Investment Strategies for Climate Change Mitigation

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Abstract

The substantial threat of anthropogenic climate change implies the reducing of greenhouse gas emissions. This thesis deals with the costs and strategies of climate change mitigation. In particular, investment strategies for climate change mitigation are investigated. The thesis is separated into five parts each focusing on subquestions of the overall research question. After an introduction into the problem of climate change and the important macro-economic mechanisms for mitigation, these subquestions are answered in separate chapters. For the analysis Integrated Assessment models are used.

First, the impacts of technological spillovers under climate policies are analyzed by means of a multi-regional model with technological change in form of interregional spillovers. Model results indicate that the higher the ratio between the spillover intensities for energy and labour efficiency, the lower are mitigation costs. As well, first-mover advantages and commitment incentives for climate policy scenarios are investigated. A multi-regional hybrid model with a more complex energy system is used for studying investments into energy technologies in detail. In climate policy scenarios the entire energy consumption is reduced, while renewable energy and CCS technologies are expanded immediately. Different regions follow quite different mitigation strategies. While ambitious climate targets can be reached with moderate global costs, the regional costs show a high variance. In addition, Integrated Assessment models are used to investigate what happens if the world will not agree on a climate friendly policy within the next years. The impacts of early investments into renewable energy technologies in first-best and second-best worlds are analyzed. Mitigation costs increase significantly, if the climate policy implementation is delayed. In contrast, early deployment of renewable energy technologies reduces the global costs. Within a five-region hybrid model the impacts of dynamics and direction of technological change under climate change mitigation are studied. It turns out that mitigation costs and strategies are quite sensitive to these variables. Further experiments indicate that the impacts depend on the set of available technologies. For studying the role of endogenous technological change for climate change mitigation, this model is extended by a new formulation of efficiency improvements. It turns out that investments into the efficiency of some energy sectors play a crucial role for low mitigation costs. In climate policy scenarios, the increased mitigation costs of technological restrictions can be overcome by R&D investments into energy efficiencies.

However, the results of this thesis demonstrate the important role of investment strategies for climate change mitigation costs. The world gains from early investments into both a broad portfolio of technologies and energy efficiencies. Thereby the immediate support and high diversity of investments mainly provide low mitigation costs.

Zusammenfassung

Der anthropogene Klimawandel verlangt die Reduktion von Treibhausgasen. Diese Arbeit beschäftigt sich mit den Kosten und Strategien zur Vermeidung des Klimawandels. Dabei werden vor Allem Investitionsstrategien der Vermeidung untersucht. Die Arbeit is unterteilt in fünf Teile, die jeweils Unterfragen der allgemeinen Forschungsfrage untersuchen. Nach einer Einleitung in das Problem des Klimawandels und Makro-Ökonomischen Mechanismen der Vermeidung werden diese Unterfragen in einzelnen Kapiteln beantwortet. Die Analyse basiert auf Integrated Assessment Modellen.

Zuerst werden die Auswirkungen von technologischem Spillover in einem Mehrregionenmodell mit technologischem Wandel in Form von interregionalem Spillover analysiert. Modellergebnisse zeigen, daß je größer der Quotient zwischen Arbeits- und Energieeffizienz steigernden Spilloverintensität ist, desto geringer sind die Vermeidungskosten. Außerdem werden die Vorteile von Vorreitern und Anreize für eine Klimapolitik untersucht. Ein mehrregionales Hybridmodell mit einem detailierten Energiesystem wird benutzt, um die Investitionen in Energietechnologieen im Detail zu analysieren. In Klimapolitikszenarien wird der gesammte Energiekonsum verringert, während erneuerbare Energie und CCS Technologieen sofort ausgebaut werden. Verschiedene Regionen verfolgen grundsätzlich untershciedliche Vermeidungsstrategieen. Während ambitionierte Klimaschutzschranken zu moderaten globalen Kosten erreicht werden können, variieren die regionalen Kosten deutlich.
Des Weiteren werden Integrated Assessment Modelle genutzt, um herauszufinden, was es bedeutet, wenn die Welt sich in den nächsten Jahren nicht auf eine klimafreundliche Politik einigen kann. Die Auswirkungen von frühzeitigen Investitionen in erneuerbare Energieen in erstbesten und zweitbesten Welten wird analysiert. Die Vermeidungskosten steigen signifikant, wenn die Implementierung von Klimapolitik verzögert wird. Hingegen verringert ein frühzeitiger Einsatz von erneuerbaren Energieen die globalen Kosten. In einem Hybridmodell mit fünf Regionen werden die Auswirkungen von Dynamik und Richtung des technologischen Wandels unter Klimapolitik untersucht. Es zeigt sich, daß die Vermeidungskosten und -strategieen sensitiv auf diese Variablen reagieren. Weitere Experimente deuten an, daß die Auswirkungen vom Spektrum der zur Verfügung stehenden Technologieen abhängt. Um die Rolle des endogenen technologischen Wandels für die Vermeidung des Klimawandels zu studieren, wird dieses Modell um eine neue Formulierung von Effiziessteigerungen erweitert. Es zeigt sich, daß Investitionen in die Effizienz von einigen Energiesektoren eine entscheidende Rolle für niedrige Vermeidungskosten spielen. In Klimapolitikszenarien können die durch technologische Einschränkungen erhöhten Vermeidungskosten durch F&E Investitionen in die Energieeffiezienz reduziert werden.

Wie auch immer, zeigen die Ergebnisse dieser Arbeit die wichtige Rolle von Investitionsstrategien für die Vermeidungskosten von Klimawandel. Die Welt profitiert von frühzeitigen Investitionen in eine große Bandbreite von Technologieen und in Energieeffizienz. Dabei erbringen vor allem die unmittelbare Förderung und die hohe Diversität der Investitionen niedrige Vermeidungskosten.

Chapter 1

Introduction

The fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) demonstrated the substantial threat of climate change. Therefore, one of the main challenges of the world is to organize climate change adaptation and mitigation for the next century. However, this thesis focuses on mitigation strategies. In order to reduce carbon emissions significantly, the whole macro-economy and energy production have to be adapted. In particular, different investment decisions are affected. This thesis deals with the question: What are investment strategies for climate change mitigation? In the following the importance of a stringent climate policy is motivated and three dimensions or climate change mitigation are explained. Within this thesis, Integrated Assessment models are used to study this dynamics. Such models calculate optimal investment strategies into energy technologies, Research and Development (R&D) and/or macro-economic capital. In addition, technological change due to investment decisions often plays a key role for the costs of climate change mitigation. In the following, different mechanisms of technological change are discussed. However, the investment decisions for climate change mitigation might be restricted due to technological or political restrictions.

The first Chapter is structured as follows: The problem of climate change is presented in section 1.1. In section 1.2. three dimensions of mitigation: reduced economic growth, factor substitution and adaptation of investment strategies are discussed. The methodology of this thesis is based on Integrated Assessment models. This model family is explained in section 1.3. The feature of technological change is described in part 1.4. Sections 1.5 and 1.6 present the aim of this thesis and show the thesis structure.

1.1 The Problem of Anthropogenic Climate Change

During the last decades the problem of anthropogenic climate change was identified by academics and largely acknowledged in the academic as well as political spheres. Emissions of different greenhouse gases, associated mainly with industrial production increase the global mean temperature via the greenhouse effect, affecting the whole Earth system. These changes imply risks for human lives as well as natural ecosystems. In the following, the impacts of different emissions on the greenhouse effect and consequently the global mean temperature are illustrated. Several identified reasons for concern demonstrate why advising a 2°C temperature target deems necessary to avoid dramatical climate change.

The greenhouse effect was first described by Tyndall and Arrhenius in the end of the 19. century (Solomon [47]). Increased greenhouse gas (GHG) emissions from industrial production raise the natural greenhouse effect. Thereby the forcing on the climate system and the global mean temperature are increased as will be explained below. In the AR4 of the Working Group I of the IPCC highlights that 0.7 °C global warming against preindustrial levels has already occured. In addition, 0.5°C future temperature increase are expected due to the interactions in the climate system. Many GHG emissions responsible for the global warming of the last decades result from the industrialization process of developed countries. This induced anthropogenic climate change is analyzed in detail since the nineties. Researchers investigate the drivers of global warming and what happens if this effect will continue during the next century. In a first step, the origin of the contributing emissions will be clarified.

The atmospheric concentrations of gases responsible for global warming, e.g. Carbon dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), F-gases and Aerosols are influenced by human activity. CO_2 emissions predominately stem from burning fossil fuels. Also the increase of CH_4 emissions can partly be explained by this aspect of industrialization. The second part of CH_4 emissions and the majority of N_2O emissions are emitted by land use change. F-gases and Aerosols result from industrial processes, the use of fossil fuel, the use of traditional biomass and land use change. CO_2 is one of the most important greenhouse gases because of the long lifetime in the atmosphere (around 70 years) and the huge amount emitted in the last decades (more than 20 $GtCO_2$ in 2000). In addition, these emissions are expected to be high for the future due to the expected continuation of burning fossil fuels. The question of what are the contributions of the different GHG emissions to the global warming effect and how could they be compared can be examined by calculating the radiative and integrated radiative forcing.

Radiative forcing is a measurement for changes in the energy balance of the Earth-atmosphere system when factors that affect the climate are changed (Solomon [47]). These factors influence the balance between incoming solar radiation and outgoing infrared radiation within the Earth's atmosphere. The global radiative balance determines the Earth's surface temperature. A deviation from the normal level of radiative balance is called radiative forcing. Higher GHG concentrations increase the atmospheric absorption of outgoing radiation. Increases in Aerosols reflect and absorb incoming solar radiation and change cloud radiative properties. The radiative forcing of short-lived gases and Aerosol depend significantly on both when and where they are emitted. However, a positive or negative radiative forcing increases or decreases the global average surface temperature.

Radiative forcing can be calculated for each year, integrating it over time results in the integrated radiative forcing. To study the impact of a one-year "pulse" of global emissions for future time horizons, the integrated radiative forcing is used. Jacobson [25], for example used this approach for studying fossil fuel organic and black carbon Aerosols compared to CO_2. Figure 1.1 illustrates the integrated radiative forcing of different current emissions in the year 2000. The forcing is calculated for a 20- and 100-years time

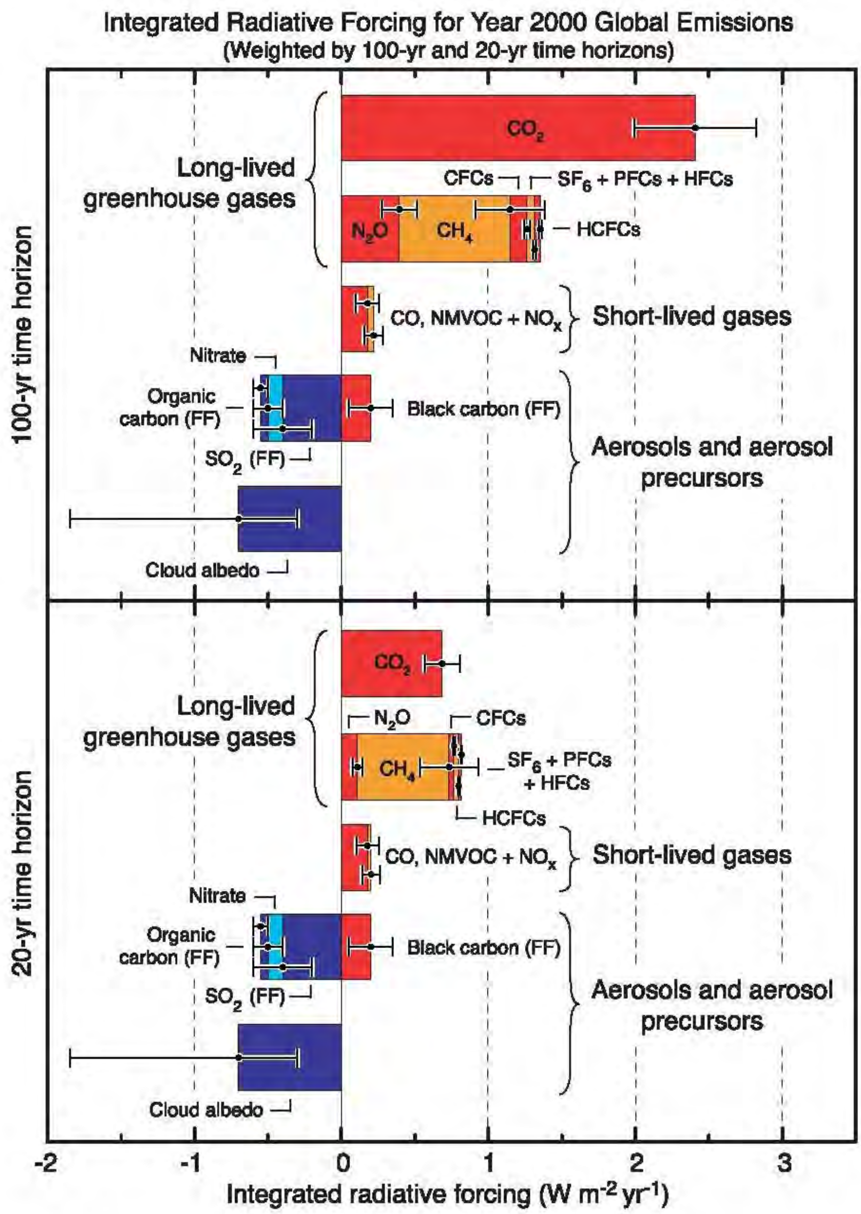

Figure 1.1: Integrated radiative forcing: Future climate impact of the current emissions (year 2000), 20- and 100-year time horizon. Shown are the following gases: carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), Chlorofluorocarbons($CfCs$), sulphur hexafluoride(SF_6), perfluorocarbons ($PFCs$), hydrofluorocarbons ($HFCs$), carbon monoxide(CO), non-methane volatile organic compound($NMVOC$), nitrogen oxides(NO_x), Organic carbon, Nitrate, sulphur dioxideSO_2, Black carbon and Cloud albedo. Source: Forster [14].

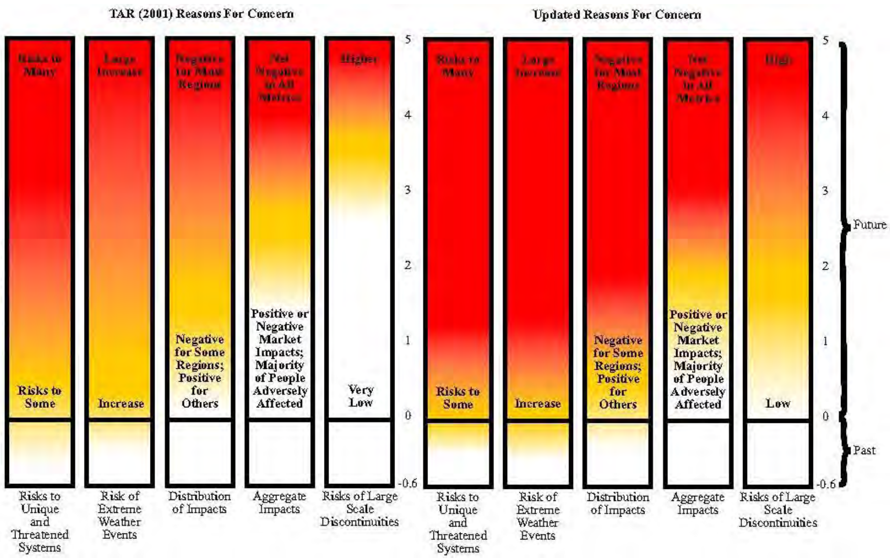

Figure 1.2: Risks from climate change by reason for concern, appraised by the IPCC Third Assessment report compared with recently updated data. Climate change impacts are depicted against increases in global mean temperature(°C) after 1980. Source: Smith et al. [43].

horizon. This indicates the future impact of these emissions on climate change. The cooling effect of Aerosols is nearly the same for both a 20-years and 100-years time horizon. In a 100-year time step, especially the CO_2 emissions show a high integrated radiative forcing representing the importance of this gas for the global warming effect. Moreover, it indicates that for an adequate analysis of climate change long-term studies are necessary.

For a more systematic comparison of the impacts of future emissions different metrics are used. For example, Global Warming Potentials (GWP) are a common metric of different short-lived and long-lived GHGs. They compare the integrated radiative forcing over a specific time period, e.g. longer than 100 years. Thereby the potential climate change impacts of different GHG emissions can be compared.

As discussed before, an increased concentration of some emissions, i.e. Aerosols reduce the radiative forcing. However, in the sum across all GHGs the greenhouse effect is intensified by increased emissions, especially in the long-run. Consequently the global mean temperature is increased. This global warming effect results in significant impacts for the Earth systems. These impacts, e.g. an expected increase in sea levels, are analyzed to identify critical temperature levels. The area of Dangerous Anthropogenic Interference (DAI) is defined. In the following, an illustration of the five reasons for concern demonstrates why the politically discussed 2°C temperature goal is necessary.

The Third Assessment Report of the IPCC identified five reasons for concern (McCarthy [32]). Each of these categories includes different impacts linked to an increased global mean temperature. The resulting so called burning embers diagram is shown in figure 1.2 (left). Each bar represents one reason for concern and the risk of it to become severe associated with the respective increase in global mean temperature. The white regions indicate neutral or low risks associated with an increase of the global mean temperature above 1990s levels. Negative impacts or more significant risks are shown in yellow and the red regions stand for substantial negative impacts or risks that are more widespread.

The first bar represents the ’Risks to Unique and Threatened Systems’. This reason for concern focuses on potentials for increased damages or irreversible losses of unique and threatened systems. Examples are coral reefs, tropical glaciers, endangered species, unique ecosystems, biodiversity hotspots and small island states. The second reason for concern is the ’Risk of Extreme Weather Events’ including extreme events with substantial consequences for societies and natural systems. In particular, the increase of the frequency, the intensity, or the consequences of heat waves, floods, droughts, wildfires or tropical cyclones belong to this category. The ’Distribution of Impacts’ is the third reason for concern. Regions, countries and populations are affected differently by climate change. Some face greater harm, and some might be less harmed or would gain from a temperature increase. The forth reason for concern are ’Aggregate Impacts’. Therefore comprehensive metrics for impacts are collected. For example, monetary damages, lives affected or lost lives are such measures. Finally, the last reason for concern focuses on the ’Risks of Large-Scale Discontinuities’. This task analyzes the likelihood that certain phenomena would occur. Such events as well are known as tipping points. Examples are the deglaciation of the West Arctic or Greenland ice sheets or a substantial reduction of the North Atlantic Meridorial Overturning Circulation.

Figure 1.2 (right) shows an updated burning embers diagram developed by Smith et al. [43]. Here, new information about impacts and vulnerability and new data are taken into account. For example an increased risk of species extinction and coral reef damages are identified. As well, more extreme weather events are observed since the Third Assessment report. New studies identify a higher vulnerability of specific populations, such as the poor and elderly. In addition, it is likely that there will be higher damages for larger magnitudes of increased global mean temperature. As well, the risk af additional contributions to sea level rise from melting of both the Greenland and possible Arctic ice sheet are now better understood. The updated reasons for concern show that smaller increases in global mean temperature are estimated to lead to significant or substantial consequences.

The update of the burning embers diagram stresses the importance of a low emission stabilization target. An temperature restriction of 2°C global mean temperature increase compared to the 1990 level is necessary. A significantly higher temperature increase would most likely result in dangerous anthropogenic interference (red area). Avoiding the necessity to deal with these impacts should rank very high on the global agenda of interests. The European Union chose a climate policy goal of a 2°C target in the EU Council 2007 [13]. However, even under a stringent climate policy scenario, the world will face some impacts of an increased global mean temperature. Therefore, at least some adaptation to climate change has to be realized under mitigation policies.

