(t,r)$, investment costs $G_I(t,r)$ and operation & maintenance costs $G_O(t,r)$. Imports of the composite good $M_G(t,r)$ increase the available gross product. This yields the following macroeconomic balance:

1. The technical description of REMIND-R 1.1 and the whole set of input data are available at http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/remind-code-1. REMIND-R is programmed in GAMS. The code is available from the authors upon request.

2. We assume a pure rate of time preference of 3% for the simulation experiments presented in later sections. The logarithmic form of the utility function implies an equal evaluation of the marginal consumption of poor and rich regions.

$$Y(t,r) - X_G(t,r) + M_G(t,r) = C(t,r) + I(t,r) + G_F(t,r) + G_I(t,r) + G_O(t,r) \qquad \forall t,r \tag{2}$$

In following the classical Heckscher-Ohlin and Ricardian model (Flam and Flanders, 1991), trade between two regions is induced by differences in factor endowments and technologies. In REMIND-R, this is supplemented by the possibility of intertemporal trade. Intertemporal trade and capital mobility, implied by trade in the composite good, causes factor price equalization and guarantee an intertemporal and interregional equilibrium. Trade is modeled in the following goods:

- Coal
- Gas
- Oil
- Uranium
- Composite good (aggregated output of the macroeconomic system)
- Permits (emission rights).

With $X_j(t,r)$ and $M_j(t,r)$ as export and import of good j by region r in period t, the following world-trade accounting identity holds:

$$\sum_r (X_j(t,r) - M_j(t,r)) = 0 \qquad \forall t,j \tag{3}$$

To co-ordinate the export and import decisions of the individual regions, and to achieve an equilibrium solution, REMIND-R uses the Negishi-approach (cf. Nordhaus and Yang, 1996; Manne and Rutherford, 1994; Leimbach and Toth, 2003). Within this iterative approach, Negishi weights are adjusted so that for each region the net present value of trade is zero.

The trade pattern in the model is governed by this intertemporal budget constraint which balances trade across all goods over the entire time horizon. A current net export of the composite good, lowering domestic consumption, is matched by a future net import of any good of the same present value during the simulation period with a reverse effect on consumption. Trade with emission permits works in a similar way. The sale of emission rights generates a surplus in the current account that has to be balanced by future imports of permits or goods.

We do not restrict trade flows by artificial bounds. In the intertemporal model framework, where productivity differences between regions are equalized by capital trade (*i.e.*, trade in the composite good), this leads to initial spikes in current account balances and an overestimation of trade flows (cf. Nordhaus and Yang, 1996). As this temporary distortion applies equally to the baseline and policy scenarios, meaningful comparative results can still be obtained. Intertemporal trade (and therefore the possibility of current account deficits) in REMIND-R significantly contributes to the growth dynamics of the world economy, which is in accordance with empirical and theoretical findings from the literature. Its isolated impact on the mitigation costs, however, is moderate.

2.2 Energy System Module

The energy system module of REMIND-R specifies energy carriers and conversion technologies. It is embedded in the macro-economy module where the techno-economic characteristics and the system of balance equations that underlie the energy system are constraints on the welfare-maximization problem.

The energy system can be considered as an economic sector with a heterogenous capital stock that demands primary energy carriers and supplies final energy carriers. The structure of the capital stock determines the energy related demand-supply structure. The sector takes financing from the capital market which is allocated among a portfolio of alternative energy conversion technologies. The techno-economic characteristics of the technologies and the endogenously evolving prices of energy and CO_2 emissions determine the size and structure of the energy sector's capital stock. Hence, the energy sector develops in moving equilibrium to the remaining economy with which it is interrelated through capital and energy markets.

The availability of technologies for the conversion of primary into final energy carriers is essential for the valuation of the primary energy carriers. In the multiregional setting, the regions' valuation of primary energy endowments is influenced by international trade opportunities. Depending on available technologies, climate change mitigation policies and induced changes in trade patterns lead to a revaluation of these endowments. This interplay has significant impact on the regional and global mitigation costs.

Table 1 presents the primary energy carriers by column and the secondary energy carriers by row. The conversion technologies indicate possible methods for converting primary into secondary energy carriers. The primary energy carriers rely on both exhaustible and renewable energy sources. The exhaustible energy carriers - coal, oil, gas, and uranium - are tradable and characterized by extraction cost functions. These functions are based on the assumption that resources are exploited in an optimal sequence. This implies that the cheapest deposits are exploited first and the marginal costs of discovering and developing new reserves are increasing. The result is a function in which marginal extraction costs rise with the cumulative amount of extraction.

Figure 2 shows the reserve endowments of exhaustible primary energy carriers. In contrast to the other three energy carriers, coal is abundant and widely available. However, Japan has hardly any fossil resources, and regions with the largest populations, especially China and India, have only relatively small endowments. The USA, Russia and ROW are well endowed, especially with coal, and their population shares are modest.

Table 1. Primary and Secondary Energy Types and Available Conversion Technologies

Secondary energy types	Primary energy types *Exhaustible* Coal	Crude oil	Natural gas	Uranium	*Renewable* Solar Wind Hydro	Geo-thermal	Biomass
Electricity	PC* IGCC* CoalCHP	DOT	GT NGCC* GasCHP	LWR	SPV# WT# Hydro	HDR	BioCHP
Hydrogen	C2H2*		SMR*				B2H2*
Gases	C2G		GasTR				B2G
Heat	CoalHP CoalCHP		GasHP GasCHP			GeoHP	BioHP BioCHP
Transport							
Fuels	C2L*	Refinery					B2L* BioEthanol
Other liquids^		Refinery					
Solids	CoalTR						BioTR

Glossary: PC – conventional coal power plant, IGCC – integrated coal gasification combined cycle power plant, CoalCHP – coal combined heat and power, C2H2 – coal to hydrogen, C2G – coal to gas, CoalHP – coal heating plant, C2L coal to liquids, CoalTR – coal transformation, DOT – diesel oil turbine, GT – gas turbine, NGCC - natural gas combined cycle power plant, GasCHP - gas combined heat and power, SMR – steam methane reforming, GasTR – gas transformation, GasHP – gas heating plant, LWR – light water reactor, SPV – solar photovoltaics, WT – wind turbine, Hydro – hydroelectric power plant, HDR – hot dry rock, GeoHP – heat pump, BioCHP – biomass combined heat and power, B2H2 – biomass to hydrogen, B2G – biogas plant, BioHP – biomass heating plant, B2L – biomass to liquid, BioEthanol – biomass to ethanol, BioTR – biomass transformation.

* This technology is also available with carbon capture and sequestration.

This technology is characterized by endogenous technological learning.

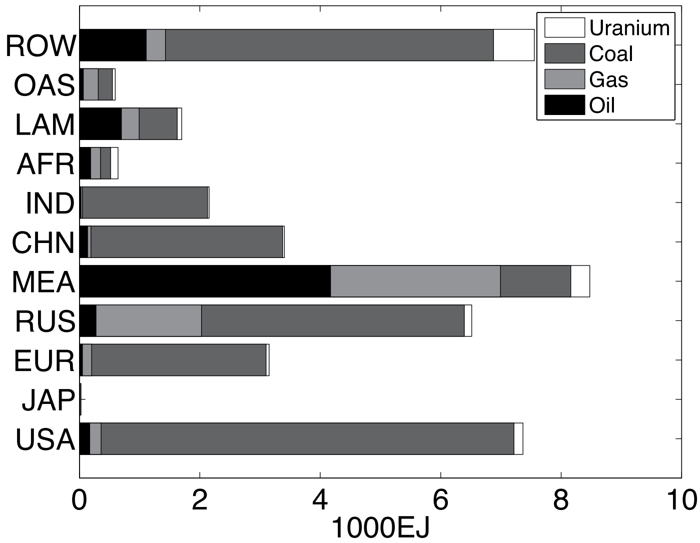
^ This secondary energy type includes heating oil.

Table 2 relates the reserves to the extraction cost functions. The initial extraction costs refer to the year 2005. The extraction costs at reserve limit are reached when the cumulative extraction equals the available reserve. Extraction can go beyond any pre-existing proven reserve limit, but extraction costs will increase. The initial assumption and the extraction cost at the reserve limit are connected by a quadratic function, which is the extraction cost curve (cf. Rogner, 1997).

Table 2. Cost Parameters of Exhaustible Primary Energy Carriers

	Coal	Oil	Natural Gas	Uranium
Initial extraction costs [$US per GJ]	2	8	5.5	30 $US/kg
Extraction costs at reserve limit [$US per GJ]	4	10	8	80 $US/kg

Figure 2. Reserve Endowments of Exhaustible Primary Energy Carriers



Source: ENERDATA. Most recent data are available on http://www.enerdata.fr/enerdatauk/index.html.

Renewable energy sources are non-tradable and subject to potential constraints that differ by grade. Harvest costs of biomass increase from 1.4 to 5.6 $US per GJ between lowest and highest grade. The production potential of biomass summed over all grades is assumed to increase up to around 200 EJ p.a. until 2050 (cf. Grahn et al. 2007). Regional shares, which are kept constant, follow Hoogwijk (2004). Bio-energy production is based on the use of ligno-cellulosic biomass and associated emissions from land-use change and management are ignored. For renewables other than biomass the grades differ in the availability factor. The two most important renewables are wind and solar. These have global potentials of at most 140 EJ and 750 EJ, with maximum availability factors of 31% and 25%, respectively (see e.g. Hoogwijk, 2004; WBGU, 2003).

Secondary energy carriers are assumed to be non-tradable across regions even though small amounts of liquid fuels are, in fact, traded internationally. Since the REMIND-R model treats crude oil as tradable, the omission bias is limited. Secondary energy carriers are converted into final energy carriers by considering mark-ups for transmission and distribution. Final energy is demanded by the macroeconomic sector at equilibrium prices.

We now turn to the most important features of the conversion technologies, all of which are employable in the model. The possibility of investing in different capital stocks provides, on the one hand, a high flexibility of technological evolution. On the other hand, low depreciation rates and long life times of energy production capacities cause inertia. Key techno-economic assumptions of selected technologies are summarized in Table 3.

Table 3. Techno-economic Characteristics of Technologies

		Techno-economic Parameters							
		Lifetime	*Investment costs*		*O&M costs*		*Conversion efficiency*		*Capture rate*
		years	$US/kW		$US/GJ		%		%
			No CCS	With CCS	No CCS	With CCS	No CCS	With CCS	With CCS
Coal	PC	55	1150	1900	1.64	2.58	42	35	90
	Oxyfuel	55		1700		2.86		34	99
	IGCC	45	1500	1800	1.89	2.93	48	42	90
	C2H2*	45	756	712	0.61	0.58	57	57	90
	C2L*	45	1000	1040	1.47	1.66	40	40	70
Gas	NGCC	45	650	1350	1.02	1.78	55	47	90
	SMR	45	300	380	0.57	0.8	75	70	90
Biomass	B2H2*	45	1400	1700	2.02	2.44	61	55	90
	B2L*	45	2500	3000	2.87	3.94	41	41	50
	B2G	45	1000		1.35		55		
Nuclear	LWR	35	2500				33~		
Renewables	Hydro	80	3000				45		
	WT#	35	1100				35		
	SPV#	35	4500				12		

Related Source References: Bauer, 2005; Gül et al., 2008; Hamelinck, 2004; Iwasaki, 2003; Ragettli, 2007; Schulz et al., 2007; Takeshita and Yamaij, 2008.

Glossary: PC – conventional coal power plant, Oxyfuel – coal power plant with oxyfuel capture, IGCC – integrated coal gasification combined cycle power plant, C2H2 – coal to hydrogen, C2L coal to liquids, NGCC – Natural gas combined cycle power plant, SMR – steam methane reforming, B2H2 – biomass to hydrogen, B2G – biogas plant, B2L – biomass to liquid, LWR – light water reactor, Hydro – hydroelectric power plant, WT – wind turbine, SPV – solar photovoltaics, CCS – carbon capture and storage, O&M – Operation and Maintenance.

* These technologies represent joint processes; capturing does not necessarily result in higher investment costs and lower efficiency in producing the main product.

~ Thermal efficiency.

\# Regional investment costs vary around the value shown.

Each region starts with a vintage capital stock which meets the statistically given input-output relations. The technical transformation coefficients for new vintages are the same for all regions and assumed to be constant. However, the following modifications apply: the transformation efficiency is improved over time for fossil power generation technologies and different technology grades are considered when renewable energy sources are used.

Electricity is the secondary energy carrier that can be produced from all primary energy carriers, and the use of fossil-fueled power stations could be augmented by CCS. However, the option of biomass power production with CCS as well as the use of electricity in the transport sector are not included in the model. Transport fuels, hydrogen and gases can either be produced from fossil energy carriers or biomass. The production of transport fuels and hydrogen could also be equipped with CCS – both for fossil-fueled and biomass-fueled facilities. The capture rate for the liquid transportation fuels is considerably lower than for hydrogen and electricity. Note that the investment costs for both biomass technologies (B2H2 and B2L) with and without CCS are quite high. The model considers that captured CO_2 needs to be transported and compressed prior to injection. Storage is assumed to be in geological formations only. There is leakage in the process of capturing, but no leakage from sequestered CO_2. Space in geological formations is generously measured for all regions.

The electricity generation technologies wind and solar PV are characterized by endogenous technological learning. The learning rate are assumed to be 10% and 20%, respectively (see e.g. Neij et al., 2003; Junginger et al., 2005; McDonald and Schrattenholzer, 2001). Investment costs can be reduced to the floor cost limit of 700 $US per kW for wind and 1000 $US per kW for solar PV. The effect of learning is limited to a region; no spillovers are considered. The initially installed capacities and the initial investment costs vary by region. However, cost differences are small. On average, initial investment costs for wind and solar PV technologies amount to 1100 $US per kW and 4500 $US per kW, respectively.

Regarding nuclear power the model only considers Light Water Reactors; their investment costs, here assumed to be 2500 $US per kW, are highly uncertain. Adverse side-effects regarding nuclear proliferation, dismantling, waste treatment, and safety are not considered. In general, the model imposes no restrictions on growth rates, or on shares in the energy mix, of any energy sources or technologies. Hence it is flexible in technology choice and maintains capital-market equilibrium for all technologies. Only one exogenous restriction is imposed in REMIND-R: For nuclear power plants, the increase of investment costs is tied to capacity expansion. A critical capacity level is set that starts at 5 GW globally in 2005 and increases by 1 GW each year. Exceeding its trend value by 10% is assumed to increase investment costs by 5%.

3. REFERENCE SCENARIOS

Before we go into a detailed discussion on the technology-related and trade-related impacts on the costs of climate policies and their regional distribution, we set up the framing of the scenario analysis. We consider two *reference* scenarios: a reference business-as-usual scenario and a reference climate policy scenario. In the following, the former is referred to as *baseline* scenario and the latter as *400ppm* scenario. The policy scenario achieves climate stabilization but without constraining the set of available technologies. In the next section, alternative constraints on the technology options available then generate different *technology* scenarios.

In the *baseline* scenario, we simulate a development as if climate change had no economically or socially important effects. The *400ppm* scenario, by contrast, takes account of climate policies designed to reduce climate change and its impacts. The control instrument is a cap on energy-related CO_2 emissions that is to stabilize the atmospheric concentration of greenhouse gases at around 400ppm CO_2eq by 2150. Notably, this emission cap requires negative energy-related CO_2 emissions at the end of the century. Van Vuuren et al. (2007) provide more details of this low stabilization scenario with respect to the exogenously given reduction of non-CO_2 greenhouse gases and land-use change emissions. Both follow optimistic assumptions on the reduction potential and costs.

The *400ppm* scenario includes an international emissions trading system based on a contraction & convergence rule of permit allocation. This rule implies a transition from status-quo allocation towards an equal per capita permit allocation until 2050. A co-operative policy regime is assumed where all regions begin emissions mitigation immediately. While this is idealistic, it provides an important point of reference.

Both reference scenarios are based on common assumptions on population growth and economic growth as given by the ADAM baseline scenario (see Edenhofer et al., 2009, *this issue*). Global population stabilizes at around 9 billion in the middle of the century. Africa is the region with highest growth and highest population (around 2.1 billion) in 2100. Economic growth by region was projected from 2005 to 2100 as shown in Figure 3. This projection involved exogenous adjustment of efficiency growth parameters of the production factors. World-wide GDP of about 42 trillion $US[3] in 2005 increases to almost $US 345 trillion in 2100. While China already provides a significant share of global GDP in the coming decades, its growth rate of 1.5% in 2100 is comparatively low; India's growth rate, for example, is 2.7%. The highly developed regions - USA, Europe, Japan - exhibit the lowest growth rates (less than 1% by 2100). They lose share in global GDP but still account for one-third of world GDP by 2100. Per capita GDP levels between regions converge rather slowly. In particular, Africa's per capita GDP in 2100 is more than 80% below the world level of $US 38,000.

Figure 4 shows how the *baseline* and the *400ppm* scenarios differ with regard to the energy system's development. Primary energy consumption[4] increases continuously from around 475 EJ p.a. in 2005 to more than 1100 EJ p.a. in 2100 in the *baseline* scenario and to almost 920 EJ p.a. in the *400ppm* scenario. While consumption of fossil resources is significantly reduced in the *400ppm* scenario, part of this reduction is made up by greater reliance on biomass, wind and nuclear energy in the short to medium term. In the long run, the *400ppm* scenario is distinguished from the *baseline* scenario primarily by the use of solar energy and the use of coal in conjunction with CCS.

3. Throughout this report, all relevant economic figures (e.g. GDP) are measured in constant international $US 1995 (market exchange rate).

4. For wind, solar and hydro energy, the quantity of primary energy consumption equals the level of the related secondary energy production.

Figure 3. Economic Growth of the World Regions

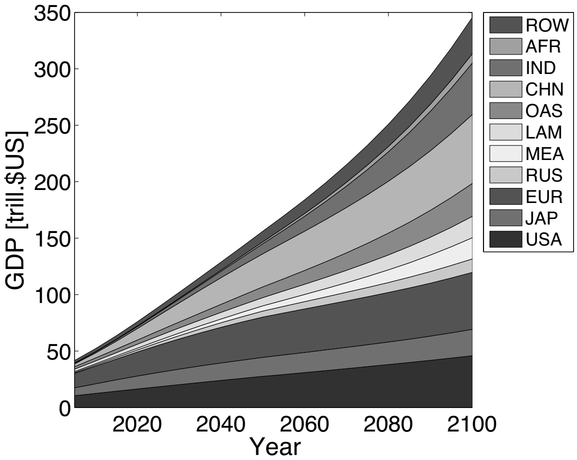
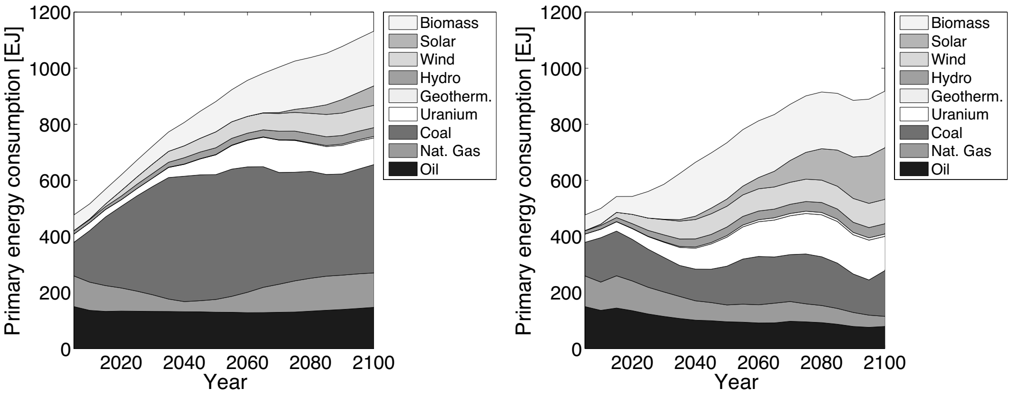


Figure 4. Consumption of Primary Energy



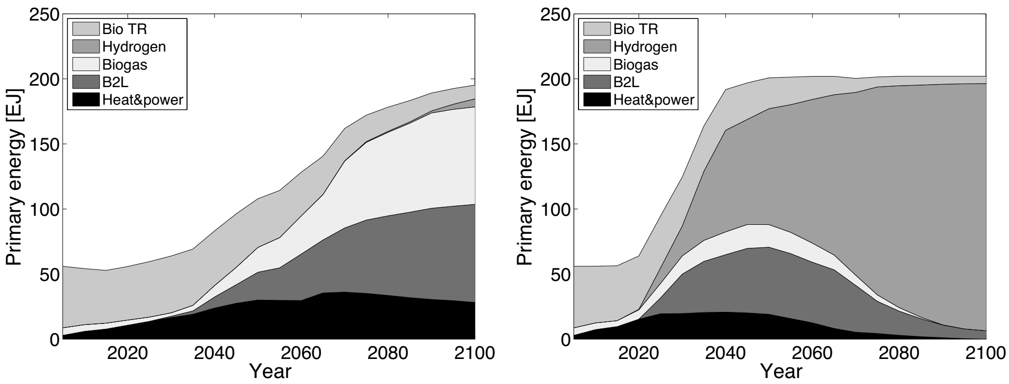
(a) Baseline scenario

(b) 400ppm scenario

In the *400ppm* scenario, biomass is also used in combination with CCS. Moreover, this is the only type of technology available in REMIND-R that helps to achieve negative emissions. In terms of the carbon capture rate, the most efficient means of combining biomass use with CCS is hydrogen production, and use of this technology dominates in the *400ppm* scenario (see Figure 5). Hence, although there is little difference in the quantity of biomass used in the *baseline* and the *400ppm* scenario, the structure of biomass use is quite different and the amount of CO_2 which is reduced by the use of biomass in the *400ppm* scenario is considerable.

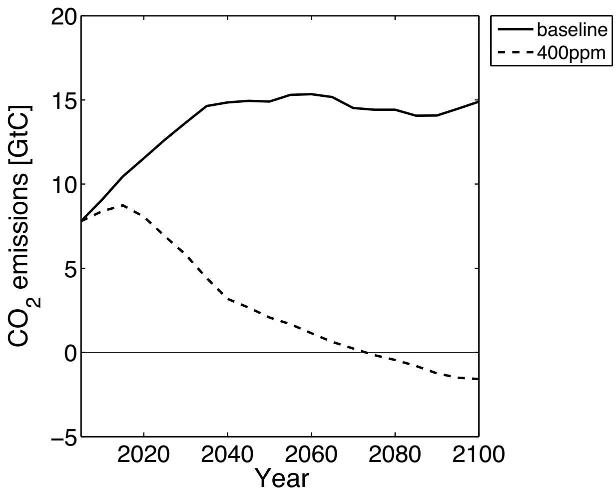
Figure 6 shows that the two reference scenarios yield entirely different emissions paths. Due to the growing coal consumption, worldwide emissions increase to almost 15 GtC in the *baseline* scenario by 2100. While this is a moderate increase compared to the growth in baseline emissions projected in

Figure 5. Use of Biomass (Abbreviations see Table 1)



(a) Baseline scenario (b) 400ppm scenario

Figure 6. World-wide Energy-related CO_2 Emissions in the Reference Scenarios



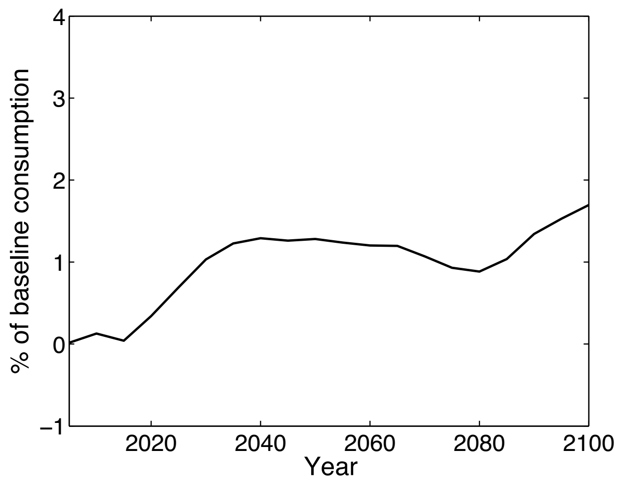
other studies such as Magne et al. (2009, *this issue*), Sano et al. (2006), and Crassous et al. (2006), the mitigation gap left by our baseline nevertheless is huge. In the *400ppm* scenario, emissions have to be reduced steeply between 2020 and 2040, and negative emissions have to be achieved by about 2080.

Large regional differences in per capita emissions can arise even in the *400ppm* scenario. The advanced industrial countries reduce their annual per capita emissions from 3-6 tC in 2005 to approximately 2 tC by 2050 and then further to 1 tC by 2100. There is hardly any increase in per capita emissions in the developing regions of the world. Except for MEA, all these regions emit less than 1 tC per capita p.a. throughout the century. Africa, Russia and LAM start to have negative emissions by 2040. Russian emissions are most striking, continuing to reduce to a per capita level of -8 tC p.a. by 2100. This is the result of Russia's high biomass potential being used in combination with CCS. Such pronounced differences in per capita emissions do not derive from the permit allocation scheme that may incorporate norms of international equity. Given the free flow of permits and the possibility of trading virtual permits that are generated by negative emissions, the separability of efficiency and equity hold (cf. Manne and Stephan, 2005). This results in the same regional development of the energy system and the emission trajectories irrespective of the permit allocation.

Figure 7 shows the evolution of global mitigation costs in the *400ppm* scenario, measured as consumption losses relative to the *baseline* scenario. Mitigation costs increase from zero to around 1.7% by 2100. The carbon price amounts to \$US 60 and 120 per tCO_2 in 2030 and 2050, respectively, and increases to more than \$US 500 per tCO_2 by 2100. This is at the lower end of the figures reported by the *Fourth Assessment Report* of IPCC (2007, p. 205) for the years 2030 and 2050, but somewhat above the IPCC figures for 2100.

Altogether, the low stabilization target in the *400ppm* scenario can be achieved at aggregated mitigation costs[5] of around 0.97% of world consumption. This estimate is in a range that the literature (e.g. IPCC, 2007 p.197f.) attributes to less ambitious stabilization scenarios. The exploration of different technological options in the next section will help explain the level and the sensitivity of global mitigation costs. Section 5 then proceeds to the regional distribution of mitigation costs, which depends on the interactions between international trade and technology options.

Figure 7: Evolution of Global Mitigation Cost (400ppm Scenario)



5. In this paper, mitigation costs are measured as percentage consumption losses in a policy or technology scenario compared to *baseline* scenario, either per year or averaged over the time horizon from 2005 to 2100.

Preliminary sensitivity analysis indicates that the differential between improvements in labor efficiency and final energy efficiencies has a significant impact on the mitigation costs. If, in contrast with our default assumption, we assume that in fast-growing regions energy efficiency improvements lag behind improvements in labor efficiency, the mitigation gap will widen and hence the mitigation costs will increase. We shall not discuss this sensitivity in more detail.

4. TECHNOLOGY SCENARIOS

We ran a set of different technology scenarios that are characterized by particular assumptions on the availability of technological options. All scenarios are subject to the same emission constraint as the reference policy scenario (*400ppm* scenario). The climate stabilization target cannot be achieved if either the CCS option or the biomass option is unavailable. The technology scenarios that remain compliant, and hence available for further analysis, are:

1. *No_renew* (investments in all renewable technologies but biomass technologies are fixed to baseline levels)
2. *Nucout* (no new capacities for nuclear technologies)
3. *CCSmin* (CCS potential is limited to 50% of the CCS amount used in the *400ppm* scenario) [6]
4. *Biomass_high* (maximum biomass potential is increased to 400 EJ p.a.)
5. *Biomass_low* (maximum biomass potential is reduced to 100 EJ p.a.)
6. *Nucout_nolearn* (restrictions of scenario *Nucout*; no learning for wind and solar technologies)
7. *Noall_butrenew* (combined restrictions of *CCSmin*, *Biomass_low* and *Nucout_nolearn* scenarios).

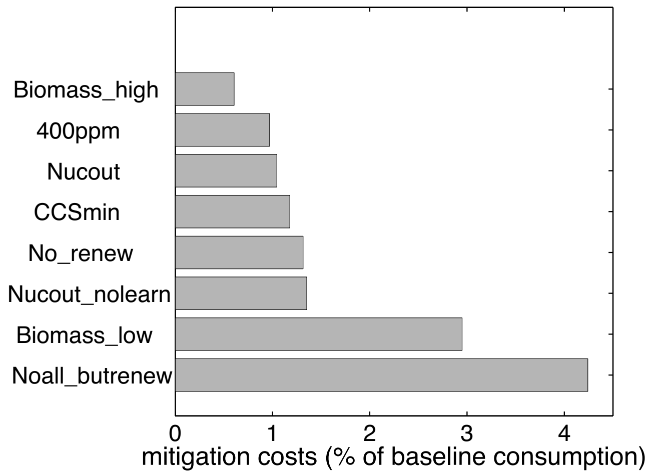
In all scenarios with altered potentials on biomass and CCS (i.e. *CCSmin, Biomass_high, Biomass_low* and *Noall_butrenew*), regional shares on the potentials are kept constant between scenarios at their reference levels.

Figure 8 shows global mitigation costs for low level stabilization at 400ppm CO_2eq under all technology scenarios and under the reference policy scenario. The option value of a single technology or a set of technological options is represented by the cost difference between the respective technology scenario and the *400ppm* scenario. Mitigation costs are lowest with a high biomass potential (*Biomass_high*) and highest when the largest number of technology options are withdrawn (*Noall_butrenew*). Nuclear technologies have an option value of less than 0.1 percentage points. With a restricted geological carbon storage reservoir (*CSSmin*), mitigation costs increase by about 0.2 percentage points compared to the *400ppm* scenario. Renewable energy technologies are more important to the

6. Note that this definition of the *CCSmin* scenario is different from the definition applied in Edenhofer et al. (2009, *this issue*).

outcome: Restricting the use of all of them, except biomass, to their baseline levels generates additional costs of more than 0.3 percentage points. Among the renewables, biomass is of critical importance. The *Biomass_low* scenario exhibits high costs, equal to 2.95% of world consumption. While this is a pronounced result, it relies on the assumption that negative emissions are needed and that tradable permits can be virtually generated by negative emissions.

Figure 8. Global Mitigation Costs

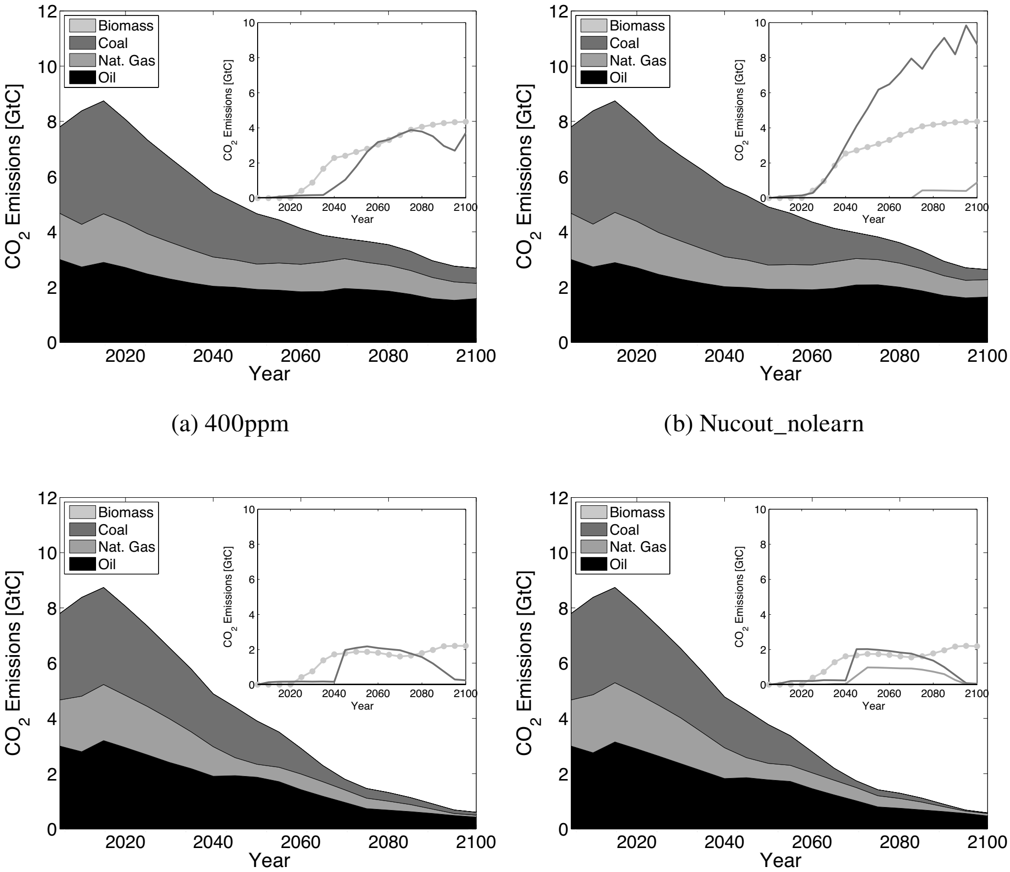


We now discuss in more detail changes in the global energy system that are linked with four scenarios that significantly differ in terms of mitigation costs: (I) *400ppm* scenario, (II) *Nucout_nolearn* scenario, (III) *Biomass_low* scenario, and (IV) *Noall_butrenew* scenario. The mitigation costs amount to 0.97%, 1.35%, 2.95% and 4.24 % of baseline consumption, respectively.

The most striking differences between the four scenarios laid out in Figure 9 relate to the emissions that get captured before being released into the atmosphere. In all scenarios, carbon capturing starts slowly around 2025. However, whereas in the *400ppm* and the *Nucout_nolearn* scenario, this amount rises to 8-14 GtC p.a. in 2100, it does not increase above 2-5 GtC p.a. in the *Biomass_low* and the *Noall_butrenew* scenario. The major part of this difference is due to different amounts of carbon capturing linked to the burning of fossil fuels. Only a minor part of the gap arises from differences in the biomass potential. In all scenarios, the respective maximum potential of biomass is employed and mostly combined with CCS. Biomass is mainly used in the transport sector but hardly at all in the electricity sector (cf. Figure 10).

In the *400ppm* scenario, coal is captured in the second half of the century by up to 4 GtC p.a.. Without the availability of nuclear technologies and learning, this capture rises to more than 9 GtC p.a. as reduced consumption of nuclear energy is compensated for mostly by increased consumption of coal whose associated emissions need to be captured (see Figure 9b, dark grey line, and Figure 10b, Coal, CCS). The missing learning effect reduces the incentive of switching to renewable technologies, with solar technologies being entirely displaced. In contrast, with a low biomass potential (see Figure 9c and Figure 10c), there is no substitution by coal combined with CCS. In fact the opposite occurs; coal consumption combined with CCS is reduced drastically. This steep drop in fossil-based CCS is due to the need to avoid the remaining emissions from this technology which in the *Biomass_low* scenario can to a lesser extent be compensated for by negative emissions from the biomass & CCS option.

Figure 9. Global CO_2 Emissions



(a) 400ppm

(b) Nucout_nolearn

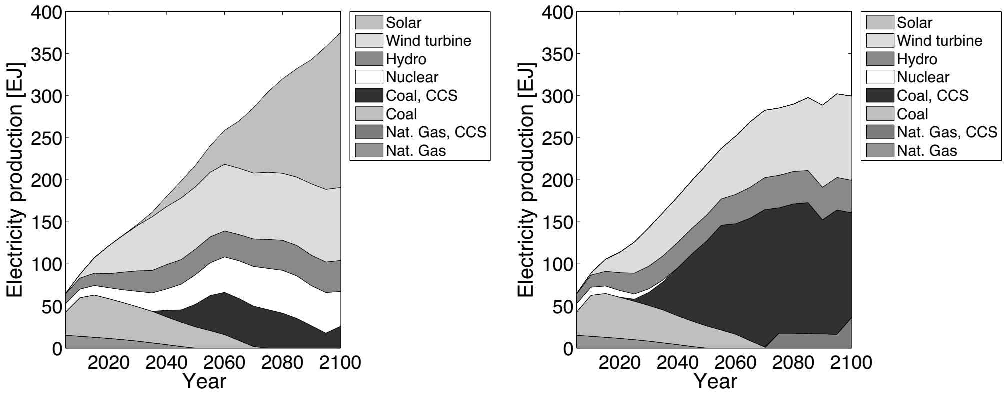
(c) Biomass_low

(d) Noall_butrenew

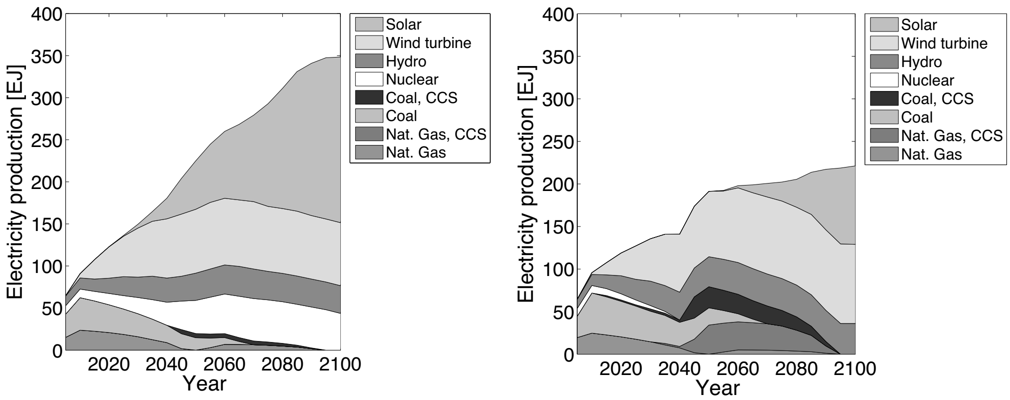
Solid lines in dark and light grey represent captured CO_2 from coal and gas consumption, respectively; solid lines with circles represent captured CO_2 from biomass use.

Surprisingly, in the scenario with an even more restricted portfolio of mitigation options (*Noall_butrenew* scenario), the amount of captured fossil emissions rises again. IGCC and NGCC technologies (defined in the glossary to Table 3) are used here to close the gap in power generation. This produces additional emissions which are compensated for by decreasing the use of oil and coal (i.e. coal to liquids) in the transport sector. There is no carbon-free substitute in the transport sector, as biomass is already used to its maximum potential. Hence, the supply of energy for use in the transport sector is reduced. But such a cut also applies to the electricity sector. Whereas all other scenarios can contain the loss of electricity production, the *Noall_butrenew* scenario reacts to the elimination of technology options with a drastic reduction in electricity production (see Figure 10d). Especially in that latter scenario, energy becomes quite expensive. While the underlying macroeconomic CES production function allows for a substitution of capital for energy, production losses and hence mitigation costs remain large.

Figure 10. Global Electricity Production



(a) 400ppm (b) Nucout_nolearn



(c) Biomass_low (d) Noall_butrenew

The analysis in this section indicates that a portfolio of different technological mitigation options is crucial for containing the mitigation costs in a low stabilization scenario. Within such a portfolio, biomass plays an important role because it represents a carbon-free substitute for oil in the transport sector. It also allows the large-scale use of coal-based power generation combined with CCS which is still producing net emissions.

5. TRADE IMPACTS

While the mitigation costs of 0.97% of world baseline consumption in the *400ppm* scenario may appear moderate on a global scale, the key question is how mitigation costs are distributed over different world regions and what factors contribute to cost differences at the regional level. We address these questions by investigating trade-related impacts and their relationship to domestic mitigation efforts based on available technology options.

As shown in Figure 11, estimated future differences in regional mitigation costs are huge. (Sub-Saharan) Africa and MEA are the most affected regions in terms of mitigation costs which range from -12% to +8%, respectively. Africa gains from climate policy. This is due mainly to the design of the international emissions trading scheme, in particular the permit-allocation rule. However, for all regions except Africa and and to some extent Russia and India, the allocation regime has only a moderate impact on the mitigation costs (see also Leimbach et al., 2009). A detailed decomposition of mitigation costs is provided by Lueken et al. (2009).

The evolution of the carbon market as represented by the flow of emission permits in Figure 12 shows Africa to be a major exporter for the rest of this century, while the USA, Europe, and MEA are major permit importers. As domestic mitigation efforts become increasingly more expensive in the importing regions, emissions trading helps them contain mitigation costs. Nevertheless, all three major importing regions face costs above the world average. This also applies to India, which becomes a buyer of emission permits in the second half of the century, while China switches from being a large buyer in the first half to a minor seller in the closing decades of the century. These observed developments in permit-trade patterns arise from growth assumptions. India is assumed to experience economic growth at higher rates than China in the medium-term and long-term. Contraction of globally available emission permits in this time span hits India harder than China.

