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. (2010), 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 model comparison,

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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.

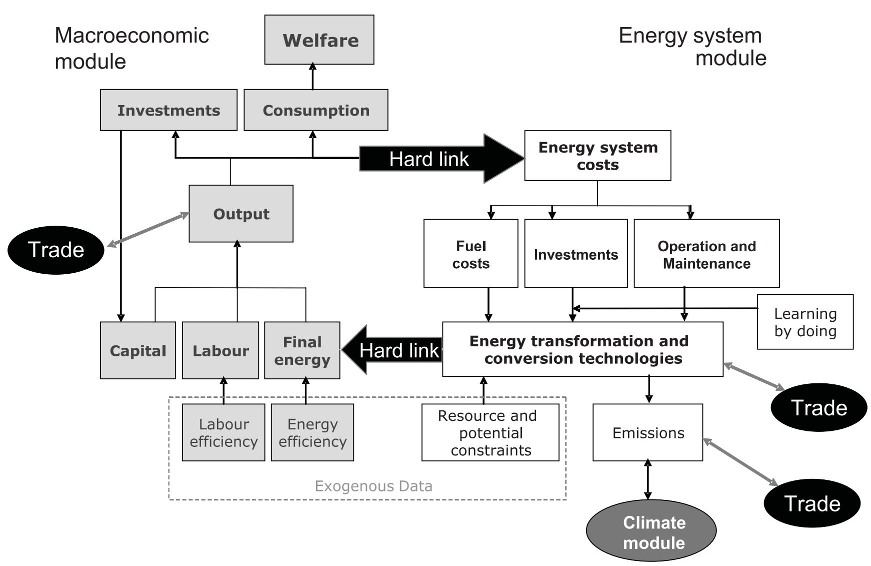
From simulation results, it transpires firstly that deep cuts in emissions—and even negative global emissions from 2075 on—are possible. Second, the loss of consumption need not exceed 2% globally in any period if a broad portfolio of technological options is available; this result is conditional on 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., 2010). 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.

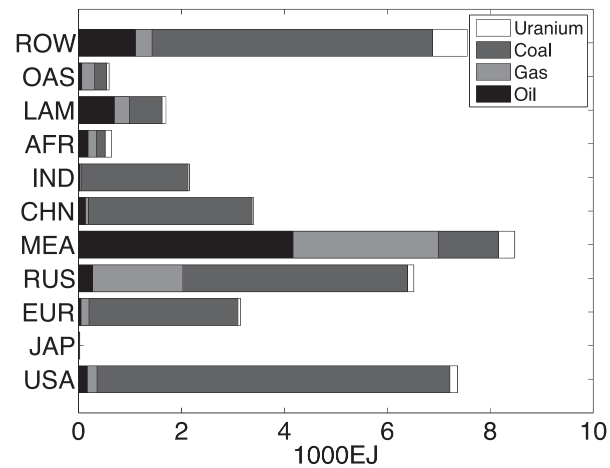
^ This secondary energy type includes heating oil.

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., 2010). 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

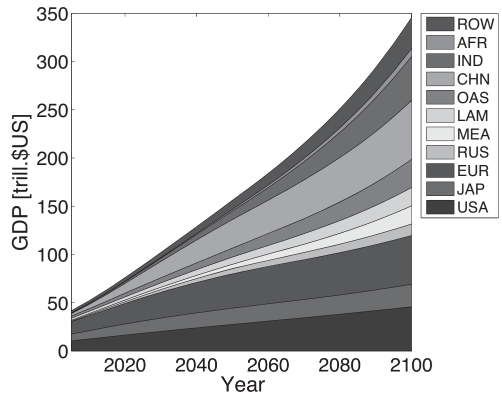
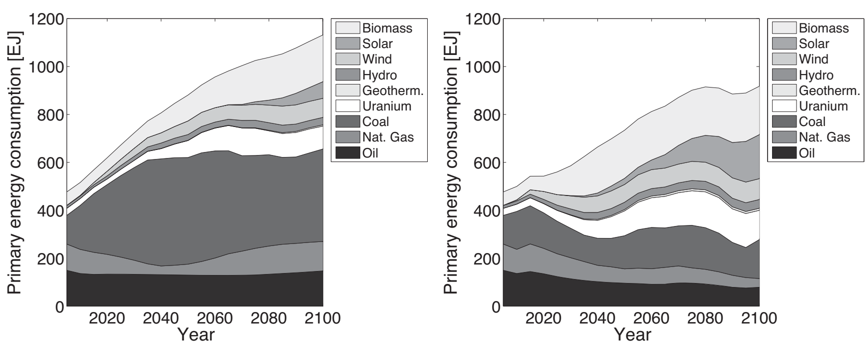