The identified 2°C target already implies significant changes of human life style and behavior. The climate change problem is a challenge that can only be solved efficiently and sustainable by a joint worldwide action. All long-lived GHG emissions increase the global warming effect independently from the area of production. Consequently, a global long-term cooperation is needed. The climate change problem could not be solved by a single region or a few completely fragmented regions. Nevertheless, each world region, each country and each small area has a different vulnerability of climate change impacts and as well different possibilities for climate change adaptation and mitigation.

Adaptation strategies depend mainly on the geographical position of a region and include water management, embankments and new crop seeds. A broad research area deals with adaptation strategies, but this thesis focuses on mitigation. Mitigation strategies are aimed at the reduction of GHG emissions and will be outlined in the following.

1.2 Dimensions of Mitigation

As described before, to avoid drastical damages due to climate change, all GHG emissions have to be reduced within the next decades and kept at low levels until at least the end of the century. The question of how emission reduction can be achieved can be analyzed by identifying separate dimensions of mitigation. The operationalization of the latter is described by mitigation options for carbon emission reduction. In the following, the dimensions and options for mitigation are presented, as well as a definition of mitigation costs and possible policy instruments for implementation.

The different dimensions of mitigation can be analyzed for example by a Kaya decomposition (Kaya[26]). This is a common tool for studying emission dynamics (e.g. Rogner [40]). Separating single reasons for emission reductions helps to identify mitigation options, which influence the amount of GHG emissions. Within the Kaya decomposition, carbon emissions F are split into four drivers: Population L, GDP per capita (Y/L), energy intensity of GDP (E/Y), carbon intensity of energy (F/E). The following equation holds:

$$F = L\left(\frac{Y}{L}\right)\left(\frac{E}{Y}\right)\left(\frac{F}{E}\right). \tag{1.1}$$

If one assumes that population reduction is not a viable option, the equation demonstrates that emission reduction can be realized in three dimensions: decreasing GDP growth, reducing the energy intensity of GDP or reducing the carbon intensity. These dimensions of mitigation can be influenced by the following mechanisms: (a) reduced economic growth, (b) factor substitution and (c) adaptation of investment strategies. In the following it is explained how these options affect the drivers of carbon emissions. The interaction between these the mechanisms for emission reductions determine the costs of climate change mitigation.

(a) Looking at historical data, during the last century economic growth was strongly correlated with carbon emissions (Raupach [39]). The industrialized regions (e.g. USA, Europe, Japan) are responsible for 86% of the cumulative historical carbon emissions (Grübler and Fujii [20]). Fast growing regions like China increased their emissions during the last decades. This trend is expected to hold on if no climate change mitigation policy is introduced. In addition, developing countries claim the right to grow without any external political restrictions for their economic growth and choice of technologies leading to an even further increase in emissions. Figure 1.3 shows a Kaya decomposition of the CO_2 emissions of China between 1971 and 2005. Studying the reasons for emissions in this fast growing country underlines the strong correlation of carbon emissions and economic growth in the past. The

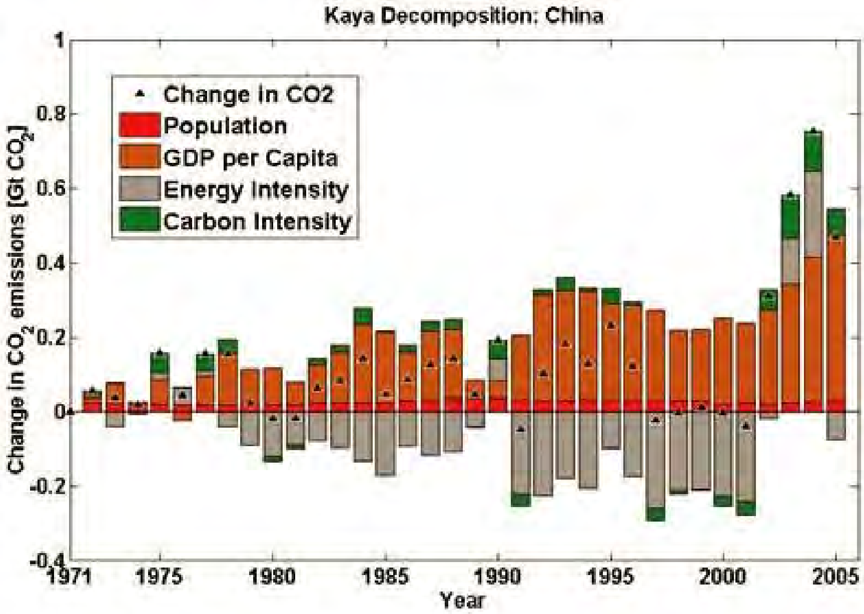

Figure 1.3: Kaya decomposition of historical CO_2 emissions for China between 1971 and 2005. Source: Steckel et al. [46]

increased carbon emissions between two years are allocated to population growth, increased GDP per capita and changes in energy and carbon intensity. As become evident by noticing the large orange shares in Figure 1.3, the fast GDP growth path of China was mainly responsible for the steep rise of carbon emissions. Since 2000 the increased energy and carbon intensity have as been driving the carbon emissions. The challenge of the next decades is to identify strategies to realize economic growth independent of carbon emissions. Consequently, the other two mechanisms for mitigation play an important role, determining the future energy demand level and the carbon intensity of the production processes.

(b) The production of each country is based on different input factors that can partly be substituted by each other. Factor substitution to reduce carbon emissions can be realized in two ways at different production levels: (i) primary energy fossil fuel switch and (ii) substitution.
Carbon emissions from technologies based on coal or oil (e.g. conventional coal power plants, diesel oil turbine) result in significantly higher emissions compared to technologies based on natural gas like a gas turbine and natural gas combined cycle power plants (Hirschberg [24]). A fuel switch towards natural gas instead of coal and/or oil results in less carbon intensive energy production.

From the macro-economic point of view the whole energy intensity of the production could be reduced for climate change mitigation. For example, a more labour and/or capital intensive production can partly substitute energy use in the macro-economic production. This implies structural changes in the production processes, for example an extended use of the service sector for the macro-economic production. As well, the increased use of electricity in the transport sector can substitute conventional means of conveyance.

(c) The production structure of GDP in a country depends mainly on investment decisions. The adaptation of investment strategies for climate change mitigation implies three tasks: (i) capital investments driving macro-economic growth, (ii) investments into technologies of the energy production and (iii) investments into technological change and efficiency improvements.

Due to the macro-economic investment decisions capital accumulation and thereby GDP growth can be influenced. As demonstrated above for China, in the past economic growth also induced carbon emissions. A growing country needs more energy for production processes and thereby as well carbon emissions may rise. In contrast, if a country switches to a more capital intensive production, the development of the capital stock becomes continuously more important for the economic growth. The investments into the energy system of a region determine the technological mix of the energy production. In 2005 25% of the total energy in the world is produced from coal, 35% by the use of oil and 21% by technologies based on natural gas. Only 13% of the world energy production was realized by renewable energy technologies (IEA [23]). If the investments into the capacity of low carbon technologies like biomass, wind, solar and nuclear are increased, the carbon intensity of the energy production can be reduced. In addition, technologies to capture carbon emissions and store these emissions in the ground (CCS technologies) might come into use to avoid drastical climate change. Therefore investments into conventional fossil fuels would be reduced.

The third task of adopted investments for climate change mitigation relates to investments into efficiencies. Some studies indicate that especially energy efficiency improvements due to technological change play a key role for climate change mitigation (Weyant [48], Löschel [30], Popp [36]). Efficiency improvements from a macro-economic point of view give the possibility to produce the same GDP with less energy. This partly decouples economic growth and energy production - the energy intensity of a region decreases. The carbon intensity as well can be influenced by technological change. New technologies with low carbon emissions have to be developed. Existing, emerging carbon free technologies will be explored for an adequate energy production under climate change mitigation policies. In the last decades the investments into research and development in the energy sector were quite small, e.g. 0.4% of the GDP in Europe in 2005. However, Nemet and Kammen [34] analyzing data about research and development investments in the energy sector in the U.S. find that a five to ten-fold increase in energy R&D investment is both warranted and feasible for climate change mitigation.

All described mechanisms for mitigation result in either reduced GDP growth, lowered energy intensity or less carbon intensity. These changes imply a deviation from a so called business-as-usual development, in which climate change is completely ignored. Thereby more investments into new technologies, less productive resources or more expensive production factors are used. The resulting differences between a climate policy and a business-as-usual world represent the mitigation costs. Mitigation costs can be measured as the increased energy system costs including the investments for the innovation of new technologies, the installation of carbon free technologies and spendings for energy resources. So the net present value of the difference of GDP or consumption in a region describes the climate change mitigation costs. This thesis focuses on the latter definition. Mitigation costs can vary significantly over time. While a climate policy regime in the short-term might include macro-economic gains, there would be a time of reconstruction with increased investment activities and lowered consumption. In addition, mitigation costs can vary between different countries and world regions. However, climate change mitigation implies costly restructuring and investments especially in the energy production and demand. Realization of such substantial deviation from the common development calls for a global policy regime. But in addition, adequate incentives have to be identified.

The presented three dimensions of mitigation describe possibilities to reduce GHG emissions. However, the challenge of political actors for the next century is to give such incentives that emission reduction can be realized without dramatic economic growth restrictions. In policy studies different strategies to achieve GHG reductions are discussed. Many policy studies are dealing with the question of what are the best policy instruments for giving the right incentives to achieve climate change mitigation. In general, it is distinguished between a carbon tax and an emission cap (see Newell and Pizer [45]). Both instruments could be installed worldwide if a cooperative policy regime for the climate change problem is installed. As well, these instruments might be installed in single regions or production sectors. A transition from a fragmented system to a cooperative climate policy is discussed. In general, many policy instruments for climate change mitigation influence the three dimensions of mitigation: per capita GDP, energy and carbon intensity.

1.3 Integrated Assessment Models

Integrates Assessment (IA) models are a valuable tool for studying the previously discussed three dimensions of mitigation and their interplay within one model. IA models combine several disciplines: They comprise macro-economic production, a detailed energy sector and a climate system. In particular, they can represent all required quantities (i.e. population, GDP, energy and carbon emissions), which is necessary for the calculation of costs and strategies for climate change mitigation. Studying climate change mitigation includes natural science, political and macro-economic aspects and as well engineering knowledge. Natural scientists identified the climate change threat and analyze the impacts of different GHG emissions. The choice of political incentives necessary to reduce such emissions is a crucial question of climate change mitigation research. As presented in the former section, investment strategies of a region determine the energy demand and the resulting carbon emissions. Due to higher energy efficiency and new low carbon technologies in the energy production a carbon emission stabilization path can be realized. This calls for engineering knowledge in a climate change mitigation analysis.

This thesis focuses on the macro-economic and energy system dimensions of climate change mitigation. Especially hybrid IA models include highly detailed energy system modules. Consequently, the interaction between technological options and macro-economic features can be studied. Within the applied models, political decisions are mainly used for the definition of exogenous basic conditions, e.g. framing the emission reduction target and the contributing regions. In this setting the question of which investment strategies are necessary for carbon emission reduction is investigated.

Early IA models dealing with climate change emulated the world as one global area without any barriers or differences between countries or world regions. However, each region chooses different mitigation strategies, faces different costs and reacts in its own way to climate change mitigation policies. Industrialized regions based their historical growth on fossil fuels and have a lock-in to carbon intensive technologies. New investments into carbon free technologies increase the costs of the energy production, but these regions are also often technological leaders and might be very successful in developing new technologies. The export of such new low carbon technologies might be profitable for industrialized regions. Developing countries that are in the process of installing their energy production sector call for information on which technology will be most important in the future. Depending on the geographical determinants, the renewable potential can vary significantly. These potentials determine for example the share and role of wind and solar energy in the future energy production mix. Different types of potential are considered: The theoretical, geographical, technical economic and implementation potential. The regionally highest potential of onshore wind energy is found for the USA: 21PWh/y, while lowest figures are found for South East Asia, Southern and Western Africa and Japan. Nevertheless, potentially high contributions of solar PV are expected in North, East and West Africa and Australia. In Japan, OECD Europe and Eastern Europe the relative potential is less (see Hoogwijk [22]). Moreover, the use of biomass might induce conflicts between cheep carbon free energy production and regional food demand. Beside the potential of renewable energy technologies, the regional endowment with fossil reserves determine the decision of the investments into the future energy mix and whether a country is willing to push climate change mitigation or not. However, perhaps losses due to reduced fossil fuel exports might be compensated partly by biomass exports in a climate policy. Because of these differences between regions influencing the climate change mitigation costs and strategies significantly, for an adequate analysis multi-regional IA models should be used. Nevertheless, a regionalization of an IA model introduces new decision options like the emission permit allocation scheme.

If the world will agree on a global climate policy regime, this cooperative solution can be realized by introducing allowances for CO_2 emissions. When looking at the regional level of climate change mitigation costs, one of the key challenges is to solve the question how to allocate emission permit rights in an equitable way. Especially under stringent emission reduction targets, the price of a traded allowance for GHG emissions might grow very fast. Regions with a surplus of emission rights might sell these permits profitably to regions, that cannot reduce their emissions as fast as other countries. The literature discusses different permit allocation schemes (Elzen [12], Chakravarty [7]). A common scheme is for example the Contraction and Convergence principle (Meyer [33]), which postulates that emission rights are allocated depending on the historical share of emissions in the beginning and converge to equal per capita emission rights later in the century (e.g. 2050). Other allocation schemes try not to claim economic growth and are oriented on the GDP growth path via an intensity rule. A few studies argue that the historical GHG emissions should be subtracted from the future emission rights, so that the cumulated emissions over time are equal for each country. Figure 1.4 shows regional mitigation costs for different emission permit allocation rules. Global mitigation costs are the same for all schemes, but their impact on the regional mitigation cost distribution is high. A detailed

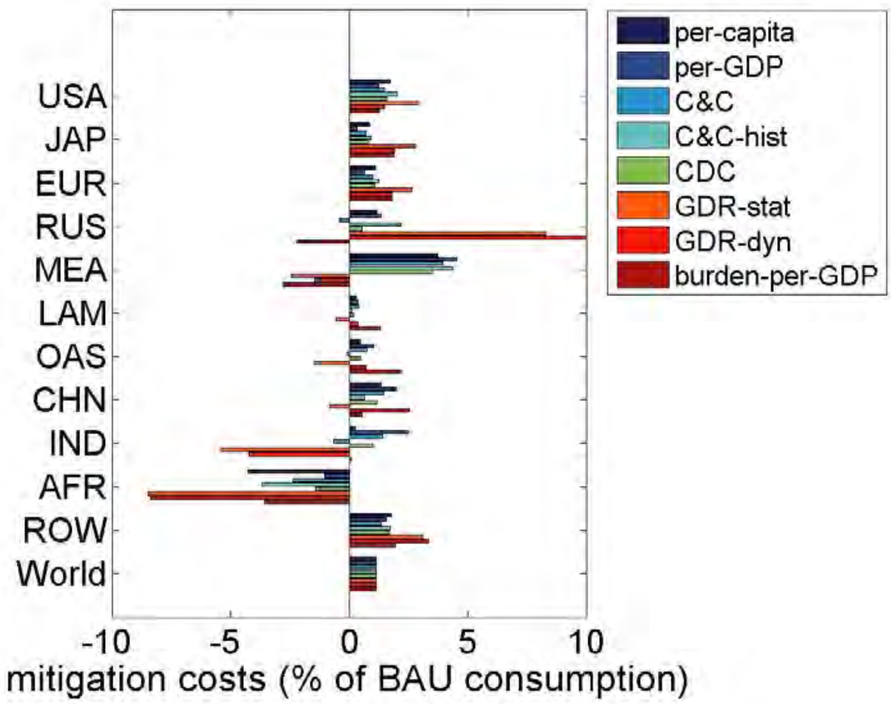

Figure 1.4: Impact of different permit allocation schemes on regional mitigation costs. Each bar represents one of the following schemes: per-capita, per-GDP, C&C (contraction and convergence), C&C-hist (contraction and convergence but historic emissions are taken into account), CDC (common but differentiated convergence), GDR-stat (responsibility and capacity index), GDR-dyn (responsibility and capacity index with dynamic adjustment of the capacity component), burden-per-GDP (mitigation gap allocated according to GDP). Source: Knopf [28].

analysis of the impacts of different emission allocation schemes is postponed to chapter 3.

In the literature many IA models dealing with climate change mitigation are documented. Different solution algorithms can be used including growth models and general equilibrium models. Examples for such models are RICE(Nordhaus [35]), MERGE (Manne [31]), DEMETER (Gerlagh [16]), MIND (Edenhofer [8]) and WITCH (Bosetti [4]). The models used in the analyses of this thesis are extended endogenous growth models of the Ramsey type. These models maximize a global welfare-function and find an optimal solution - optimal in any dimension: timing, region, technology, investment, etc. Climate change mitigation studies often assume a fully cooperative world. In such a setting, the investments, technologies and costs of emission reductions can be calculated in a first best world. Such optimal mitigation behavior and strategies are studied in Chapter 2 and Chapter 3 of this thesis. But if not all technologies installed in a hybrid model will be available due to technological, political or social restrictions, an adaptation of the climate change mitigation strategy is necessary.

Until now it is not clear, whether a completely carbon free technology will be developed in the next century, capable of producing enough energy for the global demand. But the energy system has to be rearranged for climate change mitigation even if no so called backstop-technology will be available. Also, the use of some existing low carbon technologies is strongly discussed. An extended or long-run use of nuclear power is

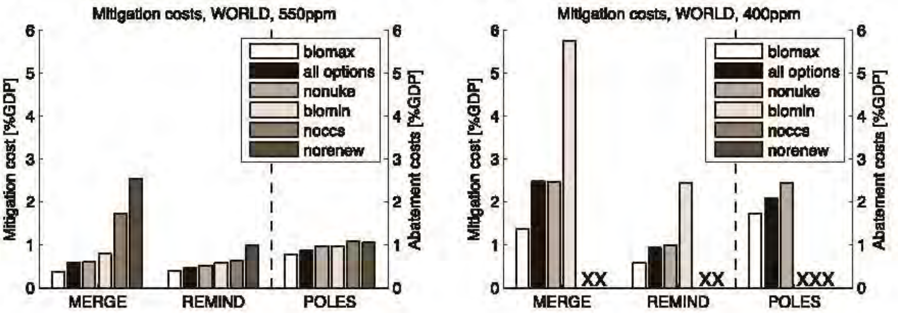

Figure 1.5: Mitigation costs for different models, stabilization scenarios and technological options. 'X' indicates, where the target is not achieved. Source: Edenhofer et al. 2010.

declined by certain countries (e.g. Germany). The question of nuclear waste and the possibility of military use of this technology scares many people. Also the installation of CCS technologies is discussed. On the one hand it is not clear how to guarantee the security of the depots and people get afraid of leakage. On the other hand it principally seems to be difficult to measure the leakage of emissions from the ground (Bradshaw [6], Friedmann [15]). As well, the intensity of the use of biomass for energy production is debated strongly. An extended use of such technologies might get in conflict with the food production and also might result in higher land-use-change emissions and increased deforestation. The impacts of technological restrictions and how to overcome such situations are analyzed in chapter 5 and 6 of this thesis.
Beside technological restrictions, the political situation may limit the area of possible solutions. The debates of the last years showed that it seems to be difficult to install a global climate change cooperation immediately. Perhaps different fragmented policy regimes will be linked together later in the century. Nevertheless, some regions will not join a climate change mitigation community anytime. Chapter 4 identifies the impacts of a delayed global climate policy and investigates the possible advantage of early deployment of renewable technologies in such a second-best world.