Even if expenditures on the permit market charge the budget of MEA more than that of the more developed economies of Europe and the USA, this cannot be the only reason for the extremely high mitigation costs for MEA. Other production-related and trade-related impacts play an important role as well. We therefore proceed from trade in permits to trade in primary energy products and its connection with domestic output and demand. Figure 13 shows domestic output and consumption, exports and imports of four such products for the *baseline* scenario. A similar pattern can also be seen in the *400ppm* scenario. It transpires that the energy market is characterized by a high degree of specialization. Only a few regions (mainly MEA, Russia and ROW) supply the international market with primary energy carriers. In many other regions, imported primary energy makes up more than 50% of domestic consumption of coal, oil and gas. MEA's specialized resource endowments favor a production structure based on fossil fuels. Regardless of the high export shares, the consumption of fossil fuels in

Figure 11. Regional Mitigation Costs (400ppm Scenario)

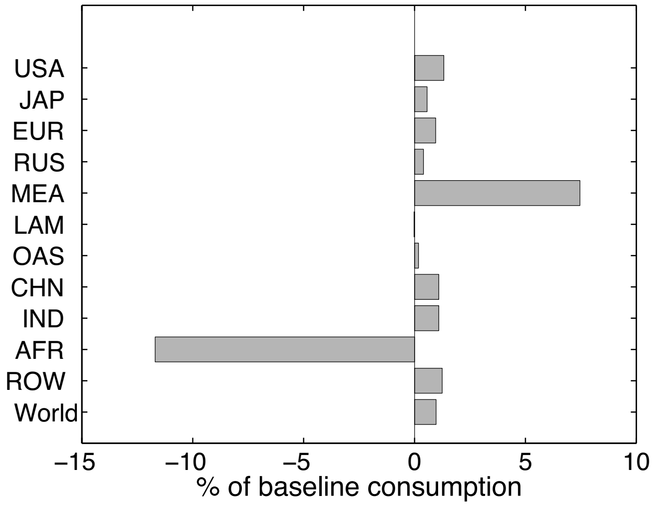
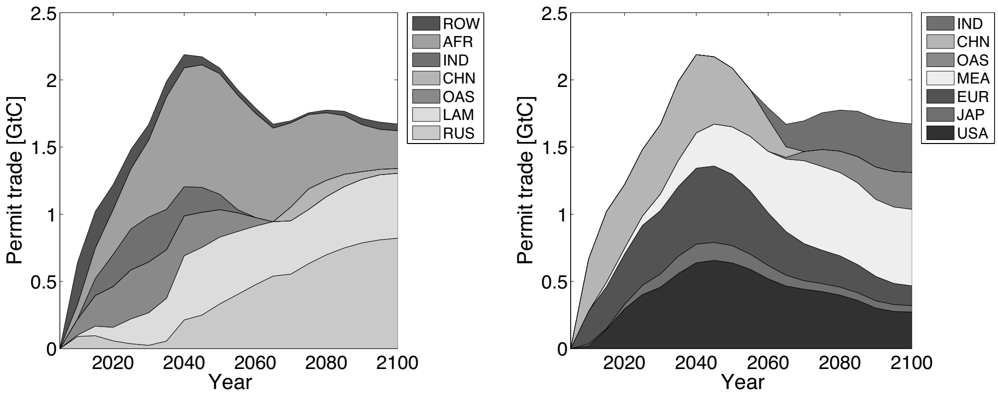


Figure 12. Trade in Emission Permits (400ppm Scenario)



(a) Export

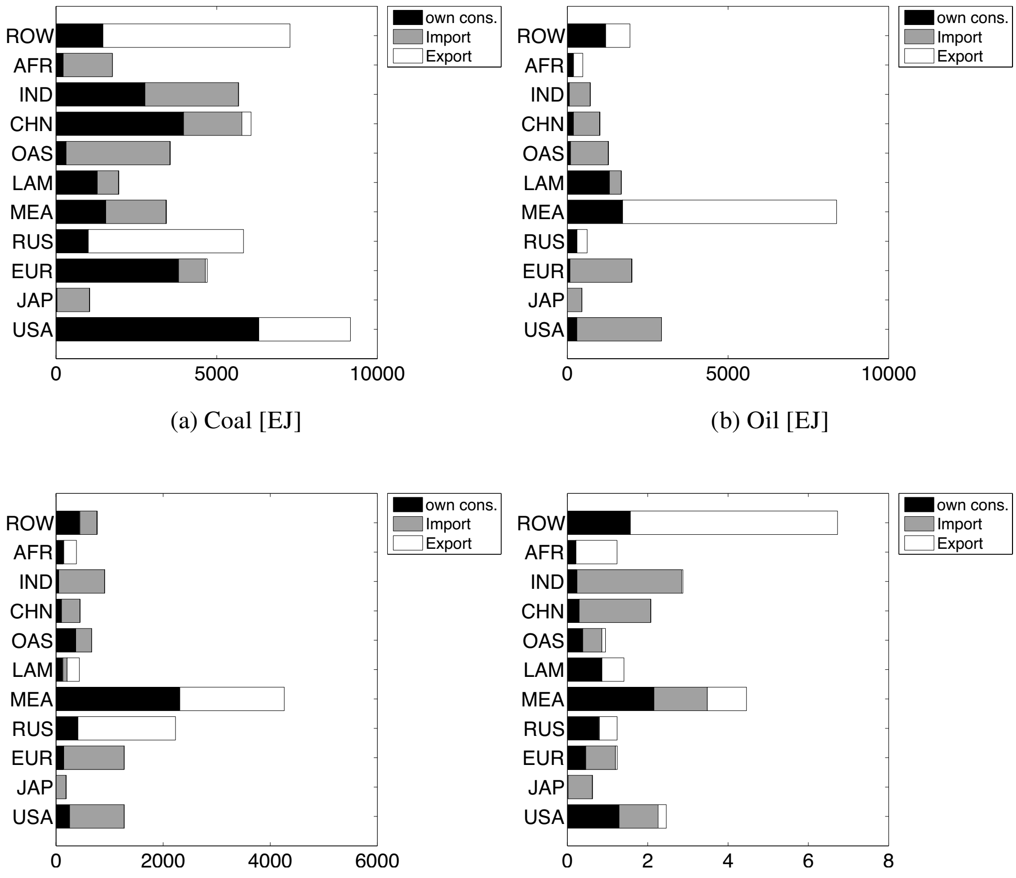
(b) Import

MEA is very high and comparable to that of the economically more potent regions USA and Europe. Therefore, restructuring the energy system in accordance with climate policies in MEA will require more effort than in other regions.

Starting from the trade data estimated in the *baseline* scenario, we now turn to the changes in trade of coal, oil, gas and the composite good brought about by adopting the policy scenario (see Figure 14). In all four panels negative values predominate which indicates a decline of the intensity of trade in the *400ppm* scenario compared with the *baseline* scenario.[7]

7. Except for natural gas, the same pattern of changes in trade holds if we measure trade for all goods in present value terms.

Figure 13. Composition of Domestic Production and Consumption of Primary Energy Carriers (Own Consumption, Exports and Imports by Region Totaled for the Period from 2005 to 2100 Using the Baseline Scenario)[8]



(a) Coal [EJ]

(b) Oil [EJ]

(c) Natural gas [EJ]

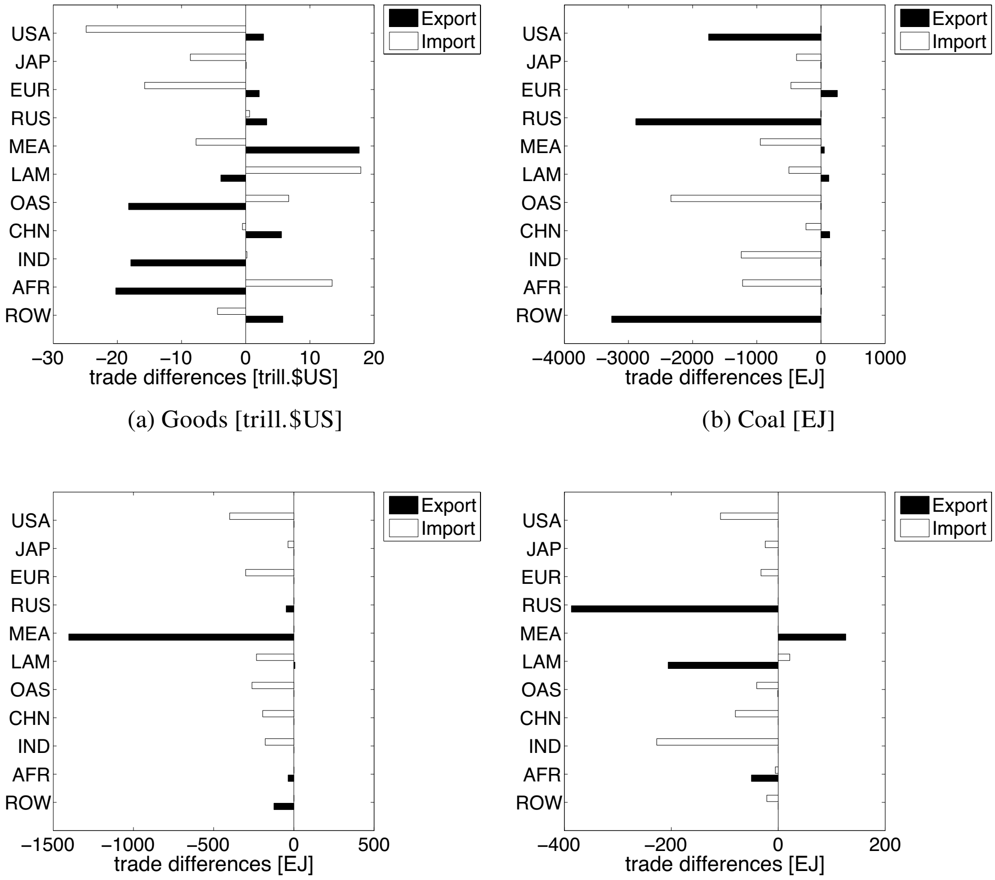
(d) Uranium [Mt Ur]

The pattern of changes in non-energy goods trade is the mirror image of regional balances in primary-energy and permits trade. This is because, trade balance changes induced by climate policy measures have to be fully compensated over the entire time horizon due to the effect of the intertemporal budget constraint. For example, a decline of net exports of primary energy products or the import of permits from one region must be compensated for by increased net exports of the composite good from that same region on a present value basis.

Trade on the coal market shows the biggest reduction. Trade-flow differences between the *400ppm* and the *baseline* scenario are initially quite large but decline over time when CCS technologies enter the market and intensify more use and trade of coal. Reductions in coal trade are at the expense of Russia,

8. Domestic production results as sum of own consumption and exports. Domestic consumption results as sum of own consumption and imports.

Figure 14. Cumulated Trade Differences Between 400ppm Scenario and Baseline Scenario



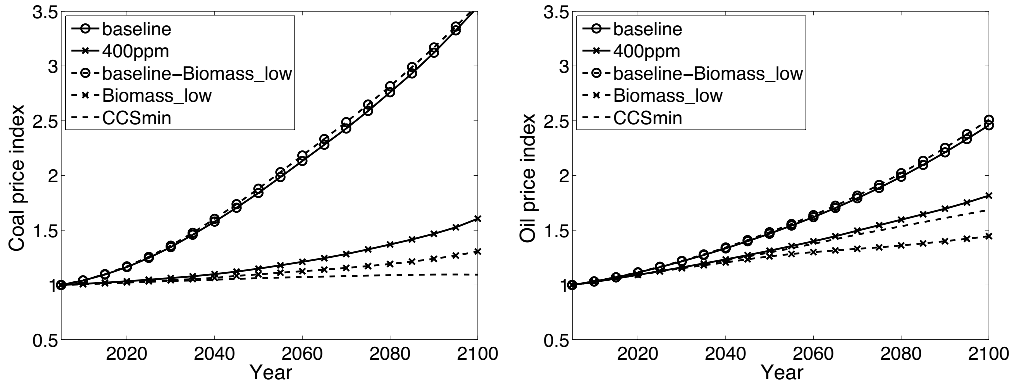
(a) Goods [trill.$US] (b) Coal [EJ]

(c) Oil [EJ] (d) Natural gas [EJ]

ROW, and in part the USA. MEA is also strongly affected through the oil market. The loss of oil-export revenues, due to the climate-policy-induced reductions in both the export volume and price of crude oil, explain part of the high mitigation costs for MEA. Figure 15 shows the price path estimated in the *400ppm* scenario falling increasingly below that in the *baseline* scenario for both coal and oil as the century progresses.

As revenues from coal and gas exports drop remarkably, why does Russia not suffer in the same way as MEA? First, long-term losses on the gas market are compensated for by short-term gains of higher present values. But more importantly, Russia can compensate for losses on the resource markets by generating additional incomes on the permit market (see Figure 12). Notably, Russia exports even more permits than it receives by allocation to the extent that tradable permits can be generated from negative emissions linked to biomass. While this results in the globally most efficient mitigation policy, Russia benefits more than other regions as it is endowed with the largest biomass potential. On

Figure 15. Development of Relative Coal and Oil Prices



(a) Coal (b) Oil

a somewhat lower level the same line of argumentation also applies to Latin America (LAM)[9].

Surprisingly, Russia can get to negative mitigation costs even if the biomass potential is reduced. Such an outcome indicates the complex linkages between the potential for using advanced energy technologies and changes in international markets. In the *Biomass_low* scenario, Russia cannot of course use as much biomass as in the *400ppm* scenario, and hence fewer permits can be sold. However, the increase in the permit price more than compensates this quantity reduction. By 2050, the permit price rises to $US 120 per tCO_2 in the *400ppm* scenario and up to $US 550 per tCO_2 in the *Biomass_low* scenario.

In the latter, regional mitigation costs differ greatly. In addition to Russia, LAM and Africa face high negative costs. In all other regions, except ROW, mitigation costs increase substantially compared with the *400ppm* scenario. The *Biomass_low* scenario does not only affect the permit market but also the resource markets. With the lower biomass potential, and therefore lower potential for emissions reduction, less fossil resources can be employed and fuels consumed. The decrease in demand accelerates the decline of exports and imports in fossil resources, and their terms of trade with the composite good fall (see Figure 15). These price and quantity effects provide a compelling picture of the interlinked impacts on mitigation costs of technology options and trade.

Within the *CCSmin* scenario oil prices are somewhat higher than in the *Biomass_low* scenario, but coal prices decline even further (see Figure 15). Overall, the impact of the *CCSmin* scenario is in the same direction as that of the *Biomass_low* scenario but more moderate. The advanced industrial regions, USA, Europe and Japan, are most adversely affected by the assumption of lower CCS potential.

9. In the study of Bauer *et al.* (2009), which introduces electricity trade in climate mitigation scenarios, it is shown how MEA could benefit from solar power generation.

Furthermore, substantial shares of coal that are used with CCS technologies are imported. Consequently, the importance of this technological option depends to a high degree on the assumption of flexible trade in coal. With the inclusion of trade costs and trade barriers the option values of the scenario *CCSmin* and other scenarios that involve high shares of coal-based CCS like *Nucout* and *Nucout_nolearn* (cf. Figure 10b, previous section) decline even further.

6. CONCLUSIONS

This study analyzes how the costs of very low stabilization scenarios depend both on the availability of technology options and on international trade. On account of the detailed specification of energy technologies in REMIND-R, this hybrid model is well-equipped to support the investigation of alternative technology scenarios. One key result is that having a large and diverse portfolio of technologies available for use to varying degrees is efficient for minimizing mitigation costs and also as a technology-development strategy. Although the option values of single technologies differ significantly in a given simulation environment, that environment can change. In the scenarios here considered, nuclear technologies can be replaced at very low costs, giving them a low option value. CCS technologies and renewable technologies are more important. For a scenario that requires negative emissions to reach the 400ppm CO_2eq concentrations goal by 2150, biomass technologies in conjunction with CCS are essential. If all technology options are available, the climate target of stabilizing the atmospheric GHG concentration at around 400ppm CO_2eq can be achieved by costs of around 0.97% of world baseline consumption. Mitigation costs are much higher if the annual biomass potential is constrained to values of 100 EJ or less.

REMIND-R considers the interdependence of investment and international trade decisions, of technological development, and the choice of technology options. Incorporating these linkages clearly improves the quality of mitigation cost estimates. Global and regional variation of mitigation costs may be due to gains and losses from emissions trading, demand and supply changes on the energy resource market, and the resulting terms-of-trade effects. While the current account structure differs little between the business-as-usual baseline and the climate policy scenario, climate policies as well as technology scenarios can change the patterns of energy trade substantially. The pattern of changes in composite good trade is the mirror image of the changes on the carbon and resource market. In the policy scenario relative to baseline, trade quantities and the prices of fossil resources decrease. Regions like the Middle East with high export shares in trade of fossil resources lose revenues and hence bear the highest mitigation costs.

In the discussed policy scenario, characterized by the need to achieve negative emissions, biomass technologies that can be combined with CCS are most attractive. This attractiveness is enhanced by allowing regions to generate additional tradable permits by negative emissions. Regions such as Russia with a high share of global biomass resources can significantly benefit from this. Due to terms-of-trade effects, in particular an increase of the international carbon price, this holds even under the assumption that only a low amount of available biomass can be transformed into energy. The interplay between biomass technologies and carbon trading highlights the interaction of technological developments and trade effects in mitigation costs assessments. Future research priorities may be to expand the scope of the interactions represented in the model by allowing for trade in secondary energy, especially electricity, by further broadening the technology portfolio (use of electricity in the transport sector), and by taking trade barriers into account.

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Chapter 4

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

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

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Abstract

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.

Keywords: climate policy, welfare redistribution, energy-economy-environment model

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 has to our knowledge 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 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 Figure 1; a mismatch of their regional demand and s upply induces trade flows. Renewable energy carriers (wind, solar, hydro and geo thermal energy) and biomass are limited by region-specific potential constraints and c annot be traded.

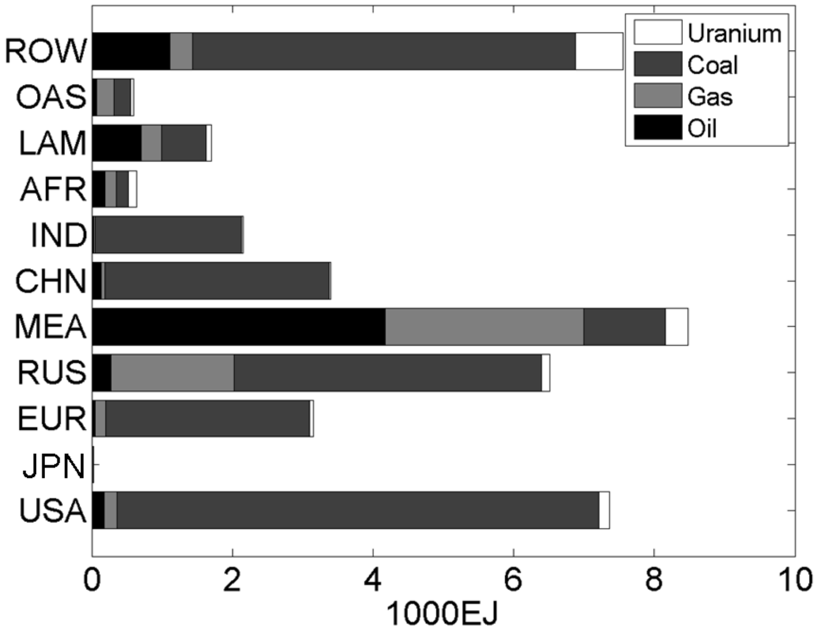


Figure 1: Reserve endowments of exhaustible primary energy carriers, based on Enerdata. Most recent data is available on http://www.enerdata.fr/enerdatauk/index.html.

Various low-carbon technologies are available in REMIND-R: renewable energy, thermal nuclear reactor and fossil- or biomass-based technologies with Carbon Capture and S torage (CCS).[4] Together with the options to increase energy efficiency or to decelerate economic growth, these technologies allow for a f lexible 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 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 equations (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), Böhringer and Rutherford (2000) and Harrison et al. (2000), are not appropriate for the analysis of mitigation costs in an intertemporal perspective.

We use the macroeconomic budget, Equation (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, Equation (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:

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

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, $\sum_i \Delta X_{E,i}$, 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.

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 $GtCO_2$ or 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 Figure 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 400ppm 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 $/t$CO_2$ to 920 $/t$CO_2$ in 2100 in the *allTech* scenario. Restrictions on low-carbon technologies cause higher prices, starting at 6 $/ t$CO_2$ (*nucfx*), 8 $/t$CO_2$ (*renewfx*) and 11 $/t$CO_2$ (*ccsoff*) in 2005.[10]

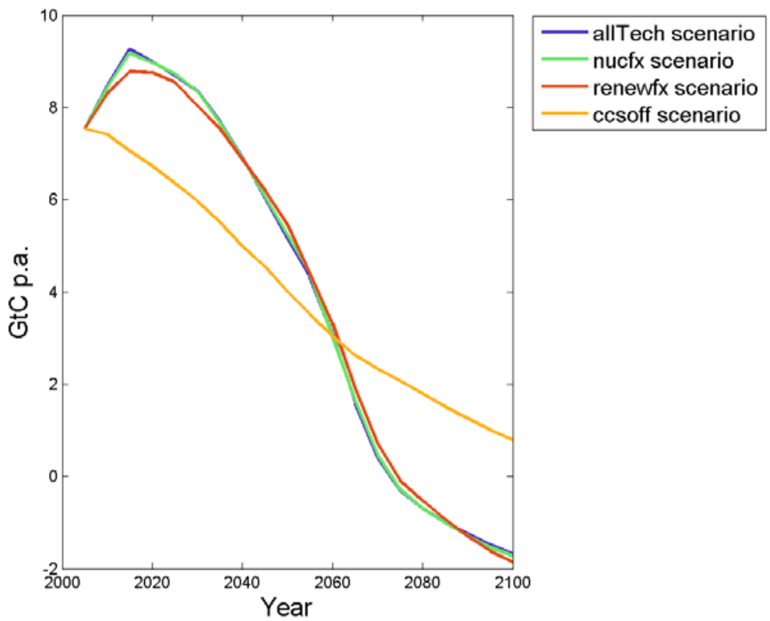


Figure 2: Global energy-related emissions of CO_2 in 2005-2100 in GtC per year.

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 by 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 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 Figure 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.

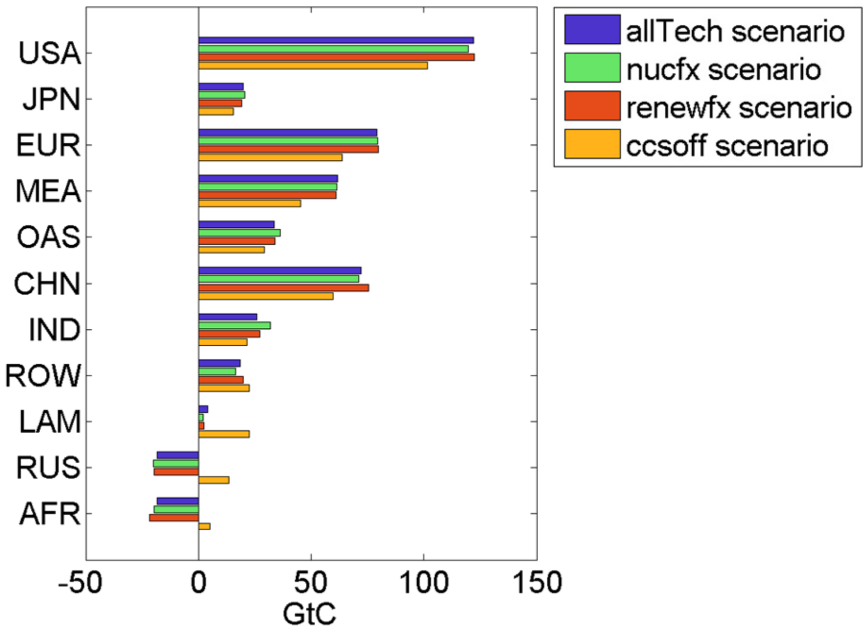


Figure 3: Cumulative regional emissions of CO_2 from the energy system in the period 2005-2100 for the technology scenarios in GtC.

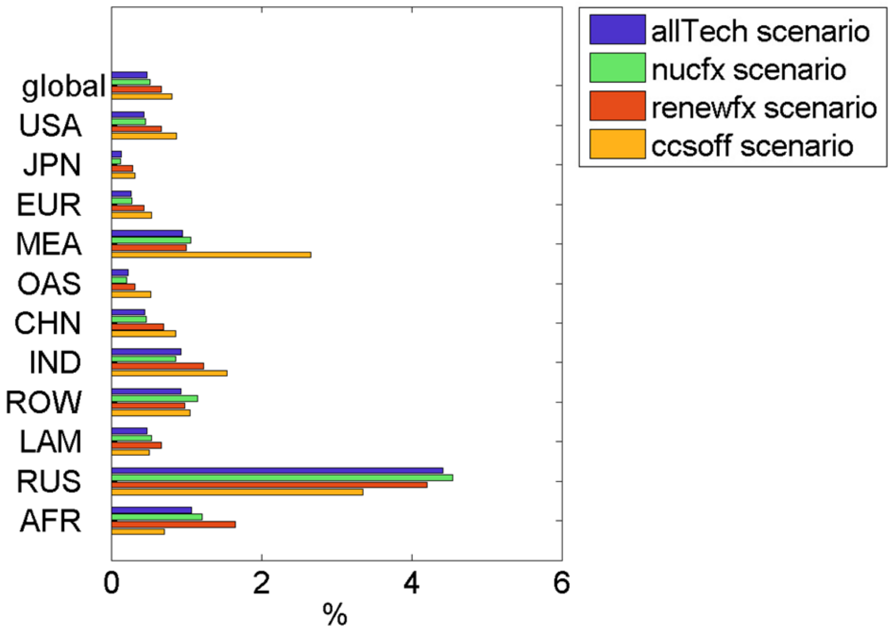


Figure 4: Global and regional consumption losses for the technology scenarios in the reference permit allocation, in % of the GDP in the *business as usual* scenario.

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 Figure 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 l ow-carbon technologies apply, 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).

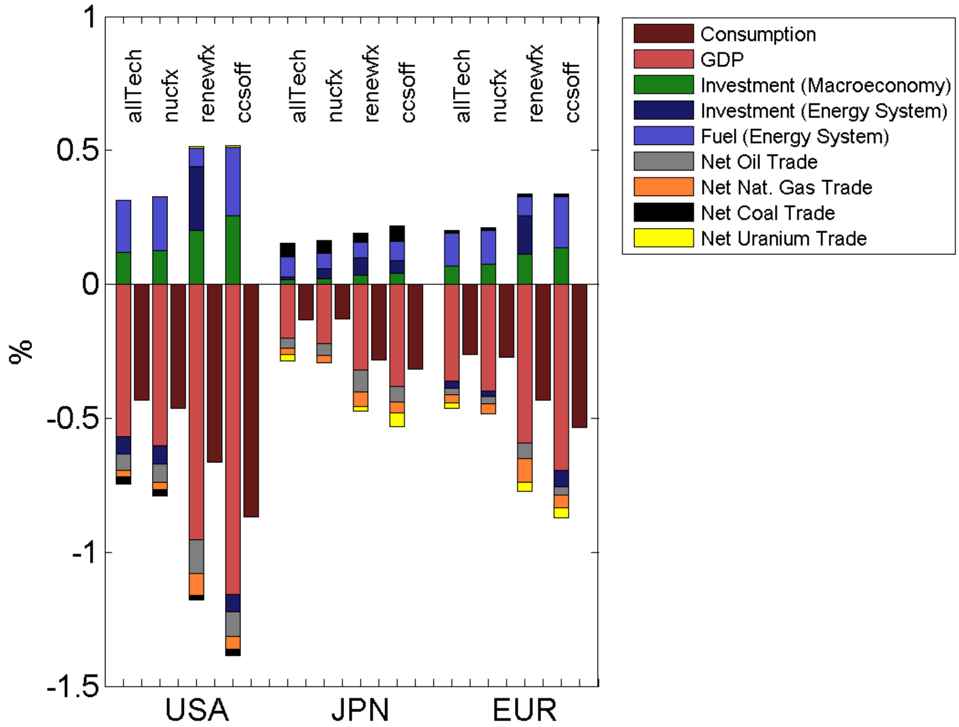


Figure 5: Decomposition of cumulative consumption losses for resource-importing industrialized regions (USA, JPN and EUR) in % of GDP. For each region and technology scenario, the brown bar shows the consumption loss, and the stacked bar left to it shows the components.

Next, we focus on s pecific results for three groups of regions, starting with resource-importing industrialized regions (USA, JPN, EUR), see Figure 5. This group can be c haracterized 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.

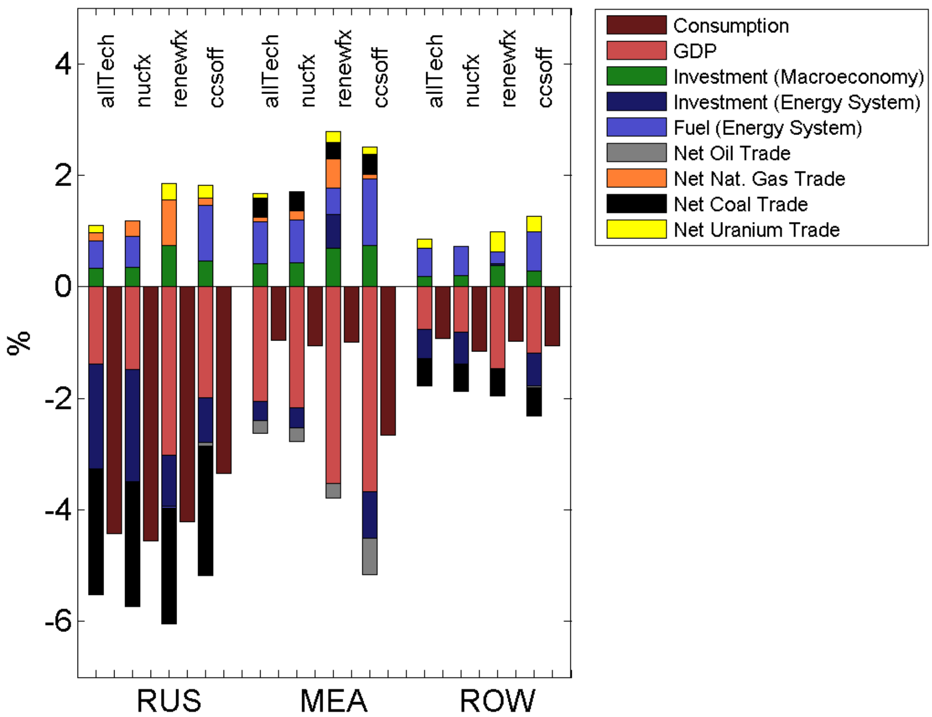


Figure 6: Decomposition of cumulative consumption losses for the major fossil fuel exporting regions (RUS, MEA and ROW) in % of GDP. For each region and technology scenario, the brown bar shows the consumption loss, and the stacked bar left to it shows the components.

The energy trade effect is more relevant for major fossil fuel exporting regions (RUS, MEA, ROW), see Figure 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.

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]

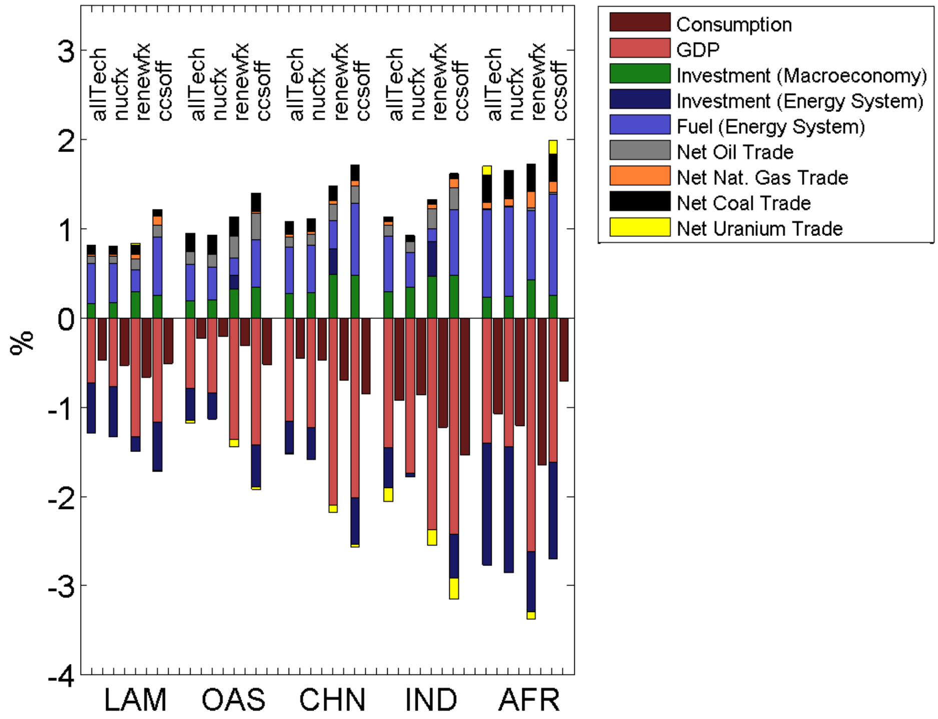


Figure 7: Decomposition of cumulative consumption losses for developing and emerging economies (LAM, OAS, CHN, IND and AFR) in % of GDP. For each region and technology scenario, the brown bar shows the consumption loss, and the stacked bar left to it shows the components.

Finally, we discuss specific results for emerging and developing economies LAM, OAS, CHN, IND and AFR (see Figure 7). Consumption losses of emerging and transition economies are mainly determined by domestic effects. Regarding energy trade components, all regions profit from reduced coal import costs under climate policy, AFR also benefits from extra natural gas and u ranium 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.

5.3. Permit Trade Effects on Regional Consumption Losses

Profits on t he 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.

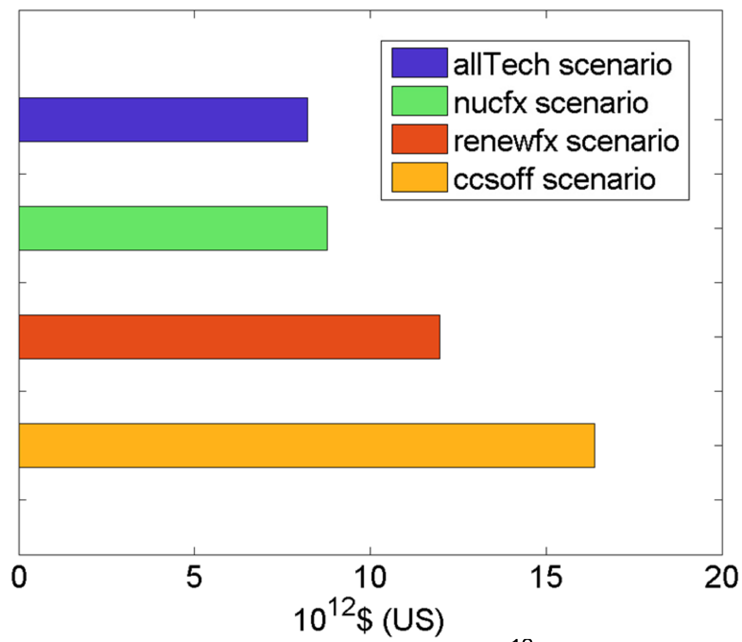
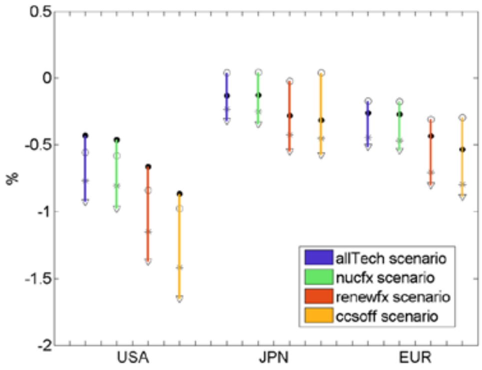


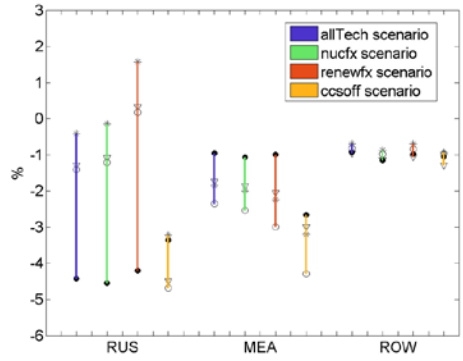
Figure 8: Global discounted value of permits in 10^{12}\$ (US).

Figure 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.

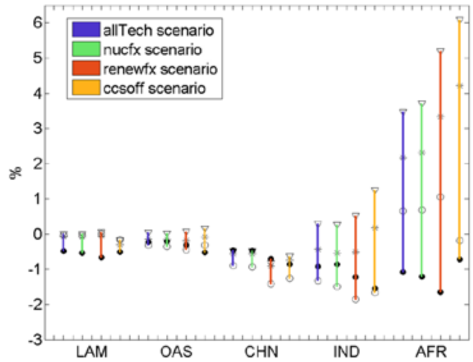
If CCS is not available, the value doubles from $8.2 \cdot 10^{12}$\$ (US) to $16.4 \cdot 10^{12}$\$ (US). The initial permit allocation scheme determines the direction and size of permit trade flows and hence the regional shares of the discounted permit value. Resulting permit trade profits add to the domestic and energy trade components.



(a) resource-importing industrialized regions



(b) major fossil fuel exporting regions



(c) developing and emerging economies

Figure 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.

Figure 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 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 multiregional 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 fuelled 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 2010). 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.

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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

Equation (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 Equation (5)):

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

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:

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

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

$$\overline{Y}^{POL}(r)+\gamma(r)\sum_{i}\overline{X}_{E,i}^{POL}(r)+\gamma(r)\overline{X}_{p}^{POL}(r)$$

$$=\overline{C}^{POL}(r)+\overline{I}^{POL}(r)+\overline{G}_{fuel}^{POL}(r)+\overline{G}_{inv}^{POL}(r)\quad\forall r \qquad (7)$$

In Equation 7, we introduce a region-specific factor γ(r), defined as:

$$\gamma(r)=\frac{\sum_{t}p_{G}^{BAU}X_{G}^{POL}}{\sum_{t}p_{G}^{POL}X_{G}^{POL}} \qquad (8)$$

The factor γ(r) revalues trade revenues in the policy scenario with respect to present value prices of the *BAU* scenario. (Please note that γ(r) is not defined if $\sum_{t}p_{G}^{POL}X_{G}^{POL}$ equals zero.)

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

$$\Delta C(r)=$$

$$\Delta Y(r)-\Delta I(r)-G_{inv}(r)-G_{fuel}(r)+\gamma(r)\left(\sum_{i}\overline{X}_{E,i}^{POL}(r)-\sum_{i}\overline{X}_{E,i}^{BAU}(r)+\overline{X}_{p}^{POL}(r)\right)\forall r$$

(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 $\Delta X_{E,i}(r) = \gamma(r)\left(\bar{X}_{E,i}^{POL}(r) - \bar{X}_{E,i}^{BAU}(r)\right)$ and $\Delta X_p(r) = \gamma(r)\bar{X}_p^{POL}(r)$, this leads to Equation (3) in Section 3.

The choice of an initial permit allocation scheme has two implications for the components in Equation (9): First, permit trade revenues are covered in $\bar{X}_p^{POL}(r)$. 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 $\bar{X}_{E,i}(r)$ are constant if the initial allocation changes. Second, a modified initial permit allocation affects good t rade revenues according to Equation (1), so that values of γ(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 s mall effect compared to redistributions from permit trade.

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[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 'dom estic 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).

[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).

[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 2005 to 2150 with an additional carbon budget of 10 GtC for the period 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).

[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).

[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

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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.

Chapter 5

The Impact of Trade Costs on Fossil Energy Carrier Trade and Implications for Mitigation Costs*

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Fossil Energy Trade and Regional Mitigation Costs: The Effect of Trade Costs

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Abstract

This paper analyzes the impact of the costs for international fossil energy trade on regional mitigation costs. Profits and costs on global markets for fossil energy carriers have a significant influence on regional mitigation costs. Hence, the assessment of model scenarios on regional mitigation costs requires an appropriate representation of fossil energy trade flows. The multi-regional energy-economy model REMIND-R is applied in this study. It allows for the assessment of mitigation strategies in a long-term perspective but overestimates trade flows of fossil energy carriers significantly unless the associated trade costs are considered. The impact on global mitigation costs is modest, because trade costs have a similar effect on modeled trade volumes in scenarios with and without climate policy constraint. However, the mitigation costs of major coal exporters are considerably lower once trade costs are accounted for. This can be explained by the result that coal export profits are reduced more strongly by trade costs in scenarios without climate policy constraint.

Keywords: Climate policy, International trade, Trade costs, Energy-economy-environment model
JEL: F18, Q32, Q52, Q56

1. Introduction

Climate change mitigation is a global challenge, but the costs of mitigation will diverge significantly among world regions [10, 12]. Restricting anthropogenic emissions enforces structural changes in the global economy. The consequential redirections of international trade flows have been identified as a potential driver on regional mitigation costs [4, 22]. As climate policy leads to strong reductions in the demand for carbon-intense energy carriers, trade in primary fossil energy carriers is of particluar interest [15, 22].

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Empirical evidence suggests that trade costs can contribute substantially to prices and hence have important economic implications on trade flows in fossil energy carriers [1]. In this paper, the costs of fossil energy carrier trade are introduced in the multi-regional hybrid model REMIND-R, thereby enhancing the representation of trade flows in order to determine the contributions of primary energy trade to regional climate mitigation costs.

Investigating model scenarios over a long time horizon is inevitable for understanding regional mitigation costs. In the following, the adequacy of different model approaches for assessing the contribution of primary energy trade to regional mitigation costs is discussed.

Interlinkages between the international transfer of energy carriers and technologic developments have recently been analyzed in multi-regional Energy System Models [9, 36, 37]. As the model structures do not account for income and expenditure in exchange to energetic transfer, the impacts on regional mitigation costs remain unclear.

By contrast, Partial Equilibrium Models cover the economic mechanics of trade as an exchange of ownership for a part of the economy and allow for calibration in accordance with empirical data for a given benchmark year. Models with distinct focus on a particular fossil energy carrier are applied to reveal the current market structure for fossil energy and prospects about some decades in the future [13, 16]. A sufficient description of long-term structural dynamics (and changes in this dynamics under mitigation policy) is not in the scope of Partial Equilibrium Models. General Equilibrium Models comprise the complete economy, allowing for a study of fossil energy trade embedded in national payment balances, but are not intended to cover long-term dynamics [3, 7].

Coupled multi-regional energy-economy hybrid models with an intertemporal growth approach describe the long-term intertemporal dynamics of regional energy systems, macroeconomies and international trade flows in simultaneous equilibrium of all markets. Compared to the other model approaches, they provide an adequate framework to analyze the comprehensive long-term dynamics within the energy system and the macroeconomy. Building on earlier applications of multi-regional growth models [30, 31], recent studies have applied models that incorporate detailled energy system modules as well as representations of global trade in fossil energy carriers in a stylized way [8, 22]. The model REMIND-R [22, 23] belongs to the latter class of models.

The representation of fossil energy trade in multi-regional hybrid models remains challenging. In REMIND-R, trade flows are described by control variables without initial conditions. The resulting specialization among trading regions exceeds the observed specialization by far, so that trade flows are strongly overestimated. On the contrary, a preference for a consumption of domestic products is found empirically ('*home bias*'). According to Samuelson [35] and, in a modern dynamic context, Obstfeld and Rogoff [32], explicitely accounting for the costs of international trade leads to a reduction of specialization, so that trade costs provide an explanation for the home bias. This study investigates the effect of trade costs on international trade within REMIND-R.

The paper is structured as follows. Section 2 describes the model REMIND-R. Section 3 documents the representation and parametrization of trade cost. Section 4 introduces the definition of model scenarios. The results are presented in Section 5. Finally, Section 6 covers a discussion of the results and proposals for further research.

2. The Model REMIND-R

REMIND-R [22, 23] 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.[1] The hard-link between the two modules ensures a simultaneous equilibrium of energy and capital markets [2]. The model comprises eleven regions[2] interconnected by trade flows of exhaustible energy carriers (coal, oil, natural gas, uranium), an aggregate macroeconomic good (measured in monetary units) and emission permits. Each region is represented by an individually calibrated macroeconomy and energy system and the objective to maximize intertemporally aggregated welfare.

The reserves of exhaustible energy carriers are unevenly distributed among regions as depicted in Figure 1, with the distribution of oil and natural gas reserves being more uneven than the distribution of coal reserves. As exhaustible primary energy carriers constitute endowments of exporting regions, trade implies an exchange of

[1] On 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. The version we use in this study (REMIND-R1.2) corresponds to the version in [23] except for minor adjustments in calibration.

[2] 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).

ownership in REMIND-R. Fossil extraction is described by an extraction cost curve for each region, so that the timing of cost increase is modeled endogenously. Trade prices include scarcity rents due to anticipation of the increasing extraction costs by the exporters.

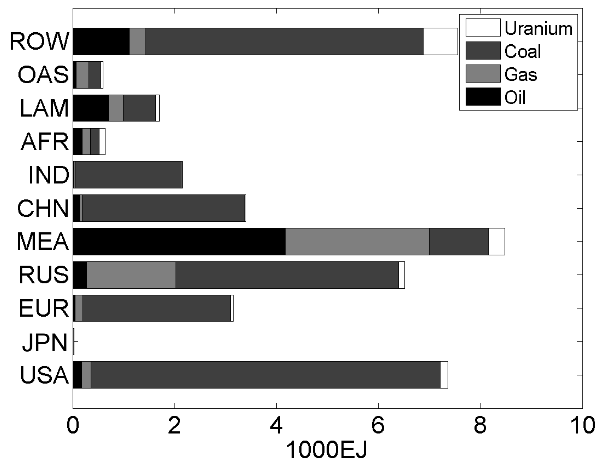


Figure 1: Reserve endowments of exhaustible primary energy carriers, based on Enerdata. Recent data is available on http://www.enerdata.fr/enerdatauk/index.html.