Figure 4. Consumption of Primary Energy

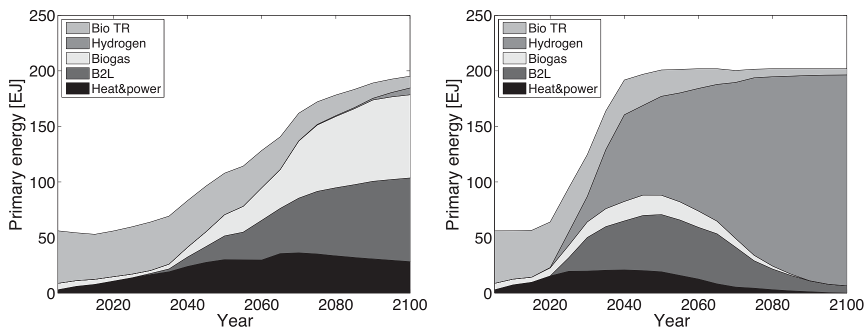


(a) Baseline scenario (b) 400ppm scenario

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.

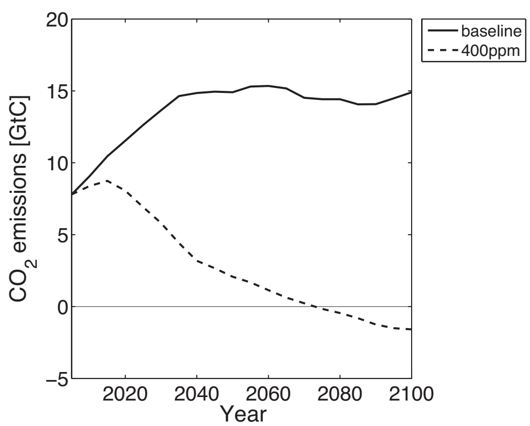
Figure 6 shows that the two reference scenarios yield entirely different emissions paths. Due to the growing coal consumption, worldwide emissions increase to almost 15 GtC in the *baseline* scenario by 2100. While this is a moderate increase compared to the growth in baseline emissions projected in

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



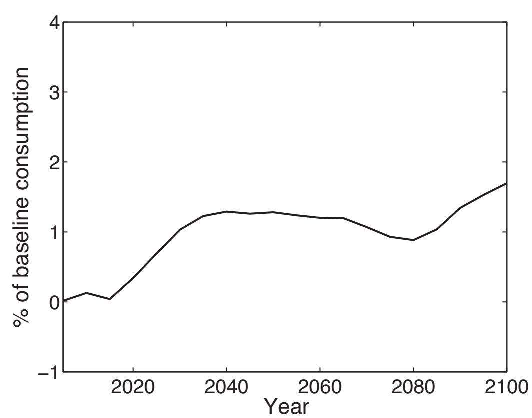
other studies such as Magne et al. (2009), Sano et al. (2006), and Crassous et al. (2006), the mitigation gap left by our baseline nevertheless is huge. In the *400ppm* scenario, emissions have to be reduced steeply between 2020 and 2040, and negative emissions have to be achieved by about 2080.

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).

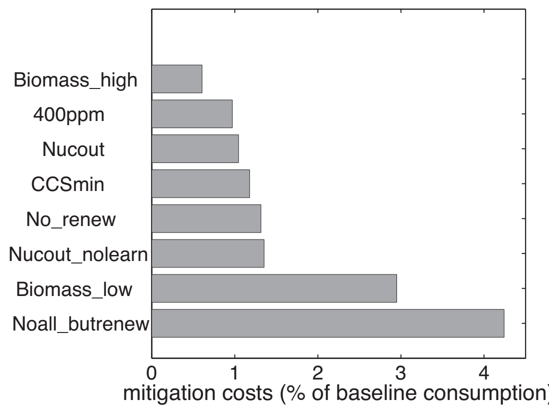
In all scenarios with altered potentials on biomass and CCS (i.e. *CCSmin, Biomass_high, Biomass_low* and *Noall_butrenew*), regional shares on the potentials are kept constant between scenarios at their reference levels.