Beside studies based on one single IA model, model comparison projects dealing with climate change mitigation have been organized in the last years. Analyzing the vast amount of results jointly enables the identification of robust effects and mechanisms for climate policies. There are some comparison projects dealing with IA models and climate change mitigation strategies and costs in both first-best worlds and under technological or political restrictions. For example in the project ADAM ([11]) the results of five models for different climate protection targets are compared. This study tried to figure out what are the robust technological strategies for climate change mitigation. Figure 1.5 demonstrates the costs of three models under six technological options for a 550ppm CO_2 eq. (left) stabilization and 400ppm CO_2 eq. (right) stabilization scenario. All five energy-economic models show that achieving low GHG concentration targets is technologically feasible and economically viable. The ranking of the importance of individual technology options is robust across the models. For all models, the aggregated costs up to 2100 are below 0.8% global GDP for the 550ppm CO_2 eq stabilization, and below 2.5% for the 400ppm CO_2 eq scenarios. The Report on Energy and Climate Policy in Europe (RECIPE, [10]) outlines roadmaps towards a low-carbon world economy. This study uses three structurally differ-

ent energy-economic models to explore possible future development paths under different athmospheric concentration targets. The results as well show that stabilizing atmospheric CO_2 concentrations at 450ppm is technically feasible and economically affordable. Carbon capture and storage (CCS) and renewable technologies have the highest potential as low-cost mitigation option. Very low stabilization requires advanced mitigation options for generating negative emissions such as biomass in combination with CCS. The power generation can be relatively easily decarbonized, while the transport sector would be more difficult to decarbonize, especially, when electrification in this sector is not possible. In addition, the results show that, if the world continues a business-as-usual scenario until 2020, global mitigation costs for reaching a 450ppm CO_2 stabilization by 2100 increases significantly. An interesting result is that even if other regions delay climate policy until 2020, Europe will enjoy a first mover advantage when unilaterally implementing climate policy.
However, this thesis deals with related research questions, but focuses more in detail on some special effects of climate change mitigation. As described in the end of chapter 1, this includes a broad portfolio of technological options, the impacts of early deployments for renewable technologies, endogenous technological change and technological spillovers.

1.4 Technological Change

A key factor for both reducing carbon and energy intensity is technological change. As discussed in the section about the dimensions of mitigation, this can be realized by different strategies. Especially within IA models these different dimensions can be studied. Beside the investments into the energy system for new technologies, the energy efficiency development is important for the costs of climate change mitigation. Both areas can be analyzed in IA models, which represent both the energy production and the macro-economy.

Many IA models include technological development by means of an exogenous formulation. Implying that technological change appears to happen independently of the knowledge level, research activities or policy decisions. Sanstad et.al [42] for example use a parameter named AEEI - the Autonomous Energy Efficiency Improvement. They highlight the importance of closer attention to the empirical basis for modeling assumptions. For example, they find substantial heterogeneity among both industries and countries, and a number of cases of declining energy efficiency. Gerlagh and van der Zwaan [17] included a parameter Autonomous Energy Service Efficiency Improvement (AESEI) in their sensitivity analysis of mitigation costs. They find evidence that this exogenous parameter has only a minor effect on the timing of emission reduction.

In contrast to the classical growth theory, new growth theory tries to explain technological innovation endogenously. Examples in the literature for this theory are Romer [41] and Grossman and Helpman [19]. They analyze the crucial question of the key drivers for regionally differentiated economic growth and about an adequate design of endogenous growth within a macro-economic model. The main challenge is to find a model formulation that describes the impact of knowledge or human capital on the productivity of a related economy. Within the literature it is differentiated between bottom-up and top-down models as well as an exogenous vs. endogenous formulation for technological change (see Löschel [30]). Endogenous technological change can be implemented in three ways into models: (a) learning-by-doing (b) Research-and-Development (R&D) and (c) technological spillovers. In the following these tools are described more in detail.

(a) When focusing on technological development, often learning curves are used for representing technological change. First Arrow [2] described learning by doing as a feature that decreases investment costs the more cumulative capacity of a technology is installed. An advantage in technological change is assumed due to the production and use of a technology. Especially in energy system models this approach is used (see Grübler [21] and Rao [37]). Sometimes, learning curves are extended by a learning by research mechanisms as described by Kypreos [29].

(b) R&D investments include all spendings into the development and improvements of technologies. These investment can be realized by firms, institutions or the government. Within models often a formulation is used that R&D investments increase production factor efficiency. For example, the labour or energy efficiency is influenced (e.g. MIND [8]). Alternatively, the stock of a production factor like knowledge is influenced by R&D investments (e.g. WITCH [5]).

(c) Spillovers are expected to foster the diffusion of new technologies (Popp [36]). This spillover can flow between production sectors, different technologies or regions. the literature distinguishes between embodied and disembodied spillovers. In addition, some models implement an absorptive capacity mechanism. Thereby the intensity of the spillovers depend on basic conditions like the regional knowledge level. Perhaps a spillovers receiving region can influence this parameter by some efforts - R&D investments for example. Keller [27] provides a comprehensive overview on international technology diffusion and spillovers.

The presented ways for implementing endogenous technological change are adequate and prefered by different types of models. Bottom-up models including a detailed energy system with a large quantity of technologies mainly include endogenous technological change by means of learning curves with learning-by-doing and/or learning-by-research mechanisms. Top-down models, that look from a more general macro-economic perspective often implement R&D functions to influence technological improvements. Some of these models also include technological spillovers. Within IA models, combining a macro-economy and an energy system, all three tools for endogenous technological change come into account. However, implementing endogenous technological change always calls for empirical evidence and parameter calibration.

For all three channels of endogenous technological change empirical evidence can be found. First, positive experience curves can be found for several production sectors, e.g. manufacturing (Argotte and Epple [1]) and service sector (Rapping [38]). In energy system models, the cumulative capacity of a technology usually determines the experience and cost reductions (e.g. Messner [44]). Second, some empirical papers tried to identify evidence for variables (e.g. trade liberalization) explaining growth. Therefore endogenous productivity change is introduced into a model via defining a parameter A for total factor productivity in the production function $Y = A \cdot F(L,T)$. The output Y is produced by the production factors L and T, e.g. labour and land. Grossman and Helpman [18] consider a two-sector, two-factor economy and interpret A as the stock of knowledge capital. Third, embodied technological spillover is analyzed in a theoretical and empirical way by Coe and Helpman [3]. Romer (1990) deals with R&D investments and human capital and describes disembodied technological spillover. These empirical studies find evidence for the described tools of endogenous technological change. But how will endogenous technological change interact with a climate policy regime?

Within the climate change mitigation analysis, often technological improvements due to climate policies is in the interest of research. Under such a policy regime, technological change is expected to help achieving emission reductions most efficiently. R&D investments can result in a less carbon and/or energy intensive production. For the analysis of this induced technological change, models have to give the opportunity to influence technological change endogenously. Depending on the technological level, possible spillovers and expected gains from R&D investments into renewable technologies, the energy production mix, and the relation of all production factors are calculated endogenously. If, in addition, a climate policy like an emission cap, technological subsidies or a carbon tax are installed, the investment strategies might be adapted. Low carbon technologies are fostered and the total energy efficiency is improved. However, even if the induced technological change is small, each technological development determines both the amount of emissions that have to be reduced and the chosen technologies for climate change mitigation and thereby also the mitigation costs (see IMCP [9]). The chapters 2 and 6 of this thesis analyze endogenous technological change in a more detailed way, focusing on technological spillovers and production sector efficiency improvements.

1.5 The Aim of the Thesis

This thesis concentrates on the field of climate change and especially on the costs of mitigation. For the quantitative analysis, Integrated Assessment models are used, which deal with different world regions. Because of the different endowments of fossil fuels, biomass, solar and wind potentials, energy efficiencies, technological levels and macroeconomic growth paths, the costs and strategies to reduce carbon emissions vary over the regions. However, the climate change mitigation costs depend on the investment strategies which include R&D expenditures, investment into new technologies, capital, etc. and which are chosen to keep a climate target. This thesis analyses these investment strategies for climate change mitigation. The first part focuses on a world with optimal conditions and free investment spendings and answers the following questions:

I How do climate change mitigation costs depend on technological spillovers? What is the effect of technological spillover bound to bilateral capital trade? Are there first mover advantages or commitment incentives due to technological spillover?

II What are the optimal long-term investments in the energy system for climate change mitigation? How differ mitigation costs and strategies between different world regions? What are the mitigation costs under different climate policy regimes?

The second part of the thesis investigates technological or political restrictions for climate change mitigation and deals with the following questions:

III How do mitigation costs increase due to delays of implementing emission caps at the global level? Can near-term public support of renewable energy technologies contain these increases? What are the effects of such a support on regional mitigation costs?

IV What are the impacts of different dynamics and directions of technological change on climate change mitigation costs and strategies? How does the impact of technological change vary under different elasticities of substitution between the production factors? How does the impact of technological change depend on the availability of energy technologies?

V When and where do R&D investments into production factor efficiency play an important role as climate change mitigation option? Can the increased mitigation costs under limited technological options be compensated by a re-allocation of investments into efficiency of energy related production factors?

1.6 Thesis Structure

This thesis is separated into five main chapters. Each chapter deals with one group of research questions presented in the previous section. The first two chapters mostly assume a perfect cooperative world with all technological options, while chapter 4 to 6 analyze climate change mitigation in a world with technological or political restrictions. For the analysis different adjusted IA models are used. Chapter 2 describes a regionalized growth model with technological spillover. Chapter 3 and 4 use a multi-regional hybrid model with a detailed energy system part and nine respectively eleven world regions. The model used in chapter 5 and 6 is based on the latter model but is scaled down to five world regions. For chapter 6 a new formulation of endogenous technological change is implemented. Chapter 7 is a synthesis chapter.

Chapter 2 focuses on technological spillovers bound to bilateral capital trade. An intertemporal optimization model is designed to analyze climate policy scenarios within a globalized world. The model MIND-RS analyses the behavior of four representative world regions. The efficiency of energy use is increased due to importing foreign capital. A technical description of the model and numerical results are presented in this chapter. The difference between mitigation policies that either take or do not take technological spillovers into account are studied. In addition, first-mover advantage and incentives for climate policy commitments are analyzed.
Leimbach, M., L. Baumstark (2010): The impact of capital trade and technological spillovers on climate policies. Ecological Economics 69, 2341-2355

Chapter 3 uses the hybrid model REMIND-R, which links a macro-economic part and a detailed energy system module. The calibration and structure of this multi-regional IA model are presented. Long-term investment changes in the energy system to attain climate protection targets are identified and compared over the modeled nine

world regions. The world regions are linked by global markets for goods, fossil resources and emission permits. In addition, different policy regimes for climate change mitigation are implemented and resulting differences of costs and trade flows are studied.
Leimbach, M., N. Bauer, L. Baumstark, O. Edenhofer (2010): Mitigation costs in a globalized world: climate policy analysis with REMIND-R. Environmental Modeling and Assessment 15, 155-173

Chapter 4 also deals with the hybrid model REMIND-R. This chapter focuses on the role of investments into renewable technologies. A set of first and second best scenarios are designed to analyze the impact of early deployment of renewable energy technologies. It is figured out whether the additional costs of a delayed climate policy can be decreased by early investments into renewable technologies. As well, it is analyzed how the emission path changes. Also the regional effects on mitigation costs due to early renewable deployment are explored for the eleven world region of REMIND-R.
Bauer, N., L. Baumstark, M. Leimbach (2011):The REMIND-R Model: The Role of Renewables in the Low-Carbon Transformation. Revised to Climatic Change, Special Issue

Chapter 5 analyses the impact of different dimensions of technological change on climate change mitigation. The dynamics and directions of technological change are varied in the model REMIND-RS. This five world region model is based on the hybrid model REMIND-R. The impacts on mitigation costs and strategies are discussed. The question of how the impacts of technological change are influenced by different assumptions about the structural settings of the world is analyzed. These structural conditions are emulated by a modified elasticity of substitution or technological restrictions.
Baumstark, L., M. Leimbach (2010): The Dimensions of Technological Change and Their Impacts on Climate Change Mitigation, submitted to Energy Policy

Chapter 6 uses the model REMIND-RS as well, but extended by a new formulation for investments into technological change of labour and different end-use energy sectors. The calibration and simulation results of such an endogenous formulation are shown in this chapter. The timing, direction and intensity of R&D investments as mitigation option are explored. A restriction of technological options rise mitigation costs. In addition, the role of investments into the efficiency of energy related production factors is analyzed under such conditions and climate mitigation policy.
Baumstark, L., M. Leimbach (2011): Endogenous Sector-specific R&D Investments into Energy Efficiency as Mitigation Option, submitted to Climatic Change

Chapter 7 synthesizes chapter 2 to 6. The results of these chapters and future research questions are discussed.

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Chapter 2

The impact of capital trade and technological spillovers on climate policies*

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Analysis

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ABSTRACT

In this paper, we present an intertemporal optimization model that is designed to analyze climate policy scenarios within a globalized world which is characterized by the existence of technological spillovers. We consider a type of technological spillovers that is bound to bilateral capital trade. Importing foreign capital that increases the efficiency of energy use represents a mitigation option that extends the commonly modeled portfolio. The technical details of the model are presented in this paper. The model is solved numerically. First model applications highlight the differences between climate policy analyses which either take or do not take technological spillovers into account. In the final part, we apply the model to investigate first-mover advantages and commitment incentives in climate policy scenarios. The existence of both is supported by simulation results.

1. Introduction

Recently, increasing attention in both research and policy-making has been given to the interaction of international trade and climate change (cf. Copeland and Taylor, 2005; Weber and Peters, 2009). Climate policies are challenged by competitiveness and carbon leakage concerns. A number of studies deal with these trade-related issues (e.g. Böhringer and Rutherford, 2002; Peters and Hertwich, 2008). In climate policy modeling, less attention is paid to other interregional effects like technological spillovers.

However, within the discussion about promising climate protection strategies, technological spillovers come to the fore. Spillovers are expected to foster the diffusion of new technologies and hence represent a component of endogenous technological change to be included into climate policy models (cf. Löschel, 2002; Popp, 2006; Gillingham et al., 2008).

The concept of technological spillover is based on the idea that technological externalities, coming along with the process of capital and knowledge accumulation, slow down the decrease of the marginal returns on capital. Keller (2004) provides a comprehensive overview on international technology diffusion and spillovers. Principally, the literature distinguishes between embodied and disembodied spillovers.[1] The former is rooted in the theoretical and empirical work by Coe and Helpman (1995) and Grossman and Helpman (1991), the latter is linked to the work on R&D investments and human capital done e.g. by Romer (1990).

Disembodied spillovers represent a kind of technological change that is driven by international diffusion of knowledge accumulated in a freely available global pool. Embodied spillovers, in contrast, represent technological change that is triggered by technological know-how embodied in foreign products or directly transferred innovations (patents).

While some empirical evidence is given (cf. Keller, 2004), the processes of disembodied and embodied technology spillovers are far from being fully understood. Therefore, only a few studies exist that investigate climate policies in the presence of technological spillovers. In Rao et al. (2006) the technological learning curves of the model MESSAGE are subject to disembodied spillovers. Cross-sectoral learning ("technological clusters") is combined with inter-regional learning. Verdolini and Galeotti (2009) and Dechezlepretre et al. (2009) study the diffusion of energy-efficient and climate change mitigation technologies based on patent data. The latter focus on a direct form of embodied spillovers where innovators transfer their inventions for the purpose of a commercial exploitation at a later point in time.

Most prominently studied are R&D spillovers and their effects on the stability of international environmental agreements (e.g. Carraro and Siniscalco, 1997; Kemfert, 2004; Nagashima and Dellink, 2008). Bosetti et al. (2008) model disembodied international energy R&D spillovers in the WITCH model. Knowledge acquired from abroad is combined with domestic R&D capital stock and thus contributes to the production of new technologies at home. For a climate policy scenario stabilizing CO_2 concentration on 450 ppm, Bosetti et al. report lower optimal energy R&D investments and strong free-riding effects among High Income countries, when knowledge spillovers are explicitly modeled. However, due to spillovers, total knowledge stocks remain unchanged and mitigation costs are slightly lower due to lower expenditure in energy R&D.

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[1] Another classification introduced by Jaffe (1998) distinguishes between knowledge spillovers, market spillovers and network spillovers.

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A few other studies exist that take disembodied R&D spillovers into account when analyzing climate policies (e.g. Goulder and Schneider, 1999; Buonanno et al., 2003), but there is hardly any climate policy study that includes embodied technological spillovers. The present study helps to fill this gap. It tries to answer the question whether first-mover advantages and incentives to join international climate agreements can be derived in a model framework that endogenize technological spillovers on the level of world regions. In this study, the first mover-advantage refers to benefits that regions which push energy-efficient technologies can expect in a climate policy setting.

The concept of embodied spillovers as followed in this study can be conceived as a process of expanding technological know-how by capital imports. With increasing economic integration through international trade and foreign direct investments, a country's productivity growth is likely to depend not only on knowledge embedded in its own technology but also in the technology imported from its trading partners.

This paper presents a multi-region growth model that allows analysis of climate policy scenarios in the presence of capital trade and technological spillovers. In the implemented model two spillover channels are considered, leading either to an increase of labor productivity or energy efficiency. While part of the real-world heterogeneity is disregarded, this paper aims to investigate the impacts of modeling embodied technological spillovers in an Integrated Assessment framework built around a stylized Ramsey-type economic growth model, similar to the approach of Bosetti et al. (2008). By focusing on long-run transitional dynamics and going beyond the common approach of studying spillover effects in a reduced-form static model, this paper contributes to both the literature on technological spillovers and on the role of endogenous technological change in climate policy modeling.

The paper is structured as follows. In Section 2, we discuss the concept of embodied spillovers, its empirical evidence and the way we implemented this feature. In Section 3, the multi-region climate policy model is presented. We apply this model in a setting of four generic regions which are selected in order to address the issues of first-mover advantages and commitment incentives. In Section 4, we describe the construction of our baseline scenarios and the definition of the climate policy scenarios. The basic co-operative policy scenario aims at limiting the increase of global mean temperature to 2 °C above preindustrial level and is based on an international CO_2 cap-and-trade system. A comprehensive discussion of the results from different model runs is given in Section 5. A sensitivity analysis shall help to assess the robustness of the results. We end with some conclusions in Section 6.

2. Embodied Technological Spillover

Embodied technological spillovers refer to situations where the presence of physical capital, produced abroad and imported, affects efficiency or productivity levels of the host economy.

While there are some similarities with the disembodied spillover concept, significant differences exist. Disembodied technological spillovers refer to international knowledge as a public good. Free flow of knowledge fosters technological innovation in places different from where they were originally conceived, thus favoring foreign followers at the expense of domestic R&D investors. In contrast, embodied spillovers are bound to foreign investments and imported goods. This provides innovators with the possibility to appropriate part of the social benefits from their R&D investments, e.g. by additional export opportunities. Embodied spillovers could make the difference that helps investors in new energy technologies to break even (Barretto and Klaassen, 2004). From the macro-perspective adopted in this study, it could thus pay off for single regions to become forerunners in climate policy. Brandt and Svendsen (2006) distinguish two types of first-mover advantages. The first type materializes in exports to countries engaging in emission reductions. The second type exists when newly developed technologies are competitive even in situations where countries do not have reduction targets.

The body of empirical research on spillover externalities has grown rapidly (e.g. Lumenga-Neso et al., 2005; Jordaan, 2005; Takii, 2004). Empirical evidence is indicated for technological spillovers from capital trade and especially for spillovers from foreign direct investments. Both types of transfer of physical capital are thought to be nearly the same, since technological know-how is embodied in the machinery that is built up abroad in either way. Therefore, both support the concept of technological spillovers applied in this paper.