Without the consideration of trade costs, a global market approach is represented by physical trade balances that require an equality of physical exports (X) and imports (M) for each tradable good (i) and time step (t), when trade flows of all world regions (r) are summed up:[3]

$$\sum_r (X(t,r,i) - M(t,r,i)) = 0 \quad \forall\ t,i \tag{1}$$

Globally leveled prices (p) are derived endogenously from shadow prices of the physical trade balance equations. A mismatch of regional domestic demand (D) and

[3]Please note in the following equations the distinction of index i covering all tradable goods (tradable energy carriers, aggregate macroeconomic good, emission permits) and index e covering only tradable energy carriers.

supply (by fossil extraction F) induces exports (X) and imports (M) of tradable energy carriers (e):

$$D(t, r, e) = F(t, r, e) - X(t, r, e) + M(t, r, e) \quad \forall\, t, r, e \tag{2}$$

An equilibrium solution for trade flows is obtained by applying the Negishi-approach [24, 26]. For each region r, monetary equivalents of all trade flows need to be balanced over the whole time horizon:

$$\sum_t \left(\sum_i p(t, i)(X(t, r, i) - M(t, r, i)) \right) = 0 \quad \forall\, r \tag{3}$$

The model calculates a Pareto optimal solution between regions, corresponding to the general market equilibrium in the absence of externalities. The solution for trade-related control variables (M, X) are not restricted by explicite initial conditions that would allow for a calibration of initial trade flows.[4]

3. Representation and Parametrization of Trade Costs

The representation of trade in REMIND-R follows a global market approach: The exchange of fossil energy carriers occurs in a common pool supplied by all exporters and drained by all importers. It is reasonable to keep this framework for the purpose of this study: The price-building mechanism on the oil-market is nearly global [29], coal markets show a tendency for integration [14, 38], and the emerging option to transport natural gas in the form of Liquefied Natural Gas (LNG) implies convergence on the natural gas markets [21].

Trade costs are represented by import costs in the model. This implies an extension of the global market approach. While exporters still supply to the global market free of charge, region-specific costs are assigned to the importers.

Import costs take the form of (i) financial costs and (ii) energetic losses. Financial costs reflect monetary expenditures for energy import, especially investment and operation costs for interregional transport including cargo-handling equipment. The product of specific financial costs and the physical energy import (M) is deduced from the importer's macroeconomic budget. Energetic losses (τ) reduce the imported

[4]Initial conditions on trade flows in the first model time step would have no significant effects on trade flows in later model time steps. Hence, they do not provide a reasonable way to calibrate trade flows in the model.

energy amount, so that only the remaining share is available to satisfy the importer's domestic demand:

$$D(t,r,e) = F(t,r,e) - X(t,r,e) + (1 - \tau(r,e)) \cdot M(t,r,e) \quad \forall\, t,r,e \qquad (4)$$

Prices for fossil energy are derived endogenously from the shadow prices of the balance equations (4). All exporting regions receive an export price that is still globally leveled ('Free on Board'-price), but importers are charged with a higher price per unit of traded energy ('Cost, Insurance and Freight'-price) as the import price reflects the importer's additional expenditures for financial costs and for the compensation of energetic losses.

The data for import costs cover the costs of international physical transportation, differentiated by fossil energy carrier and by importing region. We proceed as follows to estimate cost parameters: In a first step, the costs per unit of energy and per unit of transport distance are adopted from a literature review for each fossil energy carrier (natural gas, oil and coal). In a second step, transport distances and according costs per unit of energy are derived for bilateral relations from all major exporting regions to all importing regions.[5] In a third step, costs per unit of energy are estimated for each importer by a weighted average over all major exporters.

We start with the estimation of import costs per unit of energy and per unit of transport distance. The results and references are documented in Table 1. International natural gas transport is undertaken by pipeline or by LNG tanker [21, 33, 36]. Energetic losses are mainly due to own consumption of pressurization (pipelines) and liquefaction (LNG) [13, 36].[6] Oil and coal transport by tanker is the preferable transport option on inter-regional distances, as the respective alternative transport modes (oil transport by pipeline and coal transport by rail) are more suitable on short

[5] The consideration of cost parameters for bilateral trade relations as an intermediate step does not contradict our extended global market approach.

[6] For LNG transport, [33, 34] report ca. 1.50 \$/GJ of distance-independent financial costs, but do not report a distance-dependent component and energetic losses, so we use a value of 1.00 \$/GJ independent of distance. The monetary aggregate of costs and losses in our numbers coincides with the distance-independent costs of 1.50 \$/GJ reported by [33, 34].

energy carrier and mode of transport	financial costs per 1000 km [$/GJ]	financial costs independent of distance [$/GJ]	energetic losses per 1000 km [%]	energetic losses independent of distance [%]
nat. gas pipeline	0.4 [21, 33, 36]		2 [13, 36]	
nat. gas LNG tanker	0.08 [33, 34, 36]	1.0 [33, 34]	0.2 [18, 36]	12 [13, 18]
oil tanker	0.023 [11, 34]			
coal tanker	0.014 [16]	0.399 [16]		

Table 1: Financial costs and energetic losses for the import of fossil energy carriers. Estimates are based on [11, 13, 16, 18, 21, 33, 34, 36] as described in the text.

distances [34]. Energetic losses can be neglected for oil and coal shipping [11, 34].[7]

Next, import costs for bilateral trade relations are derived. For each importing region, the transport distances from all major exporting regions are estimated as the distance between representative major ports of the respective regions.[8] For each pair of importer and exporter, the total financial costs and energetic losses per unit of energy are then calculated as the product of distance and distance-dependent parameters, plus the distance-independent parameters.

We assume that gas transport occurs by LNG, except for pipeline transport from MEA to IND and from RUS to CHN and EUR which is the cheaper alternative on the respective distances. MEA, AFR and ROW are currently exporters of natural gas but become importers in some scenarios in the long run, so that cost parameters are defined for these regions also.

Finally, import costs for each importing region are obtained. Assuming that major exporters contribute to the global trade volume in proportion to their reserve shares (see Figure 1), the costs for each importing region are obtained by averaging

[7] For oil tanker, [36] reports lower distance-dependent costs but includes a number for distance-independent costs. For typical transportation distances of about 5000 km, their numbers correspond with our estimate.

[8] Distances are obtained from the webpage http://www.distances.com/.

REGION	Natural Gas financial costs [$/GJ]	Natural Gas energetic losses [%]	Oil financial costs [$/GJ]	Coal financial costs [$/GJ]
USA	1.8017	14.0	0.2012	0.5653
JPN	1.6850	13.7	0.2457	0.4956
EUR	1.3630	10.5	0.1491	0.5038
RUS	0	0	0	0
MEA	1.7535	13.9	0	0.5293
LAM	2.0069	14.5	0.2757	0.5191
OAS	1.5568	13.4	0.1668	0.5385
CHN	1.4902	10.6	0.2298	0.5055
IND	1.2522	8.1	0.0989	0.5486
AFR	1.5119	13.3	0.1276	0.5013
ROW	1.7996	14.0	0	0

Table 2: Region-specific parameters for the transport costs associated with fossil energy import in the revised scenario. Numbers are derived from [11, 13, 16, 18, 21, 33, 34, 36] as described in the text.

the parameters derived for pairs of importer and exporter over major exporting regions, weighted according to their reserve share (see Table 2).[9] All resulting import cost parameters are kept constant over the model time horizon.

4. Scenarios

The impact of trade costs is analysed by a comparison of two scenarios: In the default scenario, the trade of all fossil energy carriers is considered as free of costs and energetic losses. In the revised scenario, specific trade costs as defined in Section 3 are applied. The sensitivity of results is studied in additional scenarios with scaling factors on the specific trade costs parameters.

The trade costs studied in this paper cover costs for inter-regional energy trade, but not barriers to trade within exporting regions. Although initial costs of fossil extraction show significant differences among regions, empirical 'Free on Board' market prices tend to level out globally. Regions with low extraction costs often tend

[9] Reserve shares are 66% (MEA) and 34% (RUS) for natural gas, 76% (MEA), 6% (RUS) and 18% (ROW) for oil, and 41% (USA), 33% (ROW) and 26% (RUS) for coal. For natural gas imports to MEA, RUS is assumed as the origin.

to supply at a price that includes a markup due to market power or lack of export infrastructure. The present study does not represent these types of market distortions, but focuses on the impact of international trade costs. It is hence reasonable to assume the same initial extraction costs in all regions.

The level of initial extraction *costs* is chosen such that global weighted averages of resulting initial fuel *prices* in the revised scenario are in line with global prices obtained in the default scenario as well as with empirical prices. As markups from market power or infrastructure limits are not explicitly accounted for in the model, initial extraction costs parameters are higher than respective empirical data. Initial extraction costs are set to 8.0 $/GJ (oil), 3.5 $/GJ (natural gas) and 1.4 $/GJ (coal) in all scenarios.

For both the default and revised scenario, two model experiments are performed: The *business as usual* case represents the absence of a climate policy, the *climate policy* case assumes a limited budget for CO_2 emissions from the energy sector that restricts cumulated emissions in the period 2005-2100 to 400 GtC. The timing of emission reductions is not regulated. A cap and trade-system with tradable emission permits is assumed, so that reductions employ full when- and where-flexibility. Emission permits are initially allocated according to a 'contraction and convergence' scheme.[10] 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 trade in the aggregate good.

The use of a carbon budget is inspired by Meinshausen et al. [27], who find that cumulated 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 392 GtC [27]. 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 energy-related emissions in 2050-2100 is added.

[10] 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. See Meyer [28].

5. Results

The results are presented in the following steps: First, regional mitigation costs are analyzed. The decomposition of mitigation costs reveals the contributions from fossil energy carrier trade to consumption losses and the influence of trade costs on the contributions (Section 5.1). Second, the impact of trade costs on trade flows of fossil energy carriers is assessed (Section 5.2). Third, the consequences of modified trade patterns on the global and regional demand for fossil energy carriers is considered (Section 5.3). We focus on the main importers (USA, EUR, JPN, CHN) and exporters (MEA, ROW, RUS) of fossil fuels.

5.1. Trade effects on regional mitigation costs

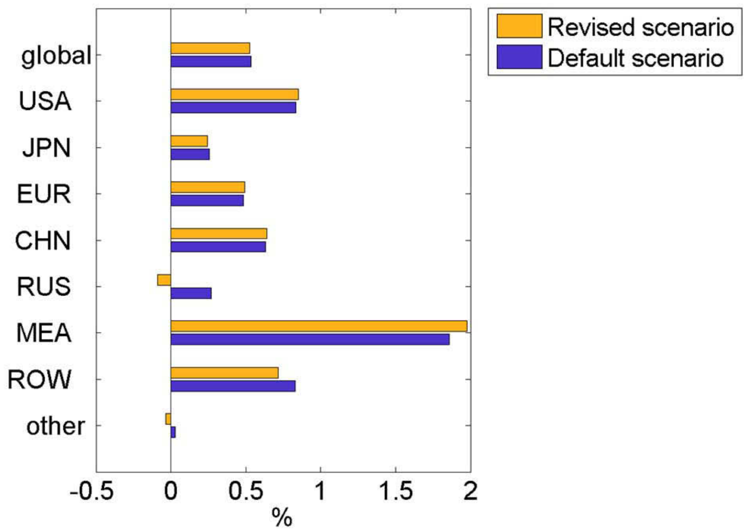


Figure 2: Global and regional mitigation costs in the default scenario (with trade costs) and the revised scenario (without trade costs)

Mitigation costs are measured as the intertemporally aggregated consumption differences between a business as usual experiment and a policy experiment. The endogenous interest rate is used for discounting. Global mitigation costs remain almost unchanged between default and revised scenario. However, the regional mitigation costs of RUS and ROW are clearly smaller in the revised scenario, whereas

MEA faces higher costs (see Figure 2). Hence, the impact of trade costs is merely a redistributional one; the three regions most affected (RUS, ROW, MEA) are the main exporters of fossil energy carriers.

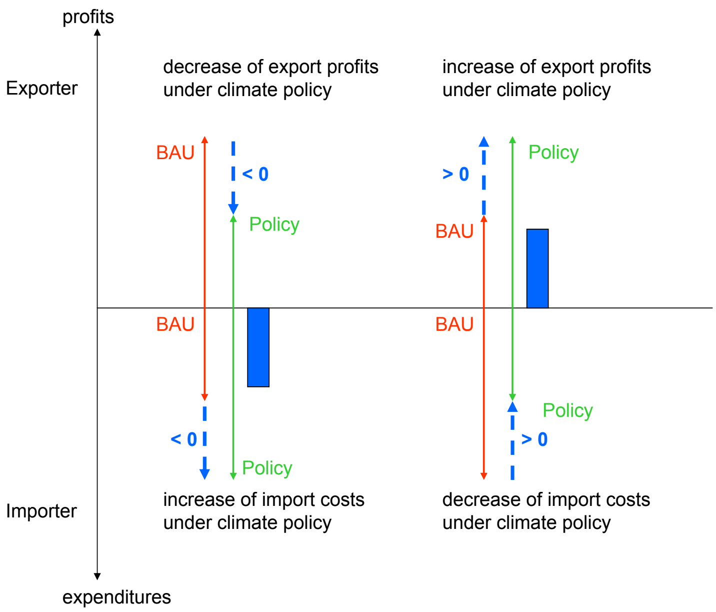


Figure 3: Schematic representation how trade effects can contribute to regional mitigation costs. Arrows represent trade profits and expenditures in the business as usual (red) and policy scenario (green) and their difference (blue). Bars represent the resulting contribution to mitigation costs. Top: From the perspective of the exporter, a decrease of export profits leads to consumption loss (left), but an increase of export profits leads to consumption increase (right). Bottom: From the perspective of the importer, an increase of import expenditures leads to consumption loss (left), but a decrease of import expenditures leads to consumption increase (right).

A decomposition of mitigation costs allows to express regional mitigation costs as the sum of monetary contributions from different effects. We apply the decomposition method by Lüken et al. [25].[11] It allows to distinguish the following effects:

[11] A formal description of the decomposition method is available on request. Decomposition methods are frequently used for the analysis of results generated by Computable General Equilibrium

- A *Domestic* component covers reactions to climate policy that occur within a region: GDP losses, a redirection of investments into capital-intense low-carbon technologies and reduced costs for fuel extraction for domestic use.[12]
- Net Trade effects: Regional expenditures and profits on international trade markets are affected by climate policy. Net trade effects comprise changed export profits (excess of revenues over extraction costs) or import expenditures due to climate policy (see Figure 3). The components of *Net Natural Gas Trade* and *Net Coal Trade* are of particular interest for the analysis of trade costs. The *Other Trade* component covers trade in oil, uranium, and emission permits.

The results are displayed in Figure 4 and Figure 5. For each region, the decomposition of consumption losses is shown for the default scenario and the revised scenario. The difference allows to understand the effects of trade costs on the consumption losses induced by climate policy.

The decomposition reveals a significant contribution of the coal and natural gas trade components to the consumption losses of major exporters of fossil fuels (RUS, ROW, MEA). For the consumption losses of major importers (USA, JPN, EUR, CHN), coal and natural gas trade are less relevant.

In the following, the coal trade component is analyzed in detail. Climate policy leads to a massive decrease in the global demand for coal, implying a devaluation of regional endowments with coal. Hence, the exporters of coal (RUS, ROW, but also USA) face reduced coal export profits under climate policy. In the revised scenario, the decrease of coal export profits is lowered, which partially explains the smaller consumption losses in these regions. In turn, a decline of coal demand and import expenditures under climate policy constitutes a positive contribution to consumption losses for importers of coal (MEA, but also JPN and CHN). In the revised scenario, the decline of coal import expenditures is lowered, so that the saving is reduced.

The reduction of profits for coal exports in the revised scenario requires further explanation. The price markup for coal exports, defined as the excess of the present

models, but existing methods serve different purposes and are not appropriate for the analysis of mitigation costs in a long-term perspective [5, 6, 17].

[12]Please note that our definition is different than the common use of the term in studies working with Computable General Equilibrium models. 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.

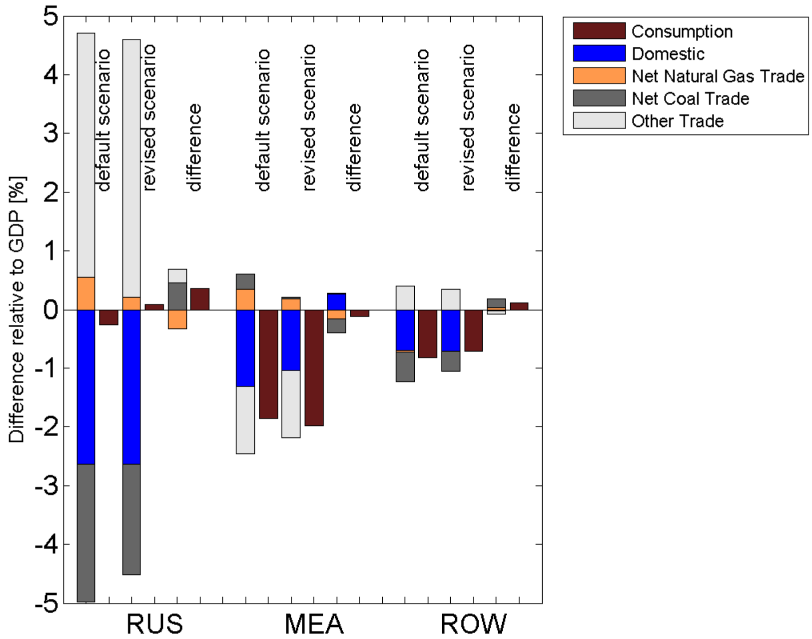


Figure 4: Decomposition of Mitigation Costs for major exporters of fossil fuels into trade-related and domestic contributions in the default scenario (with trade costs) and the revised scenario (without trade costs). For each region and scenario, the brown bar shows the consumption loss, and the stacked bar left of it shows the components.

value price[13] received by the exporter over the associated extraction costs, reflects the anticipation of scarcity (see Figure 6(a)).[14] Under climate policy, the decrease of global demand for coal over the whole time horizon leads to a smaller price markup in both the default and the revised scenario. A higher share of the global demand is supplied by domestic sources of importers in the revised scenario, so that the price markup becomes smaller, but this effect is stronger in the business as usual experiment.

[13]Present value prices account for the endogenous discounting of future prices.
[14]Figure 6 as well as the subsequent figures focus on the period 2005-2050 for reasons of clarity.

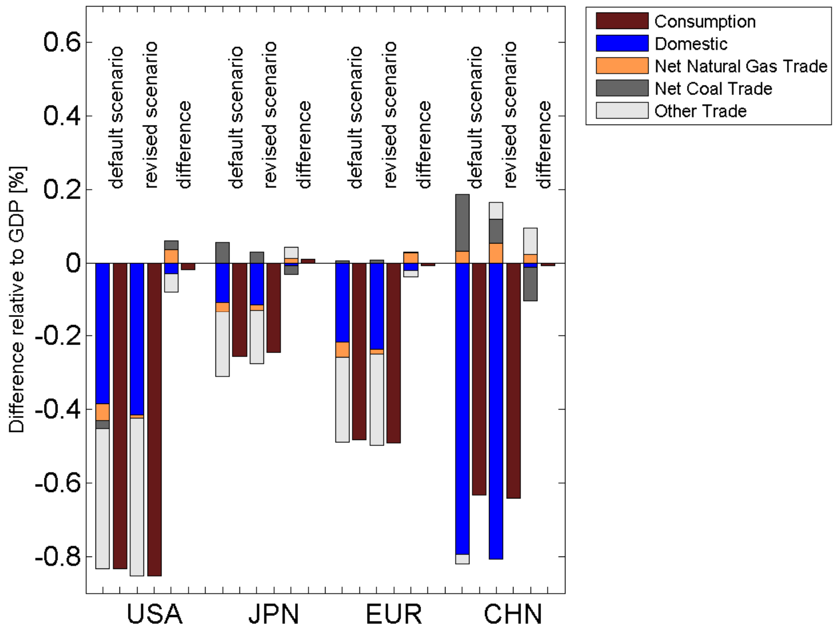
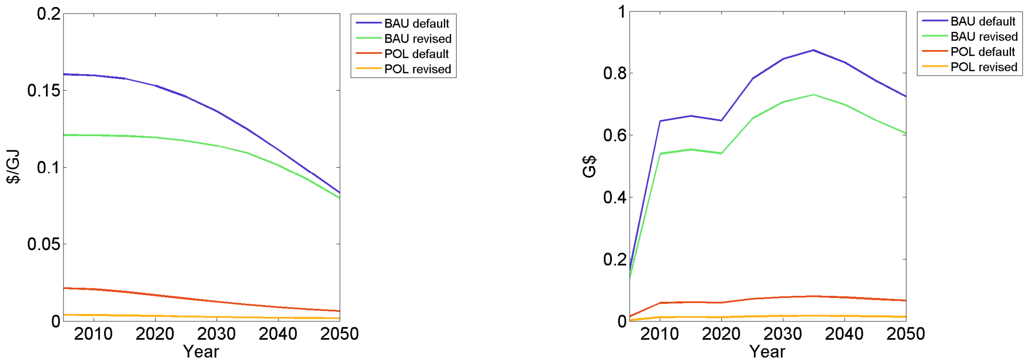


Figure 5: Decomposition of Mitigation Costs for industrialized regions and China into trade-related and domestic contributions in the default scenario (with trade costs) and the revised scenario (without trade costs). For each region and scenario, the brown bar shows the consumption loss, and the stacked bar left of it shows the components.

Hence, climate policy induces a smaller reduction of the price markup in the revised scenario. In consequence, the coal export rent, calculated as the product of price markup and export volume, is reduced under climate policy, but to a smaller extent in the revised scenario (see Figure 6(b) for RUS).

Now we turn to the natural gas trade effects. Compared to coal, opposite effects can be observed for natural gas trade. Substitution of coal by natural gas provides a transitionary option for emission reductions due to lower specific emissions of natural gas. An increase of global demand for natural gas under climate policy leads to a positive revaluation of natural gas endowments. Higher export profits constitute a



(a) Price markup (b) Rent in RUS

Figure 6: Price markup and rents for coal exports. The price markup is the difference of present value price and extraction costs per unit of energy. Right: Rent in RUS.

positive contribution to consumption losses of exporters of natural gas (RUS, MEA). On the contrary, importers of natural gas (USA, JPN, EUR) face higher import expenditures under climate policy. In the revised scenario, both the higher export profits and the higher import expenditures are lowered.

The demand for oil is not significantly affected by climate policy.[15] Therefore, the oil trade component neither contributes strongly to consumption losses, nor is it significantly modified in the revised scenario.

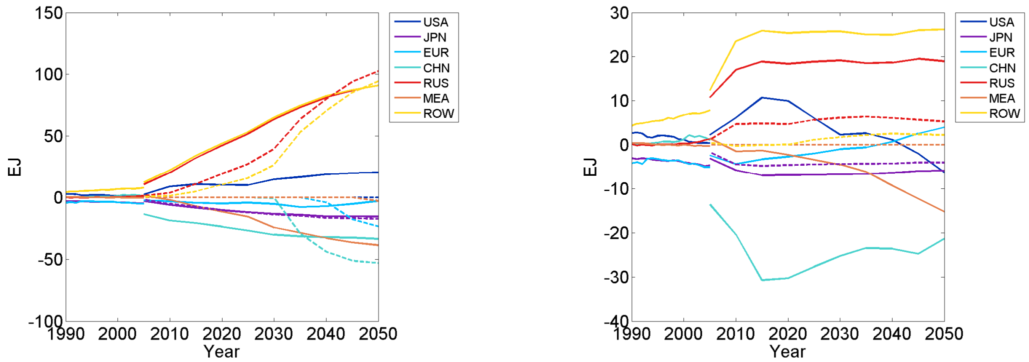
In total, the effect of trade costs on regional consumption losses is most apparent for the major export regions: MEA faces higher losses in the revised scenario due to a lower increase of profits from natural gas exports and due to a lower decline of expenditures for coal imports. RUS and ROW, in turn, benefit from a lower reduction of coal export profits. For RUS, the coal trade effect is larger than the opposite natural gas trade effect. Consumption losses of major importing regions

[15]Substitution of oil by other primary energy carriers is relatively costly in REMIND-R. Furthermore, the availability of Carbon Capture and Storage technologies with biomass feedstock allows for negative emissions that compensate for emissions from a continued oil use in the climate policy experiments.

show less differences among the default and the revised scenario, because energy trade is less important in terms of share of GDP for importers.

5.2. Fossil energy trade flows

Now we turn to the development of trade flows in time and ask how the consideration of trade costs in the revised scenario influences trade compared to the default scenario. We focus to the period 1990 to 2050 to allow for a comparison of model results for the period following 2005 with the empirical data in the preceding period.



(a) Business as usual (b) Climate Policy

Figure 7: Coal trade flows of selected regions. Solid lines 1990-2005: empirical data [19, 20]. Solid lines 2005-2050: model results in the default scenario (no trade costs). Dashed lines 2005-2050: model results in the revised scenario (with trade costs). Regional values <0 represent imports, values >0 exports. Note different scalings of y-axis in the subfigures.

Coal trade is significantly reduced in the revised scenario (see Figure 7). However, major exporters remain exporters over the observed model period in all scenarios. The most prominent exception is USA, which is a prominent coal exporter in the default scenario, but not in the revised scenario. In the year 2005, the consideration of coal trade costs leads to a collapse of the world coal market to 2 EJ, compared to empirical data of 12 EJ.[16] Only JPN, RUS and ROW trade in the model, in contrast to empirical data. Coal reserves in JPN are very limitied, so that importing coal is

[16]The global trade volume exceeds the sum of the regional flows shown in the figure, as the regions IND, OAS, LAM and AFR are omitted in the figure.

still preferable over domestic supply in the revised scenario. On the contrary, other importers prefer their domestic reserves in the revised scenario. In 2005, CHN is an exporter of coal in the empirical data, in spite of its limited reserves, which are currently overexploited. By contrast, CHN is the most important importer in the default scenario, where the overexploitation of domestic reserves does not occur.

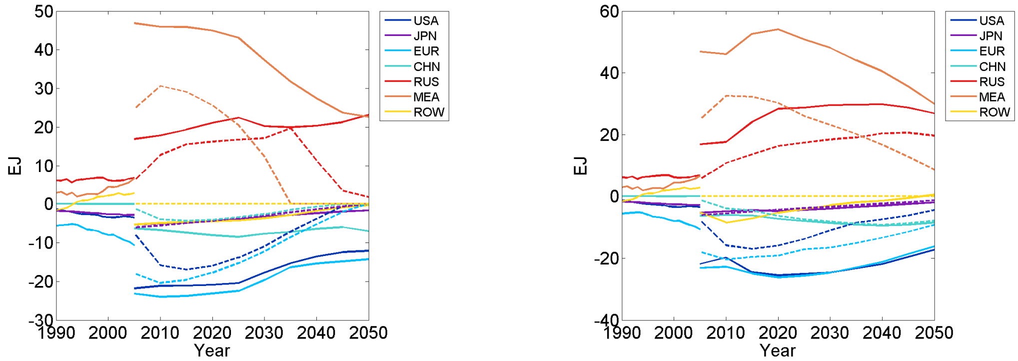
In the business as usual experiment, the coal market returns to current empirical volumes by 2015. Whereas only JPN imports in the beginning, EUR, CHN and MEA start to import coal again later on due to exploitation of their domestic endowments, and exports increase accordingly. The difference between trade flows in the revised and default scenario hence declines by the mid of the century. In 2050, coal trade flows for most regions in the revised scenario even exceed respective values in the default scenario.

Two reasons explain the postponing of global trade volume towards the mid of the century in the revised scenario: First, a reduced demand for coal in the first decades leads to a later increase in extraction costs. Second, natural gas trade is more affected by trade costs than coal in the long term. In consequence, importers prefer coal imports over natural gas imports by the mid of the century.

In the climate policy experiment, trade flows are strongly reduced compared to the business as usual case. In the revised scenario, the trade pattern observed in 2005 with only JPN importing, supplied by exports from RUS and ROW, persist over the whole time horizon.

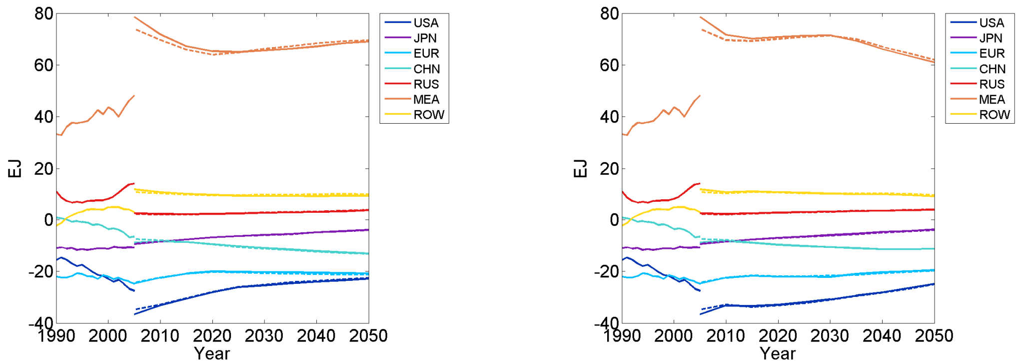
Trade flows of natural gas in the year 2005 are reduced in the revised scenario, thereby lessening the mismatch to empirical data, in particular exports of MEA and RUS and imports of USA and EUR. Real world exporters are generally also exporters in the model. Model results for trade flows of natural gas are strongly reduced over the whole model time horizon by the consideration of trade costs. This holds in both the business as usual and the climate policy experiment (see Figure 8). However, the global trade volume in the first decades exceeds current empirical values by large, indicating the relevance of other limiting factors rather than trade costs for empirical trade flows. By the mid of the century, trade flows return to levels comparable with empirical data. The decrease of trade flows in the revised scenario differs among regions: Exports of MEA are most affected. By contrast, imports to JPN are only slightly reduced because very scarce domestic fuel reserves in JPN do not allow for substitution of imports by exploitation of domestic reserves.

The influence of trade costs on oil trade is modest in the business-as-usual as well as the climate policy case (see Figure 9): The levels of regional exports and imports



(a) Business as usual (b) Climate Policy

Figure 8: Natural gas trade flows of selected regions. Solid lines 1990-2005: empirical data [19, 20]. Solid lines 2005-2050: model results in the default scenario (no trade costs). Dashed lines 2005-2050: model results in the revised scenario (with trade costs). Regional values <0 represent imports, values >0 exports.



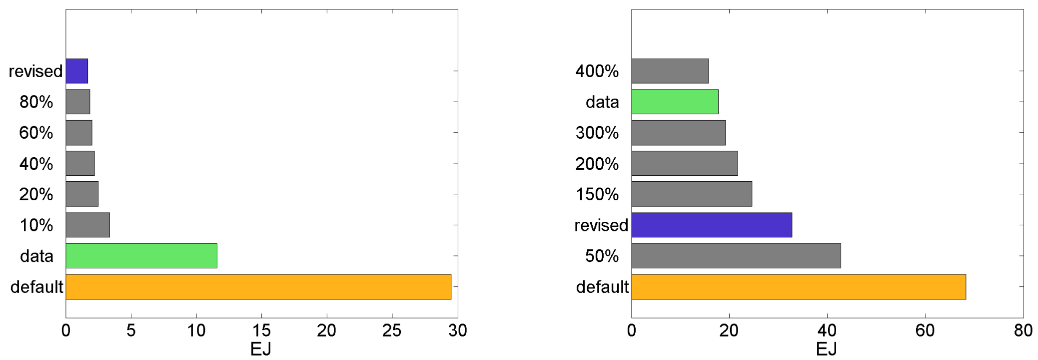
(a) Business as usual (b) Climate Policy

Figure 9: Oil trade flows of selected regions. Solid lines 1990-2005: empirical data [19, 20]. Solid lines 2005-2050: model results in the default scenario (no trade costs). Dashed lines 2005-2050: model results in the revised scenario (with trade costs). Regional values <0 represent imports, values >0 exports.

show a minor postponing from the first decades of the 21st century to subsequent years. Real world exporters are generally also exporters in the model. Regional exports and imports remain comparable to levels before 2005 in all scenarios. In 2005, trade costs mainly lead to reduced trade of the main exporter MEA and the main importer USA. Model results for exports from MEA in 2005 exceed empirical values also in the revised scenario, because current exports are reduced due to market power, which is not considered in the model.

The overall effect of trade costs is strongest for coal, followed by natural gas, as the trade costs for coal and natural gas are relatively high compared to extraction costs. As coal reserves are more distributed among regions than natural gas reserves, a substitution of imports by domestic extraction is less costly for coal, so that coal trade flows are most affected by trade costs. Oil trade flows are not strongly modified in the revised scenario. This can be explained by the low transportation costs per unit of energy for this liquid energy carrier, compared to coal as a solid energy carrier and to natural gas that is either transported in gaseous phase or as liquefied natural gas, which requires additional efforts for liquefaction and regasification.

Climate policy induces a restructuring of the demand for fossil energy carriers and associated trade flows, hence trade costs have a different impact in the business-as-usual case and the climate policy case.



(a) Sensitivity analysis, Coal (b) Sensitivity analysis, Natural Gas

Figure 10: Global trade flows in 2005. Sensitivity analysis: Different scaling factors (in %) on trade cost parameters. Blue: revised scenario (100%). Orange: default scenario (no trade costs). Green: Empirical data [19, 20] for comparison.

In a sensitivity analysis we analyze for coal and natural gas whether the remaining gap between global market volumes in the model and in the data can be sufficiently closed at all (see Figures 10(a) and 10(b)). Downscaling of coal trade costs do not impact the global trade volume strongly. If costs are scaled to 10% of the default value, the global trade volume doubles to 4 EJ. This number is still far below the observed trade volume. Hence, the global coal trade flow reacts very sensitively between trade costs as high as 10% of the default parameters and zero trade costs. Higher trade costs for natural gas result in a reduced global trade volume of natural gas; while a scaling of 300% leads to model results that still exceed empirical data, the trade volume in the model falls below the empirical value for a scaling of 400%.

The results lead to the conclusion that uncertainties in trade costs parameters in the relevant range have only a very limited influence on resulting trade flows in the year 2005. Scalings of less than 10% for coal trade costs and more than 300% for natural gas trade would be required to fully reconcile model results and empirical data on the global trade volume in 2005. As such scaling factors are not justifable from literature values on trade costs, it can be concluded that the mismatch between data and model results in 2005 cannot be closed by transport-related trade costs alone. Rather, other factors influence current empirical trade flows.

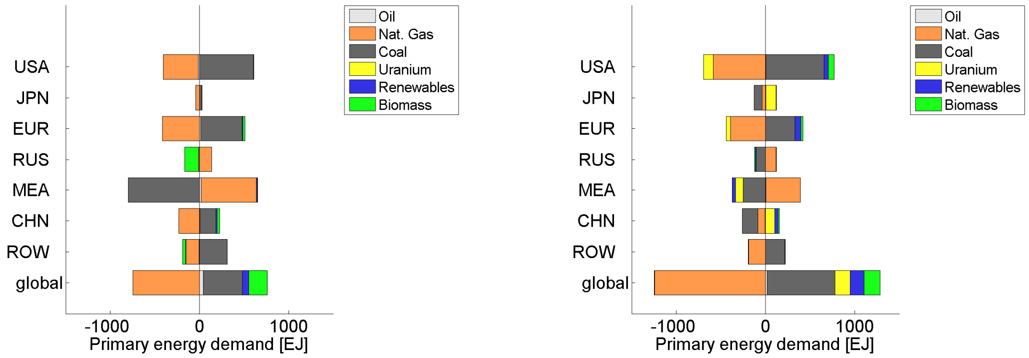
5.3. Effects on the demand for primary energy

In this Section, we turn to the effects of trade costs on the global and regional domestic primary energy demand. The consideration of trade costs leads to a differentiated effect on fuel prices in the revised scenario as shown before, which induces substitutions among primary energy carriers.

In the revised scenario, exporters consume a larger share of their reserves domestically in response to decreased export volumes (see Figure 11): ROW and USA increase their coal demand, and RUS and MEA their natural gas demand, in both the business as usual and the climate policy case. In turn, importers tend to reduce their demand for imported fossil energy carriers in the revised scenario, although this effect is obvious only for the reduced coal imports in MEA.

These results reflect the home bias in trade (Obstfeld and Rogoff, 2000): Due to trade costs, both exporters and importers consume a larger share of their endowment domestically rather than trading it, leading to a diversification of fossil fuel use across regions. This observation is in line with the results on reduced trade flows in 2005 (Figures 7 and 8).

Regions that depend on imports of natural gas *and* coal (JPN, EUR, CHN) partially substitute natural gas by coal. The reason is that natural gas is less evenly



(a) Business as usual (b) Policy

Figure 11: Domestic primary energy demand, difference of the revised scenario and the default scenario cumulated over the period 2005-2050. Positive values indicate higher demand in the revised scenario.

distributed among regions than coal. Hence, the import dependency for natural gas is high, and trade costs lead to a demand decrease. Coal is more evenly distributed among regions, so that importers have the possibility to partially substitute import by extraction of domestic reserves while almost maintaining their demand. In consequence, the coal demand is less reduced by the consideration of trade costs than the natural gas demand.

The latter argument explains also the partial substitution from natural gas to coal on the global aggregate. A decrease in the global demand for natural gas is not totally compensated by an increase in the global coal demand, but also by stronger use of other primary energy carriers that are not affected by trade costs.[17] This result reflects the flexibility of the energy system to substitute fossil fuels partly by other primary energy carriers. In consequence, a more diversified primary energy mix can be observed in the revised scenario.

6. Conclusions

International climate negotiations are challenged by a divergence of mitigation costs among world regions, especially the prospects of relatively high mitigation costs

[17] Biomass and renewable energy carriers can be assumed to be transformed into secondary energy close to their source rather than be traded internationally on a large scale.

for exporters of fossil energy carriers. Hence, a profound understanding of the devaluation of fossil energy endowments and underlying trade mechanisms is a crucial element in the analysis of long-term mitigation scenarios. Multi-regional intertemporal energy-economy models are a suitable model framework for this analysis, as they represent long-term economic dynamics, technological developments in the energy system, and international trade in a comprehensive way. However, a convincing representation of flows in this class of models is challenging.

In this paper, the costs for international trade in fossil energy carriers are introduced in the global multi-regional intergrated assessment model REMIND-R in order to enhance the representation of trade flows, rendering more reliable scenarios on regional mitigation costs possible.

The consideration of trade costs has significant consequences on regional mitigation costs. In particular, mitigation costs for coal exporters are found to be smaller, once trade costs are accounted for. As coal trade is significantly reduced even in the absence of climate policy, the reduction of export profits by major coal exporters is lower in scenarios that account for trade costs.

The effects on trade patterns differs by energy type. The consideration of trade costs leads to significant reductions of trade flows for coal and natural gas, whereas oil trade is not strongly affected. The low impact on oil trade can be explained by the low transportation costs per unit of energy for this liquid energy carrier, compared to coal as a solid energy carrier and to natural gas that is either transported in gaseous phase or as liquefied natural gas, which requires additional effort for liquefaction and regasificqation. In general, simulation results on global trade volumes in the next decades are closer to current empirical volumes in scenarios that account for trade costs.

Model results in scenarios with trade costs allow for a far better representation of empirical data on trade flows in the initial year of the model time horizon, 2005. A full reconciliation of model results and empirical result was not expected, as other impacts on real-world patterns, e.g. tariffs [32] or the exertion of market power by exporters have not been considered in this study.

A perfect match of data and model results for the year 2005 is, however, not essential for the analysis of mitigation costs in a long-term framework, as mitigation costs account for the development of trade profits and expenditures over the whole century. In case of natural gas, trade flows remain on a level far above current empirical values until the mid of the century, but this effect occurs in both the business as usual and the policy experiment, so that the impact on the mitigation costs is limited.

On the global aggregate of primary energy consumption, trade costs cause a partial substitution from natural gas to coal. The reason is that coal endowments are more evenly distributed among world regions than natural gas, so that is is preferable to compensate coal imports by domestic sources than to compensate natural gas imports by domestic sources. Furthermore, a more diverse primary energy mix emerges from scenarios that account for trade costs, because primary energy carriers that can be supplied domestically (e.g. renewable energy carriers) become competitive. This finding confirms the theoretical result by Obstfeld and Rogoff [32] that trade costs provide an explanation for a partial preference of domestic supply over imports (*home bias*).

In total, the approach to introduce trade costs in the model appears to be advantegous for a more convincing representation of trade flows, as more reliable assumptions lead to more realistic results in the revised scenario. However, further research is still recommended to enhance the representation of trade in multi-regional intertemporal hybrid models, for example a representation of price formation under strategic behaviour of exporters and importers. Furthermore, process-based descriptions of energy transport would allow to address the relevance of inertia in the development of trade infrastructure, e.g. the LNG process chain, and cost reduction potential due to technological learning.

The authors appreciate fruitful discussions with Alexander Körner and Michael Hübler.

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Chapter 6

Electricity Trade among World Regions*

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Electricity Trade among World Regions

Trade Theoretic Foundation of Energy-Economy Models

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November 14, 2008

Abstract

We introduce infrastructure investments that render possible electricity trade among world regions into a hybrid energy-economy model and we relate the results to neo-classical trade theory. The model results indicate that the trade of electricity from North Africa to Europe is only competitive in case of prudent climate mitigation policies. The electricity transmission would allow Europe to explore the huge potential of solar energy present in North Africa in exchange for goods.

Regarding the theoretical foundation four policy relevant questions are analyzed using neo-classical trade theory. First, is the introduction of trade benefitting both regions at an aggregate level? The answer for the electricity importing region is clearly positive, but for the electricity exporting region it depends on the reduction of rent incomes from other resource exports that are deteriorated by the introduction of electricity trade. Second, what is the effect on macroeconomic activity in the two regions? The analytical model suggests that the exporting region's production sector decreases, but that of the importing region increases. In the analytical model this is derived by the effect on interest rates that converge, though it is not a tradable good. Third, what is the sectoral effect for the two regions? The analysis indicates that the European electricity sector would lose from the introduction of trade. The resource and emission permit exporters lose from electricity trade because the international prices are reduced. Fourth, what is the effect on trade relations of third countries that are not involved in the electricity trade? We show that the

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introduction of electricity trade can have positive or negative effects depending on the resource trading position of the third countries prior to electricity trade. The numerical results indicate a positive effect, though it is relatively small.

The results serve as a starting point for the discussion of political barriers to implementation of such large scale infrastructure projects. The barriers are due to the negative effect on some sectors: if for example the European electricity sector loses, it would not have the incentive to invest into the infrastructure that renders possible electricity trade.

1 Introduction

Inter-continental electricity transmission is discussed as a means to mobilize the huge renewable energy potentials in order to deal with increasing scarcity of exhaustible energy carriers and to mitigate global climate change. Long-distance electricity transmission is an inevitable precondition that presupposes considerable financial means and would impose transmission losses. The techno-economic dimension of the issue is already discussed in the literature. The technological option is proven: the investment costs and the transmission losses are known from realized projects. The economic dimension is still out to be clarified. The present study is devoted to the analysis of the trade related economic dimension.