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. (2010).

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

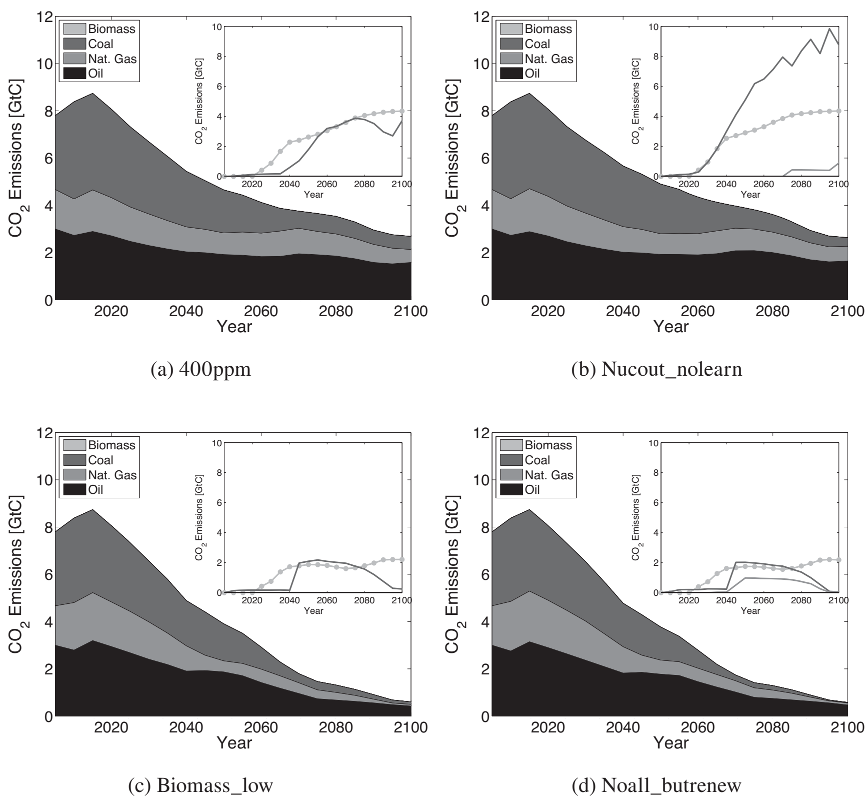


We now discuss in more detail changes in the global energy system that are linked with four scenarios that significantly differ in terms of mitigation costs: (I) *400ppm* scenario, (II) *Nucout_nolearn* scenario, (III) *Biomass_low* scenario, and (IV) *Noall_butrenew* scenario. The mitigation costs amount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