Keller (2004) analyzes empirical methods of measuring technological spillovers and distinguishes three types of econometric studies: association studies, structure studies and the general equilibrium approach. In association studies, the authors ask whether a specific foreign activity leads to a particular domestic technology outcome (e.g. Aitken and Harrison, 1999). Structure studies incorporate structural elements which include a foreign technology variable and the specification of a spillover channel or diffusion mechanism (e.g. Coe and Helpman, 1995). Empirical analyses that apply general equilibrium models are important because instead of focusing on reduced-form relationships within a subset of variables, they allow to study general equilibrium effects (e.g. Eaton and Kortum, 1996). Eaton and Kortum (2001) combine a technology diffusion model and a Ricardian model of trade. In the resulting model, trade augments a country's production possibilities for the classic Ricardian reason: trade gives access to foreign goods or, implicitly, technologies.

A majority of studies indicate positive spillover effects from foreign investments (e.g. Kokko, 1993; Blomström et al., 1999; Hejazi and Safarian, 1999; Takii, 2004; Jordaan, 2005). Takii (2004) demonstrated for several countries that foreign firms, resulting from foreign direct investments, tend to have higher productivity than domestic ones, hence improving the host country's aggregated productivity. Likewise, empirical results presented by Coe and Helpman (1995), Lee (1995), Xu and Wang (1999) and by Eaton and Kortum (2001) indicate that imported capital goods imply technological spillovers that account for significant parts of productivity changes. In contrast, the study of Keller (1998), referring to the findings from Coe and Helpman (1995), casts some doubts on the claim that patterns of international trade are important in driving R&D spillovers.

Recent empirical results have seriously challenged former findings. First, they suggest that positive externalities are less prevalent than previously thought. Second, structural factors were identified that affect the intensity of spillover effects, among them geographical distance and technological proximity (MacGarvie, 2005). Most commonly recognized is the concept of absorptive capacity indicating that spillovers have a positive effect only when domestic firms or the host region possess sufficient knowledge and skills to absorb positive externalities from foreign investments. Jaffe (1998) found that firms that do little R&D themselves suffer from competitive externalities linked to technological spillovers. A recent study by Jordaan (2005) explicitly analyzed existing indicators of absorptive capacity, notably technological differences between the host and foreign economy. The findings of Jordaan, however, are not in support of the notion of absorptive capacity, but indicate again a strong correlation between the extent of the technology gap and positive spillovers. Better proxies are needed to capture the effect of absorptive capacity. Hence, we include the concept of the technology gap but not that of the absorptive capacity in the present framework.

In following the empirical findings, we assume productivity and efficiency parameters as source and target of technological spillovers. Potential spillover gains ($spr_{i,r}$), i.e. productivity improvements, for region i depend on the technological gap between the trading partners i and r. We assume that the higher the productivity differential ($A_r - A_i$), the higher the potential spillover effect. The realized potential of technological spillovers then increases with intensity of capital trade ($X_{r,i}$) between the regions r and i. Spillover gains are, on the one hand, due to a direct productivity increase when the more efficient foreign capital is aggregated with domestic capital. On the other hand, additional know-how is generated in the process of using the imported capital stock. Both effects refer to the ratio between the imported capital and the domestic capital stock ($X_{r,i}/K_i$). By introducing spillover elasticity $\psi<1$ we assume a decreasing marginal spillover effect of capital exports. With spillover intensity Ω, this altogether yields:

$$sp_{i,r} = \left[\frac{X_{r,i}}{K_i}\right]^{\psi}\Omega(A_r - A_i) \quad \forall i,r : A_i < A_r. \tag{1}$$

The resulting productivity gains are combined with technological progress that is fueled by domestic R&D investments (see next section). This linkage can be found in modified form in Bosetti et al. (2008), Coe and Helpman (1995). Both elements of technological change are combined additively. This means that domestic R&D investments are not a prerequisite for spillovers to take effect and thus cannot be interpreted as investments in building up absorptive capacities.

The spillover intensity Ω is a key parameter. Most authors acknowledge its importance, but given the state of the literature, it is difficult to provide sound empirical foundation. Variation of this parameter (cf. Nagashima and Dellink, 2008) reveals sensitivity, yet the selected values for spillover intensity cannot be compared across different models. We provide our own sensitivity analysis in Section 5.

In an intertemporal optimizing framework, as it is the subject here, spillovers provide an additional factor of technological change which impacts regional growth dynamics. Commonly, spillovers are dealt with as an externality. This notion involves that spillovers cannot be anticipated and hence controlled by agents. However, while this view may be true for disembodied international knowledge spillovers, it is debatable in the context of embodied technological spillovers. If empirical studies suggest a link between positive productivity gains and capital trade, why should this not be taken into account by agents in decision-making and why should foresighted agents not be more proactive in attracting foreign direct investments and capital exports? Dechezlepretre et al. (2009) show that firms are willing to invest money in order to gain protection in foreign markets for their inventions, thus indicating that they are aware of technological spillovers when trying to market their superior technology there. We apply an approach where technological spillovers are anticipated by the regional actors, hence, influencing the dynamics of the control variables.

3. MIND-RS

MIND-RS is a multi-region model based on the single-region global Integrated Assessment model MIND (Edenhofer et al., 2005). MIND-RS adopts from MIND the structure of the energy system (except for the carbon capture and sequestration technology) and basic investment dynamics including R&D investments which represent a major feature of endogenous technological change. As a new channel of technological change, MIND-RS includes technological spillovers. Unlike MIND, MIND-RS separates the aggregated industrial sector into a consumption goods/service sector and an investment goods sector. Moreover, MIND-RS takes trade interactions into account. While market monopolies are excluded, trade flows represent control variables which are bound to an intertemporal budget constraint. Fig. 1 presents most of the new features of the macroeconomic system of MIND-RS.

MIND-RS represents a dynamic trade model, but does not show the sectoral detail of recursive dynamic computable general equilibrium models. By offering the feature of intertemporal investment dynamics, MIND-RS is classified as an economic growth model suited for long-term analysis. The way bilateral trade and technological spillovers are handled as endogenous variables distinguishes MIND-RS from models of a similar type like RICE (Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000) and MERGE (Manne et al., 1995; Kypreos and Bahn, 2003).

3.1. Technical Description

We restrict the description here to the relevant macroeconomic model parts. More details about the energy sector are described in Appendix B. Furthermore, in addition to some explanation on variables and parameters in this section, a compact list of them can be found in Appendix A. The following indices are used throughout the model presentation:

t	$1, 2, \ldots, T$	time periods,
i, r	$1, 2, \ldots, n$	regions,
j		tradable goods and sectors,
m	K, L, E, PE	production factors.

With $J=\{C,I,Q,P,f,ren,nf\}$ and $j\in J$ the following sectors and goods are distinguished:

C	consumption goods (tradable),
I	investment goods (tradable),
Q	fossil energy resources (tradable) or extraction sector,
P	emission permits (tradable),
f	fossil energy transformation sector,
ren	renewable energy sector,
nf	remaining energy sector.

Capitals from the above list simultaneously represent indices as well as corresponding variables. This also applies to the production factors labor (L), capital (K), final energy (E) and primary energy (PE). We denote the sectoral index and the production factor index by a subscript throughout the model presentation. For transparency reasons, we use a continuous formulation for the time and region index of the variables. Nevertheless, the model is implemented as a discrete one.

In each region, a representative agent is assumed to summarize households' consumption decisions and firms' investment and trade decisions. The objective is to maximize the welfare W

$$W(i) = \int_{t=1}^{T} e^{-\sigma t}\cdot L(i,t)\cdot \ln\left(\frac{C(i,t)}{L(i,t)}\right)dt \tag{2}$$

of n regions, where σ is the pure rate of time preference and L represents the regions' population which provides the exogenously given production factor labor. C denotes consumption.

Aggregated output is the sum of the output of the consumption goods/service sector and the investment goods sector. The production function Y_j of both sectors is specified as a CES function (with elasticity of substitution parameter ρ and input weight parameters ξ_m):

$$\begin{aligned} Y_j(i,t) = \Phi_j(i)\Big[&\xi_K K_j(i,t)^{\rho(i)} + \xi_L\Big(\theta_{L,j}(i,t)\mathcal{A}_L(i,t)L(i,t)\Big)^{\rho(i)} \\ &+ \xi_E\Big(\theta_{E,j}(i,t)\mathcal{A}_E(i,t)E(i,t)\Big)^{\rho(i)}\Big]^{\frac{1}{\rho(i)}} \quad \forall j\in\{C,I\}, \end{aligned} \tag{3}$$

Φ represents total factor productivity, K the capital stock, A_L labor efficiency, A_E energy efficiency and E the energy input. $\theta_{m,j}$ represents the share of the respective production factors with

$$\theta_{m,C} = 1 - \theta_{m,I} \quad \forall m\in\{L,E\}. \tag{4}$$

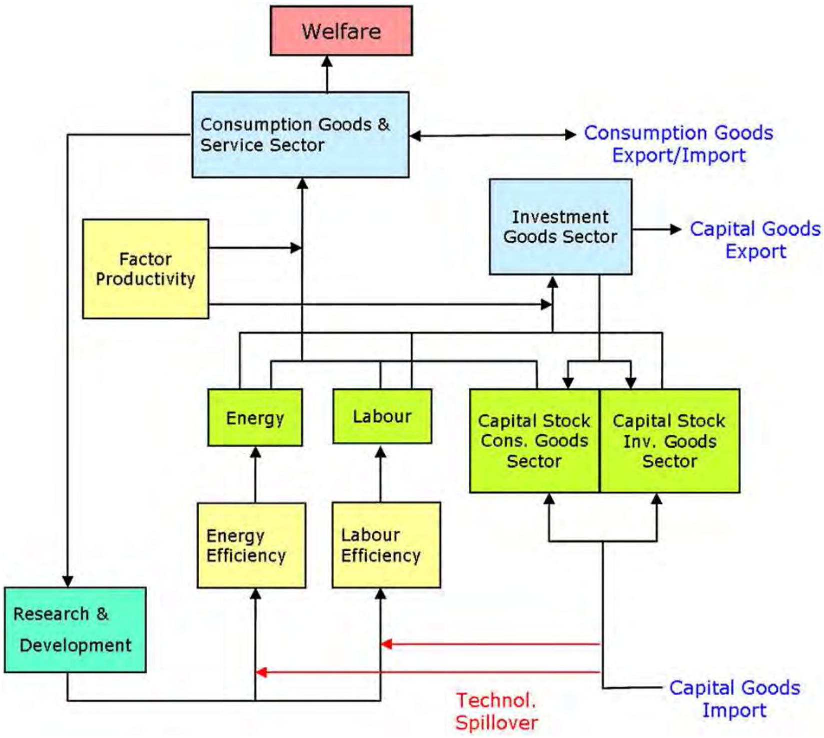

Fig. 1. Structure of the macroeconomic system of MIND-RS.

Factor market equilibrium is characterized by $\theta_{L,j} = \theta_{E,j}$. The efficiency variables are subject to R&D investments rd_m (cf. Edenhofer et al., 2005) and technological spillovers sp_m as described by equation

$$\dot{\mathcal{A}}_m(i,t) = \zeta(i)\left(\frac{rd_m(i,t)}{Y_C(i,t) + Y_I(i,t)}\right)^{\alpha_m} \mathcal{A}_m(i,t) + sp_m(i,t) \quad \forall m \in \{L,E\}. \tag{5}$$

Embodied technological spillovers increase labor efficiency and energy efficiency. These spillover effects are induced by capital exports $X_I\{r,i\}$ from region r to region i. As introduced in Section 2, we define the spillover function for all $m \in \{L,E\}$:

$$sp_m(i,t) = \begin{cases} \sum_r \left[\left(\frac{X_I(r,i,t)}{K_I(i,t)}\right)^{\psi} \Omega_m(\mathcal{A}_m(r,t) - \mathcal{A}_m(i,t))\right] & : \ \mathcal{A}_m(i,t) < \mathcal{A}_m(r,t) \\ 0 & : \ \mathcal{A}_m(i,t) \geq \mathcal{A}_m(r,t) \end{cases} \tag{6}$$

where Ω_m describes the spillover intensity and ψ the spillover elasticity of foreign investments.

The budget constraint of the consumption goods and service sector distributes the sectoral output to domestic consumption, exports $X_C(i,r)$ and R&D investments:

$$Y_C(i,t) = C(i,t) + \sum_r X_C(i,r,t) - \sum_r X_C(r,i,t) + rd_L(i,t) + rd_E(i,t). \tag{7}$$

Imports of goods $X_C(r,i)$ relax this constraint. For transparency reasons we omit trading costs, which actually are assigned to all import variables.[2]

Output of the investment goods sector, added by capital imports $X_I(r,i)$, is used for domestic investments I_j into the industrial and energy sectors, and for foreign investments $X_I(i,r)$:

$$\begin{aligned} Y_I(i,t) = {} & I_C(i,t) + I_I(i,t) + I_{nf}(i,t) + I_f(i,t) + I_Q(i,t) + I_{ren}(i,t) \\ & + \sum_r X_I(i,r,t) - \sum_r X_I(r,i,t). \end{aligned} \tag{8}$$

Capital accumulation in all sectors other than the renewable energy sector follows the standard equation of capital stock formation

$$\dot{K}_j(i,t) = I_j(i,t) - \delta_j(i) \cdot K_j(i,t) \quad \forall j \in \{C,I,Q,f\}. \tag{9}$$

In modeling the renewable energy sector, the concept of vintage capital is applied (see Appendix B).

Within an international climate policy regime, we assume that each region is allocated an amount of emission permits P. For each unit of fossil resources converted into final energy, a permit is needed. Emissions trading X_P provides the opportunity to buy and sell them. The resulting constraint for using fossil resources is given by

$$Q(i,t) + \sum_r (X_Q(r,i,t) - X_Q(i,r,t)) \leq P(i) + \sum_r (X_P(r,i,t) - X_P(i,r,t)) \tag{10}$$

[2] Within the model implemented for numerical simulations, trade costs of 5% are assumed for each traded good. This corresponds to the estimate of ad-valorem costs for ocean shipping in 2000 by Hummels (2007) which amounts to 5.2%.

where Q denotes domestic fossil resource extraction and X_Q denotes the export and import of fossil resources.

The above system of equations forms a multi-region optimization problem with a single objective function for each region. The investment and trade variables represent control variables. In order to solve this problem we apply the iterative algorithm developed by Leimbach and Eisenack (2009). In assuming that the spillover effect is taken into account when agents make investment and trade decisions, this decentralized problem is solved as a co-operative game. Trade flows are adjusted endogenously to find a pareto-optimum that provides trade benefits for all regions. The applied trade algorithm iterates between a decentralized model version where each region optimizes its own welfare based on a given trade structure, and a Social Planner model version where the regions' welfare functions are combined by a set of welfare weights. The Social Planner model derives the optimal trade structure for the given set of welfare weights, while being subject to market clearance conditions. The welfare weights are adjusted iteratively according to the intertemporal trade balance of each region which has to be leveled off in the equilibrium point:

$$\sum_r \sum_j \sum_t \left(p_j(t)X_j(i,r,t) - p_j(t)X_j(r,i,t)\right) = 0 \quad j \in \{C, I, Q, P\}. \tag{11}$$

Market prices p_j are derived from shadow prices of the decentralized model version. The model provides a first-best equilibrium solution in labor, capital and goods markets implying full employment and converging return rates across regional and sectoral investments.

3.2. Set Up of Experiments

We want to apply the described model in a set of experiments that aims to assess climate policy implication of technological spillovers. We try to analyse this in a setting of four world regions — two developed and two developing ones.

Productivity enhancing technological know-how spills over mainly from the developed to the developing world regions. However, the two developed world regions are distinguished by different degrees of labor productivity and energy efficiency. Consequently, the export of investment goods contributes relatively more to an increase of labor productivity growth in the one case and of energy efficiency growth in the other case. The interesting question to be answered is than: Does the region that takes the lead in producing energy-efficient technologies benefit in a climate policy setting (first-mover advantage)? The developing regions differ in its starting income level and its growth dynamics with the initially poorer region exhibiting higher economic growth. Assuming that by means of climate protocols the transfer of technological know-how can be intensified or restricted, the question arises: Are there incentives for developing world regions to join international agreements in the presence of technological spillovers?

To simplify the analysis we make two further assumptions. First, the developed world regions only export investment goods (this is in line with findings by Eaton and Kortum, 2001). Second, the less dynamically growing developing world region is the only exporter of energy resources.

In order to increase the clearness of our study and to avoid to get lost in an anonymous framework of investigation, we selected existing regions as representatives of the above described generic regions: the USA and Europe as the developed world regions, with higher labor productivity in the USA and higher energy efficiency in Europe, China as the fast growing developing region, and finally Rest of the World (ROW) as major resource supplier.

3.3. Empirical Foundation

The empirical foundation of MIND-RS starts from calibration results of the global model MIND. Parts of the model parameters are adopted directly (in particular those of the R&D investment functions), others needed to be regionalized.

Table 1
Initial values.

Parameter	Europe	USA	China	ROW
GDP in trill. \$US	8.8	10.0	1.16	11.2
Investment share of GDP in percent	0.22	0.24	0.27	0.24
Industrial capital stock (trill. \$US)	25.7	22.4	2.74	33.6
Cap. stock in fossil energy sector (trill. \$US)	1.4	1.6	0.27	2.8
Capital stock in extraction sector (trill. \$US)	1.1	1.4	0.22	1.8
Invest. cost renew. energy sector (\$US/kW)	1320	1383	1400	1330
Learning rate (renewable energy sector)	0.15	0.13	0.1	0.11
Industrial CO_2-emissions in GtC	1.14	1.54	0.87	2.81

The calibration is done for the 4 world regions Europe, China, the USA and rest of the world (ROW). This follows the intention of providing a good benchmark for a group of generic region. The lack of good regional data demands for restraining from conclusions that go beyond the generic region level.

Major data sources of MIND-RS are:

WDI ("World Development Indicators") database
CPI ("Common Poles Image") database
GTAP6 ("Global Trade Analysis Project") database
PWT ("Penn World Table") database
IEA ("International Energy Agency") database.

Main initial values are shown in Table 1. Deriving sound initial values for the capital stocks in the different energy sectors is most difficult because of a lack of appropriate data. In aggregating sectoral information from GTAP6 we derived estimates that in sum were significantly lower than the MIND values and would result in extreme adjustments of capital stocks in the first simulation periods. Therefore, we only use the regional shares in the global sectoral capital stocks as derived from GTAP6 and adjust the absolute level in order to avoid extreme model behavior.

With respect to the parameters of the production functions we stick to the MIND values in general. However, following findings in the literature (cf. Bernstein et al., 1999) we differentiate between a somewhat higher elasticity of factor substitution (0.4) in the aggregated industrial sectors of the developed world regions and a somewhat lower value (0.3) for the other two regions. The distribution parameters ξ_m are initialized according to the factors' usual aggregated income shares and assumed to be the same in the production functions of the consumption goods sector and the investment goods sector. Within the fossil energy sector, share parameters of 0.5 for capital and energy and substitution elasticities of 0.3 are assumed for all regions. With the elasticity and income share parameters given, we are able to compute the initial efficiency and productivity parameters (see Appendix C for a derivation of the calibration formula). These values are shown in Table 2. China exhibits

Table 2
Calibrated initial values of efficiency and productivity parameters.

Parameter	Europe	USA	China	ROW
Total factor productivity (industrial sectors)	0.34	0.45	0.42	0.33
Labour efficiency	0.5	0.8	0.02	0.85
Energy efficiency	5.24	3.45	0.64	2.55
Total factor productivity (fossil energy sector)	3.12	3.82	13.0	3.55

a remarkably high productivity in the fossil energy sector which is partly due to the fact that labor is not taken into account in this sector. Nevertheless, most of this comparative advantage is consumed by the low energy efficiency in both industrial sectors.

The CPI database provides CO_2 emissions for the base year (see Table 1). Initial resource extraction is derived from the emissions data by using the carbon content coefficient of MIND and taking trade in fossil resources into account. Initial data for resource exports are derived from IEA's World Energy Outlook (2006).