Several studies are devoted to the techno-economics of long-distance electricity transmission that is the bridge between Europe and North Africa. These studies aim at assessing the costs and necessary investments to realize this option. The authors consider the problem as one of costs and technologies. The findings are quite promising; see e.g. Czisch et al. (2001) and Trieb et al. (2006).

However, the frameworks of energy system models applied in these studies are based on optimization methods. Most commonly the objective function is a monetary cost criterion that is minimized. Costs are summed across regions and technologies. Investments and energy flows are induced, if the global cost criterion advices to do so. The models are partial equilibrium models that compute a result that fits the Hicks-Kaldor criterion.

These models do not take into account that transmission lines are infrastructure that render possible trade and that the introduction of trade is subject to the problem of improving the economic situation of some actors, but at the same time worsening that of others. These agreements are useful to gain insights into the political preferences of actors that also aim at influencing the political process known as rent seeking behavior.

Trade theory is in large part devoted to the analysis of distributional effects of trade and trade related policy instruments; see e.g. Krugman and Obstfeld (2003) and other textbooks. Trade models consider the idea of mutual exchange of at least two goods that is coordinated by the price mechanism. These models aim at finding equilibrium prices that solve the exchange relationships and analyze the effects on the various actors as trade or related instruments are introduced. An ordinary energy system model does not represent the concept of exchange and is therefore not suitable to make statements in lines with economic trade theory.

We address the issue of inter-continental electricity trade with two different approaches. We formulate an analytical three country static general equilibrium model and analyze the effect of trade on aggregate welfare as well as factor related income distribution. The regions trade resources and consumption goods. The resource is converted into electricity, which in turn is combined with capital to produce consumption goods. Resource trade can be constrained because – for example – part is non-tradable. This leads to non-equalization of resource prices. In such situation electricity trade can complement resource trade and induce regional resource price convergence. These price changes have effects on regional consumption production and consumption and additional lead to a re-valuation of the resource and capital endowments within the regions. Electricity trade can have positive or adverse regional welfare effects. Though the model is different in structure, it reconcile various general effects that are well known in trade theory like the Stolper-Samuelson theorem. The model mainly captures the relationship between resources, capital, electricity and production. The essential point is that this structure allows for trade of the intermediate product electricity.

The second approach is to apply a numerical, multi-regional, dynamic, general equilibrium model that embeds an energy system model into a macroeconomic growth model. The model is detailed in technologies and trade of primary energy carriers; the latter being endowments of the regions. The assumptions on endowments are that Europe is scarce in renewable energy sources, that are assumed to be plentiful in North Africa. We compare cases with and without electricity trade. The cases with electricity trade consider the infrastructure investments that make possible the transmission of electricity between the two regions.

The numerical economic results are decomposed and related to different effects that quantify the qualitative results of the analytical model. It turns out that all regions gain in aggregate from the introduction of electricity trade; even those not engaged in it. Hence, the negative welfare effects that were not impossible in the analytical model do not emerge in the numerical model. However, the sources of the net effect are very different in magnitude and sign across regions. Considerable negative effects were found for the European electricity sector, the macroeconomic sector in North Africa as well as the primary energy export sectors in North Africa and the rest of the world. These sectors may have serious objections against electricity trade and would not have the economic incentive to finance the investments for electricity transmission infrastructure.

The remainder of the study is organized as follows. Sec. 2 introduces the analytical model. The numerical assessment model *ReMIND* is introduced in Sec. 3. The technological and institutional details of electricity transmission technology and electricity trade relationships is presented in Sec. 4. The research questions and scenarios are given in Sec. 5. The final Sec. 7 discusses the results and concludes.

2 The Analytical Model

This section presents the analytical model and characterizes the solution. We first introduce the regional economies and the trade relationships. In a second step we lay out three different cases for trade between the regions that are analyzed in the third step. The three cases do not cover all possible varieties that the model could consider, but they are sufficient for the sake of the present study.

Fig. 1 illustrates the model structure. The model solves for a static general equilibrium at the sectoral level with interregional trade on trade markets (indicated by ellipses). It comprises three regions (indicated by the three large rectangles) distinguished by the index r; we call the regions home h, foreign f and the third t. The regions are identical with respect to the structure of the four sectors that are represented by the small rectangles: resource, energy, consumption good production and households. Each region is endowed with resources R_r^0 and capital K_r that are the property of the household sector and supplied to the resource and the consumption good production sector, respectively (marked by the blue arrows).

The resource sector allocates the R_r^0 to domestic supply R_r and net resource exports R_r^X (marked by the red arrows at the bottom). The net export of all regions has to equal zero: $\sum_r R_r^X = 0$. The amount of resources available in a region is:

$$R_r = R_r^0 - R_r^X \quad \forall\, r. \tag{1}$$

The electricity sector uses the resource to convert it into electricity E_r^0 using a linear production technology that is the same for all regions:

$$E_r^0 = \theta R_r \quad \forall\, r. \tag{2}$$

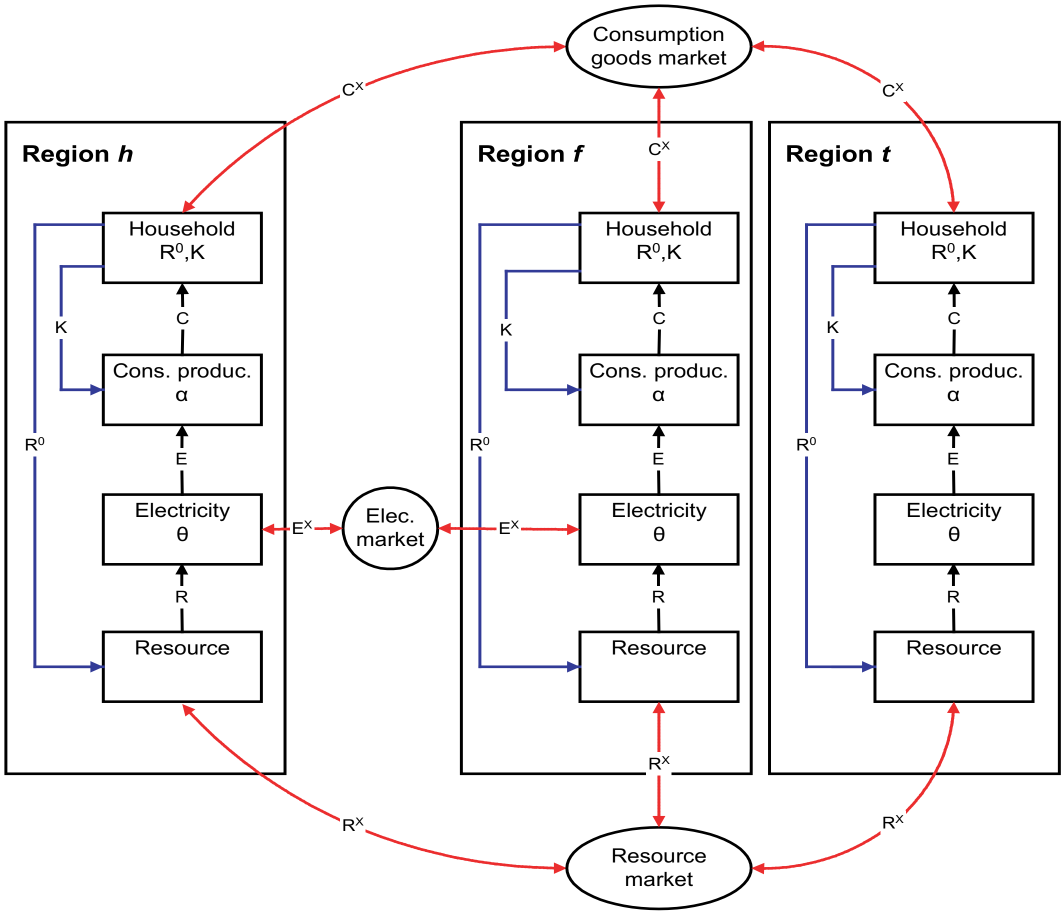


Figure 1: Structure of the analytical model.

Electricity can be traded between the regions h and f. The net exports of electricity (red arrows in the middle) of both regions sum up to zero: $\sum_{r=h,f} E_r^X = 0$. The amount of electricity available in each region is:

$$E_r = E_r^0 - E_r^X \quad \text{for } r = h, f. \tag{3}$$

The consumption good sector combines capital K_r and E_r using an ordinary Cobb-Douglas production function that is the same in each region in order to produce the consumption good:

$$C_r^0 = K_r^\alpha E_r^{1-\alpha} \quad \forall\, r. \tag{4}$$

Consumption goods can be traded. Again the net exports (red arrows at the top) summed over all regions equal zero: $\sum_r C_r^X = 0$. The amount of consumption goods available in each region is:

$$C_r = C_r^0 - C_r^X \quad \forall\, r. \tag{5}$$

The household sector maximizes its consumption that is financed from its income that it receives from supplying R_r^0 and K_r. The prices of consumption goods are normalized to one in all regions. The prices for resources and electricity in each region are p_r^R and p_r^E. Below, we consider the case some regions are subject to a constraint on the share of net resource exports σ_r. If the constraint is binding, the price of the tradable part is the world market price p^R and the price of the non-tradable part is the regional price p_r^R. Hence, the budget equation in the regions are:

$$C_r = \sigma_r p^R R_r^0 + (1 - \sigma_r) p_r^R R_r^0 + p_r K_r \quad \forall\, r. \tag{6}$$

Each region is subject to a balance of payment (BOP) that equates the sum of net export values of the traded goods. The net exports are valued with world market prices that do not necessarily coincide with the prices payed within the regions. The BOP is:

$$C_r^X + p^R R_r^X + p^E E_r^X = 0 \quad \forall\, r. \tag{7}$$

Next, the different cases of trade and endowments are introduced:

1. ***Autarchy***: No trade is considered. The case is not considered in detail. The model framework allows us to isolate the autarchy outcome.

2. ***Foreign exports resources***: We assume that home and third are identical with respect to endowments. Both are well equipped with capital, but short in resources. Foreign is well endowed with resources, but short in capital.

   (a) *Full resource trade*: All resources can be traded without any restriction. No electricity trade is allowed.

   (b) *Restricted resource trade*: The resource rich region is subject to a constraint on the share of resource exports σ_r. No electricity trade is considered.

   (c) *Restricted resource trade and electricity trade*: Like case 2(b), but electricity trade is allowed between h and f.

3. ***Foreign and third export resources***: Foreign and third are identical. They have abundant resources but only little capital. Home is short in resource, but well endowed with capital.

   (a) *Full resource trade*: Like 2(a).

   (b) *Restricted resource trade*: The resource trade restriction is applied to foreign and third.

   (c) *Restricted resource trade and electricity trade*: Like case 3(b), but electricity trade is allowed between h and f.

The restriction on resource trade can be justified in two ways. First, there are physical constraints that make a share of the resource a non-tradable good. Second, the supply is reduced in order to generate higher rent incomes; however the rationale for setting σ is not endogenous. The former reason reflects the property of solar energy sources that cannot be traded like fossil energy carriers. Anyways, restrictions on resource trade will lead to rents for the resource rich regions, if the constraint is binding. Hence, the domestic resource price of the resource rich regions will be lower than the world market price. Introducing electricity trade opens up the opportunity to circumvent the restriction. Hence, the rent income will deteriorate.

2.1 Foreign Exports Resources

A preliminary note is useful. Since the regions h and t are identical, in case 2(a) and 2(b) it is enough to analyze only the two regions h and f. The result for h and t are identical in turn.

In the case of full resource trade all regional resource prices will equalize to the world market price p^R. Efficiency in production requires the following first-order-condition for resource use of the consumption good sector:

$$p^R = \frac{\partial Y_r}{\partial E_r}\frac{\partial E_r}{\partial R_r} = (1-\alpha)K_r^{\alpha}\theta^{1-\alpha}R_r^{-\alpha} \quad \forall\, r. \tag{8}$$

We equate the efficiency conditions of the two regions h and f and consider that $R_h^X = -\frac{1}{2}R_f^X$:

$$\frac{K_h}{K_f} = \frac{R_h^0 + \frac{1}{2}R_f^X}{R_f^0 - R_f^X}. \tag{9}$$

To ease the notation we introduce the ratio of initial resource and capital endowments $\rho = \frac{R_h^0}{R_f^0}$ and $\kappa = \frac{K_h^0}{K_f^0}$, respectively. Manipulating the above expression provides an expression for foreigns net resource exports:

$$R_f^X = \frac{\kappa - \rho}{\kappa + \frac{1}{2}} R_f^0. \tag{10}$$

The ratio on the right hand side is the net resource export share of f that we denote σ_f. The net resource export share of h is $\sigma_h = \frac{-\sigma_f}{2\rho}$. Hence, foreign's resource use is $R_f = (1 - \sigma_f) R_f^0$. Eq. 10 fits with the conjecture above because foreign will export, if it is relatively well endowed with resources but relatively short in capital:

$$R_f^X \gtreqless 0 \quad \Leftrightarrow \quad \rho \lesseqgtr \kappa. \tag{11}$$

We can now determine the world resource market price using the efficiency condition of foreign Eq. 8 and the regions' resource endowments:

$$p^R = \underbrace{(1-\alpha) K_r^\alpha \theta^{1-\alpha} R_r^{0(-\alpha)}}_{\text{autarchy price in } r} (1 - \sigma_r)^{-\alpha} \quad \forall\, r. \tag{12}$$

The resource price in a region is higher (lower) compared to the autarchy case, if it exports (imports) resources. The deviation depends on the export share and the capital share.

We derive the production of consumption goods in all regions:

$$C_r^0 = \underbrace{K_r^\alpha \theta^{1-\alpha} R_r^{0(1-\alpha)}}_{\text{autarchy production in } r} (1 - \sigma_r)^{1-\alpha} \quad \forall\, r. \tag{13}$$

Domestic production is lower (higher) compared with the case of autarchy, if the region exports (imports) resources. Next, we determine the value of foreign's imports of the consumption good by making use of the BOP in Eq. 7:

$$-C_r^X = p^R R_r = (1-\alpha) K_r^\alpha \theta^{1-\alpha} R_r^{0(1-\alpha)} (1 - \sigma_r)^{-\alpha} \sigma_r \quad \forall\, r. \tag{14}$$

Using the budget equation Eq.6 and substituting the results of Eq. 12 – 14 in order to find the consumption in each region:

$$C_r = \underbrace{K_r^\alpha \theta^{1-\alpha} R_r^{0(1-\alpha)}}_{\text{autarchy cons. in } r} \left[(1 - \sigma_r)^{1-\alpha} + (1-\alpha)\sigma_r (1 - \sigma_r)^{-\alpha} \right] \quad \forall\, r. \tag{15}$$

The term in square brackets is the gain of trade factor in region r denoted with $\mathcal{G}_r$. It is larger than one, if trade occurs; i.e. $\sigma_r \neq 0$. The resource exporting region uses the revenues to import consumption goods. It produces consumption goods indirectly by employing the better production technology of the resource importing region. In turn the resource importing region can increase its production, though part of the higher output is required to finance the imports. In summary, trade is mutually benefiting for the regions compared with the case of autarchy.

A final note about the effect of resource trade on the regional interest rates is useful. Larger endowments with capital imply lower interest rates in the resource importing regions compared to the exporting region in case of autarchy. Resource imports imply – in accordance with the properties of neo-classical production functions – higher interest rates, because the available capital would increase in its marginal productivity. Hence, the convergence in regional resource prices comes with a convergence of interest rates. This finding is a variant of the general statement of the Stolper-Samuelson theorem: trade increases (decreases) the price of the production factor that is relatively abundant (scarce); see e.g. Krugman and Obstfeld (2003, p. 69). This implies redistribution of income between factors favoring capital in resource importing regions and resources in the resource exporting regions, but at the expense of the resource importing regions and capital in the resource exporting region.

Now, we turn to case 2(b) introducing the bound ϵ on the resource export share of foreign. We assume that ϵ is sufficiently small so that it indeed constrains trade. In this case the regional prices of the resource would not converge to a common world market level. The regional resource prices would be:

$$p_r^R = (1-\alpha)K_r^\alpha \theta^{1-\alpha} R_r^{0(-\alpha)} \left(1+\frac{\epsilon}{2\rho}\right)^{-\alpha} \quad \text{for } r = h, t; \tag{16}$$

$$p_f^R = (1-\alpha)K_f^\alpha \theta^{1-\alpha} R_f^{0(-\alpha)} (1-\epsilon)^{-\alpha}. \tag{17}$$

The resource exporting region f would export resources at the higher price of the other two regions, which would generate a rent from resource exports. The non-tradable part of the resource is supplied domestically at a price lower than the export price. The gains of trade are different to the case without the export constraint:

$$\mathcal{G}_f^{2(b)} = (1-\epsilon)^{1-\alpha} + \epsilon\kappa^\alpha(1-\alpha)(\rho+\frac{\epsilon}{2})^{-\alpha}; \tag{18}$$

$$\mathcal{G}_r^{2(b)} = (1+\frac{\epsilon}{2\rho})^{1-\alpha} - \frac{\epsilon}{2\rho}(1-\alpha)(1-\frac{\epsilon}{2\rho})^{-\alpha} \quad \text{for } r = h, t. \tag{19}$$

For the resource importing region h it always holds that the gains of trade in case 2(b) are lower than in the case 2(a); i.e. h always prefers free resource trade. The situation is different for the resource exporting region f. There is always a

$0 < \epsilon < \sigma_f$ that maximizes $\mathcal{G}_f^{2(b)}$. Hence, starting from the export share realized in the case of full resource trade the resource exporting region can improve its gains of trade by unilaterally constraining resource exports. However, the gains of trade reach a maximum and would then fall below the gains of trade in the case of full trade. For increasingly strict export constraints, the gains of trade would approach the value one, that is equivalent to the autarchy case. For a proof of this proposition the interested reader is referred to Appendix A of this paper.

Like above, we add a note regarding the regional interest rates. Since resource imports are lower than in case 2(a) the interest rates are lower in the resource importing countries. The effect in the resource exporting region is the opposite.

Next, we analyze case 2(c) with the restriction on resource trade but with electricity trade between h and f. In order to ease the analysis we assume that the export constraint is not so strong that it is constraining the resource exports to t in case that resource imports of h equal zero. With this assumption we exclude resource trade between h and t, which is not the aim of the present analysis.

If electricity is traded freely between h and f electricity prices equalize between both regions $p_h^E = p_f^E$. Electricity and resource prices are interrelated by the conversion process:

$$p_r^E = \theta p_r^R \quad \forall r. \tag{20}$$

From this follows that the resource prices also equalize in all regions. Therefore, the gains of trade in case 2(c) and 2(a) are the same. The trade in electricity is a substitute for the trade in resources. Owing from the results above the gains of trade in h increase, but those in f would decrease, as long as the export constraint is sufficiently weak. For very strong export constraints the effect can indeed be positive. We will come back to this point below.

If the export constraint is considered a natural barrier it enables trade of the non-tradable part of the resource in form of electricity. The owners of the non-tradable part would improve their situation from increasing resource prices because they can export the electricity generated from the non-tradable resource. However, the owners of the tradable part of the resource lose rent income because the resource price decreases towards the common world market level. The distributional effects in the resource exporting country are quite similar to the well-studied issue of export quotas; see e.g. Krugman and Obstfeld (2003, p. 252-4).

In case 2(c) domestic electricity production in h decreases compared to cases 2(a&b), because the region would only convert the domestic resource into electricity. However, electricity consumption increases because the region imports the electricity. The higher availability of electricity decreases its price and increases the interest rate.

Hence, the domestic resource owners would lose due to lower resource prices, but the capital owners would gain due to the electricity imports.

The region t gains from the trade of electricity between regions h and f. The resources available from f can now be completely imported. The lower resource prices increase domestic electricity production and improve the position of capital owners. However the decreasing resource prices would deteriorate the income of resource owners. In sum, the region would benefit from increased total consumption.

We return to the gains of trade in f that are lower in case 2(c) than in 2(b), if the export constraint is not excessively strict. The model framework is subject to a shortcoming: The resource use in all regions is the same in all three cases. It is reasonable in the subject at hand that the introduction of electricity trade would increase the availability of the non-tradable part of the resource in f. The rationale is that without trade large parts of the resource are left to lie fallow. The demand from h improves the economic value and part of the fallow are made accessible to economic activity. We can analyze this effect within the framework by forming the derivative of $\mathcal{G}_f^{2(c)}$ that is related to the resource export with respect to σ_f:

$$\frac{\partial \mathcal{G}_f^{2(c)}}{\partial \sigma_f} = (1-\alpha)(1-\sigma_f)^{-\alpha}\left(1+\frac{\alpha\sigma_f}{1-\sigma_f}\right) > 0. \tag{21}$$

This expression implies that, if region f can increase the resource after the introduction of electricity trade – without decreasing the domestic use of resources – the gains of trade would unambigouosly increase. This effect potentially works against the decrease of the gains of trade that we derived above. The net effect depends on the relative weights that are subject to parameter assumptions.

2.2 Foreign and Third Export Resources

In the following we treat the case in which the regions f and t are identical. They are assumed to be relatively well endowed with resources and relatively short in capital, which leads both to export resources to region h. The following analysis focuses on the effects on region t, when electricity trade is introduced.

The gains of trade for the regions h and f in the case 3(a) are equal to those in case 2(a), that were proven to exceed one. If the resource exporting regions are considered to constrain the exports to a fixed level $\epsilon < \sigma_{f/t}$ being identical for both their gains of trade:

$$\mathcal{G}_r^{3(a)} = (1-\epsilon)^{1-\alpha} + (1-\alpha)\kappa^{\alpha}\epsilon(\rho-2\epsilon)^{-\alpha} \quad \text{for } r = h, f. \tag{22}$$

This is structurally similar to case 2(b). The only difference is that now two regions compete for the demand of one region. There will also emerge a differnce in the resource price between the regions: the domestic resource prices in f and t are lower than the world market price that will prevail in the importing region h.

For the case with electricity trade between h and f we assume $1 + \epsilon > 2\sigma_{f/t}$ in order to exclude complicated cases of re-exports. The introduction of electricity trade will now lead to equalization of the domestic resource prices to the common world market level. The region f would use part of the non-tradable resource that is converted to electricity that is exported to region h. Hence, electricity imports from f substitute resource imports from f. Hence, the sectors of tradable resource in the two well-endowed regions lose as does the resource sector in the region h, but the value of the non-tradable resource increases.

This means that the effect on the region t from the introduction of electricity trade between h and f depends on t's resource relative endowment, thus the sign of net exports. If region t is a net exporter of resource, the decreasing international resource price due to the introduction of electricity trade decreases the rent income from the tradable part of the resource. The effect is opposite, if t is a resource importer, because then it profits from the decreasing international resource prices.

3 The *ReMIND* Model

In this Section the model *ReMIND* is at first introduced without electricity trade. The techno-economic and institutional details of electricity trade are presented in the following Sec. 4.

ReMIND is the acronym for Regional Model of Investment and Development; see also Leimbach et al. (2010). It is a global multi-regional model of the economy, the energy system and the climate system. Nine world regions[1] are represented that are interacting via trade in various goods and emissions that contribute to global warming. The regions are the agents within the model framework. The market equilibria within the regions are computed by making use of the equivalence of the social optimal solution with the decentral market solution. Between the regions a Pareto-equilibrium is computed, which will be explained below.

Within each region a social intertemporal welfare function is maximized. It depends on consumption that in turn is the residual of the economy wide income – measured in market exchange rates – after accounting for savings and variable costs of

[1]UCA (USA, Canada, Australia), EU-27, Japan, Russia, Middle East and North Africa, China, India, Africa, Rest of the World.

the energy sector. Savings are allocated on the capital market to the macroeconomic capital stock and investments into stocks of the various technologies in the energy sector. Among the technology alternatives there are some that only make sense in case of climate change mitigation policies; espec. technologies with carbon capture and sequestration (CCS). The generation of income requires capital and labor as well as energy that demands financial and primary energy carriers for its production.

The three sub-models are integrated by a hard-link. This means a single optimization problem is solved taking into account all constraints and interrelationships that characterize the sub-systems. The hard-link between the energy sector and the macro-economy guarantees simultaneous equilibria on the capital and energy markets. The energy market equilibrium is characterized by the price that equals demand and supply of energy in physical units. The capital market equilibrium is characterized by the interest rate that equals demand and supply for financial means. Moreover, the own rate of return of the macroeconomic capital stock and for all alternative energy technologies that are competitive equal the interest rate. If the own rate of return for an investment alternative falls short of the economy wide interest rate, this alternative is not competitive. The simultaneous capital and energy market equilibrium implies efficient – i.e. cost minimal – allocation of investments. For a more detailed analysis of the hard-link see Bauer et al. (2008).

The regions trade primary energy carriers (coal, oil, gas and uranium), emission permits and a generic good. The balances of payments are not required to be settled in every period. A region can temporarily accumulate net-debt, though at the end of the models time horizon in 2150 the net-debt has to equal zero.

Trade in the various goods takes place in a completely integrated world market. Demand and supply prices equalize at a common world market level. The concept of a completely integrated world market is best illustrated by the picture of a common pool to which exporters deliver goods and are rewarded at a common price that they cannot influence. Importers take goods from the pool at the same price. Equilibrium means that exports and imports equalize. This is going to be different in the case of electricity trade because the common pool does not exist anymore, but trade requires investments into transmission lines in advance in order to transport electricity from one region to another.

The solution for the trade equilibria is computed by the Negishi approach that allows for the use of optimization algorithms; see Negishi (1972). The method guarantees a Pareto equilibrium between all regions that is characterized by a set of price paths that equal supplies and demands for the traded goods. This reflects the economic idea of exchange: a region exports a good, if and only if it receives sufficient imports of another good in turn. The equilibria on the trade markets guarantee

		Primary energy types						
		Exhaustible				Renewable		
		Coal	Crude oil	Natural gas	Uranium	Solar, wind, hydro	Geo-thermal	Biomass
Secondary energy types	Electricity	PC*, Oxyfuel, IGCC*, CoalCHP	DOT	GT, NGCC*, GasCHP	LWR	SPV#, WT#, Hydro	HDR	BioCHP
	Hydrogen	C2H2*		SMR*				B2H2*
	Gases	C2G		GasTr				B2G
	Heat	CoalHP, CoalCHP		GasHP, GasCHP			GeoHP	BioHP, BioCHP
	Transport fuels	C2L*	Refinery					B2L*, BioEthanol
	Other liquids		Refinery					
	Solids	CoalTR						BioTR

Table 1: Overview on primary and secondary energy carriers, and the alternative conversion technologies represented in *ReMIND*.

Abbreviations: PC - conventional coal power plant, Oxyfuel - oxyfuel, IGCC - integrated coal gasification combined cycle power plant, CoalCHP - coal combined heat and power, C2H2 - coal to hydrogen, C2G - coal to gas, CoalHP - coal heating plant, C2L coal to liquids, CoalTR - coal transformation, DOT - diesel oil turbine, GT - gas turbine, SMR - steam methane reforming, GasTR - gas transformation, GasHP - gas heating plant, LWR - light water reactor, SPV - solar photovoltaic, WT - wind turbine, Hydro - hydroelectric power plant, HDR - hot dry rock, GeoHP - heat pump, BioCHP - biomass combined heat and power, B2H2 - biomass to hydrogen, B2G - biogas plant, BioHP - biomass heating plant, B2L - biomass to liquid, BioEthanol - biomass to ethanol, BioTR - biomass transformation.

* this technology is also available with carbon capture and sequestration (CCS).

this technology is characterized by technological learning.

efficient – i.e. cost minimal – use of the endowments and production technologies. Endowments can either be due to natural conditions like in the case of natural resources or they are subject to political agreements as in the case of emission permits. In both cases it is important to note that the efficient allocation induced by the trade equilibrium is consistent with the second theorem of welfare economics: the efficient allocation of goods on the market is separable from the distribution of the initial endowments, if markets work efficiently. This means that – assuming efficient markets – no special emphasis has to be put on the particular institutional framework of an international climate mitigation framework except for the stabilization goal, if one aims at analyzing the global costs of climate change mitigation; see e.g. Manne and Stephan (2005). This will remain valid, when we are going to introduce electricity trade below.

The model represents energy conversion technologies with respect to essential economic and engineering characteristics. The primary energy demand and CO_2 emissions are determined by capital structure of conversion technologies. Emission mitigation is achieved by restructuring the capital stock or by changing the demands for secondary energy carriers. The emissions of CO_2 could be reduced through these two reallocation mechanisms or by investing in carbon capture and sequestration, which increases the capital costs and reduces efficiency. Tab. 1 summarizes the alternative routes and technologies for converting primary into secondary energy carriers.

Primary energy carriers are either exhaustible or renewable. The former are characterized by extraction costs that are increasing with cumulative usage, while the latter are subject to a constraint on annual production potential that is differentiated by various grades. The harvest of biomass leads – additionally – to costs that are accounted for in the budget constraint of the economy.

4 Long Distance Electricity Transmission

This section deals with the electricity transmission lines that render possible trade. In Sec. 4.1 the techno-economic literature of long-distance electricity transmission is reviewed and the essential parameter values are identified and uncertainty ranges are delimited. In Sec. 4.2 the institutional aspects and the chosen setting is introduced.

4.1 Techno-Economic Assessment

To allow long-distance electricity transmission in the *ReMIND* model, a new technology was implemented in the Energy System module. A literature assessment resulted in the selection of the relevant input parameters.

In Czisch et al. (2001) the distance between different regions in Northern Africa and Europe (the German city of Kassel is chosen as ending point of the transmission line) is estimated to be about 3000 km. May (2005) analyzes three different routes with lengths between 2700 and 4000 km. In the TRANS-CSP report (Trieb et al. (2006)) for the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, two routes with about 3100 km and one of more than 5000 km are evaluated. To get a general view on the potential of electricity trade over transmission lines, we chose to study a transmission line of 3000 km.

The technology used for long-distance electricity transmissions is High Voltage Direct Current (HVDC). HVDC allows transmission on overhead lines, underground cables and sea cables. Losses are significantly lower than with AC power for transmission over long distances. HVDC converter stations may have higher investment costs than AC transformers, however, compensation of inductive and capacitive losses for long-distance AC is costly and complex so that a break-even distance of 50-100 km between the two technologies can be assumed; see e.g. Rudervall et al. (2000).

The transmission efficiency of HVDC lines is relatively high, as May (2005, p. 35) shows. The losses depend on the voltage and length of the line and range from 2.5% / 1000 km for a 800 kV line to 6% / 1000 km for a 500 kV line. This corresponds to 7.5% to 18% for a line of 3000 km. For a first assessment, we chose an efficiency of 90%.

This analysis of electricity trade between Europe and Northern Africa is limited to the consideration of HVDC lines, it is clear, however, that an actual installation of larger transmission capacities would make use of existing DC and AC infrastructure as described for example in May (2005) and Trieb et al. (2006).

As most present HVDC-projects are specially designed for the local geographic and political situations, their investment costs are difficult to compare. Data found in the literature and in official project descriptions ranges from 260$/kW (May (2005)) to 3575$/kW (NorNed project description[2]) for a cable of 3000 km. It is important to consider that location of the cable (i.e. overhead line, underground cable, shallow or deep water submarine cable) and political circumstances (crossing of different

[2] `http://www.tennet.org/english/projects/norned_/projectomschrijving.aspx`, retrieved on 25.06.2006

Input Parameter	Value Range	Reference
Investment costs (3000km, HVDC)	260$/kW	May (2005)
	450$/kW	Trieb et al. (2006)
	3575$/kW	Homepage of the NorNed Project (see footnote 2 on page 16)
Learning Rate	38%	Junginger et al. (2004), Peeters (2003)
Efficiency	82% - 92,5%	May (2005)

Table 2: Input parameters

countries, necessity of building permits...) have a very strong influence on project costs.

We chose to use the values from the TRANS-CSP report (Trieb et al. (2006)) for our study as they describe electricity transmission between the same regions than implemented in our electricity trade analysis, namely Europe and Northern Africa. Thus we implemented investment costs of 450$/kW for a 3000 km line.

In his assessment of cost reduction prospects for offshore wind farms, Junginger et al. (2004) points out that larger numbers of HVDC projects could lead to a higher degree standardization for cables and converter stations and thus to a significant decrease in investment costs. An investigation by Peeters (2003) uses data from existing projects and develops an experience curve. A learning rate of 38% is determined. A problem of this study was the small amount of data available and most cost informations did not include laying of the cables which can strongly influence final investment costs. However, considering the little current standardization and the probability of a large number of offshore wind projects in the near future, it can be assumed that a rapid decline in costs for HVDC projects is possible.

As very little data was found on experience curves for transmission lines, we chose to use the values investigated by Junginger et al. (2004) and Peeters (2003).

4.2 Institutional Setting

The institutional setting characterizes the actions of the regions, at which point of the trading process the property rights are transferred and what prices are paid. The characterization is of interest here because the model solves for a Pareto-solution between the regions and the institutional setting affects the trading relations between the regions.

The investments for the transmission infrastructure add to the energy system costs of Europe. Electricity that is delivered from MENA is rewarded with the local price in MENA; i.e. it is a free on board contract. The transmission of a unit of electricity is therefore subject to the transmission losses and the costs for transmission.

The installation of electricity generating facilities is always domestic. The possibility of foreign direct investments is not considered. However, MENA could borrow financial means from Europe to finance the investments.

The MENA region is not allowed to exercise oligopolistic market power on the markets for primary energy. Hence, prices differences are only justified by reasons of costs and technology.

5 Scenarios and Research Questions

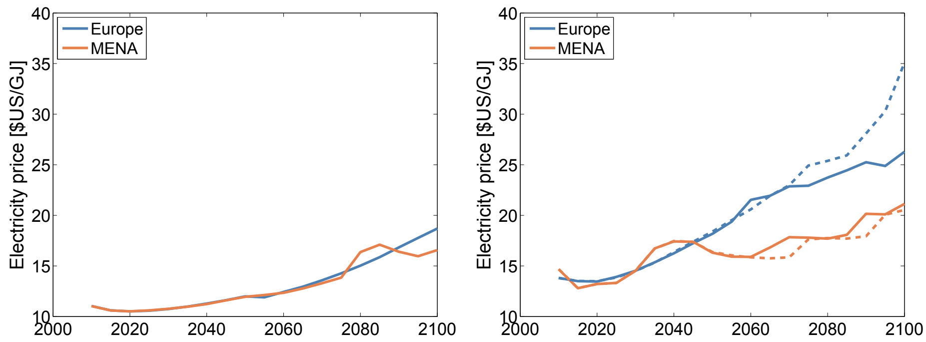
With the *ReMIND* model we compare two scenarios of climate change mitigation policies. First, we compute a business as usual scenario (BAU) without any effort to mitigate climate change. For the second scenario (POL) we impose a climate change constraint that does not allow global mean temperature to increase by more than 2°C above the pre-industrial level. The emission permits are distributed according to convergence and contraction towards equal per-capita emissions and all emission permits are fully tradable. For each of these scenarios we compute a variant without (BAU, POL) and with (BAU^+, POL^+) the option to trade electricity between Europe and MENA.

Regarding electricity trade two policy relevant questions are analyzed and we relate the numerical results (Sec. 6) to the qualitative insights of the analytical model (Sec. 2):

1. Is prudent climate change mitigation policy a pre-requisite for inducing electricity trade and how does it change the regional production and consumption as well as the electricity prices?

2. Is the introduction of trade benefitting both regions at an aggregate level? To answer this question we focus on the changes in consumption due to the introduction of electricity trade.

3. What is the sectoral effect for the two regions? The change in sectoral outputs and production factors are studied



(a) BAU scenario (b) POL & POL$^+$ scenarios

Figure 2: Electricity prices in Europe and MENA for the BAU and the POL&POL$^+$ scenarios, with interregional electricity trade (solid line) and without (dashed line). *Nota bene:* the reason that the prices do not fully converge is due to cost factors and not because of the use of oligopolistic market power as was described above.

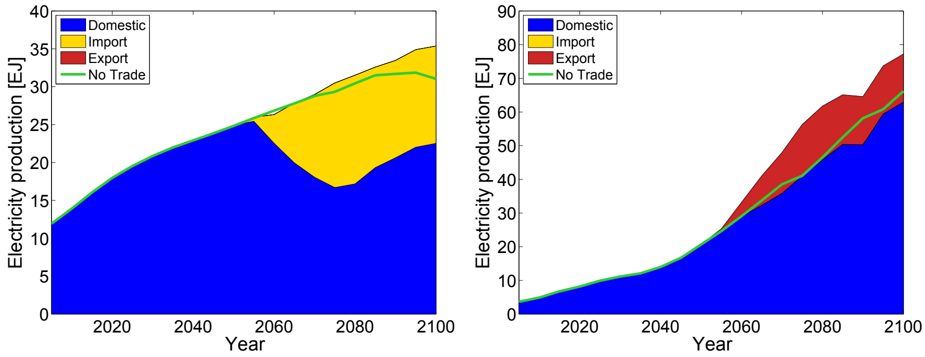
4. What is the effect on trade relations of third countries that are not involved in the electricity trade? We will analyze the effects also for the third countries that are aggregated to a rest-of-the-world (ROW) region.

We discuss the findings with respect to the insights we gained from the analytical model.

6 Results

The first of the above questions asks for the significance of climate change mitigation policies for triggering electricity trade. It turns out that the case without climate protection constraint does not induce electricity trade, because the electricity price differences in the two regions are negligible. However, the imposition of a climate change constraint would lead to remarkable and growing price differences between the two regions.

Fig. 2 shows the development of the prices. Fig. 2(a) indicates for the BAU scenario that the price differences are not sufficiently large to induce trade. For the POL scenario instead the prices would diverge; see Fig. 2(b). This is mainly due to Europe's small endowments with renewable energy sources that become more and more pressing. Allowing for the possibility of electricity trade in the case POL$^+$ leads to partial price convergence. The remaining gap is due to the 10% transmission losses and because of the infrastructure costs.



(a) Europe (b) MENA

Figure 3: Electricity production and trade in the two policy scenarios.

The price development is reflected in the production, consumption and trade flows of electricity in the two regions. Fig. 3 shows the production of electricity in the POL scenario (green line). In the POL$^+$ scenario electricity production in Europe decreases (blue area in Fig. 3(a)), but it is overcompensated by the imports (yellow area). Hence, Europe has more electricity available at lower prices.

Fig. 3(b) shows the effects for MENA. The production of electricity increases (blue plus red area), but part would go into export (red area). Domestic consumption (blue area) is slightly lower than in the case without electricity trade. Hence, MENA consumes less electricity at higher prices.

These effects are in correspondence with the findings of the analytical model. Moreover, the total electricity production in both regions would increase by trade. Hence, electricity trade uses more of the natural endowment of MENA that was non-tradable and left fallow. This issue was noted as a shortcoming of the analytical model and lead us to the effect considered in the derivative in Eq. 21.

In the following we use an economic decomposition analysis to answer the other questions. The decomposition computes the undiscounted cumulative differences between the cases POL and POL$^+$. The graphs indicate first of all the effect on consumption. The remaining bars explain the different sources that explain this effect. Positive (negative) values mean that the factor contributes to additional (less) means to finance consumption.[3]

[3]For the traded goods, which are indicated by green-yellow toned colors, this combines the price and the quantity effects. Thus, the signs of the bars do not reveal whether price or quantity changes are the reason.

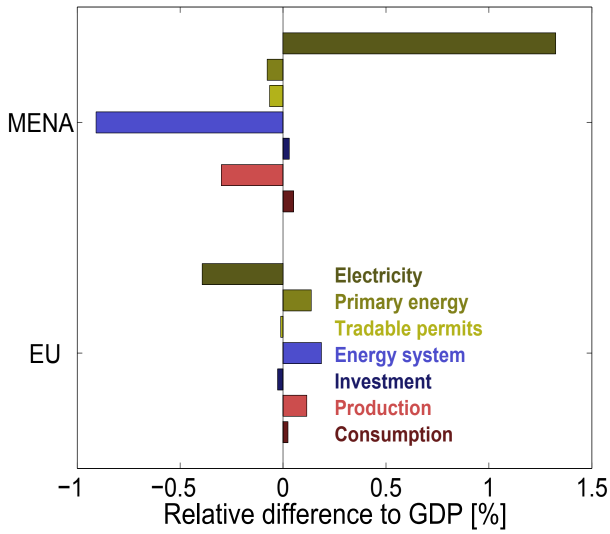


Figure 4: Decomposition of the budget equation and the inter-temporal balance of payments (BOP) for the regions Europe and MENA. The abscissa shows the cumulative differences of the case with and without trade over the period 2005 – 2105 relative to the GDP in the case without trade.

Fig. 4 presents the decomposition analysis for the regions Europe and MENA. It shows that the effect on consumption is positive for both regions, thus, the introduction of electricity trade is mutually benefittial. Since MENA is not allowed to exercise oligopolistic market power as discussed above, it is not possible that it suffers from a reduction of rent incomes from strategically constraining the resource supply.

The effect on macroeconomic activity measured in terms of GDP differences in the two regions is of opposite sign. Europe increases production because it has more electricity available, but MENA reduces macroeconomic output due to lower domestic electricity consumption. Hence, Europe can finance additional consumption from increased overall economic income, and *vice versa* for MENA. This comes with an increase of macroeconomic investments in Europe, which requires financial means that are not available anymore for consumption. The opposite holds for MENA. These effects are explained by the analytical model. The effect on investments is corollary to the effect on interest rates noted in that context: increasing interest rates in Europe are an incentive to increase investments; *et vice versa* for MENA.

The energy system costs in Europe are significantly decreased because of lower electricity production. The additional infrastructure costs that are contained in this effect are relatively small compared to the effect regarding generation capacities and

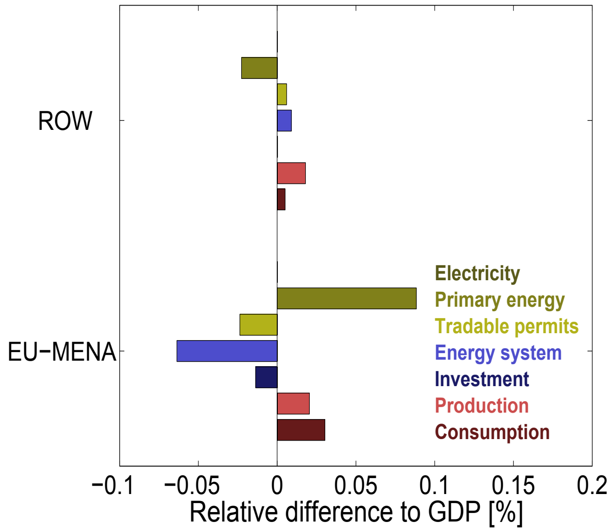


Figure 5: Decomposition of the budget equation and the inter-temporal BOP for the regions Europe and MENA. The abscissa shows the cumulative differences of the case with and without trade over the period 2005 – 2105 relative to the GDP in the case without trade.

domestic fuel production. MENA, instead, allocates more financial sources to the energy sector, since they increase the generation capacity for export.

Next we turn to the effects of traded commodities. Europe spends slightly more on tradable emission permits, but gains from less expenditures for imported primary energy carriers. The effects for MENA are negative regarding both commodities. The effects are surprisingly small. This is due to the outcome of the POL scenario in which Europe especially uses more nuclear power that it has to import from other regions than MENA. The import of electricity mainly substitutes nuclear power in Europe by electricity from solar sources. The effect on the other countries will be discussed below.

Last but not least, the effect of electricity trade is the single most important one in both regions. Europe has to finance the electricity imports (i.e. the financial flow to MENA), which is not available anymore for consumption. However, this is the source of financial means for MENA that works against the negative effects mentioned above.