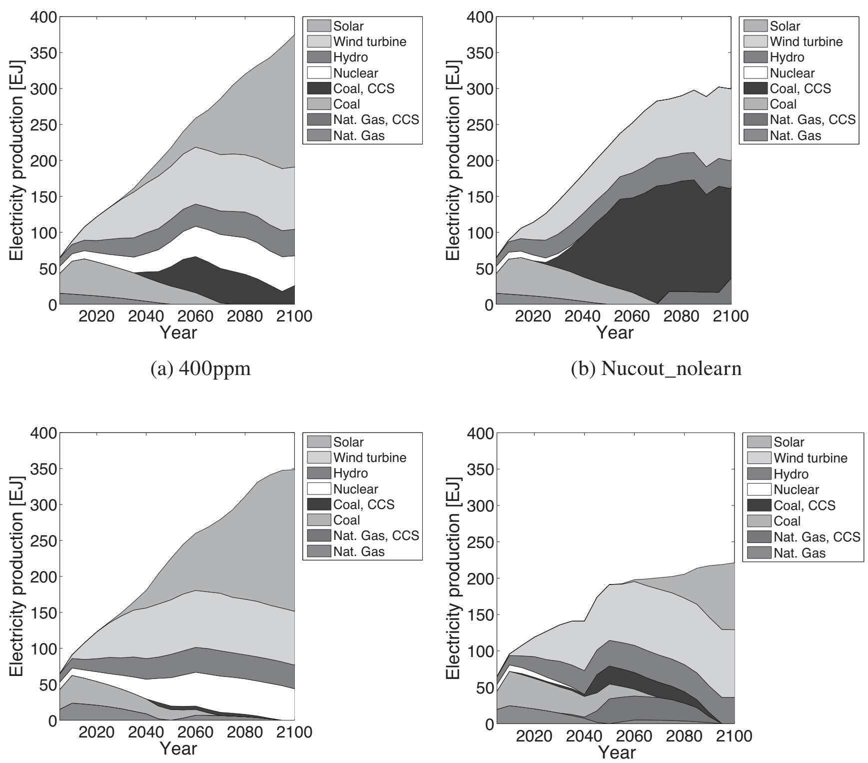
(c) Biomass_low

(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)

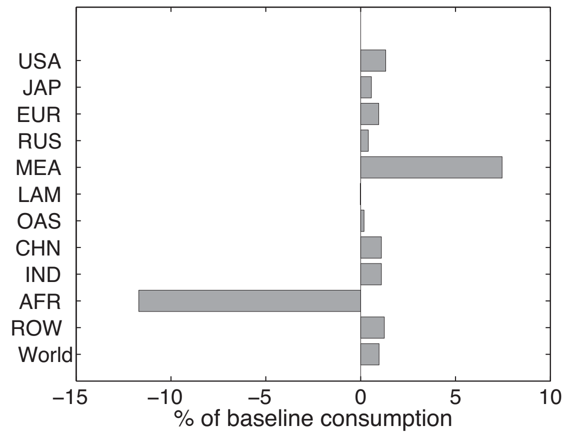
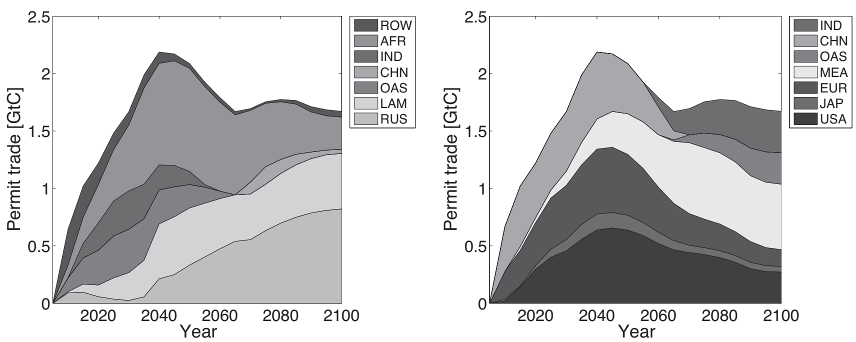


Figure 12. Trade in Emission Permits (400ppm Scenario)