Particular attention was paid to the calibration of the parameters of the marginal extraction cost curve and the learning curves in the renewable energy sector. As to the marginal extraction cost curve (see Eq. (17) in Appendix B), we adjusted the χ_3 parameter such that the regional values reflect expected scarcities and sum up to 3500 GtC — the value of global carbon reserves assumed within MIND (Edenhofer et al., 2005). The distribution of reserves follows the IEA World Energy Outlook (2002) from which we derive shares of around 10%, 20%, 10% and 60% for Europe, USA, China and ROW, respectively.

Given the difference in the learning rates (with highest learning rates for solar and wind technologies) and the different composition of the renewable energy sector in the four regions, we derived regional differentiated initial investment costs and learning rates as shown in Table 1. The learning rates which specify the percentage cost reduction for a doubling of cumulated capacities are assumed to be constant over time. The regional learning curves are not subject to international spillovers.

Although the body of empirical research on spillover externalities has grown rapidly (see Section 2), data are restricted to case studies mostly on the level of firms. On a country level, Coe and Helpman (1995, p. 874) estimated that around one quarter of benefits from R&D investments (i.e. productivity increases) in G7 countries accrue due to trade. We selected values for the spillover intensity and the spillover-trade elasticity such that in the baseline scenario around 15% of labor productivity growth in ROW is due to embodied technological spillovers. That is in the range of 10–20% indicated by Kokko (1993, p. 161). In the default model setting, we apply the same value for the labor-productivity-enhancing and the energy-efficiency-improving spillover intensity.

4. Scenario Definition

4.1. Baseline Scenarios

Based on initial data and calibration, we generate a baseline scenario that represents economic dynamics in the presence of technological spillovers. In a first step, we contrast this scenario with another baseline scenario that is based on the same set of parameters and initial values but neglects the spillover effect. Missing this aspect of endogenous technological change results in fundamentally different growth dynamics in the spillover scenario (BAU-S) and the non-spillover scenario (BAU) as shown in Fig. 2. This Figure combines historic developments and model projections. The growth difference is particularly high in China. China benefits most from technological spillovers with a strong accelerating impact on economic dynamics. Simultaneously, energy consumption and emissions are much higher in the presence of technological spillovers.

Due to this baseline growth effect and the expanded emission mitigation gap, expected mitigation costs in climate policy scenarios would be higher in the spillover than in the non-spillover scenario. Due to the public good characteristics of the atmosphere as a sink of greenhouse gases, increased emission reduction needs would also

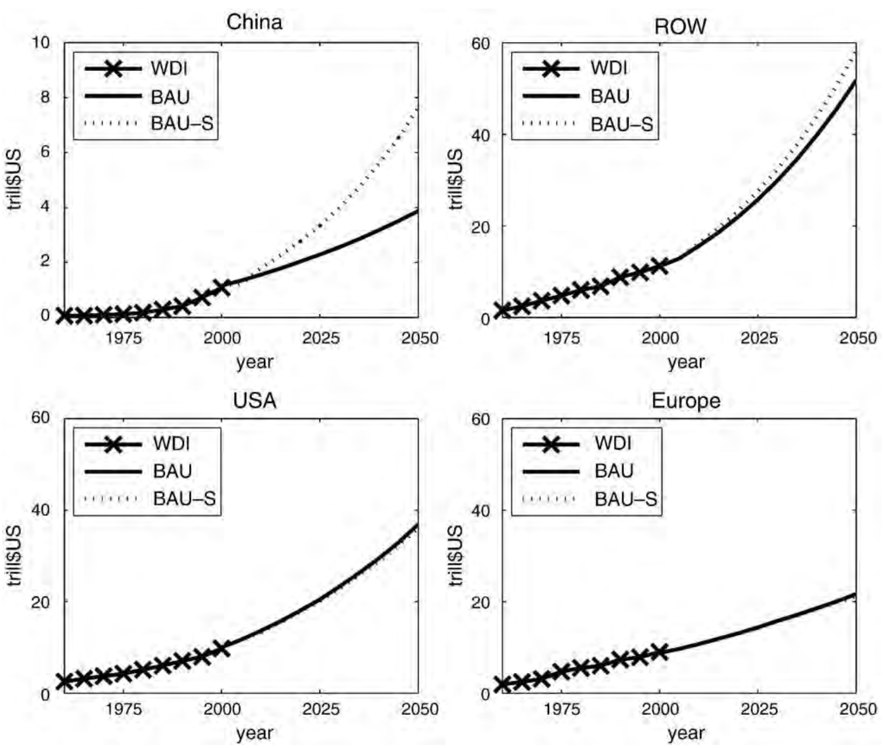

Fig. 2. GDP trajectory (until 2000, empirical data from WDI database; thereafter model simulations).

affect regions that not directly profit from the baseline growth effect. In order to disentangle this baseline effect, we constructed a new non-spillover baseline scenario. We compensate the non-spillover scenario for the missing feature of endogenous technological change by increasing energy efficiency and labor productivity exogenously by the same amount as in the spillover scenario. Consequently, similar GDP paths for the spillover baseline and the non-spillover baseline scenario (BAU-ex) are simulated. Also the CO_2 emission baselines, increasing up to 31.5 GtC in 2100, fit to each other.

However, there are still differences in the internal dynamics. In the spillover scenario, additional growth is induced by capital exports from the USA and Europe. This results in a higher degree of specialization of both regions in investment goods production. Globally, the overall share of investments on GDP is slightly higher in the spillover scenario. Moreover, there are significant differences in the trade structure. E.g., while Europe and USA are importers of the consumption good in the spillover scenario, they become goods exporters in the absence of technological spillovers.

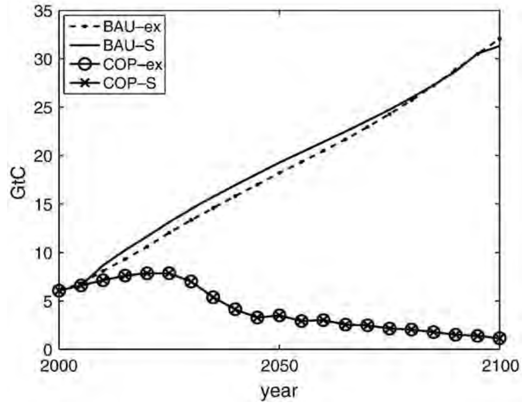

Fig. 3. Optimal CO_2 emissions.

4.2. Policy Scenarios

The baseline scenarios represent business-as-usual dynamics by neglecting the climate change problem. Within the policy scenarios this problem is taken into account. By adopting the target of the EU to limit global mean temperature increase to 2 °C above preindustrial level, the policy scenarios frame the search for optimal mitigation policies. Technically, we used the optimal emission path that meets the 2 °C target in a model run with the global model MIND (Edenhofer et al., 2005). From this global emission path we derive the amount of emission permits that can be allocated between the four regions. In allocating the permits, we follow the contraction & convergence approach (Meyer, 2000; Leimbach, 2003). In the base year 2000, permits are allocated according to the status-quo, providing the USA and Europe with a higher per capita share. Per capita allocation of permits is assumed to converge over time with equal per capita allocation achieved in 2050. The total amount of permits contracts over time, thus requiring emission reduction to keep the 2 °C temperature target.

In general, opposite spillover-related impacts affect the costs of climate change mitigation. On the one hand, the growth effect, induced by the spillover channel that increases labor productivity, enlarges the mitigation gap between the baseline and the policy scenario, hence, increases the costs. The energy efficiency effect, on the other hand, helps to fill the mitigation gap more efficiently, hence, reduces the costs. With the construction of the baseline scenario, we disentangled the baseline growth effect, allowing to analyse differences in climate policy implications between spillover scenarios and non-spillover scenarios more clearly.

While in the default setting we investigate climate policies in a co-operative world, we formulate an alternative policy scenario representing fragmented policy regimes. We consider the possibility that a single region will not join the grand coalition. The region that is not willing to accept binding emission reduction commitments is assumed to run in a business-as-usual mode, while all other regions are committed to the same amount of emission reduction as within the full co-operative policy regime. Total emissions increase compared to the co-operative policy regime. Emissions trading is allowed only between partners within the coalition. The non-committed region is partly excluded from technological spillovers. The spillover channel that affects energy efficiency is closed completely and the intensity of spillovers that increase labor efficiency is reduced up to 50%. This is a rather extreme scenario, but it reflects the idea of issue linking by combining a climate policy regime with a technology protocol and some kind of trade sanctions as it is analyzed in the literature on the stability of international environmental agreements (e.g. Carraro and Siniscalco, 1997; Barrett, 2003; Kemfert, 2004; Lessmann et al., 2009).

A list of all scenarios is provided in Appendix A.

5. Policy Analysis

5.1. Common Results

By discussing the results from model simulations, we first focus on results that are robust across spillover and non-spillover scenarios. Given the policy target, the non-spillover policy scenario COP-ex and the spillover policy scenario COP-S come up with the same optimal emission trajectory (see Fig. 3) as part of the co-operative solution. The gaps between the emission baseline trajectories and the optimal policy paths are huge. Under climate policies, emissions have to be reduced globally by around 50% in 2050 compared to the base year (2000) and up to 85% compared to the baseline.

Fig. 4 shows the regional distribution of mitigation costs. Mitigation costs are measured as the percentage loss of consumption in the policy scenario compared to the corresponding baseline scenario. Note that benefits due to avoided climate change damages are not taken into account, but will probably shift consumption losses into gains when the policy scenario is compared with a reference scenario that includes climate damages.

Irrespective of the presence or absence of spillovers, Europe faces the lowest costs (between 1% and 2% on average) in the co-operative policy scenarios and China faces the highest costs (between 5% and 6% on average). The high level of mitigation costs in China is mainly due to the high economic growth path and a comparatively low level of energy efficiency. Due to a fast contraction of globally available

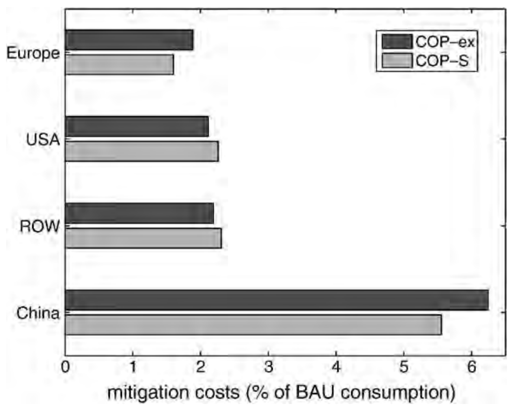

Fig. 4. Average mitigation costs in COP-ex and COP-S scenario.

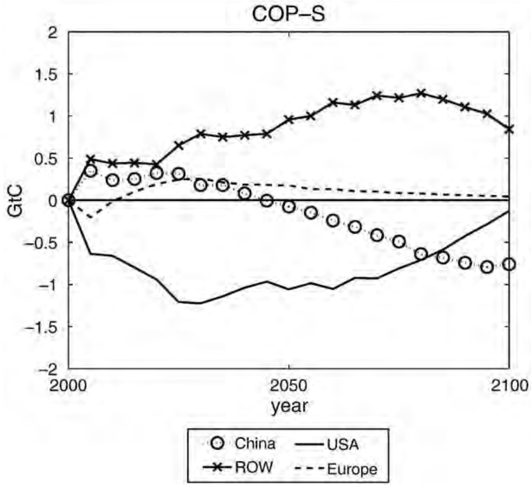

Fig. 5. Flow of emission permits in COP-S scenario.

emission permits, China suffers from a shortage of permits under the applied contraction & convergence allocation rule. Europe benefits from a higher level of energy efficiency and a lower level of carbon intensity compared to the USA. ROW is a quite heterogenous region with slow and fast growing countries. Two opposite effects have a major impact on the level of mitigation costs in ROW. Revenue losses from fossil resources export for one part of countries are accompanied by gains from emissions trading for other parts of countries.

Between 10% and 30% of the mitigation costs can be saved across all regions by emissions trading. Absolute volumes of permits traded in scenario COP-S are shown in Fig. 5. The USA buys permits over the whole time horizon. ROW sells permits of around 1 GtC per year over the whole time span. China starts as a seller of emission rights. However, as the amount of available permits contracts soon, it quickly becomes a buyer of emission permits. The opposite applies to Europe. European permit exports represent, however, only a small volume.

Trade pattern differences between the baseline and the policy scenarios are mainly represented by trade in emission permits and differences in the trade of fossil resources. Beyond that, the trade pattern is quite robust between the baseline and the policy scenarios, though it is different between the spillover and the non-spillover scenarios. On the resource market, reduced demand of Europe and USA causes export losses of ROW.

5.2. Spillovers vs. Non-spillovers

Even though mitigation cost differences between the spillover and the non-spillover scenario are moderate (cf. Fig. 4), they indicate the impact of spillover-specific mechanisms. Understanding these mechanisms may help in designing effective climate policies.

The major difference between the spillover and the non-spillover scenario in responding to climate policies is the additional possibility of intensifying and redirecting capital trade in order to employ the energy-efficiency-enhancing spillover effect in the spillover scenario. Figs. 6 and 7 show the differences in consumption goods trade and capital trade between the baseline scenarios and the corresponding policy scenarios. In general, there is less capital trade in the policy scenarios. Both the USA and Europe withhold and redirect part of their investments for restructuring their domestic energy systems. However, capital trade reduction is less distinct in the presence of technological spillovers. This is mainly due to the fact that, in contrast to the non-spillover scenario, capital trade reductions have a negative impact on the labor productivity and the energy efficiency in the spillover scenario.

Due to the attractiveness of foreign capital in the spillover scenario, trade volumes are much higher in this scenario than in the non-spillover scenario. Higher demands on the capital and permit market cause higher relative capital and carbon prices in the spillover scenario. Higher capital prices favor the capital exporters Europe and USA. Europe can profit from the improved terms-of-trade. For the USA, this positive effect is dominated by higher expenditures on the carbon market.

In contrast to the capital market, an even qualitatively different reaction can be observed on the goods market. While the USA finances permit imports (cf. Fig. 5) by additional goods exports in the COP-ex scenario, it forgoes goods imports in the COP-S scenario. In contrast, Europe uses revenues from the permit market to reduce goods exports in the non-spillover scenario but uses such revenues to increase imports of goods in the spillover scenario. This indicates better terms-of-trade in the spillover scenario.

Although ROW benefits from higher carbon prices in the spillover scenario, mitigation costs for this region are somewhat higher in the presence of spillovers. ROW suffers from a larger negative difference in resource prices between the COP-S and the BAU-S scenario than between the COP-ex and the BAU-ex scenario. In contrast to ROW, China exhibits less mitigation costs in the spillover scenario than in the non-spillover scenario, even though capital imports are reduced compared to the baseline. Capital trade reduction happens in both policy scenarios but has an efficiency-decreasing impact in the spillover scenario only. The reason for this positive mitigation cost difference is a remaining baseline growth effect. Based on the exogenously given productivity improvements in the non-spillover scenario, China shifts investments

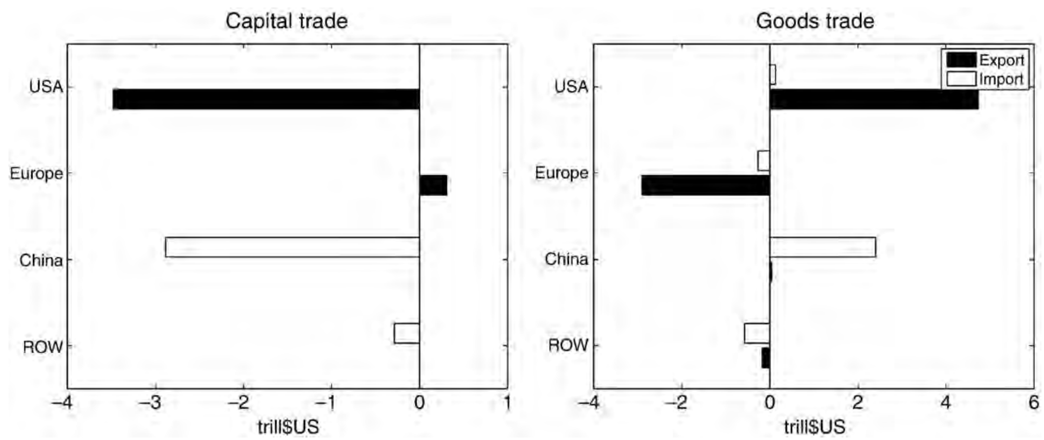

Fig. 6. Trade flow differences between policy scenario (COP-ex) and baseline scenario (BAU-ex) — cumulated net present values.

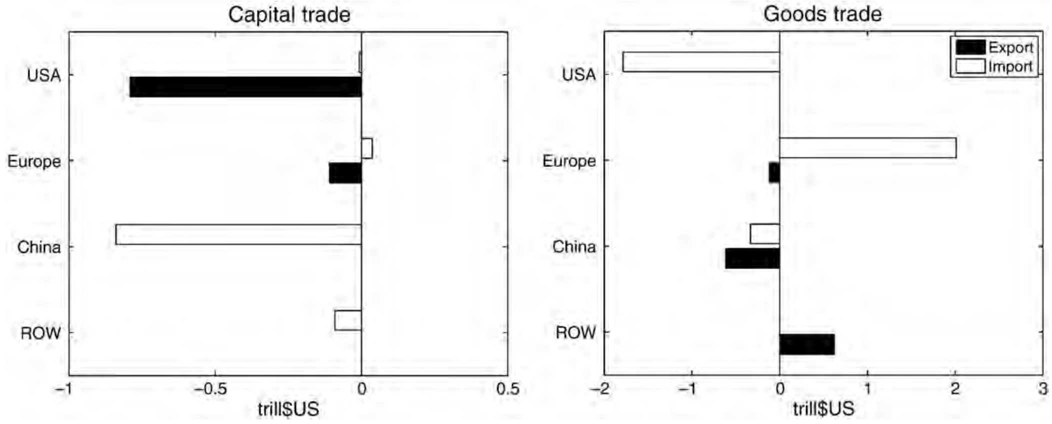

Fig. 7. Trade flow differences between policy scenario (COP-S) and baseline scenario (BAU-S) — cumulated net present values.

across sectors and time. This yields a slightly faster growing consumption path in the non-spillover scenario.

5.3. First-mover Advantage

According to available data (see Table 2), Europe has currently a higher energy efficiency than the USA. By interpreting high initial energy efficiency as a result of a first-mover climate policy, we investigate the model results for effects that represent first-mover advantages bound to the presence of technological spillovers. The question arises: Do the lower mitigation costs for Europe in the scenario COP-S compared to scenario COP-ex (cf. Fig. 4) indicate first-mover advantages?

Trade patterns are crucial. Comparing the differences in capital trade in Figs. 6 and 7, we do not observe a major redirection of capital trade flows. While this hardly provides an argument for the first-mover advantage, the fact that Europe in contrast or proportion to all other regions and in contrast to its own trade pattern in the non-spillover scenario increases its share on international trade does so.

We run an additional experiment in order to demonstrate the significance of the first-mover advantage and to exclude that Europe's relative gains are due to price effects that relate to the endogenous representation of technological change in general, but not to the energy-efficiency-enhancing spillover channel in particular. The current model design is characterized by the fact that the growth-enhancing and the energy-efficiency-enhancing effect of technological spillovers are jointly bound to capital trade. Each decision for capital imports, intended to access energy-efficient capital and know-how, simultaneously implies productivity growth which can counteract the former intention. The ratio between the intensity of both spillover effects plays therefore an important role.

In the additional experiment, we refrain from assuming a unique spillover intensity parameter Ω, but use an energy-efficiency-related spillover intensity that is tenfold higher than the original value while the labor productivity related spillover intensity is held constant.[3] Based on this single change, we simulate a baseline scenario (BAU-H) that in the same way as described in Section 4 is used to create a corresponding non-spillover baseline scenario (BAU-H-ex). Consequently, the latter differs from the BAU-ex scenario mainly due to the increased level of exogenous energy efficiency growth.