Finally, we focus on the effects on the other regions. Fig. 5 shows the same economic decomposition analysis for two regional aggregates: EU-MENA is the aggregate of the two regions engaged in electricity trade and ROW (rest of the world) is the aggregate of all other regions.

The effects on ROW aggregate are relatively small. However, consumption and GDP are increased, which implies that third countries not engaged in electricity trade gain at the macroeconomic level. The negative effect on primary energy due to reduced uranium imports by Europe was already mentioned above and discussed in the context of the analytical model. However, it is overcompensated by increased GDP, reduced energy system costs and a positive effect from emission permit trade. The analytical model showed that the qualitative effect on consumption was not *a priori* determined. It was also possible that it turns out to be negative.

For the EU-MENA aggregate we observe that consumption and GDP are both increasing, though increasing GDP requires more investments in macroeconomic capital. Moreover, the effects on energy systems costs and trade of primary energy indicate that electricity trade induces a substitution process in the energy sector towards capital intensive technologies reducing the expenditures for primary energy.

7 Discussion and Conclusions

The study of brought together the issue inter-continental electricity transmission and economic trade theory. The analysis was performed in an analytical and a numerical model framework. The analytical trade model indicated various adverse effects at the sectoral level that could even add up to negative effects at the aggregate regional level. The analytical model was used to identify the qualitative effects on the regional and sectoral levels that could be expected from numerical model results.

The numerical results of introducing electricity trade into a model with strong climate change mitigation policies were in line with the expected results. And it turned out that all regions would gain at the aggregate level. However, at the sectoral level the model indicated significant adverse effects. Most considerable are the negative effects on the European electricity sector, the macroeconomic sector and the resource exporting sector in North Africa as well as the resource exporting sector of the rest of the world.

These sectors may have major objections on the project, they could potentially be compensated by the winners of electricity trade. The key point – and here the study deviates from traditional analysis of trade and welfare – that the introduction of trade is not a public policy decision that can be influenced directly. The quest of trade is essentially connected to the investment of transmission lines; i.e. the infrastructure that renders possible trade.

Somebody needs to finance the infrastructure, but losers do not have the incentive to do so. One could consider the European electricity sector as the natural entity from a technological point of view. Differently, the North African resource export sectors could be considered as a group with sufficient financial means to undertake the investment. However, these sectors would lose from the introduction of electricity trade because it decreases their rent incomes.

The study therefore identified considerable economic and political barriers to the implementation of a infrastructure project that would reduce the costs of climate change mitigation for all regions at the aggregate level. The analysis shows that the policy advice regarding the introduction of electricity transmission infrastructure is not only about technology and cost parameters, but needs also to take into account the distributional effects of trade. Hence, the study provides useful insights by combining technology specific engineering based information with qualitative insights from economic trade theory.

A Appendix: Analytical proof for a maximum of $\mathcal{G}_f$

The proof is based on the Weierstraß theorem. Fig. 6 gives a sketch of the proof. The function $\mathcal{G}_f$ is assumed to be continuous. We know that for the case of autarchy $\sigma_f = 0$ the gains of trade equal one. For the case 2(b) we know that $\sigma_f > 0$ and $\mathcal{G}_f^{2(b)} > 1$. If the derivative at this position is negative we can conclude that there has to be at least one maximum, though the exact value of σ_f maximizing $\mathcal{G}_f$ is not determined. Hence, the task is to determine the sign of this derivative. If it is negative we conclude that there must exist a maximum. Without loss of generality we assume $\kappa > 1$.

The derivative of $\mathcal{G}_f$ taken from Eq. 18 at the location $\sigma_f^{2(b)}$ is:

$$\frac{\partial \mathcal{G}_f}{\partial \sigma_f}|_{\sigma_f=\sigma_f^{2(a)}} = (\alpha-1)(1-\sigma_f)^{-\alpha} + \kappa^\alpha(1-\alpha)\left(\rho+\frac{\sigma_f}{2}\right)^{-1-\alpha}\left(\rho+(1-\alpha)\frac{\sigma_f}{2}\right). \quad (23)$$

The sign of the derivative is negative, if the first term outweighs the second:

$$(\sigma_f-1)^{-\alpha} > \kappa^\alpha\left(\rho+\frac{\sigma_f}{2}\right)^{-1-\alpha}\left(\rho+(1-\alpha)\frac{\sigma_f}{2}\right). \quad (24)$$

This expression can be simplified by standard manipulations:

$$\left(\frac{1-\sigma_f}{\kappa}\right)^{-\alpha} > \left(\rho+\frac{\sigma_f}{2}\right)^{-1-\alpha}\left(\rho+(1-\alpha)\frac{\sigma_f}{2}\right). \quad (25)$$

The left hand side is always exceeds 1, because ,$0 < \sigma_f, \alpha < 1$ and $\kappa > 1$. The right hand side is always smaller than one due to the following reasons. The term

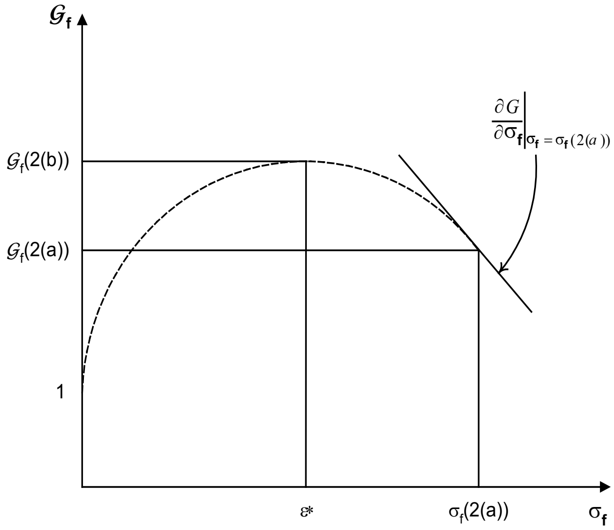


Figure 6: Sketch of the proof for a maximum of the function $\mathcal{G}_f$.

in the first parenthesis is always larger than the term in the second parenthesis. The exponent is always smaller than minus one. Hence, the right hand side is undoubtedly smaller than one. This condition determines the negative slope of the gains of trade function at the value of σ_f that emerged in case 2(a). Therefore, a unilateral reduction of exports $\epsilon < \sigma_f^{2(a)}$ would increase the gains of trade.

Continuity of the gains of trade function and the fact that the gains of trade are lower in the case of autarchy σ_f implies that there is an optimal value of ϵ that maximizes the gains of trade of the region f.

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Chapter 7

Synthesis and Outlook

The initial motivation of this thesis was to improve the understanding of major drivers influencing regional mitigation costs. Political negotiations focus mainly national emission reductions and allocation schemes of distributing emission allowances rather than on an acceptable and fair burden sharing in terms of mitigation costs. Against the background of the distributive dimension of climate policy, the aim of this thesis was to analyze the effects of the availability of low-carbon technologies, emission permit allocation schemes and energy trade on the welfare redistributions due to climate change mitigation.

The methodologic novelty of the thesis is the consideration of the three dimensions of technology, permit allocation and energy trade in a comprehensive model framework, together with the development of a formal economic decomposition method that renders a quantification of the impacts possible.

The importance of a broad portfolio of low-carbon technologies has already been underlined in previous studies. The first research question in the thesis aimed at revealing a far better understanding of the role of technologies: What is the impact of the availability of low-carbon technologies on global and regional mitigation costs? Another dimension is defined by potential devaluations of regional endowments with fossil energy carriers: What is the role of fossil energy carrier trade on regional mitigation costs, and how does it interact with the availability of low-carbon technologies? A third question asked for the influence of permit allocation schemes in a global cap-and-trade system: What are the distributive effects of permit allocation schemes, and how do they interact with the availability of low-carbon technologies? The interrelations of allocation schemes and technologies has received only few attention in existing studies. Finally, the fourth question considered interrelations of trade effects and technologies in the form of innovative infrastructure-based trade flows: What is the role of bilateral electricity transmission for regional mitigation costs?

In this chapter, I wrap up the overall conclusions of the thesis before going into the details of answering the research questions by summarizing and discussing the results from Chapters 2 to 6. Finally, an outlook on future research is given.

7.1 Synthesis: New Insights into the Distributive Impacts of Mitigation

A global policy to mitigate climate change leads to a significant redistribution of welfare among world regions due to region-specific devaluations of resource rents and to the distribution of the climate rent among the participants in a global cap-and-trade system. The redistributions lead to deviations of regional mitigation costs from the global average. Previous literature has pointed out the crucial role of low-carbon technologies to reduce global emissions and has revealed that international trade patterns are expected to change significantly under climate policy. Another strand of literature has assessed the distributive effects of permit trade under different permit allocation schemes. The novelty of this thesis lies in the approach to analyze the combined effects of technology, permit allocation and energy trade as well as their interrelations in a comprehensive model framework.

Before turning to the interrelations, the isolated effects of technology on the one hand, and trade (including trade in emission permits) on the other hand can be summarized as follows:

The availability of a broad portfolio of low-carbon technologies keeps global CO_2 prices low. It reduces global mitigation costs and - generally - also regional costs via changed macroeconomic variables that relate to domestic measures of the regions to comply with a global emission target. However, some regions might benefit from restrictions on low-carbon technologies on two different reasons. First, the exporters of permits benefit from a higher global CO_2 price. Second, particular regions benefit from a reallocation of the global emission reduction in some scenarios.

Endowments with tradable factors constitute another key impact on regional costs. As climate policy leads to a global reduction of demand for coal and oil, the resulting devaluation of coal and oil endowments contributes to relatively high mitigation costs of major exporters. The opposite holds for the exporters of natural gas and uranium, because these endowments are revalued in climate policy scenarios.[1] The determination of trade-related effects on regional mitigation costs is improved by the consideration of trade costs in the model.

From the perspective of this thesis, tradable emission permits constitute an additional factor endowment, whose initial allocation is subject to negotiations and not to natural conditions. Permit trade leads to additional regional profits or costs, which act as a pure redistribution among regions under certain assumptions. The choice of an initial allocation scheme can modify regional costs substantially.

Interrelations among the dimensions of technology and trade have not attracted much attention in previous studies. This thesis underlines the crucial role of interrelations for the distributive impacts of mitigation. Four links among technology-related effects and trade-related effects are of particular importance:

[1] The reason for the revaluation of natural gas endowments is a transitionally increased demand for natural gas due to its relatively low carbon intensity.

- A low CO_2-price reduces the monetary equivalents of traded emission permits, so that a variation of the initial permit allocation scheme has a lower redistributive impact. The importers of permits might hence see an incentive to promote the feasibility of innovative low-carbon technologies in order to keep CO_2-prices low.
- The preference order of regions for permit allocation schemes can be influenced by the availability of low-carbon technologies.
- The size of energy trade effects is subject to the availability of technologies, as shown by the example of a stronger devaluation of oils endwoments in scenarios without CCS.
- Technologies can take the role to render a new trade flow possible, for example an electricity transmission technology, which turns an untradable endowment (e.g., a huge solar potential) into an indirectly tradable (by electricity generation). Such additional trade options bear the potential to reduce global and regional mitigation costs.

Important conclusions for climate policy can be drawn from the results. International negotiations have been focused on national emission reductions so far, although the regional mitigation costs are the key variable that expresses each nation's burden to participate in the global mitigation effort. The results in this thesis might provide helpful advice for policymakers by revealing the effects on regional mitigation costs. This allows to distinguish negotiable parts of the costs (redistributions subject to the initial permit allocation) from un-negotiable ones (domestic and energy trade components).

Furthermore, climate policy should pay more attention to the relevance of the technology dimension. The international support and diffusion of innovative low-carbon technologies has received only minor attendance in previous negotiations. However, the global availability of technologies plays a crucial role not only to reduce mitigation costs on global average. Rather, it influences regional mitigation costs via complex mechanisms that are revealed in this thesis. Despite the complexity of all effects and their interrelations, the key message can be stated very clearly: Supporting innovative technologies by financing R&D and international knowledge transfer provides a chance to ease political negotiations on a global binding emission target and the initial allocation of emission permits.

Some of the results depend on the structure of the model used in the thesis, REMIND-R, and specific assumption in the considered scenarios. This defines caveats about the generalizability of the results and conclusions:

- A global cap-and-trade system is assumed. In other institutional frameworks, results and conclusions on the permit trade effect and its connection with other effects might not be applicable. But results on the domestic and energy trade effects require only the assumption of global participation. For example, a global carbon tax with domestic revenue recyling would lead to the same results, given that no uncertainties are assumed in the model (Weitzman, 1974). The regional mitigation costs reported in Chapter 4 for the reference allocation coincide with the regional costs in a global tax framework.

- According to model comparison studies, global CO_2-prices in REMIND-R are relatively modest (Edenhofer et al., 2010a; Luderer et al., 2010a). A prominent reason for that is the high degree of flexibility in the energy sector, which contains representations of a wide range of low-carbon technologies. The quantification of mitigation costs and of effects related to permit trade as well as their interpretation should be considered against this background.

- Further results are influenced by the structure of the energy sector in REMIND-R. For example, the analysis of fossil energy trade shows that oil demand is not strongly reduced by climate policy (as long as CCS is available). This is due to the fact that substitution of oil by other primary energy carriers is relatively costly.

- The separability of permit trade costs and profits from the efficient market allocation requires particular assumptions as discussed. Luderer et al. (2010b) show that the separability does not hold for the other models included in their study.[2] In the real world, limitations on the permit market or transaction costs can be expected to violate the assumptions.

- An immediate global participation in the global mitigation effort is assumed in the scenarios. The results especially on CO_2 prices and mitigation costs can hence be regarded as a lower benchmark of what can at best be attained, if world nations act immediately.

- Strategic behaviour of regions and sectors is neglected by the assessment of Pareto optimal solutions in a social planner perspective. The conclusions about acceptability of certain scenarios for particular regions or sectors are not meant to represent incentives in the strict sense of game theory.

However, the key messages and especially the qualitative assessment of the results can be expected to hold regardless of these caveats. This expectation needs to be verified by future research as described in Section 7.3.

7.2 Results and Discussion along the Research Questions

In order to answer the research questions, I followed the methodologic approach of model-based scenarios and their comparison. In preparation of the model analyses, I participated in the development, calibration and testing of the multi-regional intertemporal energy-economy modeling framework REMIND-R and its single-region precursor ReMIND-G.[3] The model structure and calibration are documented in the preceding chapters and the references given therein.

First I summarize the results for the thematic questions.

[2] Besides REMIND-R, Luderer et al. (2010b) consider the recursive-dynamic model IMACLIM-R and the intertemporal model WITCH.

[3] Please consider here and for the remainder of this chapter the Statement of Contribution in the Appendix that reveals my contribution to the model development and the analyses, results and interpretations and acknowledges the contributions of others.

Question A.1: What is the impact of the availability of low-carbon technologies on global and regional mitigation costs?

I address this question by performing policy scenarios under different assumptions on the availability of low-carbon technologies and the analysis of their differences in terms of energy mixes, trade flows and mitigation costs. In particular, the economic decomposition method allows to separate various effects how different assumptions influence regional costs. While the former is not new, the latter is a novel approach and enables me to understand results in the previous literature more in depth. The analysis considers a global single-region perspective in Chapter 2 and a multi-region perspective in the following chapters.

The well-known result that a broad portfolio of low-carbon technologies is essential to keep the global and, in general, also the regional costs of mitiagion low is confirmed in Chapter 2 and 3: Climate policy induces redirections of investments in the energy system towards technologies with lower specific emissions. The high flexiblity of the coupled energy-economy system to reallocate investments within a broad portfolio of technologies and adjusting demand to price changes implies low mitigation costs (less than 1% of consumption in Chapter 2, around 1% of consumption in Chapter 3).[4] The importance of flexibility in the coupled system also highlights the necessity to assess climate change mitigation costs in a hybrid energy-economy model framework.

Chapter 2 and 3 show that if technologies are removed from the portfolio of mitigation options, mitigation costs increase due to a reduction of flexibility. Of particular importance is the availability of biomass with Carbon Capture and Storage technology (CCS) and solar photovoltaics. Under climate policy, negative emissions generated by biomass with CCS allow for a continued use of hydrocarbons that are costly to substitute. High initial investment costs for solar photovoltaics need to be decreased by technology support that induces early learning investments. Considering individual model regions, MEA's large fossil endowments stand out.[5] They favor a production structure based on fossil fuels, so that restructuring the energy system in accordance with climate policy requires more effort than in other regions.

A comparison of the results obtained by a single-region and multi-region global model (Chapters 2 and 3) leads to the conclusion that the overall messages (global mitigation costs are on the order of 1% of consumption, a broad portfolio of options is crucial) coincide, but regional disaggregation leads to higher costs and changes the importance of options.

In Chapter 4, I shed more light into the effects on regional mitigation costs by determining the contributions of various domestic and trade-related effects. (The latter are tackled by questions A.2 and A.3.) I show that domestic effects are the major contribution to regional consumption losses in most regions and scenarios; under restrictions on low-carbon technologies, regional economies generally react by higher reductions in Gross Domestic Product. By exception, a welfare-maximizing allocation of mitigation efforts

[4] Please note that the climate policy targets in the different chapters are not exactly equivalent, so the resulting mitigation costs are not strictly comparable.

[5] MEA: model region Middle East and North Africa.

among regions leads to a decrease of GDP losses for regions RUS and LAM,[6] when CCS is not available. The reason is that RUS and LAM have a limited potential to employ other low-carbon technologies, so that these regions take a lower share in the global emission reduction.

Question A.2: What is the role of fossil energy carrier trade on regional mitigation costs, and how does it interact with the availability of low-carbon technologies?

A qualitative understanding of the influence of fossil exports on regional costs is provided by Chapter 3. Climate policy and technology scenarios change patterns of energy trade, indicated by decreased volumes and prices of fossil energy trade, in particular for coal. Hence, regions with high export share in trade of fossil resource lose revenues and bear the highest costs. However, the latter conclusion does not differentiate among coal, natural gas and oil.

Chapter 4 sheds more light into the role of fossil energy carrier trade. Again, the decomposition method turns out to be a fruightful tool for revealing the monetary impacts on regional mitigation costs. I show that climate policy induces a substitution from coal and oil to natural gas and uranium.[7] The substitution towards energy carriers with lower carbon intensity can also be observed from the results with a single-region model in Chapter 2. In a multi-regional framework, the according devaluation of oil and in particular coal endowments is an important contribution to the mitigation costs of exporters. This holds in particular for model regions RUS, MEA and ROW.[8] If CCS is not available, the compensation of emissions from continued oil use by negative emissions from biomass with CCS is not possible anymore. The model reacts by a significantly stronger devaluation of oil endowments. On the contrary, natural gas endowments are revalued, especially in scenarios where the usage of renewable energy is restricted.

The consideration of trade costs in the model reduces overestimations of specialization on international markets and according overestimations of trade flows (see answer to question B.2). It turns out that the devaluation of coal endowments due to climate policy is smaller when trade costs are accounted for, so that mitigation costs of coal exporters are lower (Chapter 5).

Question A.3: What are the distributive effects of permit allocation schemes, and how do they interact with the availability of low-carbon technologies?

First hints for answering the question are obtained in Chapter 3: As biomass with CCS allows to create negative emissions, the attractiveness of this option is enhanced by the

[6] RUS: Russia, LAM: Latin America.

[7] Uranium is not a fossil energy carrier, but a tradable primary energy carrier that is revalued by climate policy - subject to the availability of technologies. So it is useful to include it here in the debate.

[8] RUS: Russia, MEA: Middle East and North Africa, ROW: Rest of the World (Canada, Australia, Republic of South Africa, Rest of Europe).

generation of additional permits. This holds even under restrictions for a limited biomass potential, due to an increase of the carbon price. The results presented allow for a qualitative understanding of the influence of permit trade on regional costs and provide an explanation of regional costs only under the particular permit allocation rule used in the study.

This leads to the consideration of a variety of allocation schemes and the development of the formal decomposition method in Chapter 4. It turns out that the ”separability of equity and efficiency” (Manne and Stephan, 2005) holds in REMIND-R, so that the choice of an initial permit allocation scheme does not affect efficient solutions on all other markets. Domestic measures and energy trade can thus be separated from the initial permit allocation. Hence, a linear relation holds between the initial amount of permits allocated to a region and the mitigation cost of the same region.[9]

But the other way round, the impacts of the initial permit allocation on regional costs depend on the global permit market volume that is subject to the availability of low-carbon technologies. The range of redistributions implied by permit trade grows, when technologies are exluded from the portfolio of options. Hence, a broad portfolio of low-carbon technologies is important not only to keep global costs low: It reduces the redistributions implied by different permit allocation schemes, which might ease debates on the permit allocation in political negotiations. Especially rich countries that are importers of permits under most allocation schemes thus should have a vital interest to facilitate low-carbon technologies. In some instances, the exclusion of low-carbon technologies from the portfolio of options can change the region’s preference order for allocation schemes substantially.[10]

I conclude that permit allocation schemes can be designed to partially modify regional mitigation costs, for example with respect to compensating regions that are most affected by climate damages, or to increase acceptance of a climate treaty. The limits of this negotiable cost component are subject to the availability of technologies. It should be noted that these conclusions on increasing acceptance provide only hints. A reliable conclusion needs to be founded on an assessment that accounts for strategic behaviour of the actors.[11]

Question A.4: What is the role of bilateral electricity transmission for regional mitigation costs?

In Chapter 6, I consider a special case for the interrelations among the availability of technologies and international trade, namely infrastructure-based electricity transmission from MEA to EUR.[12] Based on according model extensions (see Question B.3), scenarios with and without the availability of the transmission infrastructure are analysed. An

[9] After the confirmation in Chapter 4 that the separability of equity and efficiency holds in REMIND-R, an assessment of various permit allocation schemes does not require several model scenarios anymore.

[10] This holds for model region Russia in case of the unavailability of CCS, see Figure 9(b) in Chapter 4, where the result has not been clearly pointed out.

[11] For example, previous game-theoretic analyses assessed incentives for stable climate coalitions among world regions (Lessmann et al., 2009; Lessmann and Edenhofer, 2010) and incentives of resource owners under different policies (Kalkuhl and Edenhofer, 2010).

[12] MEA: Middle East and North Africa, EUR: European Union (27 countries). The model region ’Middle East and Northern Africa’ is denoted as ’MENA’ in Chapter 6.

analytical model which is not in the scope of this thesis allows for comparison and generalization of the results.

It turns out that electricity transmission from MEA to EUR is globally profitable, but only in climate policy scenarios, and leads to a partial convergence of electricity prices and an increased electricity production in the aggregate of the two regions. Also third party regions that are not engaged in electricity trade gain at the macroeconomic level. The analytical model indicates that the profitability for MEA and third parties depends on further assumptions.

Investments into electricity trade infrastructure can be regarded as the opening of an additional trade flow which turns a non-tradable factor (MEA's solar potential) into an indirectly tradable one. EUR faces additional investment costs into the transmission line and epxenditures for importing electricity, and in turn reduces its domestic electricity production.

Now I turn to the methodological questions that are solved in preparation for answering the thematic questions.

Question B.1: How to quantify different contributions to regional mitigation costs?

The thematic research questions deal with the role of particular effects on regional mitigation costs. As a tool for providing answers, a formal method to separate and quantify individual contributions to regional costs in economic terms is presented in Chapter 4, and a preliminary version in Chapter 6.[13]

Starting point of the decomposition is the macroeconomic budget equation and the intertemporal trade balance in the model structure. Combining the equations and carefully taking intertemporal discounting into account, it is possible to express the intertemporally aggregated consumption difference between two scenarios as the sum of likewise aggregated contributions from domestic effects (e.g., changed GDP) and trade effects (e.g., additional revenues and expenditures on the permit market) for each model region. The method is applied in Chapters 4, 5 and 6.

Question B.2: How to improve the representation of fossil energy trade flows in the model?

Chapter 5 discusses the challenge of representing trade flows in intertemporal energy-economy models, but also the importance of accounting for trade flows in long-term mitigation scenarios. In the default version of REMIND-R, trade volumes of fossil energy carriers increase current empirical values by far. Accordingly, the model regions exhibit a strong degree of specialization on trade markets.

The explicit consideration of the costs of international trade in the model provides a fruightful strategy to improve the representation of fossil energy trade in REMIND-R,

[13] A more detailed documentation of the underlying calculus is found in the Appendix.

as shown in Chapter 5. Thereby, the assessment of the role of trade for regional mitigation costs was advanced considerably. The approach of accounting for trade costs in order to improve the representation of trade is in line with conceptual results in the literature (Obstfeld and Rogoff, 2000). I choose the approach to introduce trade costs in the context of an extended global market in Chapter 5, which is reasonable given currently observed convergence tendencies on the international markets for fossil energy carriers. While exporters supply to the market free of charge, importers are charged with a financial and an energetic loss component of trade costs. Cost parameters are derived from a survey of literature. The level of costs takes an average export-import-distance into account.

Question B.3: How to include trade in secondary energy carriers in the model?

The inclusion of international trade in secondary energy carriers into the structure of REMIND-R is described in Chapter 6. I follow the approach to model a bilateral trade infrastructure that is prerequisite for enabling secondary energy trade flows. The bilateral trade structure needs to be implemented both within the regionalized energy systems of participating regions and in the intertemporal trade balances of the regions. The reason to choose a bilateral structure is that in the case of electricity trade the costs of bilateral transmission infrastructure are not negligible compared to the value of the traded good.

7.3 Outlook on Future Research

As discussed in the previous section, my results are partly subject to particular characteristics of the REMIND model framework. Hence, a comparison with similar scenarios and analyses in other models is highly desirable in order to assess the robustness of my conclusions. The inclusion into a formal model comparison project would provide the most efficient way.[14]

Ideas for further research emerge from the results presented in this thesis. Some of the ideas can be realized within the existing model framework, while others require model extensions or even serious expansions of the model approach.

Within the existing model framework, the following research tasks are recommendable: The assessment of interrelations between the availability of low-carbon technologies and permit allocation schemes resulted in some unexpected conclusions on incentives for certain regions to promote the feasibility of particular technologies or the decision for particular allocation schemes. Further insights can be expected from the assessment of scenarios where low-carbon technologies are available only in some regions.

Policy scenarios that assume delayed participation in the global cap-and-trade system have recently received increasing attention (Luderer et al., 2010a). However, the distribu-

[14] Model comparison projects have been a fruitful tool in the integrated assessment community. Well-known examples are the Energy Modeling Forum (Clarke et al., 2009; Weyant, 2004), the ADAM's Model Comparison Project (Edenhofer et al., 2010a; Knopf et al., 2010a) and the RECIPE Model Comparison (Luderer et al., 2009).

tive impacts of delayed participation need further investigation by applying the analyses conducted in Chapter 4. Delayed participation leads to higher CO_2-prices equivalently to restrictions on low-carbon technologies. Hence, it can be expected that delayed participation induces similar effects as the assessment of technology scenarios (Jakob et al., 2010).

Furthemore, estimations of fossil reserves and extraction costs are highly uncertain. Sensitivity analyses on the impact of these uncertainties would be beneficial. The assessment how fossil scarcity affects *global* mitigation costs and strategies in Chapter 7.2 rises the intuition that a significant effect on regional costs can be expected.

Based on the current version of the economic decomposition method, a *time-dependent* decomposition would reveal the development of various contributions to regional mitigation costs over time. As shown in Chapters 3 and 5, profits and costs on trade markets change significantly over time for all regions. It can be expected that domestic contributions to regional costs are variable over time as well.

Another set of four further research tasks requires model extensions. First, the consideration of region-specific initial extraction costs for fossil fuels as well as the distinction of hard coal and lignite allows for a better representation of fossil energy trade in REMIND-R (Körner, 2010). The analysis of fossil trade flows and their impacts on regional costs would be more reliable if this novel model feature is taken into account.

Second, further trade flows should be included in the model to analyze their relevance for regional mitigation costs and strategies. Most prominently, the option to trade biomass and biomass-based fuel products internationally is prevalent already today and is expected to become even more important in the future (Erb et al., 2009; Heinimö and Junginger, 2009).

Third, the quality of the conclusions would benefit from further progress in the model approach to trade in general: Trade flows in the aggregated macroeconomic good are not sufficiently represented. Model results for trade volumes and the direction of trade flows in the next decades are in mismatch with empirical data. A revision of trade dynamics will clearly influence energy trade patterns as well, due to the linkage of trade revenues in the intertemporal trade balance. Current research to improve the macroeconomic good trade in REMIND-R includes regionally differentiated time preference rates and the consideration of regional investments for research and development (Leimbach and Baumstark, 2010).

Fourth, the analysis has been restricted to mitigation of CO_2 emissions in the energy sector. However, low-stabilization scenarios requires strong action to reduce also land-use CO_2-emissions and non-CO_2 emissions. Including these options modifies the regional mitigation cost patterns (den Elzen et al., 2008). The effects behind could be displayed as separate components in the economic decomposition method in order to add the multigas dimension to the analysis of effects on regional mitigation costs and their interrelations.

Expansions of the model approach beyond the social planner perspective and the assumption of a Pareto-optimal solution would be beneficial to shade more light into the distributive perspective of mitigation policy. In particular, the inclusion of strategic behavior into the model structure becomes even more important regarding the dynamics of international negotations on climate policy.

In summary, the results in this thesis, although obtained under some limiting assumptions, serve as a good starting point for several future in-depth analyses on the distributive effects of global climate change mitigation.

Chapter 8

Robust options for decarbonisation* (Appendix)

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Chapter 16

Robust options for decarbonization

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Thomas Bruckner, born in 1966, completed his doctoral studies in theoretical physics at the University of Würzburg, Germany. After four years at the Potsdam Institute for Climate Impact Research (PIK), he led the research group on Energy System Optimization and Climate Protection at the Institute for Energy Engineering at the Technical University of Berlin (2000–2008). Currently, he holds the Chair of Energy Management and Sustainability at Leipzig University, Germany. He is a fellow of the Heisenberg Programme of the German Research Foundation (DFG), a visiting scientist at the Potsdam Institute for Climate Impact Research, and a member of the Intergovernmental Panel on Climate Change. His current research focuses on integrated assessment modelling and the investigation of liberalized energy markets facing climate protection constraints.

Note: Photos and biographies of co-authors can be found in the appendix.

Since 2007, the perceptions of the international community all over the world about the dangers of climate change and about the need for vigorous response strategies have changed dramatically. This change was triggered by the release of the Fourth Assessment Report (AR4) *Climate Change 2007* by the Intergovernmental Panel on Climate Change (IPCC) and by the ongoing scientific progress in the field of global climate change. The scientific consensus reported in the AR4 received an unprecedented echo in the media and subsequently raised the public awareness concerning global climate change and its adverse impacts to an extent never seen before. As a result, the report encouraged numerous initiatives to combat global climate change – most notably the European Union's decision to reduce greenhouse gas (GHG) emissions by 20 % by 2020 (compared to the amount of GHGs emitted in 1990). In addition, more than 100 countries followed the European example and adopted a global warming limit of 2 °C or below (relative to preindustrial levels) as a long-term climate protection goal.

In order to assess the opportunity to stabilize carbon dioxide (CO_2) concentrations at a level that is compatible with the EU climate protection goal, the following issues need to be addressed. Which temperature changes are to be expected in the business-as-usual case, in other words, if no specific measures directed at mitigating climate change are implemented? Is there thus a real necessity to change course? If there is a real necessity, could cheap energy efficiency improvements solve the problem? If we need other, additional climate protection options, then which technologies are available and how great are the potential and available resources for the respective options? And finally, how should these options be combined in order to achieve least-cost climate protection?

Projected energy demand and associated business-as-usual greenhouse gas emissions

An extensive review of recent long-term scenarios (Fisher *et al.,* 2007) revealed that enhanced economic growth is expected to lead to a significant increase in gross domestic product (GDP) during the twenty-first century (see Fig. 1a) – throughout the world but especially in the developing countries and emerging markets. The expected rise in prosperity will reveal itself in a significant increase in the demand for energy services. Motivated by the first oil crisis, humankind was able to reduce the primary energy input required to produce one GDP unit (the so-called primary energy intensity) und is expected to do so further in the future (see Fig. 1b). Unfortunately, the historical improvements in energy intensities were not sufficient to fully offset the GDP growth, resulting in increased energy consumption.

The respective increase in energy efficiency in the scenarios is more than compensated by the anticipated huge economic growth. In the business-as-usual case,

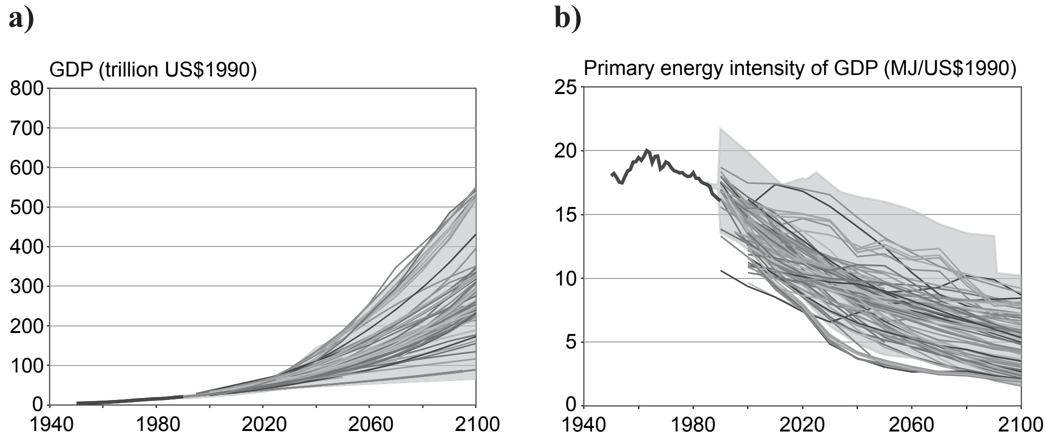

Fig. 1. a) Projected global economic growth and b) changes in primary energy intensity. (*Source:* adapted from Fisher *et al.,* 2007, pp. 180 and 184)

the demand for global primary energy is therefore projected to increase substantially during the twenty-first century (see Fig. 2 a).

Similarly to the development of the primary energy intensity, the carbon intensity (the amount of carbon dioxide emissions per unit of primary energy) is – with few exceptions – projected to decrease as well (see Fig. 2 b). This development reflects the global tendency to initially replace coal by oil and subsequently oil by gas, nuclear energy, and renewable energies.

Despite the substantial decarbonization projected to take place during the entire twenty-first century, even in the reference scenarios that do not include any explicit policies directed at mitigating climate change, the overwhelming majority of the emission projections exhibit considerably higher emissions in 2100 compared with those in 2000 (see Fig. 3 a). Due to the long life-time of carbon dioxide, this implies increasing carbon dioxide concentrations and in turn, increasing changes in global mean temperature throughout the twenty-first century. Figure 3 b shows the respective changes (together with the uncertainty range due to differences in the applied general circulation models, right-hand bars) for representative emission scenarios (so-called SRES scenarios, see Nakicenovic *et al.,* 2000) taken from the set of emissions scenarios shown in Figure 3 a.

The threat of global climate change: avoiding the unmanageable

Compared with the preceding Third Assessment Report, the IPCC AR4 reflects a considerable improvement in our understanding of global warming. The report itself and the ongoing scientific progress achieved since then show an increasing recognition that the severity of the global climate change problem has been significantly underestimated in the past (Smith *et al.,* 2009; Meinshausen *et al.,* 2009).

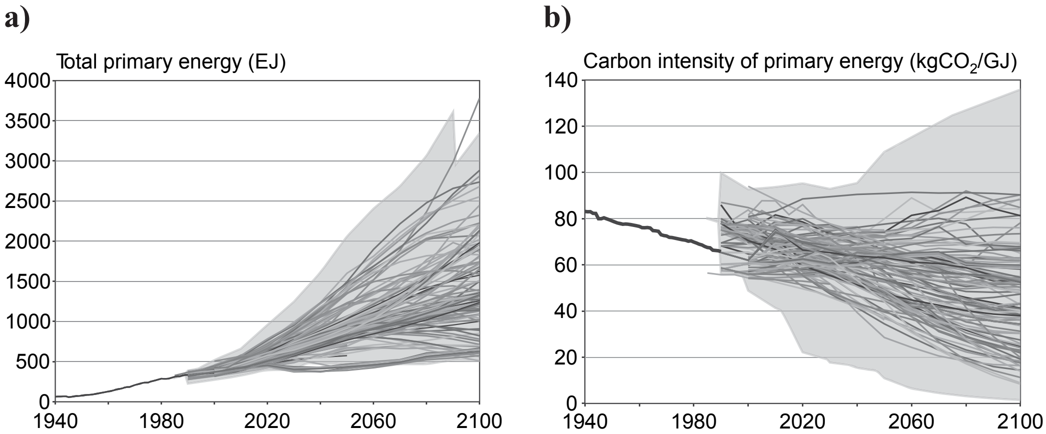

Fig. 2. a) Projected increase in primary energy supply and b) expected carbon intensity changes. (*Source:* adapted from Fisher *et al.,* 2007, pp. 183–4)

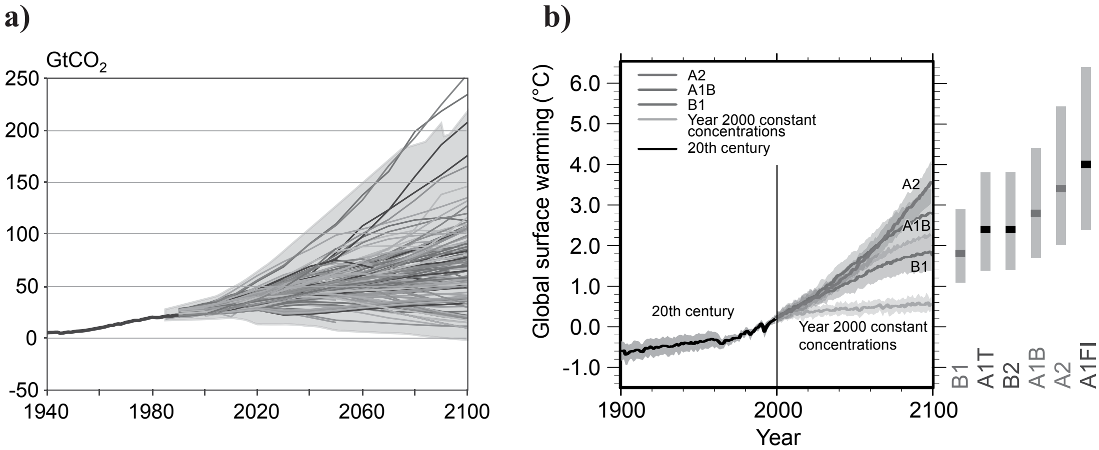

Fig. 3. a) Projected growth of carbon dioxide emissions and b) associated global mean temperature changes (relative to the temperature in 2000). (*Source:* adapted from Fisher *et al.,* 2007, p. 187; IPCC, 2007, p. 14)

According to its mandate, the IPCC is charged with summarizing the published scientific findings on global warming, its potential impacts, and opportunities to mitigate them. As a scientific council, the IPCC itself is not allowed to give specific policy recommendations concerning a suitable ceiling on global mean temperature rise to avoid dangerous interference with the climate system. Nevertheless, the information provided in AR4 (see Yohe *et al.,* 2007) supports the prominent climate protection goal that seeks to constrain global mean temperature change to less than 2 °C. This temperature threshold has been recommended by various advisory groups (e.g., the German Advisory Council on Global Change) in the past and became the official climate protection goal of the European Community in 2005.

Since then, more than 100 countries have adopted this global warming limit (Meinshausen *et al.,* 2009).

Assuming a best-guess climate sensitivity, staying below 2 °C implies that the CO_2-equivalent concentration would need to be stabilized at below 445 ppm (see Fig. 4 a), compared to current concentrations of about 430 ppm CO_2-equivalent. That effectively means that we are already right at the limit of acceptable GHG concentrations in our atmosphere. Consequently, global emissions must decline significantly over the coming decades, with a global peak in emissions in the next five years. By 2050, emissions need to be reduced well below 50 % (compared with the emissions in 2000). Halving emissions by 2050 would still bear the risk of exceeding 2 °C with a probability of up to 50 %. Stronger emission reduction and more stringent stabilization goals are obviously necessary to decrease this probability.[1]

The boundaries of the corresponding emissions corridor shown in Figure 4 b are based on the range of scenarios discussed in the literature that stabilize at 2 °C (with high probability), and are not necessarily admissible emissions paths themselves. Those paths that exhibit high values in the first half of the century have to decline rapidly thereafter and to become low-lying trajectories in the second half of the twenty-first century. A delay in implementing effective emission mitigation measures at an early stage might even require negative emissions in the long term, and would be extremely difficult to achieve. One possibility to achieve negative emissions is by using biomass energy in combination with carbon capture and storage technologies (BECCS) – an option that has recently attracted increasing scientific interest.

Energy efficiency improvement: necessary, but not sufficient

Achieving the deep emission reductions discussed above requires a comprehensive global mitigation effort. Existing climate protection strategies in industrialized countries need to be further tightened. Simultaneously, ambitious mitigation measures need to be implemented in developing countries, where most of the increase in greenhouse gas emissions is expected in the coming decades (Fisher *et al.,* 2007, p. 199). Fortunately, numerous options are available that can facilitate the achievement of this goal:

- Improvement in energy efficiency
- Switching between fossil fuel types (e.g., replacement of coal by gas)
- Zero- or low-carbon energy conversion technologies (e.g., renewable energies)

[1] A recent discussion of this issue was provided by Meinshausen *et al.* (2009).

a)

CO_2-eq concentration (ppm)	Global mean temperature increase above preindustrial at equilibrium, using "best estimate" climate sensitivity (°C)	Peaking year for CO_2 emissions	Change in global CO_2 emissions in 2050 (% of 2000 emissions)
445-490	2.0-2.4	2000 - 2015	-85 to -50
490-535	2.4-2.8	2000 - 2020	-60 to -30
535-590	2.8-3.2	2010 - 2030	-30 to +5
590-710	3.2-4.0	2020 - 2060	+10 to +60
710-855	4.0-4.9	2050 - 2080	+25 to +85
855-1130	4.9-6.1	2060 - 2090	+90 to +140

b)

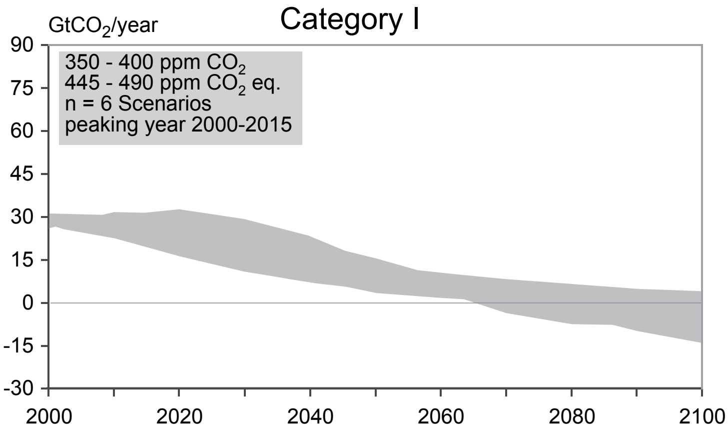

Fig. 4. a) Different carbon dioxide concentration ceilings (expressed in terms of CO_2-equivalent concentrations), their corresponding global mean temperature changes, latest point in time to shift to declining emissions and percentage emissions reduction in 2050 required to obey the stabilization goal. b) Set of emission pathways which meet the most stringent goal listed in the left-hand table. To meet the low stabilization level some scenarios deploy removal of carbon dioxide from the atmosphere (negative emissions). (*Source:* adapted from Fisher *et al.,* 2007, p. 199 and p. 229)

- Capture and storage of carbon from fossil fuels
- Reduction of non-CO_2 greenhouse gases (multi-gas strategy)
- Mitigation through improved land-use (e.g., reduced deforestation and afforestation)

Strategies to reduce multi-gas emissions can help achieve climate protection targets at substantially lower cost compared with emission mitigation efforts that address the release of carbon dioxide only. This is especially the case during the first half of the century, but in the long run it is essential to achieve deep reductions of carbon dioxide in any case, since carbon dioxide has a very long life-time (more than 20 % of emissions remain in the atmosphere over thousands of years, Archer *et al.,* 2009). In addition, land-use mitigation options could provide 15 – 40 % of the total cumulative abatement over the twenty-first century. Most such options are projected to be cost-effective strategies across the entire century (Fisher *et al.,* 2007, p. 172).