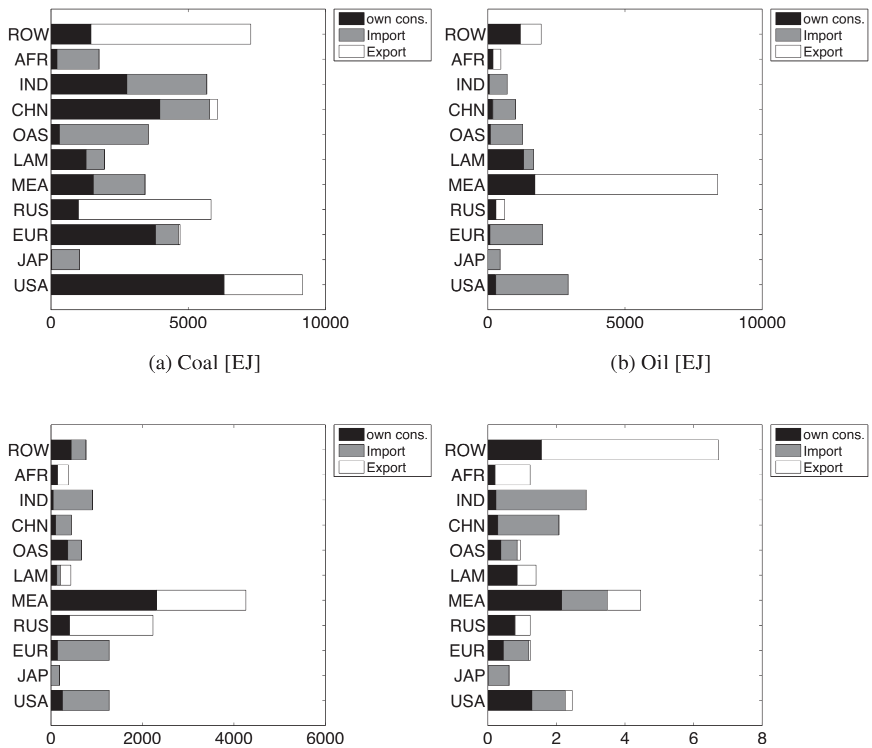
(a) Export (b) Import

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]

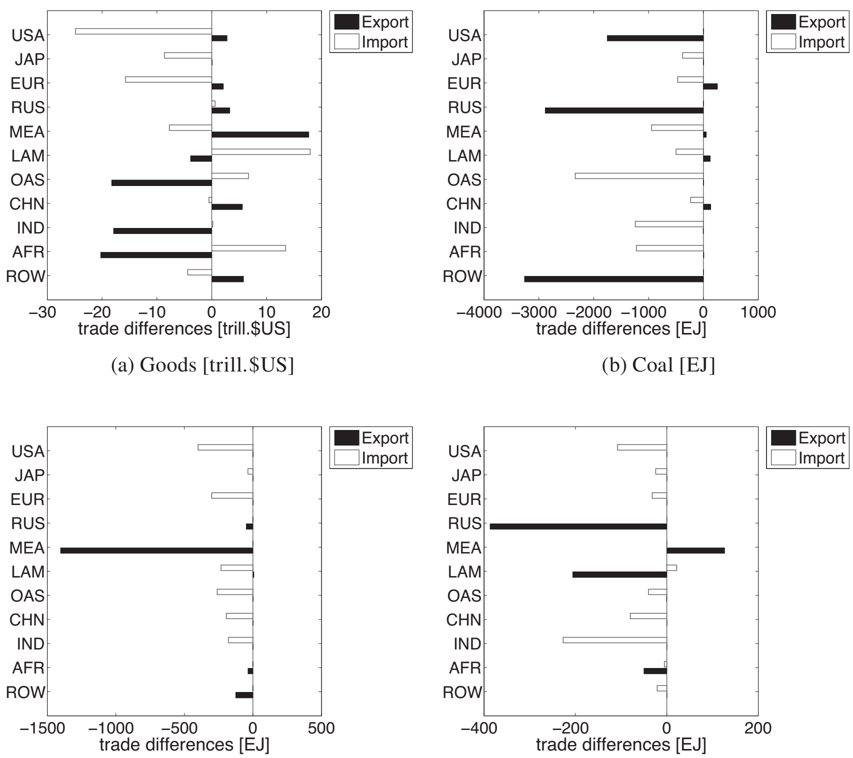
(d) Uranium [Mt Ur]

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]

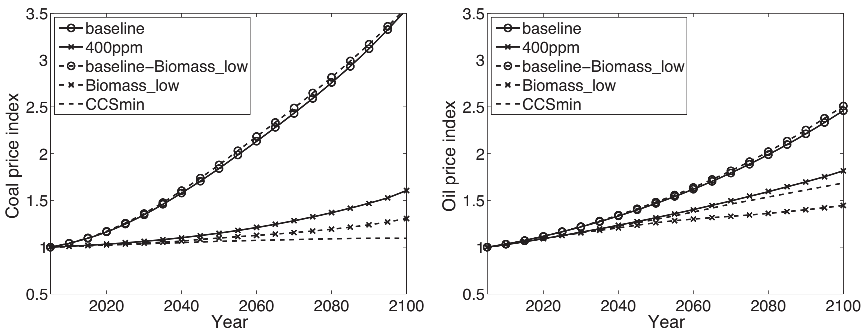
(c) Oil [EJ]

(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 $US 120 per t$CO_2$ in the *400ppm* scenario and up to $US 550 per t$CO_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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