Fig. 8 shows the mitigation costs for the new set of policy scenarios (COP-H and COP-H-ex). While mitigation costs compared to the default scenario (see Fig. 4) decrease in general, cost reductions are most remarkable in China. This clearly demonstrates the first order effect of spillovers. China exhibits the highest technology gap in energy efficiency and hence profits most from energy-efficiency-improving technological spillovers. Moreover, it turns out that Europe can furthermore reduce mitigation costs in the presence of spillovers. Mitigation costs are reduced to 1.27% which is 0.44 percentage points less than the mitigation costs in the non-spillover scenario.[4] In particular, Europe's share both in capital exports and in goods imports increases compared to the baseline scenario (see Fig. 9). Why? The reason for this is the differentiated spillover channel.

The high labor efficiency of the USA, which is subject to spillovers, made capital exports from the USA most attractive in general. Under the condition of a carbon-constrained world, however, energy efficiency becomes more important. Foreign investments from Europe become more attractive because they embody technological know-how that contributes to a higher extent to an increase in energy efficiency of capital importing regions than technological spillovers from investments goods of the USA.

This causal relationship explains the higher capital export of Europe in the COP-H scenario compared to the BAU-H scenario and indicates a first-mover advantage in the presence of technological spillovers. It results in substantially less mitigation costs for Europe in scenario COP-H compared to scenario COP-H-ex. Continually improved terms-of-trade allow Europe to increase their shares in global trade at the expense of the USA.

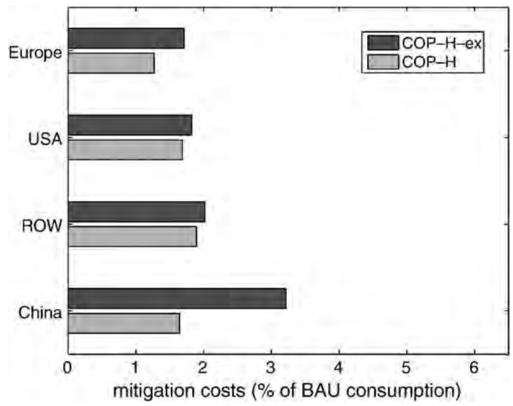

Fig. 8. Average mitigation costs of the scenarios COP-H-ex and COP-H.

[3] In Section 5.5, parameter Ω is subject to a comprehensive sensitivity analysis.

[4] The mitigation cost difference between the non-spillover and the spillover scenario amounts to 0.13 and 0.14 percentage points for ROW and the USA, respectively. Both regions benefit in the spillover scenario from a shift of capital trade in time.

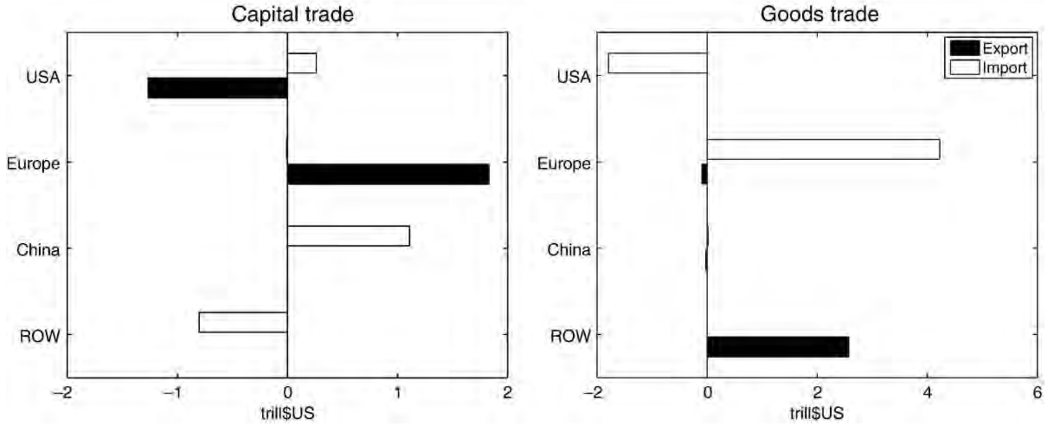

Fig. 9. Trade flow differences between policy scenario (COP-H) and baseline scenario (BAU-H) — cumulated net present values.

5.4. Fragmented Policy Regime

We finally investigate fragmented policy scenarios where China does not join the climate policy regime. Under these scenarios, trade pattern and mitigation costs change substantially. China will suffer from receiving less technological spillovers. Unless the labor-productivity-enhancing spillover channel is completely opened (as in scenario NoCH-0 — see Fig. 10), this loss cannot be compensated by a relaxed emission constraint which allows the use of cheap fossil fuels for a longer time. Depending on the design of the restrictiveness of the trade or technology protocol that come into force, the additional mitigation costs can be huge. Closing the energy-efficiency increasing spillover channel and restricting labor-productivity enhancing technological spillovers by 25% (NoCH-25) results in mitigation costs of 14% for China. With a 50% reduction of labor-productivity-increasing spillovers, costs increase to around 27% (see Fig. 10).

For the other regions, losses compared to the co-operative solution slightly change.[5] Nevertheless, Europe cannot fully employ its first-mover advantage. To avoid this situation, it is important that technology protocols and trade sanctions do not only affect energy-efficient technologies but products with embodied technological know-how in general. Under such circumstances, there would be clear incentives for China to accept commitments.

5.5. Sensitivity Analysis

We carry out sensitivity analyses to test robustness of results. In particular we investigate into the sensitivity of:

- consumption and mitigation costs to spillover intensity Ω
- consumption and mitigation costs to R&D efficiency ζ.

We selected those parameters that presumably have a huge impact, but have a weak empirical foundation. The spillover intensity relates to the extent of endogenous technical progress with a high impact on economic growth. The same applies to the R&D parameter which represents the efficiency of R&D investments into labor efficiency improvements. The variation of parameter values is always the same for each region.

For all variations we see smooth and well-behaved changes.[6] This indicates numerical robustness. Nevertheless, sensitivity is quite high in some cases. With respect to the spillover intensity, significant impacts can be demonstrated for all regions, in particular for China (see Fig. 11 in Appendix D). However, while China faces drastic changes in consumption as well as in mitigation costs, for the USA we observe high sensitivity of mitigation costs but moderate changes in consumption. For Europe even changes in mitigation costs are moderate. Differences in sensitivities of mitigation costs are due to the growth effect of the labor-efficiency-enhancing spillover channel. This spillover channel is more intensively used in the baseline scenario than in the policy scenario.

Within the selected range of variation, economic growth is very sensitive to the R&D efficiency parameter in all regions. The higher the efficiency of R&D investments into labor efficiency improvements, the higher the growth (see Fig. 12 in Appendix D). Consequently, a climate-policy-induced shift from R&D investments (and capital imports), that increase labor efficiency, into R&D investments (and capital imports), that increase energy efficiency, results in higher mitigation costs in all regions but Europe. Europe benefits in the short-run from the redirection of the other regions' expenditures to energy-efficiency-improving capital imports (for which Europe is most attractive).

6. Conclusions

In this paper, we analyzed the implications of modeling embodied technological spillovers. We presented a multi-region growth model with endogenous technological change and discussed its application in a climate policy context. In the presence of spillovers that enhance labor efficiency and energy efficiency, two opposite spillover effects impact mitigation costs. While a growth effect tends to increase mitigation costs, energy efficiency improvements reduce mitigation

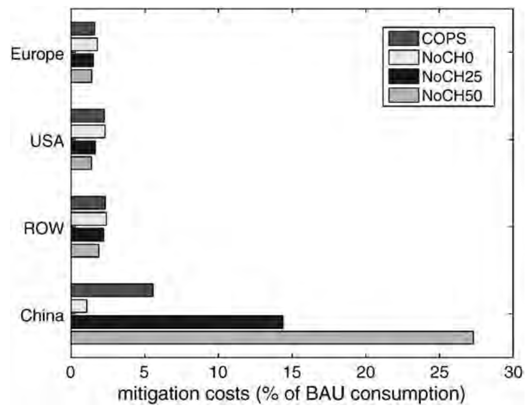

Fig. 10. Mitigation costs in fragmented policy regime.

[5] Partly lower mitigation costs for the committed regions are outweighed by higher climate change risks due to the increased amount of emissions.

[6] Changes of differential measures as mitigation costs are obviously not as smooth as those of the basic variables.

costs. The higher the ratio between the spillover intensities that either increase energy efficiency or labor productivity, the lower are the mitigation costs for all regions. Importing foreign capital that increases the efficiency of energy use represents a mitigation option that extends the commonly modeled portfolio. In consequence of this option, associated terms-of-trade effects favor capital-exporting regions in climate policy scenarios.

Advantages in energy saving technologies thus pay off in climate policy scenarios. This finding gives support to the hypothesis that there are some benefits for forerunners in climate policies. This relationship would be more distinctive if we considered not only advantages in energy-efficient technologies but also in carbon-free energy technologies. From the sensitivity analysis, it furthermore turns out that this first-mover advantage is the larger the higher the efficiency of domestic R&D investments in labor productivity growth is, making labor-efficiency-enhancing capital imports less attractive and energy-efficiency-enhancing capital imports more attractive. Both results emanate from modeling the embodied type of technological spillovers, but cannot be derived in a model with disembodied spillovers only.

Simulations of policy scenarios that include embodied technological spillovers discover various incentives for single regions to take active part in climate policies. In particular, it turns out that restrictions on technology transfers will provide incentives for developing world regions to join a climate policy regime; this is in line with findings from the literature on the stability of international environmental agreements which are mainly based on disembodied spillovers. In addition, this study showed that it is important that restrictions on technology transfers do not only affect energy-efficient technologies but products with embodied technological know-how in general.

All model results are subject to a number of assumptions and simplifications, in particular:

- limited empirical foundation (this applies for example to the differentiation between the intensity parameters of the labor productivity and the energy efficiency spillover function)
- neglecting the impact of absorptive capacities
- foreign and domestic goods are considered as perfect substitutes, which results in undue specialization
- limited disaggregation of the energy sector; neglect of the option of carbon capturing and sequestration (neglecting this option results in higher average mitigation costs than those simulated by the global reference model MIND).

This list gives rise to future research demand.

Appendix A. Parameters, Variables and Scenarios

Symbol	Set/index
i, r	Region
j	Sector
m	Production factor
t	Time
z	Time step, five years
τ	Vintages of renewable
Symbol	**Parameter**
σ	Discount rate
δ	Depreciation rate
$\rho(i)$	Substitution elasticity in consumption and investment goods sector
ρ_f	Substitution elasticity in fossil energy sector
ξ_m	Weight parameter for factor m in aggregated production function
ξ_m^f	Weight parameter for factor m in fossil energy sector
$\Phi_j(i)$	Total factor productivity in sector j in region i
$D(i)$	Primary energy efficiency in region i
$\zeta_m(i)$	Productivity of R&D investments in improving efficiency of factor m in region i
α_m	Parameter of efficiency-augmenting R&D function
ψ	Parameter of spillover function

Appendix A (*continued*)

Symbol	Parameter
Ω_m	Spillover intensity
$\mathcal{K}_{max}(i,t)$	Maximum productivity in extraction sector in region i at time t
$k(i,t)$	Conversion coefficient in region i at time t
$\nu(i)$	Inverse learning rate in resource sector in region i
μ	Learning dampening factor
$\chi_1(i)$	Parameter of marginal extraction cost curve in region i
$\chi_2(i)$	Parameter of marginal extraction cost curve in region i
$\chi_3(i)$	Parameter of marginal extraction cost curve in region i
χ_4	Parameter of marginal extraction cost curve
$l(t)$	Load factors of vintages for renewable energy production
$w(t)$	Weights for vintages for renewable energy production at time t
$fC(i)$	Floor investment costs of vintages in region i
$\gamma(i)$	Learning parameter in renewable energy sector in region i
Symbol	**Control variable**
θ_m, j	Share of factor m in sector j
$rd_L(i,t)$	R&D investments in labor efficiency in region i at time t
$rd_E(i,t)$	R&D investments in energy efficiency in region i at time t
$I_j(i,t)$	Investment in sector j in region i at time t
$X_I(i,r,t)$	Export of investment goods from region i to region r at time t
$X_C(i,r,t)$	Export of consumption goods from region i to region r at time t
$X_Q(i,r,t)$	Export of resources from region i to region r at time t
$X_P(i,r,t)$	Export of emission permits from region i to region r at time t
Symbol	**State variable**
$K_j(i,t)$	Capital stock of sector j in region i at time t
$A_L(i,t)$	Labor efficiency in region i at time t
$A_E(i,t)$	Energy efficiency in region i at time t
$cQ(i,t)$	Cumulative resource extraction in region i at time t
$\mathcal{K}(i,t)$	Production factor of extraction sector in region i at time t
$V(i,t)$	Vintage of renewable energy capacities in region i at time t
$\kappa(i,t)$	Variable investment costs of vintages in region i at time t
$cN(i,t)$	Cumulative installed capacity in region i at time t
Symbol	**Other variable**
W	Welfare
$C(i,t)$	Consumption in region i at time t
$L(i,t)$	Labor in region i at time t — exogenous
$E(i,t)$	Total energy in region i at time t
$Y_C(i,t)$	Output in consumption goods sector in region i at time t
$Y_I(i,t)$	Output in investment goods sector in region i at time t
$I(i,t)$	Total investment in region i at time t
$sp_L(i,t)$	Spillover in labor efficiency to region i at time t
$sp_E(i,t)$	Spillover in energy efficiency to region i at time t
$I_{nf}(i,t)$	Investment in other energy sector in region i at time t — exogenous
$E_f(i,t)$	Fossil energy in region i at time t
$E_{ren}(i,t)$	Renewable energy in region i at time t
$E_{nf}(i,t)$	Energy from other energy sources in region i at time t
$PE(i,t)$	Fossil primary energy in region i at time t
$mC(i,t)$	Marginal extraction costs in region i at time t
$Q(i,t)$	Resource extraction in region i at time t
$EM(t)$	Global CO_2 emissions at time t
$LU(t)$	CO_2 emissions from land-use change at time t
$P(i,t)$	Emission permits in region i at time t — exogenous
$p_j(t)$	World market price (net present value) of good j r at time t
Symbol	**Scenario**
BAU	Business as usual without spillovers
BAU-S	Business as usual with spillovers
BAU-ex	Business as usual with exogenous technological change
BAU-H	Business as usual with spillovers; high energy-efficiency spillovers
BAU-H-ex	Business as usual with exog. techn. change; high energy-efficiency spillovers
COP	Co-operative policy scenario without spillovers
COP-S	Co-operative policy scenario with spillovers
COP-ex	Co-operative policy scenario with exogenous technological change
COP-H	Co-operative policy scenario with spillovers; high energy-efficiency spillovers
COP-H-ex	Co-op. pol. scenario with exog. techn. change; high energy-efficiency spillovers
NoCH-0	China is not part of the policy regime; no energy-efficiency-enhancing spillovers
NoCH-25	Like NoCH-0; labor-productivity-enhancing spillovers reduced by 25%
NoCH-50	Like NoCH-0; labor-productivity-enhancing spillovers reduced by 50%

Appendix B. Energy Sector Equations

B.1. Final Energy Sector

The fossil, renewable and remaining energy production sectors deliver final energy

$$E(i,t) = E_f(i,t) + E_{ren}(i,t) + E_{nf}(i,t). \tag{12}$$

In the fossil energy sector, final energy is generated according to the following CES production function (with the production factors capital K_f and primary fossil energy PE):

$$E_f(i,t) = \Phi_f(i)\left[\xi_K^f K_f(i,t)^{\rho_f} + \xi_{PE}^f(\mathcal{D}(i)\cdot PE(i,t))^{\rho_f}\right]^{\frac{1}{\rho_f}} \tag{13}$$

In the renewable sector, final energy is produced based on the active vintages V and the respective load factors l:

$$E_{ren}(i,t) = \sum_{\tau} l(t-\tau)\cdot V(i,t-\tau)\cdot w(\tau). \tag{14}$$

w is a weighting factor that represents the still active part of the vintages. Each vintage is a function of the investments I_{ren} (see Eq. (21)) and considered to exist over τ time steps.

The remaining energy sector provides energy E_{nf} from nuclear power, hydro power and traditional biomass sources. Its future supply is given exogenously.[7]

B.2. Fossil Resource Extraction Sector

Primary fossil energy is produced from energy resources Q and net resource imports:

$$PE(i,t) = k(i,t)\cdot\left[Q(i,t) - \sum_r (X_Q(i,r,t) - X_Q(r,i,t))\right]. \tag{15}$$

k represents a conversion factor that converts carbon into Joule. The extraction of fossil resources is restricted by the capacity constraint

$$Q(i,t)\cdot mC(i,t) = \mathcal{K}(i,t)\cdot K_Q(i,t). \tag{16}$$

mC denotes the marginal cost of extraction (i.e. the price of resources) and $\mathcal{K}$ represents the productivity of the capital stock in the extraction sector. The marginal cost of extraction are derived from the so-called Rogner curve

$$mC(i,t) = 1 + \frac{\chi_2(i)}{\chi_1(i)}\left(\frac{cQ(i,t)}{\chi_3(i)}\right)^{\chi_4}. \tag{17}$$

The cumulative amount of extraction cQ is given by

$$cQ(i,t+1) = cQ(i,t) + z\cdot Q(i,t). \tag{18}$$

The productivity of the capital stock in the extraction sector is subject to learning-by-doing and evolves according to:

$$\mathcal{K}(i,t+1) = \mathcal{K}(i,t)\left[1 + (\mathcal{K}(i)_{max} - \mathcal{K}(i,t))\left(\frac{z\cdot v(i)}{\mathcal{K}(i)_{max}}\left(\left(\frac{Q(i,t)}{Q(i,0)}\right)^{\mu} - 1\right)\right)\right]. \tag{19}$$

Total anthropogenic CO_2 emissions sum up CO_2 emitted by burning fossil fuels and emissions from land-use change:

$$EM(t) = \sum_i Q(i,t) + LU(t). \tag{20}$$

Q represents the carbon content of extracted fossil fuels.

[7] The global value of the production of the remaining energy sector used in MIND is distributed according to the regional shares of this kind of energy consumption in the CPI baseline scenario.