A tremendous decrease in energy intensity in the coming decades is essential if we are not to transgress the aforementioned 2 °C guardrail. Technological improvements and structural changes are expected to result in considerably lower greenhouse gas emissions than would otherwise be experienced. Assuming energy and carbon intensities frozen at current levels, for instance, would imply hypothetical average cumulative business-as-usual emissions that are roughly twice as high (see Fig. 5 a) as the baseline emissions projected for the suite of emissions trajectories depicted in Figure 3 a. The same message is visualized in Figure 5 b. Once again, assuming no improvement in the energy intensity (for instance, in the case of the SRES A2 scenario considered here), would result in considerably higher hypothetical emissions, even under business-as-usual conditions.

Many low-cost options to improve energy efficiency and to change the relative shares of fossil fuels in the provision of end energy are already contained in the baseline development. Therefore, there is restricted potential to achieve deep emission reductions by additional cost-effective energy efficiency improvement and fossil fuel switching measures.

An example showing a stabilization of the carbon dioxide concentration at 550 ppm is given in Figure 5 b where the (additional) contribution of demand reductions is small compared with the shares achieved by switching to low-carbon fuels (including shifts to nuclear energy and renewables) and carbon sequestration technologies (scrubbing). In order to achieve deep emission reductions (e.g., more than 50 % by 2050 compared to 2000), energy efficiency improvement and fossil fuel switching measures do not suffice. In addition, the application of low-carbon technologies becomes imperative.

Innovative low-carbon technologies

Fortunately, numerous technologies exist which are capable of providing final energy while producing no or significantly less carbon dioxide compared with conventional fossil fuel burning (renewables, nuclear energy, and carbon capture and storage).

As Table 1 shows, there is abundant technological potential for renewable energies worldwide that would, in principle, suffice to meet even the highest projections of the total global primary energy demand in 2100 (see Fig. 2). The available wind potential (600 EJ/yr) alone would hypothetically be able to cover the entire primary energy demand of the world in 2005 (490 EJ). Even higher potentials are estimated for solar and geothermal energy (see Kohn, this volume).

Some important sources (especially wind and solar energy) exhibit an intermittent

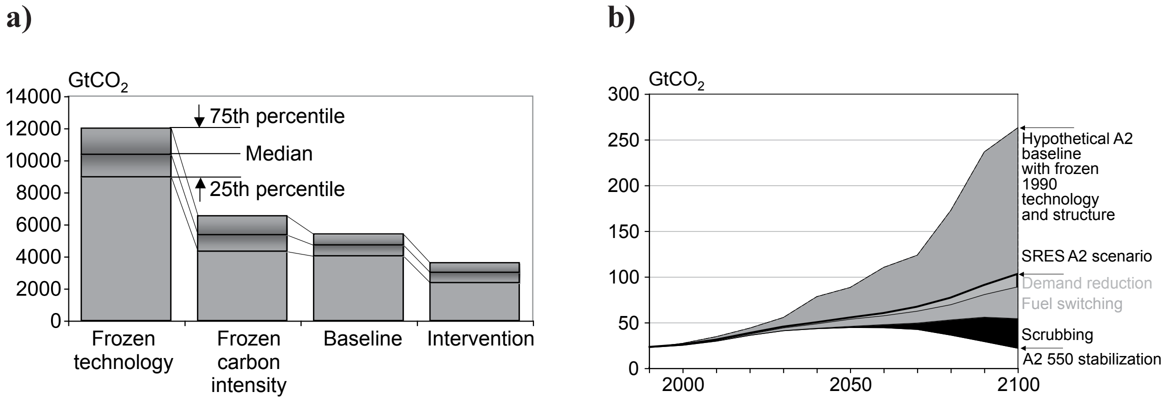

Fig. 5. a) Range of the global cumulative emissions emitted until 2100 for the different non-intervention scenarios shown in Fig. 3 a. 'Frozen technology' refers to the range hypothetical scenarios would exhibit without any improvement in energy and carbon intensities. The next bar shows the cumulative emissions assuming frozen carbon intensities and the third bar exhibits those emissions expected in the baseline (non-intervention) scenarios – where both energy and carbon intensity improvements are taking place. b) Contribution of different mitigation options to achieve a stabilization of carbon dioxide concentrations at 550 ppm (assuming a baseline development according to the IPCC SRES A2 baseline scenario without measures and policies directed at reducing GHG emissions). (*Source:* Fisher *et al.,* 2007, pp. 219–20)

availability dependent on daytime, season and weather conditions. In addition, renewable energy sources (with the exception of large-scale hydro-energy) are widely dispersed compared to fossil fuel deposits. Innovative concepts are available which can mitigate these drawbacks considerably by a combination of distributed usage (including appropriate communication strategies), storage, demand response, increased power system stability through the use of flexible alternating current transmission systems (FACTS) and interregional exchange (see Luther, this volume). Although renewables are in principle able to substitute fossil fuels completely, further research is needed to design integrated systems that exhibit low costs for the systems services envisaged here.

Nuclear energy is able to produce electricity with no (if only emissions at the power plant site are considered) or medium to low carbon emissions (if upstream emissions related to fuel supply and the construction of the power plants are taken into account). Under the present design of light-water reactors with a 'once-through' fuel cycle, however, the finite uranium resources (see Table 1) constrain the ability of nuclear energy to be the main lasting alternative to fossil fuel usage. Fast-spectrum reactors operated in a 'closed' fuel cycle by extracting the unused uranium and plutonium produced would solve this problem, albeit by accepting that reprocessing of the spent fuel increases the proliferation risks and security concerns. Beyond the long-term fuel resource constraints without recycling, there

Table 1. *Summary of global energy resources (including potential reserves) and their share of primary energy supply in 2005 (490 EJ). For renewable energies the technical potential is shown which takes into account conversion efficiencies as well as constraints on the available area. In contrast to the economic potential no explicit reference to cost is made.* (*Source:* Sims *et al.,* 2007, p. 264)

Energy class	Specific energy source	Estimated available energy resource (EJ)	2005 share of total supply (%)
Fossil energy	Coal (conventional)	> 100 000	25.0
	Coal (unconventional)	32 000	
	Gas (conventional)	13 500	21.0
	Gas (unconventional)	18 000	
	Coalbed methane	> 8 000	0.3
	Tight sands	8 000	0.7
	Hydrates	> 60 000	
	Oil (conventional)	10 000	33.0
	Oil (unconventional)	35 000	0.6
Nuclear	Uranium	7 400	5.3
	Uranium recycle	220 000	
	Fusion	* $5x10^9$	
Renewable	Hydro (>10 MW)	60/yr	5.1
	Hydro (< 10 MW)	2/yr	0.2
	Wind	600/yr	0.2
	Biomass (modern)	250/yr	1.8
	Biomass (traditional)		7.6
	Geothermal	5000/yr	0.4
	Solar Photovoltaics	1600/yr	< 0.1
	Ocean (all sources)	** 7/yr	0.0

* estimated ** exploitable

are major barriers to an extended usage of nuclear energy. They comprise huge investment costs associated with investment uncertainties, unresolved waste management issues, security aspects in general, and – for some countries – the resulting adverse public opinion (Sims *et al.,* 2007, p. 254). As in the case of renewables, for advanced nuclear systems to make a higher contribution to the total share of energy would also require substantial cost reductions. Worldwide, only a few consortia are able to build nuclear power plants. With the current generation of power plants rapidly approaching the end of its lifetime, a significant share of the capacity of the nuclear industry is already needed even to secure a constant contribution made by nuclear energy to overall electricity production. On a global scale, sharing nuclear know-how is significantly constrained by commercial interests and security concerns. This could cause a significant bottleneck in attempts to solve the climate problem involving a pronounced contribution from nuclear energy.

Fossil fuel usage in combination with carbon capture and storage (CCS) technologies is a further option whereby a share of the future global energy supply could be produced with significantly lower carbon dioxide emissions. From a resource perspective, lower power plant efficiencies would result in an accelerated depletion of the fossil fuel resources. Due to the abundant availability of coal and potentially also hydrates (see Table 1), this, however, would not impose a major restriction on extensive application of coal-fired CCS technologies.

Although CCS can play a role in mitigating global climate change – at least as a transitional technology – its actual contribution may nevertheless be limited by the restricted availability of suitable geological disposal opportunities as well as by concerns about unintended leakage, risks associated with an accidental release of carbon dioxide, and environmental consequences. While deep ocean sequestration is another option, ocean eddy diffusion could potentially lead to a much larger region being affected with undesirable consequences than would be the case for sequestration in geological formations. Moreover, residence times of sequestered carbon dioxide are expected to be in the order of hundreds of years in the ocean, while potentially orders of magnitudes larger in formations. Finally, some of the authors (Edenhofer *et al.,* 2005; Held *et al.,* 2006) have suggested bond schemes to utilize the investigative power of the capital market to search for the most trustworthy combinations of CCS operators and geological formations. Such schemes are much harder to envisage for ocean sequestration. For all of these reasons, current schemes to operationalize CCS focus on geological formations rather than the deep ocean. CCS technologies imply higher costs compared to conventional fossil conversion, so that substantial cost reductions would be necessary to make this option an attractive one.

Low-concentration stabilization scenarios

The role of oil/gas prices

Currently the world experiences significant changes in the prices of raw materials and energy in particular. Though primary energy prices have returned to moderate levels, the future availability of fossil energy carriers is unclear. Scarcity of resources is reflected in high extraction costs, which in turn imply high energy prices. Increasing oil and gas prices influence technological change in the following ways. First, they foster additional investments in exploring and exploiting new and more costly oil fields including those holding non-conventional oil. Second, increasing oil prices make options like coal-to-liquid profitable if coal is relatively abundant and cheap. In a climate protection scenario, the extensive use of coal can only become an option if it is combined with CCS. In a scenario assuming relatively cheap coal and expensive oil and gas, the 'clean' coal option becomes more important compared to a scenario exhibiting low costs for all fossil fuels (see Fig. 6). Third, high oil prices may also improve overall energy efficiency, reducing the emissions up to the end of the century even in scenarios without any explicit mitigation policies or measures. It should be noted that long-term price trajectories of fossil fuels are quite uncertain. It is less uncertain that prices of oil and gas will increase faster than the price of coal because of the large coal reserves. However, large negative externalities associated with coal production and coal usage are likely to increase the cost of coal in the long run.

Figure 6 reveals the relative importance of different emission mitigation options in achieving a stabilization of the carbon dioxide concentration at 450 ppm as obtained with the model REMIND, developed at the Potsdam Institute for Climate Impact Research (see Bauer *et al.,* 2008; Leimbach *et al.,* 2009).[2]

The upper boundary of the corridor shows the business-as-usual emission trajectory which is dependent on the costs of fossil fuels. It is noteworthy that the increase of oil and gas prices does not alter the portfolio of mitigation measures substantially. Energy efficiency improvements (here including shifting between use of different fossil fuels, co-generation, and changing demand for final energy) play an important role in meeting this goal. A further considerable reduction of the emissions is realized through the application of CCS technologies, applied to both fossil fuels and biomass. Other renewables, especially solar photovoltaics and wind energy, as well as nuclear energy (light-water reactors), contribute significant shares. Although included in the general analysis, fast breeder reactors did not find application here because of their high capital costs compared to other mitigation options.

[2] REMIND comprises a top-down optimal growth model of the world economy combined with a bottom-up technology-rich description of the global energy supply system. In addition, the model contains a carbon cycle and climate system sub-module. Taken together, these modules are able to determine least-cost climate protection paths that are compatible with prescribed ceilings on global mean temperature change (e.g., the 2 °C EU climate protection guardrail). In contrast to traditional integrated assessment models, the model especially takes into account the possibility of induced technological change. In order to achieve this goal, learning curves are used in an endogenous way. This specific feature allows the determination of long-term cost-efficient strategies that minimize the integral climate protection cost over the entire time span considered (e.g., 150 years).

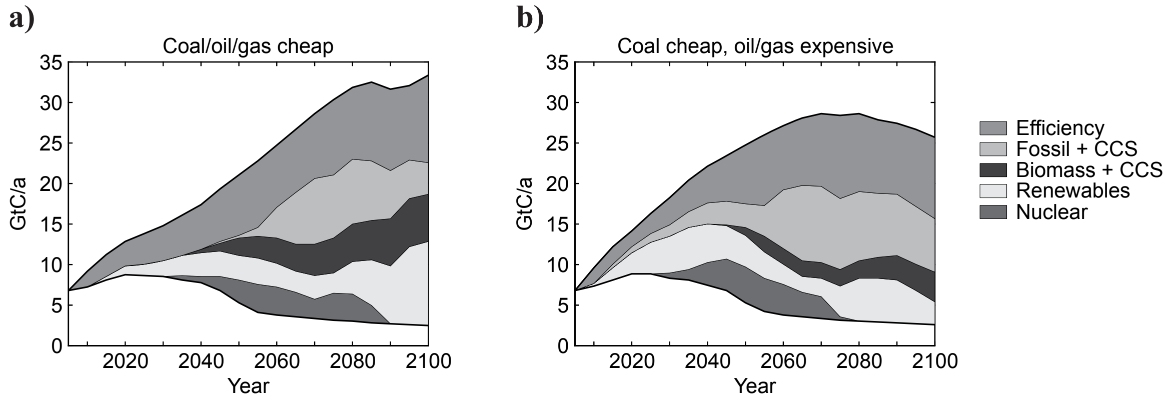

Fig. 6. The contribution of various mitigation options computed with the model REMIND for achieving the climate change stabilization target (450 ppm carbon dioxide). The upper boundary indicates the business-as-usual emissions, while the lower boundary represents the emissions in the mitigation scenario. The gap in between is filled by the contributions (so-called 'wedges') of emission mitigation options distinguished by the differently shaded areas. Panel a) shows the results for the case with cheap fossil fuels; panel b) shows the case with high costs for oil and gas. The pure rate of time preference for both cases is 3 % per year (see below).

The role of discounting

The Stern Review (2006) has launched an exciting debate about the appropriate pure rate of time preference.[3] The report argued that the pure rate of time preference is an ethical value judgment about the weight and importance of future generations in current investment decisions. It points out that there is no ethical reason why future generations should be regarded as less important in current investment decisions than the current generation. However, the pure rates of time preference observed on capital markets are much higher than the rate derived from ethical considerations. The Stern Review states that a pure rate of time preference of 0.1% is in accordance with intergenerational justice. Some authors choose a pure rate of time preference of 3 % in accordance with empirically observed behaviour on capital markets (see for example Toth, 1995). However the issue is much more complex, as Frederick *et al.* (2002) showed in an overview on the concept and measurement of discounting.

A lower pure time preference rate (1% per year) favours – already in the business-as-usual (BAU) scenario – the application of emerging technologies for using renewable energies (especially wind and biomass energy sources in early decades of

[3] In economics, the pure rate of time preference is used to quantify how present consumer utility is valued compared to future consumer utility. Someone with a high time preference is focused substantially on his well-being in the present and the immediate future, while someone with low time preference places more emphasis on his well-being in the distant future. In this subsection only the issue of the pure rate of time preference is discussed and not the related issue of the inter-temporal elasticity of substitution, which is assumed to be equal to one.

the twenty-first century, see Fig. 7) while reducing, in part, the necessity to use CCS technologies.

Figure 8 shows the influence of excluding some of the different low-carbon technologies discussed above. As can be clearly seen, the exclusion of CCS technologies would result in a significant increase in the emission mitigation costs computed with the model REMIND. Compared to that, abstaining from applying additional renewables in order to combat global climate change would have a small influence, whereas the exclusion of nuclear energy would result in additional costs that are almost negligible compared to the overall mitigation burden.

Creating a novel global energy system: the challenge ahead

As already pointed out above, achieving deep emission reductions requires a comprehensive global effort which includes both a complete change in the energy supply of industrialized countries and the establishment of low-carbon systems in developing countries and emerging markets – in short, nothing less than the creation of a completely novel global energy supply system. This would represent a true paradigm change compared with the current fossil-based energy systems and would take several decades to implement. In order to achieve this goal, the emissions mitigation measures must start immediately and rapidly engage the entire world. There is no time to waste. In a common effort, industrialized countries have to use their scientific capacity and creativity to develop and apply low-carbon technologies and to prove that a high standard of living can be sustained while producing considerably lower emissions in order to facilitate the early adoption of these technologies in the fast-growing emerging markets. The ultimate goal is a global carbon-free society.

Designing a cost-effective strategy to meet the climate protection targets discussed above (e.g., to limit global mean temperature increase to less than 2 °C relative to the preindustrial value) is a complex and dynamic problem. Although some conventional technologies (most notably, combined heat and power) might become economically viable once the costs of emission certificates increase, a major contribution towards achieving deep emissions reductions must be provided by the application of innovative low-carbon technologies. Unfortunately, some of these technologies are still prohibitively expensive. Anticipating learning capability and associated cost-reduction potential, however, is a key to resolving this problem.

While from an aggregated economic point of view, instantaneous massive investments into low-emission technologies seem to be optimal (Edenhofer *et al.,* 2006), more myopic agents (such as energy suppliers) may collectively act in such a way that the present-day energy system is conserved and consequently the global economy remains trapped in a suboptimal state.

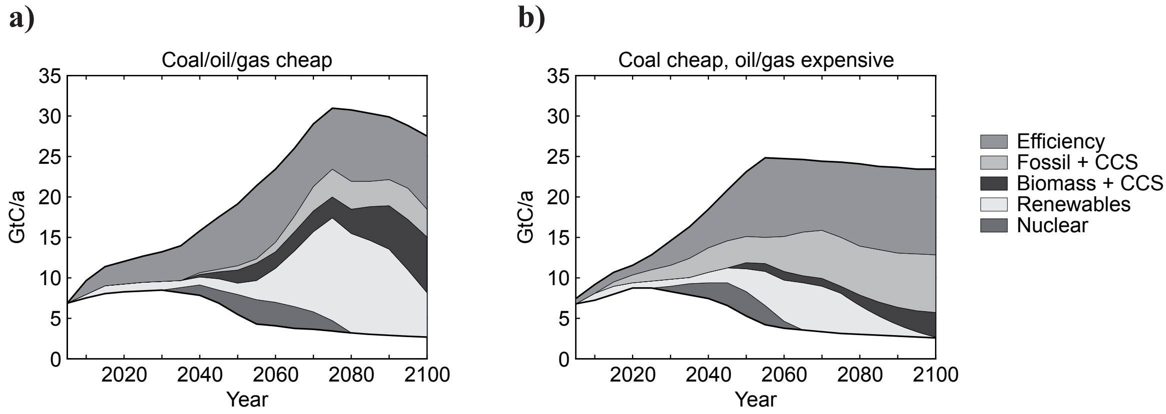

Fig. 7. Results of REMIND computations based on the same model assumptions as in Fig. 6 with the difference that a pure rate of time preference of 1% per year is applied.

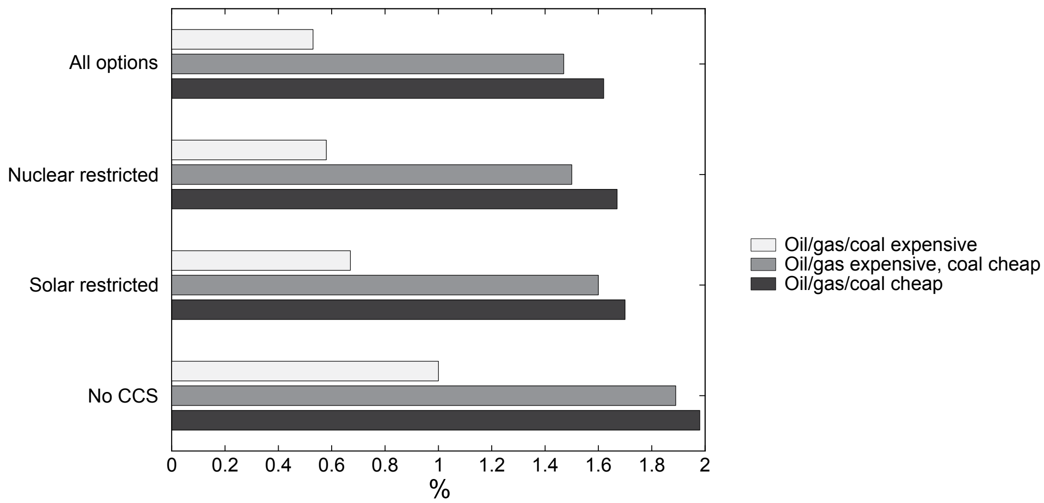

Fig. 8. (Monetary) consumption differences (i.e., relative reduction of per capita consumption in the stabilization case compared to the business-as-usual scenario). In the 'all options' case, all greenhouse gas mitigation opportunities discussed in Figures 6 and 7 (energy efficiency improvement combined with fuel shifting, renewables, nuclear energy and the application of CCS) are taken into consideration irrespective of their business-as-usual usage. In the other cases, some options are restricted to their respective usage in the business-as-usual scenario (REMIND model results, pure rate of time preference of 3 % per year).

Therefore, low-carbon technologies can only enter the market place if the cost of fossil fuel usage is increased significantly (e.g., through a worldwide carbon certificate market or carbon tax, see Edenhofer *et al.,* this volume). Without a reasonable price for carbon there are simply not enough incentives for firms and investors to foster a search process for the most cost-effective low-carbon technologies.

Fortunately, there are some recent promising initiatives in this direction: Chancellor Merkel has proposed a global carbon trading system, which would allow the reduction of emissions according to the 2 °C limit, at the same time implementing an allocation scheme that endows each citizen with the same emission rights. This proposal presupposes a global carbon market – otherwise the costs imposed on industrialized countries would not be acceptable. Negotiations have already started to harmonize and link the European Emission Trading Scheme with emission trading schemes emerging in California and elsewhere in the United States. The appropriate timing is essential because of the need for a continued signal to the carbon markets. Emissions trading, and related flexible mechanisms, are likely to remain a core element of any post-2012 regime.

Admittedly, emissions trading is only one necessary condition for achieving low stabilization targets. In fact, the Stern Review found that only 40 % of the low-carbon future can be financed through the carbon market (Stern, 2006). What is needed is a comprehensive suite of policies to shift the International Energy Agency's estimated figure of USD 20 trillion of energy investments by 2030 into low-carbon technologies and to assure these investments in the first place. On the national level, policy frameworks such as quota schemes or feed-in tariffs – or even a reasonably designed technology policy supporting demonstration projects for CCS but also for solar thermal power plants and other innovative technologies – are recommended. These would in particular allow the cost reductions inherent in technologies with high learning potential to be realized. On the international level, new innovative technology co-operation mechanisms will be required to both deploy existing technologies in emerging economies and develop and share new low-carbon technologies.

From a long-term perspective, a comprehensive global emission mitigation effort requires enhanced innovation to create novel low-carbon technologies, incentives to support their initial diffusion and the internalization of external costs (e.g. through emissions trading). Such a response to the dangers of global climate change would induce a transition towards a truly sustainable global energy system as a glorious 'side effect'.

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Chapter 9

A Global Carbon Market and the Allocation of Emission Rights* (Appendix)

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A global carbon market and the allocation of emission rights

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Abstract

Given that the 2°C implies that a certain budget of emissions may still be emitted it is debated how these emission rights could be allocated among the nations. The national emission reduction commitments and possible allocation rules of an emission budget play a major role in international negotiations as the idea predominates that these allocations will determine the distribution of the burden of climate protection. We point out here the importance of an international emission trading scheme (ETS) and analyse a number of allocation schemes and their influence on the regional mitigation costs based on an intertemporal general equilibrium model. Major differences can be discovered between the allocation schemes pursuing the "allocation of emission rights" versus "allocation of reduction efforts". But the allocation rule accounts only for one part of the overall mitigation costs and the full determination of these costs is much more complex. Beside the allocation rules the mitigation costs also depend on technological progress and on trade effects related to the devaluation of fossil resources. In that context the ethical presumptions and their implications on the assessment of the different allocation schemes are evaluated in terms of justice. Moreover the institutional requirements for a global cap and trade system are discussed.

Keywords: Emission trading, allocation rule, allocation of CO_2, justice, greenhouse development rights, C&C, emission reduction.

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1.1. Introduction

To pave the way for a new climate agreement has turned out to be extremely challenging. The negotiators struggle to make the required emissions reductions binding under international law and to agree on a burden-sharing among nations. Despite the fact that the G8 (Major Economics Forum, 2009) as well as the Copenhagen Accord (UNFCCC 2010) refer to the 2°C target, the current pledges of the nations would lead to a temperature increase of more than 3°C by 2100 (Rogelj et al., 2010). A reasonable climate policy architecture thus needs to (1) specify a binding overall carbon budget that is in line with the 2°C target, (2) decide on the regional allocation of this budget and (3) create the institutional framework for a global carbon market.

Given that the 2°C implies that a certain budget of emissions may still be emitted, it is debated how these emission rights could be allocated among the nations (e.g. WBGU 2009, den Elzen 2010, Chakravarty et al. 2009). The national emission reduction commitments (e.g. the pledges in the Copenhagen Accord, 2009) and possible allocation rules of an emission budget play a major role in international negotiations as the idea predominates that these allocations will determine the distribution of the burden of climate protection. We point out here the importance of an international emission trading scheme (ETS) and analyse a number of allocation schemes and their influence on the regional mitigation costs based on an intertemporal general equilibrium model. Major differences can be discovered between the allocation schemes pursuing the “allocation of emission rights” versus “allocation of reduction efforts”. But the allocation rule accounts only for one part of the overall mitigation costs and the full determination of these costs is much more complex. Beside the allocation rules the mitigation costs also depend on technological progress and on trade effects related to the devaluation of fossil resources. In that context the ethical presumptions and their implications on the assessment of the different allocation schemes are evaluated in terms of justice. Moreover the institutional requirements for a global cap and trade system are discussed.

1.2. Establishing an International Emissions Trading Scheme

Emission of CO_2 has to get a price that reflect the limitations of the deposit space of the atmosphere and that reflects the scarcity of the remaining atmospheric carbon budget that may still be deposited in the atmosphere in order to keep below the 2°C temperature goal. A price for CO_2 emissions can be introduced in two different ways: either by introducing a tax regime with national CO_2 taxes, or by a global ETS where emission rights are allocated among the nations and can be traded between countries. From the perspective of economy theory, taxes and emission trade are equivalent in a world without uncertainty. It has up to now been an economic commonplace that the allocative effects of taxes and quantity instruments will not differ from each other if the climate damages and/or costs of mitigation are known. However, in the case of uncertainty of the social planner and firms about damages and costs it can be shown that both instruments are no longer equivalent. Originally, Weitzmann (1974) formulated this model as a "flow problem" in which the damages are related to the annual rather than the cumulative emissions. Therefore, this frame of reference developed by Weitzman (1974) has first been regarded as inadequate for the climate problem. The climate problem however is a "stock pollutant" problem where the damages of climate change are determined by the cumulated budget of emissions, i. e. by the stock which is deposited in the atmosphere. It can, however, be shown that the basic statements of the Weitzman model are also valid for a "stock problem". Newell and Pizer (2003) demonstrated that under certain assumptions a tax is advantageous on the short-term; on the long-term, however, emission trading as a quantity instrument should be preferred. The reason for this is that in the long-term the damage function will, due to the accumulation of emissions, become steeper than the costs of emission mitigation which only depend on the flow of emissions. On the condition of a long-term "steep" damage function, the advantageousness of quantity control could already be derived in the original Weitzman model. In the light of the results, a tax solution should be preferred in the short-term and only in the long-term emissions trading should be opted.

It is, however, questionable if the selected model framework is suitable for the climate problem: Here, the social planner or a well-intentioned government plays against "nature", as the future climate damages and/or mitigation costs are uncertain. Thus, the decisive problem of the economy of climate change will not at all get into sight.

Large amounts of fossil fuels have to be left in the ground when climate policy is taken seriously. This makes it obvious that in case of a climate policy that wants to comply with a global carbon budget, the CO_2 tax would need to rise over time corresponding to the modified Hotelling rule (Edenhofer and Kalkuhl, 2009). But how will the suppliers of coal, oil and gas react on it? They will accelerate the extraction of their resource with the risk that the global carbon budget will be exceeded despite of a rising CO_2 price (see also the discussion about the "Green Paradox" in Sinn 2008 and Edenhofer and Kalkuhl, 2009). A CO_2 tax is therefore no effective instrument because it is rational for the resource owners to bring forward the extraction of fossil resources: otherwise, they need to expect that future profits will be strongly reduced. This incentive does not exist for emissions trading since a budget of emission rights is determined here a priori. The budget approach in combination with a global ETS has thus the potential to cut the Gordian knot of climate policy.

1.3. Distributional aspects of climate policy

In the following we will concentrate on the distributional effects of a global cap and trade emission trading scheme and evaluate different burden sharing regimes according to their level of global equity. It becomes clear that when CO_2 is strictly limited, mitigation is not only a technical issue but becomes a distributional question: how are emission allowances allocated among nations? What is a fair burden sharing and what is accepted by all players? On the global level it can be shown that the costs for climate protection are moderate (Stern 2007, Edenhofer 2006, Edenhofer 2010), but on the regional level the assessments are weaker and vary much more in their conclusions (e.g. den Elzen 2008 et al.). Not only (i) the allocation rule determines the mitigation costs, but also (ii) the national mitigation costs and potentials for climate-friendly technologies as well as (iii) the devaluation of fossil resource stocks that will in particular affect the oil and gas exporting countries (see Lüken et al., 2010). Getting a better understanding of the contribution of each of these three factors is crucial for achieving an international commitment for climate change mitigation. It is of utmost importance to show on the one hand that mitigation is technically feasible and on the other hand to give policy makers a robust assessment of the regional costs at hand, that are to be expected for the mitigation of climate change. Only model calculations can determine the magnitude of these three effects. We present here results of such an analysis being calculated with the model REMIND-R (Leimbach et al, 2010) and refer to results published in Lüken et al. 2010.

1.3.1. The REMIND model

REMIND-R consists of a macro-economy model coupled to an energy system model with a hard link. It is disaggregated into 11 World regions. The macro-economic module has a representation of long-term economic growth in an intertemporal optimization framework in the tradition of Ramsey (1928) and runs in a social planner mode. This type of growth model is widely used for integrated assessments of mitigation policies in a long-term perspective. The energy system module consists of a detailed technology based structure. Exhaustible energy carriers are modeled by endogenous extraction and price formation (Hotelling, 1931). A detailed representation of low-carbon technologies (including endogenous learning-by-doing) is the core of this module. REMIND-R allows the representation of trade by an exchange of ownership, what is fundamental for the determination of associated rents and effects on regional consumption. The model runs in a cost-effectiveness mode. Crucial assumptions within the modeling framework are that perfect foresight of the social planner is assumed and no strategic behaviour of actors is considered (Pareto optimum). This implies that the actual emissions of each region are independent of the allocation scheme and the allocated emission permits, i.e. the model allows the separability of equity and efficiency.

In the scenarios discussed here, a global cap and trade system is assumed with the assumption of an immediate start of global mitigation action with a setup of an international carbon market from 2010 onwards. The time horizon considered for all simulations presented here is 2005-2100. In the following scenarios, a global budget of

905 GtCO_2 from 2010-2100 is given as a binding global emission cap, leading to a ~60% probability to keep the 2°C target. The allocation of emission rights are distributed among the 11 World regions according to different allocation schemes that are described in the following.

1.3.2. Allocation of emission rights

As argued above, the distribution of emission allowances is one of three effects influencing the global reallocation of resource rents. The approaches how to distribute the initial emission allowances is heavily debated in international negotiations. As the trading of permits allows creating extra regional costs or revenues (den Elzen and Lucas (2005), Leimbach et al. (2010), Rose et al. (1998)) it is clear that the allocation of permits among nations is subject to different perceptions about fairness. Here we analyse different allocation schemes and evaluate them against the ethical criteria presented earlier in the book.

Often the difference of allocation schemes is discussed along the categories allocation-based or outcome-based (Rose et al. 1998), i.e. either an allocation scheme that focuses on the initial permit allocation of emission rights (before trading) or on the outcome (in monetary terms) of such an initial allocation. We introduce here a second category distinguishing "allocation of *emission rights*" versus "allocation of *reduction effort*". Regimes that allocate emission rights are e.g.:

- *per capita:* allocation of emission rights in proportion to population, as e.g. proposed by the German WBGU approach (WBGU 2009);
- *per GDP:* allocation of emission rights in proportion to a region's share in global GDP; so-called Vattenfall proposal;
- *C&C:* contraction and convergence where the regional shares in of global emissions rights converge linearly from status quo (2005 emissions) to equal-per-capita in 2050 (e.g. Meyer 2000);
- *C&C-hist:* contraction and convergence as described above but historic emissions since 1990 are taken into account in that sense that equal emission rights are assumed for the period from 1990-2005. Regions that have emitted more than

they are entitled get a lesser amount of emission allowances for the period 2050-2100.

- *CDC:* allocation of emission rights according to "common but differentiated convergence", see Höhne et al. (2006), where industrialized countries have to reduce their emissions immediately, whereas least developed countries may still emit until a certain threshold is reached. By 2050 a convergence of per capita emissions is aimed for.

Beside these allocation schemes that distribute the "cake" of emissions (blue colors in Figure 1) there are also proposals that aim at allocating the global mitigation reduction effort ("burden") of the mitigation challenge, i.e. they define a rule for distributing the reductions required relative to the baseline level. In contrast to the above mentioned allocation schemes, the allocation of the burden could imply that some countries are assigned less than zero emissions, i.e. that they have to buy additional emission permits from other countries even if they could completely decarbonizes their domestic energy system. The most prominent proposal of this kind is the Greenhouse Development Rights Framework (Baer et al. 2007) that distributes the global mitigation effort in terms of historic responsibility and economic capacity. Our analysis shows that this approach can substantially alter the distributional effect of climate policy. The investigated burden allocation regimes are (in red colors in Figure 1).

- *GDR (static)*: Greenhouse Development Rights (Baer et al. 2007). The allocation of emission reduction commitments result according to the *Responsibility and Capacity Index* (RCI), a composite index based on historic responsibility and economic capacity. The historic responsibility is quantified in terms of the cumulative emissions from 1990-2005. The capacity is determined by the amount of individual income in excess of a pre-defined per-capita development threshold. Thus it depends on the income distribution within nations. The higher historic responsibility and the higher the capacity, the higher is the aggregated responsibility-capacity index (RCI). The static form of the GDR framework means: for each time step, the global mitigation burden in terms of the difference between the baseline emissions and the emissions in the climate stabilization scenario is distributed in proportion to the 2005 value of the responsibility-capacity index. The allocation of a region thus equals its baseline emissions minus the region's share of the global mitigation gap.

- *GDR (dynamic)*: Distribution of the global mitigation gap according to the RCI Index, albeit with dynamic adjustment of the capacity component to account for the fact that GDP and therefore capacity in the regions change over time (see second edition of the GDR framework, Bear et al., 2008). In order to demonstrate the effect of dynamical adjustments, we calculate a time-dependant RCI by scaling the RCI with the regional GDP growth rates. For each time-step, the reduction relative to the baseline is then distributed in proportion to the time-dependant RCI.
- *Burden per GDP*: the mitigation gap is allocated according to GDP. This leads to higher reduction efforts for those who have a higher GDP and therefore a higher capacity.

1.3.3. Effect on regional mitigation costs

The global mitigation costs remain unaffected from the different allocation schemes (see Figure 1) as the model allows the separability of equity and efficiency. But the different allocations schemes have a major impact on the regional distribution of mitigation costs. It is noticeable that a major difference of the regional costs can be traced back to the difference between the allocation schemes where the emission *rights* (in blue tones) are distributed and the ones where the reduction *effort* (in red tones) is assigned.

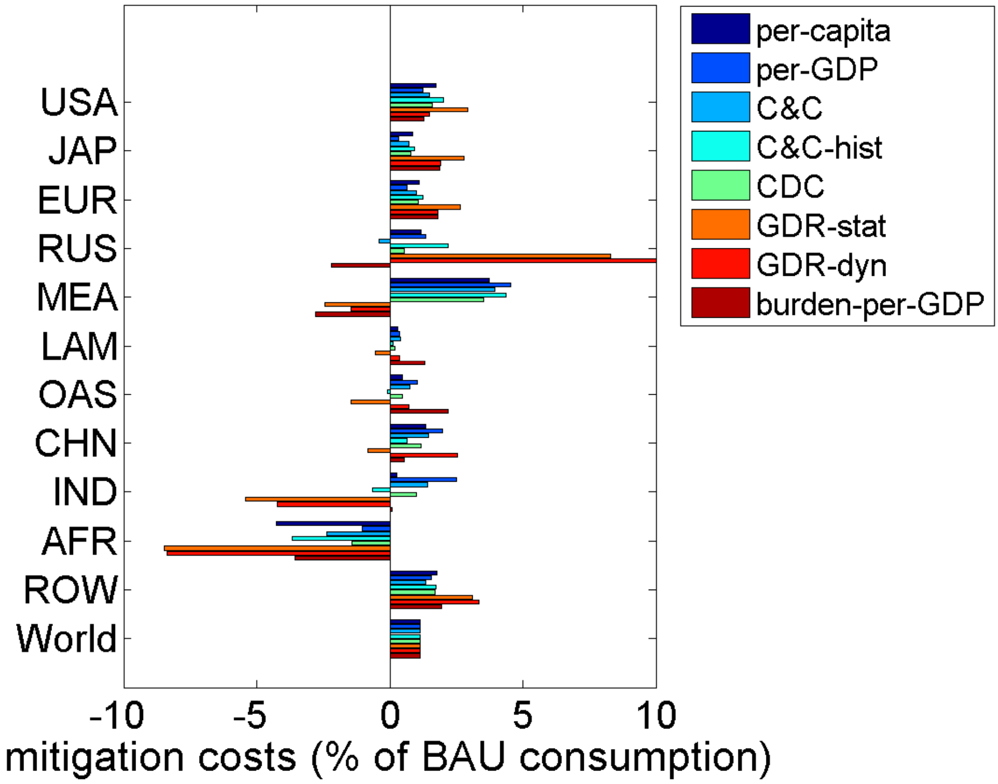

Figure 1: Mitigation costs as percentage of BAU consumption in dependence of different allocation schemes. Welfare effects are measured in terms of consumption losses relative to baseline aggregated over time at a discount rate of 3%. Blue colors indicate allocation schemes, where the emission rights are distributed; red colors those where the reduction efforts are distributed.

The ReMIND model projects that among the first group of allocations that distributes the emission allowances (*per capita, per GDP, C&C, CDC*), the industrialized countries (USA, Japan, Europe) face consumption losses that are with 1-2% relative to baseline close to the world average. This is due to the fact that these countries can transform their energy systems relatively easily given their higher GDP and have therefore a higher potential for the required investments (see below). Exporters of fossil resources, however, suffer highest consumptions losses (here mainly the Middle East). It is interesting to note that some fossil fuel exporters can abdicate from having a lower income. Russia, e.g., has to slow down its gas exports but on the other hand it can benefit from using the CCS technology in combination with biomass to extract CO_2 emissions from the atmosphere and generate "negative emissions" (see chp. 4.2.). Countries in transition, such as China or regions such as Latin America report losses below global average. Africa, however, benefits largely from climate policy due to the sale of emission rights. Africa is the only region exhibiting appreciable welfare gains from the global mitigation policy for all effort sharing allocation schemes. Consumption gains are highest for the per capita allocation scheme. It is not very astonishing that industrialized countries would benefit from an allocation according to *per GDP*, whereas countries in transition as China or India or least developed countries, such as countries in Africa, would benefit form an allocation scheme according to *per capita*.

This picture changes substantially for some regions when the reduction effort allocation schemes are considered. In the default GDR scenario net sellers of emission rights benefit substantially from an “allocation of reduction efforts” scheme: this gives rise to substantial welfare gains for Africa, India and the Middle East. The high-income industrialized countries (USA, Europe, Japan) are characterized by high historic emissions and per-capita GDP, thus their allocations are substantially smaller than in the C&C, CDC and GDP shares scenarios. In fact, as demonstrated by the calculations in Bear et al. (2007), the static application of the GDR-framework results in negative emissions for the USA, UK and Germany as early as 2020-2025, i.e. these countries would be obliged to purchases emission rights even in the hypothetical case of a complete elimination of domestic greenhouse gas emissions. In absolute terms, the mitigation costs borne by the USA and the EU exceed the global total average of mitigation costs (Figure 1). Not surprisingly, this allocation scheme would result in the highest mitigation costs of all schemes considered here for the high-income industrialized countries.

The dynamic GDR framework results in a considerable increase of mitigation costs compared to the static case for fast-growing economies such as China, India and Russia. For high-income industrialized countries, by contrast, the aggregated relative welfare losses decrease to a level that is only moderately higher than the global average.

An additional calculation shows that the allocation of the mitigation effort according to *burden per GDP* results in a similar picture as the GDR approach. This lets us conclude that the main difference between the GDR and the traditional approaches is not so much due to the different index that is used for the allocation, but that the main difference is related to the difference between the allocations of the emission rights in contrast to the allocation of the reduction burden.

To quantify the contribution of other two effects besides the endowment of emission permits, we apply here an economic decomposition method that allows decomposing regional consumption losses into domestic and trade-related components (details of the method see Lüken et al., 2010). For this analysis we consider the per-capita allocation scheme.

The domestic effect consists of changes in GDP, macroeconomic investments, energy investments and fuel costs. Reductions in economic output (GDP losses) constitute the major contribution to the overall consumption losses. Reduced macroeconomic growth goes along with lower investment into the macroeconomic capital stock, thereby partly counterbalancing the GDP loss and thus exceeds the consumption loss in most regions. In the energy system, a shift from fossil fuel-intense technologies towards capital-intensive low-carbon technologies leads to positive contributions from saved fuel costs and negative contributions from increased investment costs in the energy system.

The contribution of energy trade to consumption loss is rather low compared to domestic effects for all regions. In contrast to the permit trade effect, the domestic effect and the energy trade effect remain the same for all allocation schemes.

In summary it can be concluded that for the industrialised countries the differences of mitigation costs due to different allocation schemes are lower than one would expect, as the allocation rule is only one of three determining factors. This aspect could lead to some leeway in international negotiations. On the other hand, the distributional impacts for developing countries and least developed countries are enormous. Moreover, the differences between individual regions are large: whereas USA, Europe and Japan have to face costs for every allocation scheme, Africa could generate large revenues from an ETS.

Above all, Luderer et al. (2009) showed that the uncertainties between model outcomes concerning the regional mitigation costs are significant with respect to different allocation schemes. Models with low technical flexibility show a stronger influence of the allocation rules on the regional mitigation costs than models with high technological flexibility. A crucial conclusion can be drawn: The higher the technological flexibility the lower are the climate rents that are created and the lower will the allocation conflicts be. A further reason for the uncertainty about the regional costs is that the (model) assumptions differ widely about how easy economies can be decarbonised and which technical potential exists for the individual technologies. In order to reduce this uncertainty in the estimation of the regional costs, the governments should ensure that an international expert group will be commissioned with cost estimations. The international work on such issues will create mutual trust and a common basis for speedy negotiations.

1.4. Ethical evaluation of allocation schemes

According to the model results, the various possible allocation rules do not differ in their globally aggregated costs, but greatly differ in their impact on regional and national abatement costs. This fact raises fundamental normative questions. Therefore, the dispute in political debates and international negotiations about allocation schemes is mostly about different views of “justice”, “equity” or “fairness” (see chp 3.2.1). UNFCCC 1992, Art. 3.1, also takes this into account by referring to “equity” and “common but differentiated responsibilities and respective capabilities”, without however defining these concepts. Because of the normative nature of permit allocation, the allocation issue has also been widely discussed within political philosophy and ethics, see for example Arler 2001, Baer/Athanasiou 2007, Caney 2009, Meyer 2009. In the following sections, this normative-ethical question will be discussed, particularly in the light of the triangle conception of justice evolved in ch. 3, with its three dimensions of basic needs fulfilment , sufficient opportunities and fair procedures.

Thus, what can be regarded as a just rule for allocation of tradable emissions allowances among nations? An important preliminary decision in any case is , whether the allocation of emission permits is more regarded (i) as an instrument to solve general problems of global injustice like poverty, etc. (“complete perspective” of allocative justice), or (ii) as an "isolated" problem of justice, sometimes also called "local justice", fading out other distributive questions. Note that the suitability of the "complete view" allocation to solve more general problems of global injustice is decisively restricted, because by allocating emission permits, only the distribution of monetary wealth in terms of GDP can be changed directly, and only to a limited extent. , Other important aspects of justice such as political structures, access to processes or the distribution of other important economic goods or ecosystem services however cannot be targeted directly by a permit allocation.

From our point of view, a certain permit allocation is not an ethical end in itself, but merely one instrument among others for realizing ethical claims. Therefore, both the complete and the isolated perspective can be ethically acceptable. However, there are some essential ethical preconditions for that respectively. For in the end discussing these ethical conditions for the "isolated" respectively the "complete perspective", at first a closer look on some prevalent proposals for allocations and their often implicit ethical assumptions is helpful:

The "isolated" perspective

Although most proposals for allocation schemes are mixed proposals regarding the ethical principles involved, different categories of allocation rules can be distinguished systematically with regard to their predominant underlying principle of justice. According to this, there are three most prevalent types of allocation schemes within the political discourse that obviously adopt a more isolated view, namely (A) equality, (B) compensation of historical emissions, and (C) grandfathering.

GROUP (A): Equality

The most prominent and probably most discussed proposal at all is equal *per capita* allocation of emission rights (e.g. Agarwal/Narain 1991, WBGU), which can be seen in the tradition of liberal equality. It belongs to the isolated view of the allocative problem, because it only cares about equality in regard to emission rights, but not about equality concerning other forms of wealth, other goods or resources, or others. *C&C*, but also most proposals that include historical emissions for reasons of distributive justice, like

C&C hist, essentially are more or less mere variations of such an isolated idea of distributive equality. They only differ from the *per capita* proposal in some temporal aspects of equal per capita emission rights (e.g. within each year, or within a life-span, or after some years of transition period, or equal average per capita emission rights within an entire nation since the beginning of industrialization). Common to all allocations of group (A) is the idea of equal opportunities (J. Rawls, G.A. Cohen, R. Dworkin, etc.).

Despite its intuitive appeal, some critique on this kind of allocations could be brought forward (compare Caney 2009, 130-133): More general critique on allocations of group (A) refers to general critique on liberal equality (e.g. by sufficiency-oriented theories, see chp. 3.2). But even if one favours liberal equality and the isolated view, it is not clear why to aim for equality of emission rights because bearing emission rights as a resource endowment or as a property right ethically cannot be regarded as an end in itself (see ch. 3.2.2 and Sen 1997, 353-369). Why not rather aiming for equality of some kind of benefits from emission rights, e.g. in terms of GDP or utility, or opportunities such as access to energy, or equality of benefits from emissions during a life-span (chp. 3.2.4)? However, it is very difficult to identify benefits and opportunities from emission rights and particularly from past emissions more concretely, or to operationalise concepts like "during a life-span". Furthermore, it is hard to determine "equal access to energy" within the framework of an ETS, without at the same time rewarding maintaining, or even providing undesirable incentives for creating high carbon intensity in the energy sector. A focus on equality of benefits from emissions in terms of GDP could even feed higher energy intensity in addition to higher carbon intensity. Note that such side effects and incentive structures have to be considered for every proposal for allocating emission allowances.

From our perspective of justice (chp. 3.2), the most important aspect within an isolated view of permit allocation is not the focus on equal benefits in terms of GDP or equal access to energy. Rather, emission permits currently are extremely, though not equally important resources for every society, insofar as they are required for fulfilling basic needs and for creating crucial economic opportunities for everyone (chp. 3.2.2). Thus, one could argue for a *per capita* allocation, although the claim to equality in this case would be a mere means to roughly provide these claimed goods for everyone. Since practically it is very hard to determine regional differences in the need for emission permits in order to provide basic needs fulfilment and equal access to economic processes and crucial economic goods, equal allocation of emission permits seems a fairly good approximation. For these reasons, *per capita* (or similar proposals) could serve as a just allocation in the sense of ch. 3, if one accepts the isolated view. In addition, it leads to the positive side effect for gains for some poorer countries, which can support their development.

GROUP (B): Compensating historical emissions
For example *C&C hist* or the so called Brazilian Proposal (La Rovere 2002) can also be based on the idea of compensation or retribution of wrongdoings (i.e. past emissions with regard to the damages they cause, or benefitting from past emissions as immoral "free-riding", see chp. 3.2.4) rather than on ideas of distributive justice. Such allocation rules are isolated views, too. The ethical reasons for better not taking into account past emissions (neither due to corrective and retributive nor due to distributive justice) have already been presented in chp. 3.2.4. This also applies to those proposals from group (A), which take additionally into account past emissions.

GROUP (C): Grandfathering
The principle of grandfathering, which has considerable vogue in industrialised countries, is implied in *per GDP*, or weaker in *CDC* and *C&C*. It does not meet with the approval of the triangle of justice, since its mere focus on property rights and on keeping the status quo does not go together with the claims of the three dimensions of justice, particularly in regard to eradication of poverty. Caney (2009, 128) even states, that no moral or political philosopher defends the principle of grandfathering.

The only ethically acceptable reason for a transition period from status quo to equal per capita allocation could be the protection of socio-economic systems in industrialised countries in order to secure basic needs fulfilment and sufficient opportunities there.

However, to achieve this, e.g. 2020 as convergence year should be fairly sufficient. Therefore, if e.g. *C&C* with its component of grandfathering was pursued, the year of convergence should be much earlier than 2050.

The "complete" perspective

GDR, as was explained above, takes into account historical emissions, but also to a large extend the economic capacity of nations. Taking a complete perspective, *GDR* uses permit allocation to target more general global distributive problems such as poverty and global inequality. Within the international climate change negotiations the discussion of the *GDR* approach drew more attention to poverty and global inequality of wealth as problems of global injustice.

Beside *GDR*, also *burden per GDP* and proposals that more directly focus on the expected outcome (in terms of GDP) take a complete perspective and focus on more general problems of global injustice. The advantage of "outcome-based" approaches in comparison with "allocation-based" (based on the criterion of capacity) is that the former more directly take into account the other factors of regional abatement costs beside the allocation rule.

Nonetheless, an allocation scheme that aims at global redistribution of wealth in order to support the realisation of moral rights according to the three dimensions of justice (chp. 3.2.2) can be regarded as just, if one adopts a complete view. If "outcome-based" allocation schemes are preferred rather than "allocation-based" ones, the difference between burden sharing and allocation of rights has to be taken into account because of the very different outcomes of both of them (see above).

"Isolated" vs. "complete" perspective

What is now the "right" perspective? Caney (2009) argues for a total view, and Posner/Weisbach 2010, 121, on the other hand, argue for an isolated view, mainly because of political-practical reasons. We consider both the isolated perspective, e.g. of a *per capita* allocation, and the complete perspective, e.g. the *GDR*, with an allocation which aims at a just global redistribution as ethically acceptable. But the shortcomings and ethical conditions of both perspectives as pointed out above should be kept in mind. A further important ethical condition in each case is the *overall* bundle of political measures and instruments in terms of justice or injustice. This concerns the related procedures as well as the overall outcome (distribution of wealth) and other aspects: If one adopts the isolated view, it is ethically absolutely demanded that at least other political instruments and measures fully provide basic needs fulfilment and sufficient opportunities for everyone within fair procedures. And on the other hand, if a complete view is preferred, the interplay of the according allocation with other political measures in regard to total outcome as well as procedures and side effects have to be considered.

Beside these two kinds of permit allocation, which have been valued as just from a pure ethical perspective, some other allocation rules can be seen as just, too, under two conditions: First they have been decided in a fully fair procedure, which is demanded in any case. Second, the overall bundle of political measures and instruments and their results is in line with the claims of justice (chp. 3.2). However, these two ethical conditions might be hard to meet for most other proposals.

To come back to the practical-political level, a slight advantage of *per capita* as isolated view allocation is that this principle is simple, transparent and supported by intuition. This is distinct from much more complex allocations pursuing the complete perspective. In addition, permit allocation should not be overloaded by claiming a complete view, because many governments of wealthier countries are not only reluctant to pursue ambitious climate mitigation, but even more to pave the way for a global redistribution. While *per capita* or similar proposals constitute the minimum of fairness that is acceptable for most Southern countries, which would prefer type (B) or “complete perspective” allocations, these proposals are rejected by Western countries, e.g. the USA, because of the relatively high expected costs for them compared with group (C) allocations (Posner/Weisbach 2010, 122). Maybe bringing forward approaches like *GDR* can help poorer countries to achieve in the end at least an agreement on *per capita* within international negotiations, while starting with *per capita* could mean to end up with grandfathering approaches.

Fortunately, there is an important leeway within the difficult political negotiations due to (i) the fact that some of the allocation rules do not really differ a lot in terms of outcome (see Figure 1), (ii) our assumption that more than one allocation rule could be regarded as just under certain conditions, dependent on the overall bundle of measures, and (iii) the possibility to reduce conflict potential in this context by technological innovation and technology transfer, which would reduce mitigation costs.

1.5. Institutional requirements for a global ETS

If the carbon budget is managed by a fiduciary institution, a clear signal will be given to the markets that no emission in excess of the budget will be issued. A global system of regional and national climate central banks should undertake the task to ensure an economically efficient compliance with the carbon budget. For this purpose, an institution which acts as a climate bank needs to issue emission rights in such a way that the firms themselves can decide at what time they reduce emissions and which technologies they will use. Depending on the economic situation, the central climate banks can limit or extend the temporal flexibility by issuing certificates.

Such a system cannot be implemented overnight. But an important question is if there is still enough time to incrementally achieve an international agreement, e.g. by linking regional emission trading markets (Flachsland et al., 2008). Model calculations show that the costs could increase by half if a global agreement would only be launched in 2020 instead of 2010 (Luderer et al., 2009). In case of a further delay, one even has to give up the 2°C target.

The emissions trading scheme can have the potential to be an instrument that can contribute to justice in a twofold way. Firstly, the global cap of emissions can be kept efficiently and effectively below 2°C, as the overall amount of emission rights is restricted. Secondly, a global ETS allows a fair burden sharing of the mitigation effort and with it the chance to decrease global injustice. If poorer countries get more emission rights as they need for themselves, as was argued above, they can sell the unutilized emission rights and create a climate rent. Such a global reallocation of rents (from fossil fuel owners to owners of emission rights) has to be accompanied by institutional settings that impede the danger that national elites enrich personally instead of investing the rents from emission trading in enabling a sustainable development for the poorest.

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Statement of Contribution

The core chapters of this thesis, Chapters 2 to 6, as well as the appendix Chapters 8 and 9 are the result of collaborations in this PhD project between the author of this thesis and his advisors and colleagues. The author of this thesis has made extensive contributions to the contents of the papers, from conceptual design, implementation, visualisation and interpretation of results to writing of the papers.

This section details the contribution of the author to the papers and acknowledges major contributions of others.

Chapter 2 (Bauer et al., 2010)

In preparation of this chapter, the author contributed to the parametrization, testing and documentation of the single-region model REMIND, to visualization tools and to the organization of the model code. The author was responsible for the coupling of the climate system model to the other parts of the model. Implementation and testing of the coupling was done in collaboration with Alexander Lorenz by about equal shares. The author provided a minor contribution to implementation and execution of the particular scenarios discussed in this paper and to analysis and interpretation of results.

Chapter 3 (Leimbach et al., 2010b)

This chapter uses the multi-region model REMIND-R developed by Leimbach et al. (2010a). The author contributed to the parametrization, testing and documentation of the model, in particular the modified version REMIND-R1.2, to visualization tools and to the organization of the model code. The author was responsible for the coupling of the climate system model to the other parts of the model. Implementation and testing of the coupling was done in collaboration with Alexander Lorenz by about equal shares. The author participated in the analysis and interpretation of the results in this paper. The subsequent Chapters 4 to 6 use the model REMIND-R as documented in this chapter with minor adjustments in the calibration.

Chapter 4 (Lüken et al., 2011)

The author developed and implemented the decomposition method presented in the paper together with Nico Bauer, partly building on the preliminary version in Chapter 6. Gunnar Luderer provided fruitful ideas about the integration of the permit trade. The research question how domestic and trade-related effects on regional mitigation costs are influenced by the availability of technologies and the initial allocation of emission permits was developed in close cooperation of Ottmar Edenhofer, Nico Bauer, Gunnar Luderer and the author. The author guided the definition of model scenarios, in particular the representation of a climate policy target by a cumulative carbon budget. All model calculations and graphs were done by the author. The interpretation of results was done by the author in cooperation with Nico Bauer. The text of the chapter was written by the author, with revisions by Nico Bauer and all other coauthors of the article.

Chapter 5 (Lüken et al., 2010)

The author developed the research question of this chapter how the costs of fossil energy carrier trade influence trade patterns and regional mitigation costs together with Marian Leimbach and Nico Bauer. The author contributed the implementation and parametrization of trade costs in the model, conducted the model experiments, and made the visualization of results. In close cooperation with Nico Bauer and Marian Leimbach, the author analyzed and interpreted the results. The text of the chapter was written by the author, with revisions by Nico Bauer and all other coauthors of the article.

Chapter 6 (Bauer et al., 2009a)

Together with Nico Bauer, the author developed and implemented the decomposition method presented in the paper, which is a preliminary version of the method in Chapter 4. The implementation of infrastructure-based secondary energy trade in the model as well as the execution of model experiments and the visualization of results was undertaken by Sylvie Ludig and the author in close cooperation by about equal shares. Furthermore, the author contributed to the interpretation and discussion of the results.

Chapter 8 (Appendix) (Bruckner et al., 2010)

In preparation of this chapter, the author contributed to the parametrization, testing and documentation of the single-region model REMIND, to visualization tools and to the organization of the model code. The analysis of the influence of fossil scarcity and the time preference rate (Section ”Low-concentration stabilization scenarios”) rests on model experiments and the visualization and interpretation of their results, done by the author together with Markus Haller.

Chapter 9 (Appendix) (Knopf et al., 2010b)

In preparation of this chapter, the author contributed to the parametrization, testing and documentation of the multi-region model REMIND-R, to visualization tools and to the organization of the model code. The model experiments, visualization and interpretation of results on the impact of various permit allocation schemes (Figure 1) is due to Brigitte Knopf and the author of the thesis.

REMIND - Technical Documentation*

*This is an extract of the Technical Documentation of REMIND, available at http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/remindcode-1.

REMIND: The equations

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ReMIND is a modeling environment that is developed for the implementation of energy-economic models in a multi-regional framework. The current framework provides a number of features that allows the representation of energy carriers and conversion technologies with various techno-economic characteristics. Moreover, the macroeconomic part contains a nested CES function that can have any structure. The regional models are solved as optimal growth models with equilibrium at the energy and capital markets. The regional models are linked by trade in energy carriers, tradeable permits and the generic goods, thus, the markets for traded goods are in equilibrium as well. The present documentation introduces the *GAMS* implementation of the model code. It gives an introduction to the abstract structure of the model and the modeling possibilities. The present documentation does not introduce the particular realisation of a model version. Hence, the documentation opens up the possibility to implement individual realisations of energy-economy models.

Contents

1 Preliminary remarks

1.1 Model Versions

The REMIND model comprises different model versions. The versions differ with respect to the number of regions and the climate module used to run policy scenarios.

The REMIND model is designed in a multi-regional structure. We maintain two model versions: **REMIND-R** is a multi-regional model which includes inter-regional interactions. **REMIND-G** represents the whole world as the only region. In this paper, we document both model versions. We point out explicitely if an equation shows varieties between the versions or is just included in one versions.

Both versions are coupled to a climate module. We use either a simple box-model or the more sophisticated **ACC2** model.

1.2 Notation convention

We use the following convention on notation:

- **Variables** are written as capital latin letters. Variables which occur only in the Negishi procedure and in the climate module are written in fractur, e.g. $\mathfrak{T}$. (Please note an exception: $\mathfrak{M}$ is used for mappings.)
- **Parameters** are written as greek letters. Exception: initial and boundary conditions on variables are denoted as the associated variable plus index, although they are parameters. (E.g.: K_0 is the initial value associated with the variable "capital" K.)
- **Sets and Subsets** are written as small latin letters.
- **Mappings** are written as M with index and $\mathfrak{M}$ with index. Mappings are used in GAMS to identify certain combinations of members of more than one set. The concept of mappings is explained in sec. 1.4.

Indices are used for additional distinctions, e.g. of subsets.

Additional symbols denote some special cases which may occur in any of the four types defined just above:

- Temporal changes of an items are symbolized by "Δ". (E.g.: ΔS is the change in the amount of a stockable quantity.) The time step length is symbolized by Δt.
- A hat denotes cumulative values. (E.g.: $\hat{Z}$ is the cumulated capacity of a technology.)

1.3 Sets: The 'lattice' of the equations

Sets and subsets form the 'lattice' on which the equations are defined.

- t is the set of time steps from the initial point t_0 to the end point t_{end}.

- r is the set of regions.
  - In REMIND-G, r contains only one element representing the whole world.
  - In REMIND-R, r contains more than one element, representing disjunctive parts of the world.
- v is the set of economic factors (production factors and capital types as well as the macroeconomic output).
- **Energy types** e**:** Various energy types like coal, electricity, natural gas for household use are defined and grouped into subsets according to their characterstics (for example: primary, secondary, and final energy types e_p, e_s, e_f).
- **Technologies** c**:** This group covers all transformation technologies in the energy transformation or CCS chain. Again, there are subsets according to different characteristics).
- **Grade levels** g**:** Some items are characterized by different levels of quality.

1.4 Mappings: combining set elements

Mappings are used in GAMS to define combinations of set elements in order to avoid redundancy in the code. Consider the following example:

In the secondary to final energy transformation equation (cf. sec. 3.3.2, eq. 25), the variables "demand for secondary energy" (D_S) and "production of secondary energy" (P_S) are indexed by time step, region, secondary energy type (e_s), final energy type (e_f), and transformation technology (c).

The equation is evaluated for all time steps and all regions ($\forall\ t, r$) and all defined combinations of secondary energy type, final energy type and technology ($\forall\ M_{s\to f}$). The definition of the mapping contains the desired combinations $e_s \times e_f \times c$. This reduces the number of single equations generated in the compilation process, as "meaningless" combinations can be avoided.

Mappings can also be used in a summation index.

1.5 Equations and symbols used in the equations

The model equations are documented in the following chapters. The variables, parameters, sets/subsets and mappings are explained in tables at the end of each section sorted by these four groups. GAMS code notations are marked by a `special font`. The basic sets and subsets named above in sec. 1.3 are not included in the tables again due to their high frequency of occurence.

2 Economy module

2.1 The Intertemporal Social Welfare Function (welffun)

The objective of the optimization is to maximize the total discounted intertemporal welfare U. It is calculated from the time dependent regional utility $\tilde{U}(t,r)$ by summing about all regions r weighted by their Negishi weight $W(r)$ and summing about all time steps taking into account the pure time preference rate $\zeta(r)$. Δt is the time step length. In REMIND-G, Negishi weights $W(r)$ do not appear in the code.

$$U = \sum_r \left(W(r) \sum_{t=t_0}^{t_{end}} \left(\Delta t \cdot e^{-\zeta(r)(t-t_0)} \tilde{U}(t,r) \right) \right) \tag{1}$$

The region- and time dependent annual welfare $\tilde{U}(t,r)$ is calculated from consumption $C(t,r)$ and labour (equivalent to population) $L(t,r)$, assuming an intertemporal elasticity of substitution of 1:

$$\tilde{U}(t,r) = L(t,r) \cdot \ln \left(\frac{C(t,r)}{L(t,r)} \right) \qquad \forall\ t,r \tag{2}$$

In the code, equations (1) and (2) are combined:

$$U = \sum_r \left(W(r) \sum_{t=t_0}^{t_{end}} \left(\Delta t \cdot e^{-\zeta(r)(t-t_0)} L(t,r) \cdot \ln \left(\frac{C(t,r)}{L(t,r)} \right) \right) \right) \tag{3}$$

C	consumption	cons
L	labour (equivalent to population)	vari("lab")
U	total discounted intertemporal welfare	welf
$\tilde{U}$	region- and time dependent annual utility	
W	Negishi weight	w
Δt	time step length	ts
ζ	time preference rate	disrate

2.2 Budget equation (budget)

Exports of the final good (X_G) are deduced from macroeconomic output $Y(t,r)$, imports of the final good (M_G) are added, taking specific trade costs τ_T into account, which are assigned to the importeur. The resulting output is used for consumption, $C(t,r)$, for investments into the capital stock, $I(t,r)$,[1] and for the energy system cost components fuel costs $G_F(t,r)$, investments $G_I(t,r)$ and operation & maintenance $G_O(t,r)$.

[1]Please note that the capital stock dynamics of the energy sector is treated separately in the energy system module. Associated investments enter the macroeconomic budget as investment costs $G_I(t,r)$.

$$Y(t,r) - X_G(t,r) + (1-\tau_T) M_G(t,r) \geq C(t,r) + I(t,r) + G_F(t,r) + G_I(t,r) + G_O(t,r) \quad \forall\, t,r \tag{4}$$

C	consumption	`cons`
G_F	fuel costs	`costfu`
G_I	investment costs	`costin`
G_O	operation & maintenance costs	`costom`
I	investments into individual stocks of capital	`invest`
M_G	imports of the final good	`Mpgood`
X_G	exports of the final good	`Xpgood`
Y	macroeconomic output	`vari("inco")`
τ_T	specific trade costs	`tradecost`

2.3 The Production Function (`production`)

The production function is a nested 'CES' (constant elasticity of substitution) production function. The macroeconomic output Y is generated by the inputs capital K, labour L, and total energy E. The generation of total energy is described by a CES production function also, whose input factors are CES function outputs again. Sector-specific final energy types represent the bottom end of the 'CES-tree'.

In the code, you will find only the general form of the production function. It calculates the amount of factor output in a time-step and region, $V(t,r,v_{out})$, from the associated factor input amounts $V(t,r,v_{in})$ according to the following quantities:

- parameter $\phi(r, v_{out})$: total factor productivity
- parameter $\rho(r, v_{out})$. ρ is calculated from the elasticity of substitution, σ, according to the relation

$$\sigma = \frac{1}{1-\rho}$$

- $\theta(t, r, v_{in})$: efficiency. It is calculated as the product of an initial value and a time-dependent scaling factor.

All outputs (intermediate outputs and GDP) in the CES-tree represent monetary values.

$$V(t,r,v_{out}) = \phi(r,v_{out}) \cdot \left(\sum_{M_{CES}} (\theta(t,r,v_{in}) \cdot V(t,r,v_{in}))^{\rho(r,v_{out})} \right)^{1/\rho(r,v_{out})} \quad \forall\, t,r,v_{out} \tag{5}$$
$$M_{CES} = (v_{in} \times v_{out}) \in \mathfrak{M}_{CES}$$

The mapping M_{CES} assigns the correct input types v_{in} to each output v_{out}.

On top of the CES-tree, macroeconomic output/GDP is calculated from capital, labour, and total energy:[2] If ϕ' and ρ' denote the total factor productivity and substitution elasticity, resp., associated with GDP, we thus have[3]

$$Y(t,r) = \phi'(r) \cdot \left((\theta_K \cdot K)^{\rho'(r)} + (\theta_L \cdot L)^{\rho'(r)} + (\theta_E \cdot E)^{\rho'(r)} \right)^{1/\rho'(r)} \quad \forall\ t,r \tag{6}$$

E	total final energy (as a production factor)	`vari("en"`
K	capital	`vari("kap"`
L	labour (equivalent to population)	`vari("lab")`
V	amount of production factor output	`vari(in)`
Y	macroeconomic output	`vari("inco")`
θ	efficiency	`eff('2005'),effscal`
ρ	parameter, calculated from substitution elasticity σ	`cesdataout("rho")`
ϕ	total factor productivity	`cesdataout("phi")`
$\mathfrak{M}_{CES}$	combination of input types and associated output	`cescomp`

2.4 Capital stocks (`kapmo,kapmo0`)

To calculate the capital stock K, its amount in the previous time step is devaluated by an annual depreciation factor δ_k and enlarged by investments I. Both depreciation and investments are expressed as annual values, so the time step length Δt is taken into account.

$$K(t+1,r) = K(t,r) \cdot (1 - \Delta t \cdot \delta_k(r)) + \Delta t \cdot I(t,r) \quad \forall\ t,r \tag{7}$$

Initial values are assigned from exogenous data K_0:

$$K(t_0,r) = K_0(r) \quad \forall\ r \tag{8}$$

I	investments	`invest`
K	capital stock	`vari("kap")`
K_0	Initial values for V	`cesdataout("inp")`
δ_k	annual depreciation factor	`cesdataout("delta")`
Δt	time step length	`ts`

2.5 Labour (`labbal`)

The labour available in every time step and every region, $L(t,r)$, comes from exogenous data $L_t(t,r)$:

[2] Set v_{out} contains the element 'GDP', mapping M_{CES} assigns the v_{in}-elements 'capital' $K(t,r)$, 'labour' $L(t,r)$, and 'total energy' $E(t,r)$.

[3] For clarity, the arguments of K, L, E and the associated efficiency parameters have been dropped here.

$$L(t,r) = L_t(t,r) \quad \forall\ t,r \tag{9}$$

L	labour available in every time step and every region	`vari("lab")`
L_t	exogenous data for available labour	`datapop`

2.6 Final Energy balance (`balfinen`)

The final energy balance equals the production of final energy P of type e_f in time-step t and region r to its demand as an input factor of the production function $V(t,r,e_f)$.

$$V(t,r,e_f) = P_f(t,r,e_f) \quad \forall\ t,r,e_f \tag{10}$$

P_f	final energy production	`feprod`
V	production factor	`vari`

2.7 Trade balances and restrictions

This chapter applies to REMIND-R only!

Trade balances of energy, final good, and permits (`tradebal1`, `tradebal2`, `tradebal3`)

In each time step, exports X_i and imports M_i of each tradeable entity are globally balanced. This applies for exports and imports of each energy type e_T (X_E, M_E), final good (X_G, M_G), and emission permits (X_Q, M_Q):

$$\sum_r (X_E(t,r,e_T) - M_E(t,r,e_T)) = 0 \ \ \forall\ t,e_T \tag{11}$$

$$\sum_r (X_G(t,r) - M_G(t,r)) = 0 \ \ \forall\ t \tag{12}$$

$$\sum_r (X_Q(t,r) - M_Q(t,r)) = 0 \ \ \forall\ t \tag{13}$$

Emission permit trade restriction (`perm_restr`)

To avoid fictious permits generated from negative emissions, permit exports X_Q must be lower than the initial allocation of permits Q_{init} by region and time step:

$$X_Q(t,r) < Q_{init}(t,r) \ \ \forall\ r,t > t_0 \tag{14}$$

M_E	energy imports	`MpRes`
M_G	import of final goods	`MpGood`
M_Q	permit imports	`MpPerm`
Q_{init}	initial allocation of permits	`emicap`
X_E	energy exports	`XpRes`
X_G	export of final goods	`XpGood`
X_Q	permit exports	`XpPerm`
e_T	tradable energy type	`entra`

2.8 Emissions permit allocation (`perm_alloc`)

This chapter applies to REMIND-R only!

To calculate the initial allocation of emission permits Q_{init} (`emicap`), three different scenarios are possible:

Contraction and Convergence

$$Q_{init}(t,r) = \left(\lambda(t) \cdot \frac{L(t,r)}{\sum_r L(t,r)} + (1-\lambda(t)) \cdot \frac{Q_0(r)}{\sum_r Q_0(r)}\right) \cdot Q^{ES}_{CO_2}(t) \quad \forall\ t,r \tag{15}$$

The convergence parameter λ increases linearly from zero at the beginning of the time horizon (2005) to 1 at the convergence time (2050).

Intensity: Proportional to BAU-GDP

$$Q_{init}(t,r) = \frac{Y_{BAU}(t,r)}{\sum_r Y_{BAU}(t,r)} \cdot Q^{e}_{CO_2}(t) \quad \forall\ t,r \tag{16}$$

Multistage

For each time step, every region is assigned to one subset (r_1 to r_4) with different calculation of the initial allocation Q_{init}. The assignment is based on the per capita income levels of the BAU scenario.

- r_1: Q_{init} follows emissions in the business as usual.
- r_2: Q_{init} is proportional to GDP in the business as usual (Y_{BAU}).
- r_3: Q_{init} is fixed to a value proportional to GDP in the business as usual in t'. t' is the last time step where the region was grouped into r_2.
- r_4: Remaining permits are distributed following a contraction and convergence procedure.

$$Q_{init}(t,r) = Q_{BAU}(t,r) \quad \forall\ t,r \in r_1 \tag{17}$$

$$Q_{init}(t,r) = 0.15 \cdot Y_{BAU}(t,r) \quad \forall\ t,r \in r_2$$

$$Q_{init}(t,r) = 0.15 \cdot Y_{BAU}(t',r) \quad \forall\ t, r \in r_3$$

$$Q_{init}(t,r) = \left(\lambda(t) \cdot \frac{L(t,r)}{\sum_{r' \in r_4} L(t,r')} + (1-\lambda(t)) \cdot \frac{Q_0(r)}{\sum_{r' \in r_4} Q_0(r')}\right) \cdot \left(Q^e_{CO_2}(t) - \sum_{r' \notin r_4} Q_{init}(t,r')\right) \quad \forall\ t, r \in r_4$$

$Q^e_{CO_2}$	global energy-related CO_2 emissions	`en_emi - lucemi`
$Q_{init}(t,r)$	initial permit allocation	`emicap`
Q_0	emissions in the year 2000 (data)	`dataes`
Q_{BAU}	energy-related CO_2 emissions in the business-as-usual (data)	`emi_bau`
Y_{BAU}	GDP in the business-as-usual (data)	`gdp_bau`
λ	convergence parameter	`lambda`

3 Energy System Module

3.1 Energy system costs

3.1.1 Fuel costs (`ccostfu`)

Fuel costs are associated with the use of exhaustible primary energy (fossils, uranium) and biomass. In the latter case, resources are divided into several grades, and each grade has fixed specific costs. In the former case, specific fuel costs are a function of previous cumulative extraction (**"Rogner-curve"**).

$$
\begin{aligned}
G_F(t,r) = & \sum_{M_{e_p \leftrightarrow g}} \left(\tau_F(r,e_p,g,t) \cdot P_p(t,r,e_p,g)\right) \\
& + \sum_{e_r} \left(\chi_1(r,e) + \chi_2(r,e) \left(\frac{\sum_t \Delta t F(t,r,e_r)}{\chi_3(r,e)} \right)^{\chi_4(r,e)} F(t,r,e_r) \right) \qquad \forall t,r \qquad (18)
\end{aligned}
$$

$$
M_{e_p \leftrightarrow g} = (e_p \times g) \in \mathfrak{M}_{e_p \leftrightarrow g}
$$

In REMIND-G, fuel extraction F is replaced by primary energy production P_p.

F	fuel extraction of primary energy e_p or e_r	`fuelex`
G_F	overall fuel costs	`costfu`
P_p	primary energy production	`peprod`
τ_F	cost per unit of fuel e_q with grade level g	`dataperen("cost")`
χ_i	parameters to characterize the exhaustible fuel cost curve (i=1,2,3,4)	`datarog`
e_r	exhaustible primary energy tpyes	`petyrog`
$\mathfrak{M}_{e_p \leftrightarrow g}$	combinations of primary energy types and grade levels (covers only biomass)	`peren2rlf`

3.1.2 Investment Costs (`ccostin`)

Specific investment costs of learning technologies are a model-endogenous variable; those of non-learning technologies are exogenous parameters. Total investment costs G_I are the product of specific costs and capacity additions ΔZ:

$$
\begin{aligned}
G_I(t,r) = \sum_{M_{e \to e}} \Bigg(& \sum_{c_{NL}} \left(\tau_{INL}(r,c_{NL}) \sum_{M_{c \leftrightarrow g}} \Delta Z(t,r,c_{NL},g) \right) \\
& + \sum_{c_L} J(t,r,c_L) \sum_{M_{c \leftrightarrow g}} \Delta Z(t,r,c_L,g) \Bigg) \qquad \forall\, t,r
\end{aligned} \qquad (19)
$$

$$M_{e\to e} = (e_{in} \times e_{out} \times c) \in \mathfrak{M}_{e\to e}, \qquad M_{c\leftrightarrow g} = (c \times g) \in \mathfrak{M}_{c\leftrightarrow g}$$

In equation 19, $\mathfrak{M}_{c\leftrightarrow g}$ is restricted to c_{NL} or c_L, resp. through the second step summation.

G_I	investment costs	`costin`
J	specific investment costs per unit of capacity addition of a learning technology c_L	`investcost`
ΔZ	addition to the capacity of technology c of grade level g	`deltacap`
τ_{INL}	specific investment costs per unit of capacity addition of a non-learning technology c_{NL}	`data("inco0")`
c_{NL}	non-learning energy transformation technology	`nolearnte(te)`
c_L	learning energy transformation technology	`learnte(te)`
$\mathfrak{M}_{e\to e}$	definition of general energy transformation	`temapall`
$\mathfrak{M}_{c\leftrightarrow g}$	combination of technologies and grade levels	`teall2rlf`

3.1.3 Operation and Maintenance Costs (`ccostom`)

O & M costs result from

- maintenance of existing facilities according to their capacity (**fixed O &M costs**) and
- operation of energy transformations according to the amount of produced secondary and final energy (**variable O &M costs**).

Addition of both contributions yields total O & M costs C_O:

$$G_O(t,r) = \sum_{M_{e\to e}} \left(\tau_{fix}(r,c) \sum_{M_{c\leftrightarrow g}} \Big(\big(\tau_{INL}(r,c_{NL}) + J(t,r,c_L)\big) \cdot Z(t,r,c,g) \Big) + \tau_{var}(r,c) \cdot \Big(P_s(t,r,e_p,e_s,c) + P_f(t,r,e_s,e_f,c) \Big) \right) \quad \forall\ t,r \tag{20}$$

$$M_{e\to e} = (e_{in} \times e_{out} \times c) \in \mathfrak{M}_{e\to e}, \qquad M_{c\leftrightarrow g} = (c \times g) \in \mathfrak{M}_{c\leftrightarrow g}$$

G_O	operation & maintenance costs	`costom`
J	specific investment costs for adding capacity of a learning technology c_L	`investcost`
P_s	production of secondary energy	`seprod`
P_f	production of final energy	`feprod`
Z	capacity of technology c	`cap`
P_s	production of secondary energy	`seprod`
P_f	production of final energy	`feprod`
τ_{fix}	fixed specific O&M costs	`data("omf")`
τ_{INL}	specific investment costs per unit of capacity addition of a non-learning technology c_{NL}	`data("inco0")`
τ_{var}	variable specific O&M costs	`data("omv")`
c_{NL}	non-learning energy transformation technology	`nolearnte(te)`
c_L	learning energy transformation technology	`learnte(te)`
$\mathfrak{M}_{e\to e}$	definition of general energy transformation	`temapall`
$\mathfrak{M}_{c\leftrightarrow g}$	combination of technologies and grade levels	`teall2rlf`

3.2 Energy Balance Equations

Energy balance equations equate the production P of and demand D for each primary, secondary and final energy; so the general structure is:

$$\sum_{all} P_j = \sum_{all} D_j \quad \forall\, t, r \;\; j \in \; \{p, s, f\}$$

where "all" means all possible ways of energy transformation relevant for the respective transformation stage (primary, secondary, final).

3.2.1 Primary Energy Balance (`pebal`)

$$\sum_{M_{e_p,g}} \sum_{M_{p\to s}} P_p(t, r, e_p, e_s, c, g) = \sum_{M_{p\to s}} D_p(t, r, e_p, e_s, c) \quad \forall\, t, r \;\; \forall\, e_p \qquad (21)$$

$$M_{p\to s} = (e_p \times e_s \times c) \in \mathfrak{M}_{p\to s}$$

D_p	demand for primary energy	`pedem`
P_p	production of primary energy	`peprod`
$\mathfrak{M}_{e_p,g}$	combination of primary energy types and grade leves	`enty2clf`
$\mathfrak{M}_{p\to s}$	definition of primary to secondary energy transformation	`pe2se`

3.2.2 Secondary Energy Balance (`sebal`)

The secondary energy balance comprises the following terms:

- Secondary energy can be produced (P_s) from primary or (another type of) secondary energy ($e_{in} \to e_p, e_s$).
- Secondary energy can be demanded (D_s) to produce final or (another type of) secondary energy ($e_{out} \to e_{s'}, e_f$).

- Own consumption of secondary energy occurs from the production of secondary and final energy, and from CCS technologies. Own consumption is calculated as the product of the respective production (P_s, P_f, or R as the amount of CO_2 in the respective CCS chain step) and a coefficient ξ. The 2nd, 3rd and 4th argument of ξ define the underlying transformation process and the 5th argument specifies the consumed energy type. Mapping M_{own} defines possible combinations.
- Couple production is modeled as own consumption, but with a negative ξ.
- Stockable secondary energy (e_s) can be transferred to storage (ΔS).

$$\begin{aligned}
&\sum_{M_{p\to s}} P_s(t,r,e_p,e_s,c) + \sum_{M_{s\to s}} P_s(t,r,e_{s'},e_s,c) \\
&+ \sum_{M_{own}} \left(\xi(r,e_p,e_{s'},c,e_s) \cdot P_s(t,r,e_p,e_{s'},c)\right) \\
&+ \sum_{M_{own}} \left(\xi(r,e_{s'},e_f,c,e_s) \cdot P_f(t,r,e_{s'},e_f,c)\right) \\
&+ \sum_{M_{own}} \sum_{M_{c\to CCS}} \left(\xi(r,q_i^{ccs},q_{i+1}^{ccs},c,e_s) \cdot R(t,r,q_i^{ccs},q_{i+1}^{ccs},c,g)\right) \\
&= \sum_{M_{s\to f}} D_s(t,r,e_s,e_f,c) + \sum_{M_{s\to s}} D_s(t,r,e_s,e_{s'},c) \\
&+ \Delta S(t,r,e_s) \qquad \forall\, t,r \;\; \forall\, e_s \quad (22)
\end{aligned}$$

$$M_{p\to s} = (e_p \times e_s \times c) \in \mathfrak{M}_{p\to s}$$

$$M_{s\to s'} = (e_s \times e_{s'} \times c) \in \mathfrak{M}_{s\to s'}$$

where e_s and $e_{s'}$ denote two not necessarily different secondary energy types.

$$M_{s\to f} = (e_s \times e_f \times c) \in \mathfrak{M}_{s\to f}$$

$$M_{own} = (e_{in} \times e_{out} \times c \times e_{own}) \in \mathfrak{M}_{own}$$

$$M_{c\to CCS} = (c \times g) \in \mathfrak{M}_{c\to CCS}$$

D_s	demand for secondary energy	`sedem`
P_f	production of final energy	`feprod`
P_s	production of secondary energy	`seprod`
R	amount of CO_2 in the ith step of the CCS chain to be transformed to the next one using technology c with grade level g	`ccs`
ΔS	change per time in stock of e_s if e_s is a stockable quantity	`deltaenty`
ξ	own consumption coefficient	`dataoc`
q_i^{ccs}	CCS (captured CO_2) of stage i, i=1,...,4	`ccsco2(enty)`
$\mathfrak{M}_{p\to s}$	definition of primary to secondary energy transformation	`pe2se`
$\mathfrak{M}_{s\to s'}$	definition of secondary to secondary energy transformation	`se2se`
$\mathfrak{M}_{s\to f}$	definition of secondary to final energy transformation	`se2fe`
$\mathfrak{M}_{own}$	definition of own consumption	`oc2te`
$\mathfrak{M}_{c\to CCS}$	combination of technology and grade levels for CCS	`teccs2rlf`

Final Energy Balance

The final energy balance is placed in the economy module. See section 2.6.

3.3 Energy Transformation Equations

Taking the technology-specific transformation efficiency η into account, the equations describe the transformation of an energy type to another type; note that energy entering a transformation is *demanded* (D_j), the resulting energy is *produced* (P_k):

$$\eta(t,r,c)\cdot D_j(t,r,c) = P_k(t,r,c) \quad \forall\ t,r \ \ \forall\ c \ \ j,k \in p,s,f \tag{23}$$

and the allowed combinations of j and k are primary to secondary, secondary to secondary, and secondary to final energy.