B.3. Renewable Energy Sector

Vintage capital V is built up by investments and transformed into capacity units by taking the floor costs fC and the variable investment costs κ into account:

$$V(i,t+1) = z\cdot\frac{I_{ren}(i,t)}{fC(i) + \kappa(i,t)}. \tag{21}$$

Similar to the extraction sector, endogenous technological change takes place in the renewable energy sector. Based on the cumulated installed capacity cN, with

$$cN(i,t) = cN(i,t-1) + V(i,t), \tag{22}$$

productivity of the renewable energy sector changes:

$$\kappa(i,t) = \kappa(i,0)\cdot\left(\frac{cN(i,t)}{cN(i,0)}\right)^{-\gamma(i)}. \tag{23}$$

Appendix C. Equations of Calibration

The first-order partial derivatives of the production function for consumption goods Y_C are

$$\frac{\partial Y_C}{\partial L} = \Phi_C^{\rho}\xi_L\theta_{L,C}^{\rho}\mathcal{A}_L^{\rho}L^{\rho-1}Y_C^{1-\rho}, \tag{24}$$

$$\frac{\partial Y_C}{\partial E} = \Phi_C^{\rho}\xi_E\theta_{E,C}^{\rho}\mathcal{A}_E^{\rho}E^{\rho-1}Y_C^{1-\rho} \tag{25}$$

and

$$\frac{\partial Y_C}{\partial K_C} = \Phi_C^{\rho}\xi_K K_C^{\rho-1}Y_C^{1-\rho}. \tag{26}$$

So the income shares are

$$\begin{aligned}
\frac{\partial Y_C}{\partial L}\frac{L}{Y_C} &= \Phi_C^{\rho}\xi_L\theta_{L,C}^{\rho}\mathcal{A}_L^{\rho}\left(\frac{L}{Y_C}\right)^{\rho}\\
\frac{\partial Y_C}{\partial E}\frac{E}{Y_C} &= \Phi_C^{\rho}\xi_E\theta_{E,C}^{\rho}\mathcal{A}_E^{\rho}\left(\frac{E}{Y_C}\right)^{\rho}\\
\frac{\partial Y_C}{\partial K_C}\frac{K_C}{Y_C} &= \Phi_C^{\rho}\xi_K\left(\frac{K_C}{Y_C}\right)^{\rho}.
\end{aligned} \tag{27}$$

This can be used for the calibration. Given the start values Y_{C0}, L_0, E_0, K_{C0}, we can derive

$$\begin{aligned}
&\frac{\partial Y_C}{\partial K_C}\frac{K_C}{Y_C} = \Phi_C^{\rho}\xi_K\left(\frac{K_C}{Y_C}\right)^{\rho} = \xi_K\\
&\Rightarrow \Phi_C^{\rho}\left(\frac{K_C}{Y_C}\right)^{\rho} = 1 \rightarrow \Phi_C = \frac{Y_{C0}}{K_{C0}}
\end{aligned} \tag{28}$$

$$\begin{aligned}
&\frac{\partial Y_C}{\partial L}\frac{L}{Y_C} = \Phi_C^{\rho}\xi_L\theta_{L,C}^{\rho}\mathcal{A}_L^{\rho}\left(\frac{L}{Y_C}\right)^{\rho} = \xi_L\\
&\Rightarrow \Phi_C^{\rho}\theta_{L,C}^{\rho}\mathcal{A}_L^{\rho}\left(\frac{L}{Y_C}\right)^{\rho} = 1 \rightarrow \mathcal{A}_{L0} = \frac{Y_{C0}}{\theta_{L,C}L_0\Phi_C} = \frac{K_{C0}}{\theta_{L,C}L_0}
\end{aligned} \tag{29}$$

$$\begin{aligned}
&\frac{\partial Y_C}{\partial E}\frac{E}{Y_C} = \Phi_C^{\rho}\theta_{E,C}^{\rho}\mathcal{A}_E^{\rho}\xi_E\left(\frac{E}{Y_C}\right)^{\rho} = \xi_E\\
&\Rightarrow \Phi_C^{\rho}\theta_{E,C}^{\rho}\mathcal{A}_E^{\rho}\left(\frac{E}{Y_C}\right)^{\rho} = 1 \rightarrow \mathcal{A}_{E0} = \frac{Y_{C0}}{\theta_{E,C}E_0\Phi_C} = \frac{K_{C0}}{\theta_{E,C}E_0}.
\end{aligned} \tag{30}$$

The same applies for Y_I.

Appendix D. Sensitivity Analysis

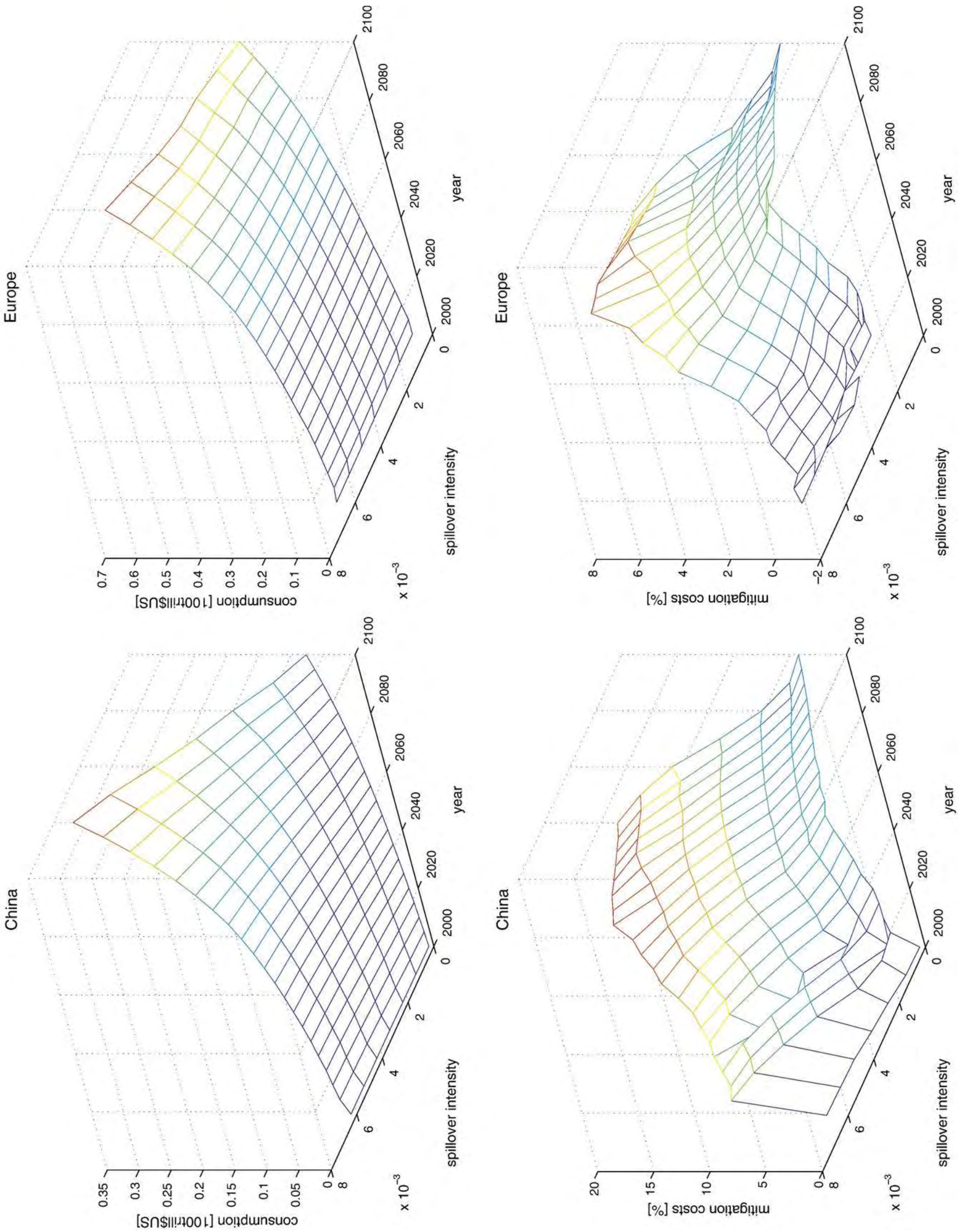

Fig. 11. Sensitivity of consumption and mitigation costs to spillover intensity.

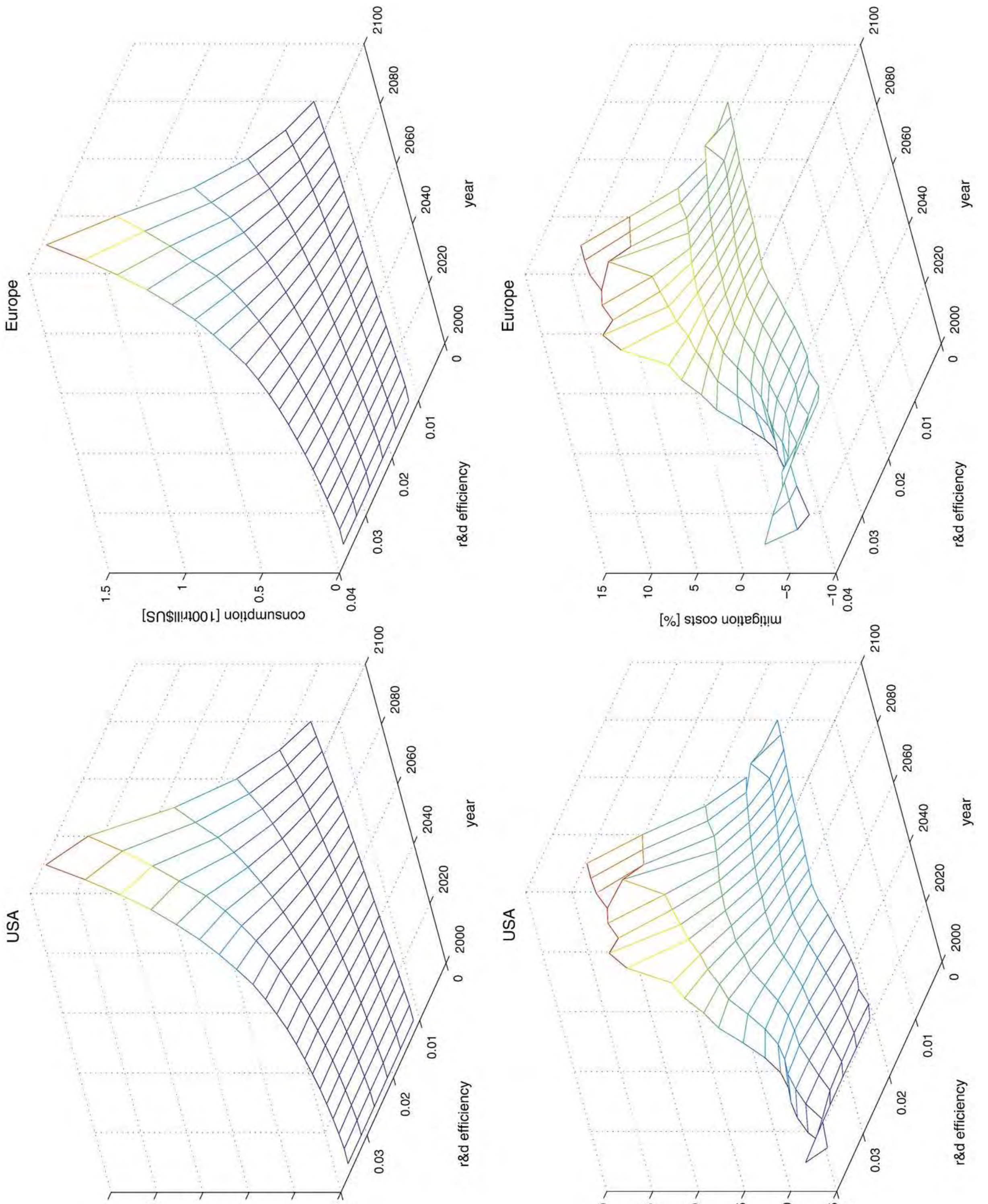

Fig. 12. Sensitivity of consumption and mitigation costs to R&D efficiency.

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Chapter 3

Mitigation costs in a globalized world: climate policy analysis with REMIND-R*

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Mitigation Costs in a Globalized World: Climate Policy Analysis with REMIND-R

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Abstract Within this paper, we present the novel hybrid model REMIND-R and its application in a climate policy context based on the EU target to avoid a warming of the Earth's atmosphere by more than 2°C compared to the pre-industrial level. This paper aims to identify necessary long-term changes in the energy system and the magnitude of costs to attain such a climate protection target under different designs of the post-2012 climate policy regime. The regional specification of mitigation costs is analyzed in the context of globalization where regions are linked by global markets for emission permits, goods, and several resources. From simulation experiments with REMIND-R, it turns out that quite different strategies of restructuring the energy system are pursued by the regions. Furthermore, it is demonstrated that the variance of mitigation costs is higher across regions than across policy regimes. First-order impacts, in particular, reduced rents from trade in fossil resources, prevail regardless of the design of the policy regime.

Keywords Climate policy · Energy–economy–environment modeling · Energy system · International trade

1 Introduction

Climate change is recognized as a major global threat that the current and the next generations have to deal with. Science is asked to provide evidence for climate change, but also to help policy-making by exploring options of adaptation and mitigation. Model-based quantitative analyses are frequently used in climate policy decision-making. A number of energy–economy–climate models were developed and applied over the last decade—e.g., RICE [30], MERGE [22, 26], MiniCAM [8], IMAGE [1], G-Cubed [25], MESSAGE-MACRO [29], POLES [20], AIM [19], DEMETER [12], MIND [6], FAIR [9], E3MG [2], WITCH [4], Imaclim-R [5]. For an overview, see [36] and [18]. The survey given by [18] indicated that, most recently, major progress was made in modeling endogenous and induced technological change (see also [7, 24]).

The energy sector is a key sector for technological change, as well as for promising mitigation strategies. A portfolio of different technological options and a flexible investment dynamic are crucial in transforming the energy system in a climate-friendly way. Technological potentials differ between regions and mitigation costs depend on regional interactions. Only a few models take all these aspects into account. Bottom-up models can provide a detailed description of energy technologies. However, they have been criticized for ignoring economic feedbacks of different energy pathways [17]. Top-down models, in contrast, have addressed macroeconomic consequences of energy and climate policies. While also representing some microeconomic realism (e.g., captured in consumer preferences and substitution elasticities) in the absence of structural breaks in the development and consumption styles, top-down models are poor in technological explicitness.

We present the hybrid model—REMIND-R—that couples a macroeconomic system module with a highly

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disaggregated energy system module (cf. [3]). Hybrid models bridge the gap between conventional top-down and bottom-up modeling approaches [17] and become the preferable tool in supporting policy-making. [11] stress the importance of hybrid models and their dynamic formulation in providing consistent policy analyses, in particular due to the endogenous formulation of investment decisions, which allows for an explicit description of evolving specific capital stocks and technology mixes. In REMIND-R, mitigation cost estimates are based on technological opportunities and constraints in the development of new energy technologies. Most essentially, technological change in the energy sector (as represented in bottom-up models) is embedded in a macroeconomic environment (as represented by top-down models) that, by means of investment and trade decisions, governs regional development. Altogether, this provides a new level of climate policy decision support and a basis for assessing future climate policy regimes.

Based on the EU target to avoid a warming of the Earth's atmosphere by more than 2°C compared to the pre-industrial level, this paper aims to identify the magnitude of costs to attain such a climate protection target under different designs of the post-2012 climate policy regime. The regional specification of mitigation costs is analyzed in the context of globalization where regions are linked by different global markets for emission permits, goods, and resources. Three alternative scenarios of climate policy regimes, based on a different initial allocation of emission rights, have been investigated: (1) contraction and convergence, (2) intensity target, and (3) multi-stage approach. It turns out that the ambitious climate target can be achieved at costs of around 1.5% of global gross domestic product (GDP). Differences between the regional costs are, however, large. In contrast, mitigation costs across different policy regimes differ less. Nevertheless, for each region, there is one policy regime which is more beneficial than all others.

In contrast to previous policy regime analyses (e.g., [10, 38]) and in following actual discussions on the possibility of very low stabilization, this analysis considers more advanced stabilization targets and provides new technology scenarios. It comes up with a much broader variation of regional mitigation costs based on a detailed description of the regional energy systems and trade linkages.

In Section 2, we present the model REMIND-R and discuss its components in some detail, including important assumptions and empirical foundation. Results from REMIND-R simulations for a reference (i.e., business-as-usual) scenario are given in Section 3. The main focus of the paper is on the analysis of climate policy scenarios, which are presented in Section 4. Section 5 shall provide some conclusions.

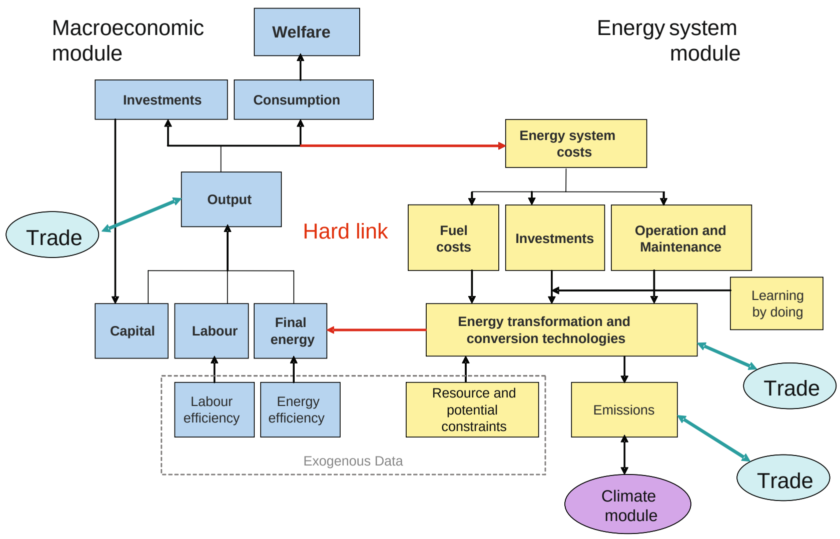


Fig. 1 Structure of REMIND-R

2 Model Description REMIND-R

REMIND-R is a novel multi-regional hybrid model, which couples an economic growth model with a detailed energy system model and a simple climate model (see Fig. 1). The individual regions are coupled by means of a trade module. Only a few other hybrid models exist that are based on economic growth models—MERGE, Imaclim-R, and WITCH are the most well-known. With MERGE and WITCH, REMIND-R shares the same intertemporal structure, but is distinguished from both by a higher degree of technological resolution in the energy sector. This feature expands the range of mitigation options, which are mainly based on a switch between energy technologies, and compensates for a restricted representation of technological learning. Whereas WITCH is more elaborated in modeling R&D investments and knowledge spillovers, REMIND-R is more advanced in addressing trade issues. Moreover, the model has no exogenous restrictions that provide maximum growth rates or maximum shares in the energy mix for energy sources or technologies. Such restrictions of the solution space can quite often be found in energy system modeling but are not justified from our point of view. Each restriction can be surmounted by innovation and investment.

A complete technical description of REMIND-R is beyond the scope of this paper. We restrict ourselves to just a few equations within this section. For a detailed documentation, we refer to our web site.[1]

The applied version—REMIND-R 1.0—includes nine world regions:

1. UCA—USA, Canada, Australia
2. EUR—EU27
3. JAP—Japan
4. CHN—China
5. IND—India
6. RUS—Russia
7. AFR—Sub-Saharan Africa (including Republic of South Africa)
8. MEA—Middle East and North Africa
9. ROW—Rest of the world (including Latin America, Pacific Asia, and the rest of Europe)

The population development of all regions follows an exogenous population scenario [39]. World population grows from 6.6 billion in 2005 to 9.0 and 10.0 billion in 2050 and 2100, respectively.

2.1 Macro-economy Module

The world-economic dynamics over the time horizon 2005 to 2100 is simulated by means of the macro-economy module in REMIND-R. The time step is 5 years. Each region is modeled as a representative household with a utility function $U(r)$ that depends upon the per capita consumption. With assuming the intertemporal elasticity of substitution of per capita consumption to be close to one, it holds:

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

$C(t,r)$ represents consumption in time-step t and region r, $L(t,r)$ represents labor (equivalent to population), and ζ represents the pure rate of time preference.[2] It is the objective of REMIND-R to maximise global welfare W that results as a weighted sum of the regional utility functions:

$$W = \sum_{r} (w(r) \cdot U(r)). \quad (2)$$

REMIND-R is run in the cost-effectiveness mode when it is used for climate policy simulations, i.e., climate policy targets are integrated into the model by an additional constraint (e.g., upper bound for temperature increase).

Marco-economic output, i.e., GDP, is determined by a "constant elasticity of substitution" (CES) function of the production factors labor, capital, and end-use energy. End-use energy is the outcome of a nested tree with additional CES production functions (see Fig. 2). Each production function calculates the amount of output (intermediate outputs and GDP), $V(t,r,v_{\text{out}})$, from the associated factor input amounts $V(t,r,v_{\text{in}})$ according to the following quantities:

- Parameter $\rho(r, v_{\text{out}})$: ρ is calculated from the elasticity of substitution[3] σ according to the relation

  $$\sigma = \frac{1}{1-\rho}$$

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

[2]We assume a pure rate of time preference of 3% for the simulation experiments presented in later sections.