3.3.1 Primary Energy to Secondary Energy (`pe2setrans`)

The transformation technology's efficiency η can be constant in time (c_{η_c}) or time dependent ($c_{\eta(t)}$); in the latter case, production P_s is replaced by the equivalent product of capacity addition ΔZ and load factor ν to assign the η value valid at the time step of the capacity addition (compare with sections 3.5.3 and 3.5.1):

$$D_p(t,r,e_p,e_s,c) = \frac{1}{\eta(r,c_{\eta_c})} P_s(t,r,e_p,e_s,c_{\eta_c}) + \sum_{M_{c_s\leftrightarrow g}} \nu(r,c_{\eta(t)})\Delta t \sum_{M_{c\leftrightarrow t_l}} \frac{\omega(r,t_l,c_{\eta(t)})\Delta Z(t-t_l,r,c_{\eta(t)},g)}{\eta(t-t_l,r,c_{\eta(t)})} \ \forall\ t,r\ \forall\ M_{p\to s} \tag{24}$$

$$M_{p\to s} = (e_p \times e_s \times c) \in \mathfrak{M}_{p\to s}$$

$$M_{c_s \leftrightarrow g} = (c_s \times g) \in \mathfrak{M}_{c_s \leftrightarrow g}$$

$$M_{c \leftrightarrow t_l} = (c_{vin} \times t_l) \in \mathfrak{M}_{c \leftrightarrow t_l}$$

D_p	demand for primary energy	`pedem`
P_s	production of secondary energy	`seprod`
ΔZ	addition to the capacity of technology c of grade level g	`deltacap`
η	efficiency of technology c, can depend on time or not	`data("eta")`, `dataeta`
ν	load factor of technology c	`data("nu")`
ω	weight factor of addition to technology c's capacity prior to initial time	`datacap("omeg")`
t_l	life time	`tlt`
c_{η_c}	technology with constant η	`teneta(te)`
$c_{\eta(t)}$	technology with η variable over time	`teeta(te)`
$\mathfrak{M}_{p \to s}$	definition of primary to secondary energy transformation	`pe2se`
$\mathfrak{M}_{c_s \leftrightarrow g}$	combination of secondary energy technologies and grade levels	`tese2rlf`
$\mathfrak{M}_{c \leftrightarrow t_l}$	set of possible combinations of vintage technologies and life time indices	`tlt2te`

3.3.2 Secondary Energy to Secondary/Final Energy (`se2fetrans`, `se2setrans`)

Secondary Energy to Final Energy (`se2fetrans`)

$$\eta(r,c) \cdot D_s(t,r,e_s,e_f,c) = P_f(t,r,e_s,e_f,c) \quad \forall\, t,r \;\; \forall\, M_{s \to f} \qquad (25)$$

$$M_{s \to f} = (e_s \times e_f \times c) \in \mathfrak{M}_{s \to f}$$

Between Secondary Energy types (`se2setrans`)

$$\eta(r,c) \cdot D_s(t,r,e_s,e_{s'},c) = P_s(t,r,e_s,e_{s'},c) \quad \forall\, t,r \;\; \forall\, M_{s \to s'} \qquad (26)$$

$$M_{s \to s'} = (e_s \times e_{s'} \times c) \in \mathfrak{M}_{s \to s}$$

D_s	demand for secondary energy	`sedem`
P_f	production of final energy	`feprod`
P_s	production of secondary energy	`seprod`
η	efficiency of technology c	`data("eta")`
$\mathfrak{M}_{s \to s'}$	definition of secondary to secondary energy transformation	`se2se`
$\mathfrak{M}_{s \to f}$	definition of secondary to final energy transformation	`se2fe`

3.4 Stock equations (`stockenty`, `stockconst`)

Stock change (`stockenty`)

$$S(t+1,r,s) = \Delta t \cdot \Delta S(t,r,s) + S(t,r,s) \quad \forall\, t,r \;\; \forall\, s \tag{27}$$

Initial values of stocks (`stockenty0`)

$$S(t_0,r,s) = 0 \quad \forall\, r \;\; \forall\, s \tag{28}$$

Constraint on stock quantities (`stockconst`)

$$S(t,r,s) \leq \psi_S(r,s) \quad \forall\, t,r \;\; \forall\, s \tag{29}$$

S	amount in stock of quantity s	`stock`
ΔS	change in stockable quantity s per time	`deltaenty`
ψ_S	capacity of stock of quantity s	`stockmax`
s	stockable quantity	`stockty(enty)`

3.5 Capacities

3.5.1 Capacity constraints for energy transformations (`capconstse`, `capconstse2se`, `capconstfe`)

Capacity constraints for primary to secondary energy transformation (`capconstse`)

$$P_s(t,r,e_p,e_s,c) = \sum_{M_{c_s \leftrightarrow g}} \nu(r,c) \cdot \nu_g(r,c,g) \cdot Z(t,r,c,g) \quad \forall\, t,r \;\; \forall\, M_{p \to s} \tag{30}$$

$$M_{p \to s} = (e_p \times e_s \times c) \in \mathfrak{M}_{p \to s}, \qquad M_{c_s \leftrightarrow g} = (c_s \times g) \in \mathfrak{M}_{c_s \leftrightarrow g}$$

Capacity constraints for secondary to secondary energy transformation (`capconstse2se`)

$$P_s(t,r,e_s,e_{s'},c) = \sum_{M_{c_s \leftrightarrow g}} \nu(r,c) \cdot \nu_g(r,c,g) \cdot Z(t,r,c,g) \quad \forall\, t,r \;\; \forall\, M_{s \to s'} \tag{31}$$

$$M_{s \to s'} = (e_s \times e_{s'} \times c) \in \mathfrak{M}_{s \to s'}, \qquad M_{c_s \leftrightarrow g} = (c_s \times g) \in \mathfrak{M}_{c_s \leftrightarrow g}$$

Capacity constraints for secondary to final energy transformation (`capconstfe`)

$$P_f(t,r,e_s,e_f,c) = \sum_{M_{c_f\leftrightarrow g}} \nu(r,c)\cdot Z(t,r,c,g) \quad \forall\, t,r \;\; \forall\, M_{s\to f} \tag{32}$$

$$M_{s\to f} = (e_s \times e_f \times c) \in \mathfrak{M}_{s\to f}, \qquad M_{c_f\leftrightarrow g} = (c\times g) \in \mathfrak{M}_{c_f\leftrightarrow g}$$

P_f	production of final energy	`feprod`
P_s	production of secondary energy	`seprod`
Z	capacity of technology c	`cap`
ν	load factor associated with technology c	`data("nu")`
ν_g	scaling of the load factor ν dependent on grade level g	`dataren("nur")`
$\mathfrak{M}_{p\to s}$	definition of primary to secondary energy transformation	`pe2se`
$\mathfrak{M}_{s\to s'}$	definition of secondary to secondary energy transformation	`se2se`
$\mathfrak{M}_{s\to f}$	definition of secondary to final energy transformation	`se2fe`
$\mathfrak{M}_{c_s\leftrightarrow g}$	combination of secondary energy technologies and grade levels	`tese2rlf`
$\mathfrak{M}_{c_f\leftrightarrow g}$	combination of final energy technologies and grade levels	`tefe2rlf`

3.5.2 Capacity constraints for CCS technologies (`capconstccs`)

$$R(t,r,q_i^{ccs},q_{i+1}^{ccs},c,g) = Z(t,r,c,g) \quad \forall\, t,r \;\; \forall\, M_{c\to CCS} \;\; \forall\, M_{CCS} \tag{33}$$

$$M_{CCS} = (q_i^{ccs}\times q_{i+1}^{ccs}\times c), i=1,...,4, \in \mathfrak{M}_{CCS}, \qquad M_{c\to CCS} = (c\times g) \in \mathfrak{M}_{c\to CCS}$$

R	amount of CO_2 in step i of the CCS chain to be transformed to the next one using technology c with grade level g	`ccs`
Z	capacity of CCS transformation technology with grade level g through technology c	`cap`
q_i^{ccs}	CO_2 emissions in step i of the CCS process chain	
$\mathfrak{M}_{CCS}$	definition of CCS steps and associated technologies	`ccs2te`
$\mathfrak{M}_{c\to CCS}$	combination of technology and grade levels for CCS	`teccs2rlf`

3.5.3 Capacity Depreciation (`ccap`)

Capacities depreciate either according to a vintage depreciation scheme (c_{vin}) or exponentialy (c_{exp}):

$$\begin{aligned} Z(t,r,c,g) = &\left(\sum_{M_{c\leftrightarrow t_l}} \Delta t\cdot\omega(r,t_l,c_{vin})\cdot\Delta Z(t-t_l,r,c_{vin},g)\right)\\ &+\Delta t\cdot\Delta Z(t-1,r,c_{exp},g)\\ &+(1-\Delta t\cdot\delta_c(r,c))\cdot Z(t-1,r,c_{exp},g) \qquad \forall\, t,r \;\; \forall\, M_{c\leftrightarrow g} \end{aligned} \tag{34}$$

$$M_{c\leftrightarrow t_l} = (c_{vin}\times t_l) \in \mathfrak{M}_{c\leftrightarrow t_l}, \qquad M_{c\leftrightarrow g} = (c\times g) \in \mathfrak{M}_{c\leftrightarrow g}$$

Initial capacities (ccap0)

Initial capacities of technologies with exponential depreciation are assigned from data; they are assumed to have a grade level $g = 1$:

$$Z(t_0, r, c_{exp}, g = 1) = Z_0(r, c_{exp}) \quad \forall\ r \ \ \forall\ c_{exp} \tag{35}$$

Z	capacity of technology c	`cap`
ΔZ	addition of capacity	`deltacap`
δ_c	depreciation of technology c	`data("delta")`
ω	weight factor of addition to technology c's capacity prior to initial time	`datacap("omeg")`
Z_0	initial capacity of technology c_{exp}	`data("cap0")`
t_l	life time	`tlt`
c_{exp}	technologies with exponential capacity depreciation	`expte(te)`
c_{vin}	technologies with vintage capacity depreciation	`vinte(te)`
$\mathfrak{M}_{c\leftrightarrow g}$	combination of technologies and grade levels	`teall2rlf`
$\mathfrak{M}_{c\leftrightarrow t_l}$	set of possible combinations of vintage technologies and life time indices	`tlt2te`

3.5.4 Cumulated Capacities (capcummo)

$$\hat{Z}(t+1, r, c_L) = \sum_{M_{c\leftrightarrow g}} \Delta t \Delta Z(t, r, c_L, g) + \hat{Z}(t, r, c_L) \quad \forall\ t, r \ \ \forall\ c_L \tag{36}$$

$$M_{c\leftrightarrow g} = (c \times g) \in \mathfrak{M}_{c\leftrightarrow g}$$

Initial cumulated capacities (capcum0)

$$\hat{Z}(t_0, r, c_L) = \hat{Z}_0(r, c_L) \quad \forall\ r \ \ \forall\ c_L \tag{37}$$

$\hat{Z}$	cumulated capacity of a learning technology c_L	`capcum`
ΔZ	addition to capacity of a learning technology c_L of grade level g	`deltacap`
$\hat{Z}_0$	initial cumulated capacity of a learning technology c_L	`data("ccap0")`
c_L	learning technologies	`learnte(te)`
$\mathfrak{M}_{c\leftrightarrow g}$	combination of technologies and grade levels	`teall2rlf`

3.6 Learning equation (llearn)

$$J(t, r, c_L) = \alpha(r, c_L) \cdot \hat{Z}(t, r, c_L)^{\beta(r, c_L)} + \tau_{IL}(r, c_L) \quad \forall\ t, r \ \ \forall\ c_L \tag{38}$$

This is equivalent to the common formulation of learning curves in the literature

$$J(t, r, c_L) = \tilde{\alpha}(r, c_L) \cdot \left(\frac{\hat{Z}(t, r, c_L)}{\hat{Z}(t_0, r, c_L)} \right)^{\beta(r, c_L)} + \tau_{IL}(r, c_L) \quad \forall\ t, r \ \ \forall\ c_L$$

with

$$\alpha(r, c_L) = \frac{\tilde{\alpha}(r, c_L)}{\hat{Z}(t_0, r, c_L)^{\beta(r, c_L)}} \quad \forall\, r \;\; \forall\, c_L$$

where $\tilde{\alpha}$ represents the difference between initial costs and floor costs. β is calculated from the learning rate (relative cost decrease when cumulated capacities double), $\tilde{\beta}$:

$$\beta(r, c_L) = \frac{\ln(1 - \tilde{\beta}(r, c_L))}{\ln 2} \quad \forall\, r \;\; \forall\, c_L$$

J	specific investment costs for adding capacity of a learning technology c_L	`investcost`
$\hat{Z}$	cumulated capacity of technology c	`capcum`
τ_{IL}	floor costs of a learning technology c_L	`data("inco0")`
α, β	learning parameters of a learning technology c_L	`data("learna")`, `data("learnb")`
$\tilde{\alpha}$	difference between initial costs and floor costs	
$\tilde{\beta}$	learning rate	
c_L	technology which develops through learning (learning technologies)	`learnte(te)`

3.7 Resource and Potential Constraints

3.7.1 Fuel extraction (`fuelconst2`)

For exhaustible energy types (fossils, uranium) and biomass, fuel extraction equals primary energy production. In REMIND-R, import M_E and export X_E of tradable primary energy types $E_{T,p}$ is added, taking specific trade costs τ_T into account.[4] This contribution is not included in the REMIND-G code.

$$\sum_{M_{p \to s}} P_p(t, r, e_x, e_s, c, g) = F(t, r, e_x, g) - (X_E(t, r, e_{T,p}) - (1 - \tau_T) M_E(t, r, e_{T,p})) \quad \forall\, t, r \;\; \forall\, M_{e_x, g} \tag{39}$$

$$M_{p \to s} = (e_p \times e_s \times c) \in \mathfrak{M}_{p \to s}, \qquad M_{e_x, g} = (e_x \times g) \in \mathfrak{M}_{e_x, g}$$

[4] τ_T represents energetic losses here, whereas in case of final good import, τ_T represents monetary costs (see sec. 2.2).

F	fuel extraction of an exhaustible resource e_x of grade level g	fuelex
M_E	energy import	MpRes
P_p	production of primary energy	peprod
X_E	energy export	XpRes
$e_{T,p}$	tradable primary energy type	entrape
e_x	exhaustible ressource	petyric(enty)
$\mathfrak{M}_{e_x,g}$	combination of exhaustible energy types and grade leves	enty2clf
$\mathfrak{M}_{p\to s}$	definition of primary to secondary energy transformation	pe2se

3.7.2 Constraints on energy production from renewable sources (renconst, renconst2)

Constraint on secondary energy production from renewable sources (renconst)

This equation assings upper limits Π_c on the *technical potential* of secondary energy production technologies from renewable sources (c_{ren}).

$$\pi_c(r, g, c_{ren}) \geq \nu_(r, c_{ren}) \cdot \nu_g(r, c_{ren}, g) \cdot Z(t, r, c_{ren}, g) \quad \forall\, t, r \;\; \forall\, M_{c_{ren} \leftrightarrow g} \quad (40)$$

$$M_{c_{ren} \leftrightarrow g} = (c_{ren} \times g) \in \mathfrak{M}_{c_{ren} \leftrightarrow g}$$

Constraint on renewable primary energy (biomass) production (renconst2)

$$\pi_e(r, e_p, g) \geq F(t, r, e_p, g) \quad \forall\, t, r \;\; \forall\, M_{e_p \leftrightarrow g} \quad (41)$$

$$M_{e_p \leftrightarrow g} = (e_p \times g) \in \mathfrak{M}_{e_p \leftrightarrow g}$$

F	extraction of primary resource e_p of grade level g	fuelex
Z	capacity of technology c	cap
ν	load factor of technology c	data("nu")
ν_g	scaling of the load factor ν dependent on grade level g	dataren("nur")
π_c	maximal production (according to technology c_{ren}) of secondary energy from non-exhaustible resource via c_{ren}, g	dataren("maxprod")
π_e	maximal production of primary energy from primary resource e_p of grade level g	dataperen("maxprod")
c_{ren}	renewable energy transformation technologies	ter(te)
$\mathfrak{M}_{c_{ren}\leftrightarrow g}$	combination of renewable technologies and grade levels (mapping $\mathfrak{M}_{c_\leftrightarrow g}$ is restricted on subset c_{ren})	teall2rlf
$\mathfrak{M}_{e_p\leftrightarrow g}$	combinations of primary renewable energy types and grade levels	peren2rlf

3.8 The Emission Equations

3.8.1 Production and Capture of Emissions (`emissions`)

Emissions of type q result from primary to secondary energy transformation or transformations within the chain of CCS steps (Leakage).[5]

The equation describes CO_2 released into the atmosphere and CO_2 capture for storage as two different emission types. In primary to secondary energy transformation processes, both types can be generated.[6]

$$Q(t,r,e_{in},e_{out},c,q) = \sum_{M_{p\rightarrow s}} \gamma(r,e_p,e_s,c,q)\cdot D_p(t,r,e_p,e_s,c) + \sum_{M_{CCS\rightarrow Q}} \sum_{M_{c\rightarrow CCS}} \gamma(r,q_i^{ccs},q_{i+1}^{ccs},c,q)\cdot R(t,r,q_i^{ccs},q_{i+1}^{ccs},c,g) \quad \forall\, t,r \quad \forall\, M_{c\rightarrow Q} \tag{42}$$

$$M_{c\rightarrow Q} = (e_{in}\times e_{out}\times c\times q)\ \in \mathfrak{M}_{c\rightarrow Q}, \qquad M_{p\rightarrow s} = (e_p\times e_s\times c) \in \mathfrak{M}_{p\rightarrow s}$$

D_p	demand of primary energy	`pedem`
P_s	production of secondary energy	`seprod`
Q	amount of emissions from type q produced by conversions explained in $\mathfrak{M}_{c\rightarrow Q}$	`emi`
R	transformation in the CCS chain from step q_i^{ccs} to q_{i+1}^{ccs} using technology c with grade level g	`ccs`
γ	emission of type q per energy flow in the transformation e_{in} into e_{out} using c	`dataemi`
q	emission type (CO_2, captured CO_2)	`enty`
q_i^{ccs}	CCS (captured CO_2) of stage i, i=1,...,4	`ccsco2(enty)`
$\mathfrak{M}_{CCS\rightarrow Q}$	definition of leakage from CCS transformations	`ccs2tele`
$\mathfrak{M}_{c\rightarrow CCS}$	combination of technology and grade levels for CCS	`teccs2rlf`
$\mathfrak{M}_{c\rightarrow Q}$	definition of emissions from a transformation	`emi2te`
$\mathfrak{M}_{p\rightarrow s}$	definition of primary to secondary energy transformation	`pe2se`

3.8.2 The CO_2 emission constraint (`emiconst`)

REMIND-R:

The initial allocation of permits to a region (Q_{init}) must cover the sum of emissions Q over all domestic emitting processes plus its permit exports X_Q minus its permit imports M_Q.

$$\sum_{M_{c\rightarrow Q}} Q(t,r,e_{in},e_{out},c,CO_2) + X_Q(t,r) - M_Q(t,r) \le Q_{init}(t,r) \qquad \forall\, M_{emicon} \tag{43}$$

[5] Emissions associated with secondary to final transformation or the usage of final energy, e.g. combustion of transport fuels, are transferred to the underlying secondary energy production.

[6] Further emission types could easily be added into this structure.

REMIND-G:
The equation is used for experiments with an exogenous emission time path Q_{exog}.

$$\sum_{M_{c\to Q}} Q(t, r, e_{in}, e_{out}, c, CO_2) \leq Q_{exog}(t, r) \quad \forall\ M_{emicon} \tag{44}$$

$$M_{c\to Q} = (e_{in} \times e_{out} \times c \times q)\ \in \mathfrak{M}_{c\to Q}$$

Mapping $\mathfrak{M}_{emicon}$ contains combinations of regions, time steps and emissions types to be considered in the respective emission constraint time path. In other words: It governs which region caps which emission type in which time step:

$$M_{emicon} = (t \times r \times CO_2)\ \in \mathfrak{M}_{emicon}$$

M_E	emissions permit import	`MpPerm`
Q	amount of emissions from type $q = CO_2$ produced by conversions specified in $\mathfrak{M}_{c\to Q}$	`emi`
Q_{init}	initial permit allocation	`emicap`
X_E	emissions permit export	`XpPerm`
Q_{exog}	exogenous time path for energy-related total CO_2 emissions	`dataemiconst`
$\mathfrak{M}_{c\to Q}$	definition of emissions from a transformation	`emi2te`
$\mathfrak{M}_{emicon}$	combination of regions, time steps and emission types to be considered in the respective emission constraint	`emicon`

3.8.3 Total emissions (`emissions2`)

REMIND-R:
The equation calculates total global CO_2 emissions per time step, $Q^{tot}_{CO_2}$ for the calculation of radiative forcing in the climate module. Exogenous land use-change emission data are added.

$$\sum_{r} \sum_{M_{c\to Q}} Q(t, r, e_{in}, e_{out}, c, CO_2) + Q^{lu}_{CO_2} = Q^{tot}_{CO_2}(t) \quad \forall\ t \tag{45}$$

REMIND-G:
The equation calculates energy-related global CO_2 emissions, exogenous land use-change emission data enter the climate module separately.

$$\sum_{r} \sum_{M_{c\to Q}} Q(t, r, e_{in}, e_{out}, c, CO_2) = Q^{e}_{CO_2}(t) \quad \forall\ t \tag{46}$$

$$M_{c\to Q} = (e_{in} \times e_{out} \times c \times q)\ \in \mathfrak{M}_{c\to Q}$$

Q	amount of emissions from type $q = CO_2$ produced by conversions specified in $\mathfrak{M}_{c\to Q}$	emi
$Q^e_{CO_2}$	energy-related global CO_2 emissions	emifos
$Q^{tot}_{CO_2}$	total global CO_2 emissions	en_emi
$Q^{lu}_{CO_2}$	land use-change global CO_2 emissions (data)	lucemi
$\mathfrak{M}_{c\to Q}$	definition of emissions from a transformation	emi2te

3.8.4 SO_2 and Aerosol emissions (so2emi, cscouple, cscouple0)

Both SO_2 and Aerosol emissions from the energy system are not modeled explicitely but parametrized according to the following equations, shown here for SO_2 (for Aerosols, they work exactly the same way):

Coupling SO_2 to CO_2 (so2emi)

$$Q^e_{SO_2}(t) = H(t) \cdot Q^e_{CO_2}(t) \quad \forall\ t \tag{47}$$

SO_2 conversion factor (cscouple)

The conversion factor $H(t)$ can change over time with a constant rate ΔH:

$$H(t+1) = H(t) \cdot (1 - \Delta H) \tag{48}$$

SO_2 conversion factor initial value (cscouple0)

$$H(t_0) = H_0 \tag{49}$$

H	conversion factor	cso2
$Q^e_{CO_2}$	energy-related global CO_2 emissions	REMIND-G: emifos, REMIND-R: en_emi
$Q^e_{SO_2}$	energy-related global SO_2 emissions	eso2
H_0	SO_2 conversion factor initial value	
ΔH	change rate of conversion factor	desulphur

3.9 The CCS Equations (ccsbal, ccstrans, ccsconst)

CCS Balance (ccsbal)

The right hand side of the equation calculates the total amount of CO_2 captured (Q with argument q_1^{ccs}) from all relevant emitting processes.[7] This amount enters the CCS process chain, R,[8] (left hand side).

$$\sum_{M_{c\to CCS}} R_1(t, r, g) = \sum_{M_{c\to Q}} Q(t, r, e_{in}, e_{out}, c, q_1^{ccs}) \quad \forall\ t, r \tag{50}$$

[7]Note that "CO_2 captured" is treated as an emission type distinct from CO_2 released into the atmosphere (see sec. 3.8.1 also).

[8]Variable R has further arguments which are not relevant in this equation.

$M_{c\to CCS} = (c \times g) \in \mathfrak{M}_{c\to CCS}, \qquad M_{c\to Q} = (e_{in} \times e_{out} \times c \times q) \ \in \mathfrak{M}_{c\to Q}$

Transformation in the CCS chain (`ccstrans`)

Processes in the CCS chain are subject to leakage. The amount R of CO_2 in step $i+1$ is thus the amount R of CO_2 in the previous step i times 1 minus specific emission coefficient γ.[9]

$$(1-\gamma(q_i^{ccs}, q_{i+1}^{ccs}, c, CO_2)) \cdot R(t, q_i^{ccs}, q_{i+1}^{ccs}, c, g) \\ = R(t, q_{i+1}^{ccs}, q_{i+2}^{ccs}, c, g) \qquad \forall\ t\ \ \forall\ M_{CCS}\ \ \forall\ M_{c\to CCS} \qquad (51)$$

Constraint on CCS injection (`ccsconst`)

$$\sum_{t'=t_0}^{t} \Delta t \cdot R(t', r, q_3^{ccs}, q_4^{ccs}, c, g) \le \psi_{CCS}(r, g) \quad \forall\ t\ \ \forall\ M_{c\to CCS} \qquad (52)$$

$M_{CCS} = (q_i^{ccs} \times q_{i+1}^{ccs} \times c), i = 1, ..., 4, \in \mathfrak{M}_{CCS}, \qquad M_{c\to CCS} = (c \times g) \in \mathfrak{M}_{c\to CCS}$

Q	amount of CO_2 emissions produced by conversions explained in $\mathfrak{M}_{c\to Q}$	`emi`
R	amount of CO_2 in step i of the CCS chain to be transformed to the next one using technology c with grade level g	`ccs`
γ	specific CO_2 emissions in the transformation q_i^{ccs} into q_{i+1}^{ccs} using c	`dataemi`
ψ_{CCS}	maximal cumulative injection for CCS of grade level g	`dataccs("quan")`
q_i^{ccs}	CCS (captured CO_2) of stage i, i=1,...,4	`ccsco2(enty)`
$\mathfrak{M}_{c\to CCS}$	combination of technology and grade levels for CCS	`teccs2rlf`
$\mathfrak{M}_{c\to Q}$	definition of emissions from a transformation	`emi2te`
$\mathfrak{M}_{CCS}$	definition of CCS steps and associated technologies	`ccs2te`

[9]Note the different index numbers in the second and third arguments of R on the left hand and right hand side of the equation.

4 Climate Module

4.1 ACC2 (Interface and further reference)

The climate and carbon chemistry module $ACC2$ calculates the climate system dynamics in response to various radiative forcings given in annual resolution.

For a model description, please refer to Kanaka and Kriegler (2007).

ACC2 is coupled to REMIND via emissions of $CO2$, $SO2$, and aerosols from the energy system. By linear interpolation, REMIND values are converted to annual resolution. Other emissions are taken from exogenous data.

In policy experiments, a guardrail on global mean temperature increase is assigned as an extra constraint.[10]

4.2 Simple box model

The implementation of the simple box model follows the elaboration by Kriegler and Bruckner (2004).

Carbon cycle

$$\hat{Q}_{CO_2}(t) = \sum_{t'} Q^{tot}_{CO_2}(t') \quad \forall\, t' = 1, ..., t \tag{53}$$

$$\begin{aligned}\mathfrak{C}(t+1) &= \mathfrak{C}(t)\\ &+ \frac{\Delta t}{2}\Big(\sigma_{source} \cdot \hat{Q}_{CO_2}(t) + \epsilon \cdot Q^{tot}_{CO_2}(t) - \sigma_{sink} \cdot (\mathfrak{C}(t) - \mathfrak{C}_H)\\ &\quad + \sigma_{source} \cdot \hat{Q}_{CO_2}(t+1) + \epsilon \cdot Q^{tot}_{CO_2}(t+1) - \sigma_{sink} \cdot (\mathfrak{C}(t+1) - \mathfrak{C}_H)\Big) \quad \forall\, t\end{aligned} \tag{54}$$

$$\mathfrak{C}(t_0) = \mathfrak{C}_0 \tag{55}$$

Radiative forcing

$$\mathfrak{R}_{CO_2}(t) = \kappa \cdot \frac{\ln(\mathfrak{C}(t)/\mathfrak{C}_H)}{\ln 2} \quad \forall\, t \tag{56}$$

$$\mathfrak{R}_{SO_2}(t) = \frac{\iota_D \cdot Q^{e}_{SO_2}(t)}{Q^{e}_{SO_2,1990}} + \frac{\iota_I \cdot \ln(1 + Q^{e}_{SO_2}(t)/Q^{nat}_{SO_2})}{\ln(1 + Q^{e}_{SO_2,1990}/Q^{nat}_{SO_2})} \quad \forall\, t \tag{57}$$

$$\mathfrak{R}(t) = \mathfrak{R}_{CO_2}(t) + \mathfrak{R}_{SO_2}(t) + \mathfrak{R}_{OGHG}(t) \quad \forall\, t \tag{58}$$

Temperature equations

[10] $ACC2$ can handle other guardrails as well, e.g. an ocean acidification limit. The coupling to the energy system does not yet support these alternative guardrails.

$$T(t+1) = T(t)+\Delta t\frac{1}{2}\left(\mu_{drive}\frac{\ln 2}{\kappa}\mathfrak{R}(t) - \mu_{damp}T(t) + \mu_{drive}\frac{\ln 2}{\kappa}\mathfrak{R}(t+1) - \mu_{damp}T(t+1)\right) \quad \forall\, t \tag{59}$$

$$T(t_0) = T_0 \tag{60}$$

The estimation of the parameters μ_{drive} and μ_{damp} takes climate system factors like climate sensitivity, ocean heat capacity and vertical diffusivity into account.

$\hat{Q}_{CO_2}$	cumulative CO_2 emissions	`cume`
$Q^e_{SO_2}$	SO_2 emissions in tgs per a	`eso2`
$Q^{tot}_{CO_2}$	total global CO_2 emissions	`en_emi`
T	global mean temperature relative to preindustrial level	`temp`
$\mathfrak{C}$	atmospheric CO_2 concentrations	`conc`
$\mathfrak{R}$	total radiative forcing	`ftot`
$\mathfrak{R}_{CO_2}$	CO_2 radiative forcing	`fco2`
$\mathfrak{R}_{SO_2}$	SO_2 direct and indirect radiative forcing	`fso2`
ϵ	conversion factor gtc into ppmv	`cconvi`
ι_D	direct aerosol forcing in 1990 (W per m^2)	`dso1990`
ι_I	indirect aerosol forcing in 1990 (W per m^2)	`iso1990`
κ	radiative forcing for a doubling of CO_2 (W per m^2)	`fcodb`
μ_{damp}	temperature damping factor	`alpha`
μ_{drive}	temperature driving factor	`mu`
σ_{sink}	ocean biosphere as CO_2 sink	`sigma`
σ_{source}	ocean biosphere as CO_2 source	`b`
$\mathfrak{C}_0$	initial atmospheric CO_2 concentration	`c1995`
$\mathfrak{C}_H$	preindustrial atmospheric CO_2 concentration	`c0`
$\mathfrak{R}_{OGHG}$	radiative forcing of other GHGs - external input	`foghg`
$Q^e_{SO_2,1990}$	SO_2 emissions in 1990 in tgs per a	`so1990`
$Q^{nat}_{SO_2}$	natural SO_2 emissions in tgs per a	`enatso2`
T_0	global mean temperature in 2005 relative to preindustrial level	

5 Negishi procedure

This chapter applies to REMIND-R only!

The Negishi procedure adjusts the Negishi weights W in an iterative process around the model optimization. The implementation follows Leimbach and Toth (2003). In each iteration step, new Negishi weights are determined as follows:

- Trade deficits $\mathfrak{T}$ of each tradable entity (specified by indizes: tradable energy E, final good G, emission permits Q) are calculated from imports M and exports X:

$$\mathfrak{T}_E(t,r,e_T) = X_E(t,r,e_T) - M_E(t,r,e_T) \;\; \forall\; t,r,e_T \tag{61}$$

$$\mathfrak{T}_G(t,r) = X_G(t,r) - M_G(t,r) \;\; \forall\; t,r$$

$$\mathfrak{T}_Q(t,r) = X_Q(t,r) - M_Q(t,r) \;\; \forall\; t,r$$

- Shadow prices $\mathfrak{p}$ of each tradable entity are determined from the marginals of the associated trade balance (see sec. 2.7). In case of permits, the maximum of trade balance marginal and emission summation (see sec. 3.8.3) is considered:[11]

$$\mathfrak{p}_E(t,e_T) = \left|\frac{\partial U}{\partial(\sum_r (X_E - M_E))}\right| \;\; \forall\; t,e_T \tag{62}$$

$$\mathfrak{p}_G(t) = \left|\frac{\partial U}{\partial(\sum_r (X_G - M_G))}\right| \;\; \forall\; t$$

$$\mathfrak{p}_Q(t) = \max\left(\left|\frac{\partial U}{\partial(\sum_r (X_Q - M_Q))}\right|, \left|\frac{\partial U}{\partial(\sum_r \sum_{M_{c\to Q}} Q + Q^{lu}_{CO_2} - Q^{tot}_{CO_2})}\right|\right) \;\; \forall\; t$$

- The **intertemporal trade balance** $\mathfrak{b}$ of each region is determined as the sum of trade volumes of all tradable entities. Trade volumes are products of trade deficits and associated shadow prices. i is the iteration step:

$$\mathfrak{b}_i(r) = \sum_t \left(\sum_{e_T} \mathfrak{p}_E(t,e_T)\mathfrak{T}_E(t,r,e_T) + \mathfrak{p}_G(t)\mathfrak{T}_G(t,r) + \mathfrak{p}_Q(t)\mathfrak{T}_Q(t,r)\right) \forall\, r,i \tag{63}$$

[11] Arguments of model variables are omitted here for clarity.

- Weighting factors $\mathfrak{W}$ express regional economic power by adding the product of final good shadow price times consumption to the intertemporal trade balance:

$$\mathfrak{W}(r) = \sum_t \left(\mathfrak{p}_G(t) C(t,r) + \sum_{e_T} \mathfrak{p}_E(t, e_T) \mathfrak{T}_E(t, r, e_T) + \mathfrak{p}_G(t) \mathfrak{T}_G(t, r) + \mathfrak{p}_Q(t) \mathfrak{T}_Q(t, r) \right) \ \forall\, r \tag{64}$$

- Non-normalized Negishi weights $\tilde{W}$ are calculated from intertemporal trade balances, weighting factors, and the non-normalized Negishi weights from the previous iteration step:

$$\tilde{W}_{i+1}(r) = \tilde{W}_i(r) \cdot \left(1 + \mathfrak{b}_i(r) \frac{\Delta i \ln(i) + 2\Delta i}{\sum_r \mathfrak{W}(r) + \mathfrak{W}(r)} \right) \quad \forall\, r, i \tag{65}$$

  Δi is a parameter used to control the iteration step size. If $\mathfrak{b}$ approaches zero, the correction of the weights $\tilde{W}$ gets smaller, and the iteration converges.

- Finally, normalization yields the Negishi weights W:

$$W(r) = \frac{\tilde{W}_i(r)}{\sum_r \tilde{W}_i(r)} \tag{66}$$

$Q_{CO_2}^{tot}$	total global CO_2 emissions	`en_emi`
W	Negishi weights	`w`
$\tilde{W}$	Non-normalized Negishi weights	`NW`
$\mathfrak{b}$	intertemporal trade balance	`defic`
$\mathfrak{p}$	Shadow prices	`PVP1,2,3`
$\mathfrak{T}$	Trade deficits	`trade1,2,3`
$\mathfrak{W}$	Weighting factors	`weight`
$Q_{CO_2}^{lu}$	land use-change global CO_2 emissions	`lucemi`
Δi	parameter	`parm`
e_T	tradable energy type	`entra`

Documentation of The Economic Decomposition Method*

*Unpublished Working paper written during the preparation of Chapter 4.

Decomposition of Consumption Losses

Documentation in Preparation for the Publication Lüken et al., The Role of Technological Availability for the Distributive Impacts of Climate Change Mitigation Policy

Michael Lüken*

Feb 21, 2010

Decomposition of Consumption Differences for One Scenario

We start with the **macroeconomic budget** equation,

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

and the **intertemporal trade balance**,

$$\sum_t \left(\sum_i p_{E,i}(t) X_{E,i}(t,r) + p_p(t) X_p(t,r) + p_G(t) X_G(t,r) \right) = 0 \quad \forall\ r \tag{2}$$

For the sake of the following arguments, we can simplify the equations: We just need the left hand side of the macro budget, [1] and we just consider one tradable good besides the macro good, X_E:

$$Y(t,r) - X_G(t,r) = ... \quad \forall\ t,r \tag{3}$$

$$\sum_t \left(p_E(t) X_E(t,r) + p_G(t) X_G(t,r) \right) = 0 \quad \forall\ r \tag{4}$$

In order to combine the macro budget (3) and the trade balance (4) to display contributions of different tradable goods, we need 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):

$$p_G(t) \cdot Y(t,r) - p_G(t) \cdot X_G(t,r) = ... \quad \forall\ t,r \tag{5}$$

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[1]For all other components in the macro budget, the following works the same way as for Y

We sum over all time steps:

$$\sum_t p_G(t)Y(t,r) - \sum_t p_G(t)X_G(t,r) = ... \quad \forall\, r \tag{6}$$

Now we can combine (6) and (4), as both are expressed with respect to present value prices $p_i(t)$:

$$\sum_t p_G(t)Y(t,r) + \sum_t p_E(t)X_E(t,r) = ... \quad \forall\, r \tag{7}$$

Decomposition of Consumption Differences for a Pair of Scenarios

In order to analyze differences between a reference scenario ("R") and a climate policy scenario ("POL"), 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. (6) for both experiments.

$$\sum_t p_G^R \cdot Y^R - \sum_t p_G^R \cdot X_G^R = ... \quad \forall\, r \tag{8}$$

$$\sum_t p_G^R \cdot Y^{\mathrm{POL}} - \sum_t p_G^R \cdot X_G^{\mathrm{POL}} = ... \quad \forall\, r \tag{9}$$

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:

$$\sum_t \left(p_E^R(t)X_E^R(t,r) + p_G^R(t)X_G^R(t,r)\right) = 0 \quad \forall\, r \tag{10}$$

$$\sum_t \left(p_E^{\mathrm{POL}}(t)X_E^{\mathrm{POL}}(t,r) + p_G^{\mathrm{POL}}(t)X_G^{\mathrm{POL}}(t,r)\right) = 0 \quad \forall\, r \tag{11}$$

For the reference experiment, we can easily combine (8) and (10):

$$\sum_t p_G^R Y^R(t,r) + \sum_t p_E^R(t)X_E^R(t,r) = ... \quad \forall\, r \tag{12}$$

But for the policy experiment, eq.s (9) and (11) contain different price vectors for the good trade component. Hence we rewrite the left hand side of eq. (9) by multiplying the good trade component by a fraction equal 1:

$$\sum_t p_G^R Y^{\mathrm{POL}} - \sum_t p_G^R X_G^{\mathrm{POL}} \cdot \frac{\sum_t p_G^{\mathrm{POL}} X_G^{\mathrm{POL}}}{\sum_t p_G^{\mathrm{POL}} X_G^{\mathrm{POL}}} = ... \quad \forall\, r \tag{13}$$

Please note that p_G^{POL} and X_G^{POL} are time dependent, but the temporal aggregate, $\sum_t p_G^{\mathrm{POL}} X_G^{\mathrm{POL}}$, is constant in time. So the denominator is a constant and we can pull it into the outer sumation:

$$\sum_t p_G^R Y^{\mathrm{POL}} - \sum_t \left(\frac{p_G^R X_G^{\mathrm{POL}}}{\sum_t p_G^{\mathrm{POL}} X_G^{\mathrm{POL}}} \right) \cdot \sum_t p_G^{\mathrm{POL}} X_G^{\mathrm{POL}} = \ldots \quad \forall\, r \tag{14}$$

By defining

$$\gamma = \sum_t \left(\frac{p_G^R X_G^{\mathrm{POL}}}{\sum_t p_G^{\mathrm{POL}} X_G^{\mathrm{POL}}} \right) \tag{15}$$

this simplifies to

$$\sum_t p_G^R(t) Y^{\mathrm{POL}}(t,r) - \gamma(r) \sum_t p_G^{\mathrm{POL}}(t) X_G^{\mathrm{POL}}(t,r) = \ldots \quad \forall\, r \tag{16}$$

Now we can combine macro budget (16) and trade balance (11) for the climate policy scenario:

$$\sum_t p_G^R(t) Y^{\mathrm{POL}}(t,r) + \gamma(r) \sum_t p_E^{\mathrm{POL}}(t) X_E^{\mathrm{POL}}(t,r) = \ldots \quad \forall\, r \tag{17}$$

The term $\gamma(r)$ can be interpreted as an region-specific correction factor. It provides us the bridge between the different price metrics.

In the following, we use the following definitions to simplify notation (analogous definitions apply to the other variables):

$$\bar{Y}(r) := \sum_t p_G(t) \cdot Y(t,r) \qquad \bar{X}_{E,i}(r) := \sum_t p_{E,i}(t) \cdot X_{E,i}(t,r) \tag{18}$$

Then we can write the decomposed consumption in the business as usual experiment as follows:

$$\begin{aligned} &\bar{Y}^{\mathrm{R}}(r) + \sum_i \bar{X}_{E,i}^{\mathrm{R}}(r) \\ &\quad = \bar{C}^{\mathrm{R}}(r) + \bar{I}^{\mathrm{R}}(r) + \bar{G}_{\mathrm{fuel}}^{\mathrm{R}}(r) + \bar{G}_{\mathrm{inv}}^{\mathrm{R}}(r) \quad \forall\, r \end{aligned} \tag{19}$$

The decomposed consumption for the policy scenario reads

$$\begin{aligned} &\bar{Y}^{\mathrm{POL}}(r) + \gamma(r) \sum_i \bar{X}_{E,i}^{\mathrm{POL}}(r) + \gamma(r) \bar{X}_p^{\mathrm{POL}}(r) \\ &\quad = \bar{C}^{\mathrm{POL}}(r) + \bar{I}^{\mathrm{POL}}(r) + \bar{G}_{\mathrm{fuel}}^{\mathrm{POL}}(r) + \bar{G}_{\mathrm{inv}}^{\mathrm{POL}}(r) \quad \forall\, r \end{aligned} \tag{20}$$

From (20) and its business as usual counterpart (19) we determine the differences of the components in absoulte terms:

$$\sum_t p_G^R(t) Y^{\text{POL}}(t,r) + \gamma(r) \sum_t p_E^{\text{POL}}(t) X_E^{\text{POL}}(t,r) = ... \quad \forall\ r \tag{21}$$

From Equation (20) and its business as usual counterpart, Equation (19), we determine absolute differences of the components. (Dividing by GDP in the *BAU* scenario, $\bar{Y}^{\text{R}}(r)$, yields relative differences.) Hence, the consumption difference can be decomposed as follows:

$$\begin{aligned} \Delta C(r) =& \Delta Y(r) - \Delta I(r) - \Delta G_{\text{fuel}}(r) - \Delta G_{\text{inv}}(r) \\ &+ \gamma(r) \left(\sum_i \bar{X}_{E,i}^{\text{POL}}(r) - \sum_i \bar{X}_{E,i}^{\text{R}}(r) + \bar{X}_p^{\text{POL}}(r) \right) \quad \forall\ r \end{aligned} \tag{22}$$

We calculate the *net* energy trade effect by subtracting the share of $\Delta G_{\text{fuel}}(r)$ that can be attributed to fuel export from $\Delta X_{E,i}(r)$. Remaining extraction costs cover domestic fuel use. With the definitions $\Delta X_{E,i}(r) = \gamma(r)(\bar{X}_{E,i}^{\text{POL}}(r) - \bar{X}_{E,i}^{\text{R}}(r))$ and $\Delta X_p(r) = \gamma(r)\bar{X}_p^{POL}(r)$, this leads to Equation (3) in the Publication Lüken et al., The Role of Technological Availability for the Distributive Impacts of Climate Change Mitigation Policy. In preparation for Energy Policy.

From eq. (22) follows a linear relation between $\Delta C(r)$ and $\Delta X_p(r)$ with a slope of -1:

$$\Delta C(r) = -1 \cdot \Delta X_p(r) + \Delta C_0(r) \quad \forall r \tag{23}$$

where $\Delta C_0(r)$ is the consumption loss due to other effects rather than permit trade (domestic effects, energy trade effects).

Please note that the definition of $\Delta X_p(r)$ includes the correction term $\gamma(r)$. This means that the slope of -1 cannot be directly translated into a monetary one-by-one relation. Rather, an additional revenue of 1\$ on the permit market leads to a decrease of consumption loss of $\gamma \cdot 1\$$. In model experiments with REMIND-R, $\gamma(r)$ is found to be on the order of 0.8 to 0.9.

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