[3]The assumed values for the substitution elasticities (see Fig. 2) are comparable to the values assumed by [13, p. 49]. Regarding the nesting structure of the energy composite, we tried to replicate the basic structure of energy system services composed of mobile and stationary energy uses. Both are combined by a very low elasticity of substitution.

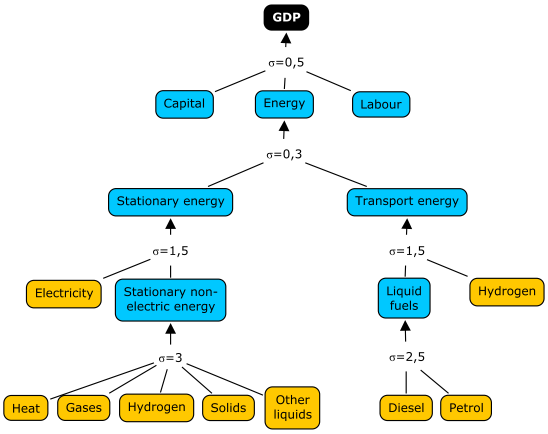


Fig. 2 CES production structure in the macro-economy module

- Efficiency parameter $A(t, r, v_{\text{in}})$: It is calculated as the product of an calibration-based initial value and a time-dependent growth rate parameter.

It holds:

$$V(t, r, v_{\text{out}}) = \left(\sum_{M_{\text{CES}}} (A(t, r, v_{\text{in}}) \cdot V(t, r, v_{\text{in}}))^{\rho(r, v_{\text{out}})} \right)^{1/\rho(r, v_{\text{out}})} \quad \forall\, t, r, v_{\text{out}}. \tag{3}$$

The list M_{CES} assigns the correct input types v_{in} to each output v_{out}.

The produced GDP of a region is used for the regional consumption $C(t, r)$, investments into the macroeconomic capital stock, $I(t, r)$, all expenditures in the energy system, and for the export of the composite good X_G. Energy system costs consist of fuel costs $G_F(t, r)$, investment costs $G_I(t, r)$, and operation and maintenance costs $G_O(t, r)$. Imports of the composite good M_G increase the disposable gross product. This yields the following macroeconomic balance equation:

$$Y(t, r) - X_G(t, r) + M_G(t, r) \geq C(t, r) + I(t, r) + G_F(t, r) + G_I(t, r) + G_O(t, r) \quad \forall\, t, r. \tag{4}$$

Macroeconomic investments enter a conventional capital stock equation. Changes in the efficiency $A(t, r, v_{\text{in}})$ of the individual production factors are given by exogenous scenarios. For all energy production factors, efficiency change rates are defined in relation to labor productivity changes, assuming, e.g., that efficiency improvement for the production factors hydrogen and electricity is higher than labor productivity growth, but for solids and heat, it is lower. The rate of labor productivity change itself is based on a time profile that starts on a level that is in accordance with empirical data [32] and ends at a predefined level, which amounts to 1.2% for the developed world regions, 2.0% for China, Russia, and ROW, and 2.5% for Africa, India, and MEA. The transition from the initial to the final growth rate level also differs between regions. The resulting pattern of economic growth (see Fig. 4 in Section 3) resembles that found in the literature (e.g., [14, p. 868]; [33, p. 901]). It is characterized by decreasing growth rates and gradual convergence of per capita incomes.

2.2 Energy System Module

The energy system module (ESM) of REMIND-R comprises detailed technical and economic aspects of energy transformation. It is based on the energy system structure as it is designed for the single-region model REMIND-G. The ESM depends, on the one hand, on the macroeconomic output, which is used for financing investments into energy transformation capacities, fuel costs spendings, and expenditures for operation and maintenance (see Eq. 4). It provides, on the other hand, final energy $P_f(t, r, e_s, e_f, c)$ that is used in the macroeconomy:

$$V(t, r, e_f) = \sum_{M_{s \to f}} P_f(t, r, e_s, e_f, c) \quad \forall\, t, r, e_f. \tag{5}$$

The list $M_{s \to f}$ describes the possible combinations of secondary energy types e_s, final energy types e_f, and technologies c. Similar energy balances that equate production and demand exist for primary and secondary energy. Leontief-type technologies with efficiency parameter η

$$\sum_d \eta(t, r, c, d) \cdot D_p(t, r, e_p, e_s, c, d) = P_s(t, r, e_p, e_s, c) \quad \forall\, t, r, e_p, e_s, c \tag{6}$$

transform primary energy D_p into secondary energy P_s based on different vintages d. Analog equations apply for the transformation of secondary energy into secondary energy of higher value and of secondary into final energy. More than 50 different transformation technologies are represented in the ESM (see Table 1 for an overview on primary-energy-transforming technologies). Technologies are bound to capacities, which constrain the production potential. New capacities can be built up by investments. The efficiency of some technologies is assumed to increase over time, but only for new vintages.

Multiple primary energy sources are available in the ESM. There are renewable primary energy sources that can be used in each period without changing the costs of utilization in subsequent periods. However, they cannot be used unboundedly. Region-specific and energy source-specific potentials are defined here. In addition, the potentials are classified into different grades, which, as a result of optimization, leads to a gradual extension of the use of renewable energy sources.

Besides, there are exhaustible primary energy sources where the costs rise with increasing cumulative extraction region-specifically and energy source-specifically. Our assumption on the scarcity of exhaustible resources is based on data from ENERDATA.[4] Figure 3 shows the reserves of exhaustible primary energy carriers differentiated by energy sources and regions. Table 2 shows the cost parameters for the exhaustible resources. For all regions and energy types, the respective extraction curve starts at the initial extraction costs. The extraction costs at reserve limit are exactly met, when extraction reaches the reserve limit. The initial extraction costs and those at the reserve margin are connected by a quadratically increasing function. Extraction of the primary energy types beyond the reserve limit can be extended, but the extraction costs continue to follow the quadratic increase. The assumptions on extraction costs of fossil resources are at the bottom edge of estimations to be found in the literature (e.g., [34]).

As for exhaustible primary energy sources, the use of fossil energy leads to CO_2 emissions, while the application of carbon capture technologies can contribute to a strong decrease of CO_2 emissions. 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. However, space in geological formations is generously measured for all regions. There is leakage in the process of capturing, but by assumption, no leakage occurs from sequestered CO_2. Transformation technologies that use biomass

[4]Most recent data are available on http://www.enerdata.fr/enerdatauk/index.html.

Table 1 Overview on primary and secondary energy carriers and the available conversion technologies

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

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

[a]This technology is also available with carbon capture and sequestration (CCS)

[b]This technology is characterized by endogenous technological learning

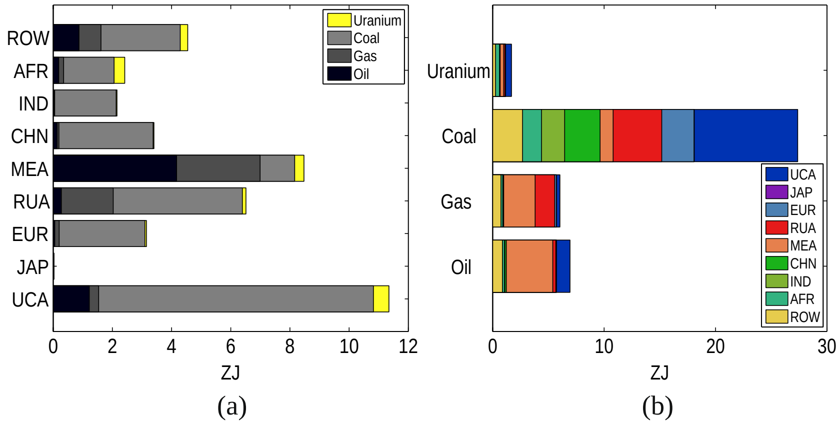


Fig. 3 Overview on reserves of exhaustible primary energy carriers. **a** Countries. **b** Energy carriers. Source: ENERDATA

Table 2 Overview on cost parameters of exhaustible primary energy carriers

	Coal	Oil	Natural gas	Uranium
Initial extraction costs [$US per GJ]	1.5	3.5	3.5	$30\,\frac{\$US}{kg}$
Extraction costs at reserve limit [$US per GJ]	3.5	6	6	$80\,\frac{\$US}{kg}$

can also be complemented by CO_2 capturing provided that they are used to produce fuels or hydrogen. It is assumed that the production potentials for biomass will increase until 2050 to around 200 EJ, where the long-term potential is reached. All these assumptions demand for sensitivity analyses as part of future research.

The investment costs for each technology are the same in each region, with the exception of two learning technologies, which are characterized by the fact that their investment costs decrease by a certain percentage (the learning rate) with each doubling of the cumulated regional capacities. We assume learning rates of 10% and 20% for the wind turbine and the solar photovoltaics technology, respectively.

When transforming secondary energy into final energy carriers, real transformation options are of lesser interest, but the distribution infrastructure is of particular importance. Except for hydrogen, which can be used for transportation and stationary energy, each secondary energy source will be transformed into exactly one final energy carrier. Losses that occur in the distribution of secondary energy are estimated based on statistical data differentiated by region. In modeling the transport sector, the current model version does not take the use of electricity into account.

2.3 Trade Module

The model REMIND-R calculates a pareto-optimal solution that corresponds with a global planner solution and/or a cooperative solution[5]. With this approach, it is guaranteed that the necessary emission reductions are carried out cost-efficiently and that all trade interactions are directed at increasing welfare in general and lowering mitigation costs in particular.

Trade is modeled in the following goods:

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

With $X_j(t,r)$ and $M_j(t,r)$ as export and import of good j of region r in period t, the following trade balance equation holds:

$$\sum_r (X_j(t,r) - M_j(t,r)) = 0 \quad \forall\, t,\, j. \tag{7}$$

In order to coordinate the export and import decisions of the individual regions, REMIND-R uses the Negishi-approach (cf. [23, 27]). In this iterative approach, the objective functions of the individual regions

[5]In cases without or with internalized externalities (applies to the climate change externality and technological learning), the pareto-optimal solution computed by REMIND-R corresponds also to a market solution.

are merged to a global objective function by means of welfare weights w (cf. Eq. 2).

A particular pareto-optimal solution can be obtained by adjusting the welfare weights according to the intertemporal trade balances $B^i(r)$:

$$B^i(r) = \sum_t \sum_j \left(p^i_j(t) \cdot [X^i_j(t,r) - M^i_j(t,r)] \right) \quad \forall\, r, i \tag{8}$$

$$w^{i+1}(r) = f(w^i, B^i(r)) \quad \forall\, r, i, \tag{9}$$

where i represents the iteration index, which is skipped from the equations above and $p^i_j(t)$ represents world market prices derived as shadow prices from Eq. 7. The higher the intertemporal trade balance deficit of a region, the more the welfare weight of this region needs be lowered. A lower weight has the result that goods exports into this region contribute less but exports from this region contribute more to the global welfare function. This mechanism ensures that regions reduce their intertemporal trade balance deficits.

With the new set of weights, we compute a new solution from which we derive $B^{i+1}(r)$. The welfare weights are iteratively adjusted in a way such that

$$\sum_r \mid B^{i+1}(r) \mid \; < \; \sum_r \mid B^i(r) \mid \quad \forall\, i \tag{10}$$

and

$$\lim_{i \to \infty} B^i(r) = 0 \quad \forall\, r, \tag{11}$$

i.e., the intertemporal trade balance converges to zero for each region.

The trade pattern that will result from model runs is highly impacted by the intertemporal trade balance constraint. Each export of composite goods qualifies the exporting region for a future import (of the same present value), but implies for the current period a loss of consumption. Trade with emission permits works similarly to goods trade. Emission rights are distributed free of charge in the different policy regimes according to different allocation rules. The revenues from the sale of emission rights prove completely advantageous for the selling regions in the way that it generates entitlements for future re-exports of permits or goods. Each unit of CO_2 emitted by combusting fossil fuels $E(t,r,c)$ using technology c needs to be covered by emission certificates (either allocated $Q(t,r)$ net of exports $X_P(t,r)$ or imported $M_P(t,r)$):

$$\sum_c E(t,r,c) \leq Q(t,r) - X_P(t,r) + M_P(t,r) \quad \forall\, t, r. \tag{12}$$

In REMIND-R, trade in financial assets, represented by trade in the composite good, guarantees an intertemporal and interregional equilibrium. The carbon price and the interest rate can be viewed as the outcome of speculation in forward-looking asset markets. Models omitting trade in financial assets cannot derive a full intertemporal equilibrium in capital and simultaneously in other markets. In many energy–economy–climate models, trade in permits is the only feature of international trade. Welfare improvements by the reallocation of capital or the reallocation of mitigation efforts over regions or time are possible in these models when intertemporal efficiency is violated. In contrast to this model design, REMIND-R derives a benchmark for a first-best intertemporal optimum in all markets.

2.4 Climate Module

Within the REMIND-R framework, the climate module is represented as a set of equations that restrict the welfare optimization. This version of REMIND-R integrates a simple climate model [31]. For basic model equations, as well as for parameter values and initial values, see [21].

The climate module considers the impact of greenhouse gas emissions and sulphate aerosols on the level of global mean temperature. The emission of sulphates is directly linked to the combustion of fossil fuels in the energy sector. The radiative forcing of both the non-CO_2 greenhouse gases and the CO_2 emissions from land use change is taken into account by exogenous scenarios. The former follows the SRES B2-scenario (model AIM) and the latter combines the same scenario type with the additional assumption of frozen CH_4 and N_2O emissions after 2005. The climate sensitivity—as the most important parameter of the climate module—is set to 2.8°C. In Section 4.6, we briefly discuss the sensitivity of mitigation policies on this parameter.

3 Reference Scenario

In the reference scenario ("business-as-usual" scenario), we simulate a development as if climate change has no economically and socially important effects. The

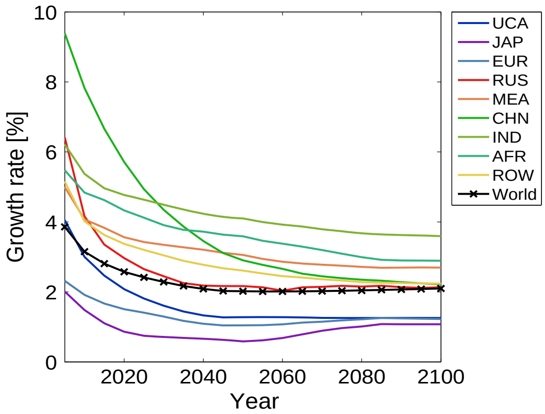


Fig. 4 GDP growth rate

world-wide GDP of about 47 trillion \$US[6] in 2005 will increase to 412 trillion \$US in 2100. Figure 4 shows the growth rates of the GDP for each region. China starts with a very high growth rate of 9.3%, which will, however, decrease to 2.2% until 2100. India and Africa have the largest growth rates of approximately 3.6% and 2.9% at the end of the century, whereas the regions UCA and EUR have a growth rate of 1.2%. While the relative gap between poor and rich regions is becoming shorter, significant differences in the per capita income still exist in 2100.

The development of the energy system is shown in Fig. 5. The primary energy consumption[7] is increasing continuously in the next hundred years from almost 470 EJ in 2005 to more than 1,400 EJ in 2100. A weakening annual increase in primary energy consumption is due to the population scenario, the decreasing growth of demand in the developed countries, and the increasing cost of fossil energy sources.

The primary energy mix remains mostly based on fossil energy sources. Whereas the use of oil and gas remains almost constant, the use of coal is strongly increasing.

The economic attractiveness of coal is due to its lower costs, the assumptions of flexible trade, and that the use of coal is not subject to any regulations. There is, however, a continuous increase of extraction costs which, around the middle of the century, makes the use of other energy sources competitive. Hydro energy and especially wind energy will increasingly be used. The use of biomass will also increase after 2030, which is due to its increasing availability. Solar energy sources are not employed in the reference scenario; nuclear energy will be used as a considerable supplement for coal at the end of the century. However, as extraction costs of uranium increase quickly, coal consumption is increasing again at the end of the century. Actually, on the regional level, there is a permanent increase in the use of coal in several developing countries, while there is a cutback of coal consumption in the middle of the century and a stabilization on a lower level afterwards in all industrialized countries.

Figure 5b shows which secondary energy sources are produced. The secondary energy production will increase to around 900 EJ in 2100; the share of electricity in particular will increase from roughly 19% to 44%. In contrast, the use of the low-value energy sources "solids" and "other liquids" will decrease.

From the analysis so far, it inevitably results that there will be an increase of emissions. This is mostly due to the conversion of coal into electricity. The world-wide emissions amount to approximately 21 GtC (76 Gt CO_2) in 2100 (see Fig. 6). The increase of emissions is quite high in the early decades—with a doubling of the emissions between 2005 and 2025. The temporary decrease of the emissions around 2060 accompanies the interim reduction of the use of coal. In 2100, approx. 75% of the emissions in the energy sector originate from the combustion of coal. Shares of approx. 15% and 10% are allotted to oil and gas, respectively.

Large regional differences in the per capita emissions can be observed. While the industrialized countries increase their per capita emissions until 2025 and keep them on a high level (5–9 tC per year) thereafter, they rise to approx. 2–3 tC in China, India, and MEA. Africa remains on a consistently low level with less than 1 tC per capita.

4 Model Analysis of Climate Policy Regimes

4.1 Description of the Policy Regimes

The following analyses are based on the 2°C EU climate policy target. While assuming a cooperative world, within each policy scenario, a global emission path has to be determined that meets the 2°C target. Within REMIND-R, the energy-related CO_2 emissions are under the control of the decision-maker only. Exogenous scenarios are applied for the development of

[6]Throughout this report, all relevant economic figures (e.g., GDP) are measured in constant international \$US 2003 (market exchange rate).

[7]The primary energy consumption of the renewable energy sources wind, solar, and hydro power is put on the same level as the related secondary energy production.

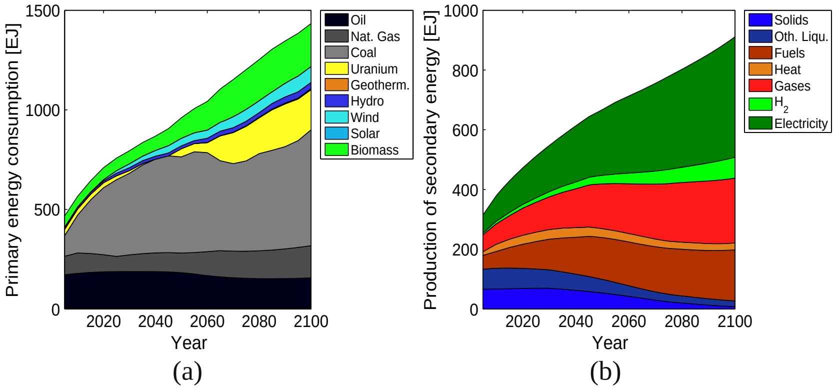


Fig. 5 Global consumption of primary and production of secondary energy sources in the reference scenario. **a** Primary energy. **b** Secondary energy

other greenhouse gas emissions. In the current model setting, drastic emission reductions would have been provided by the energy sector. While particular technologies generate negative emissions (e.g., the use of biomass in combination with CCS), we assume that, on a regional level, emissions are positive. Global energy-related CO_2 emissions have to be reduced by 50% until 2035. The atmospheric CO_2 concentration reaches its maximum at around 415 ppm in 2030.

In the analysis of how and at which costs such a reduction path can be achieved, we investigate three different designs of an international cap and trade system (cf. [16]). In such a system, tradable emission rights will be allocated to the individual regions as of 2010. The endogenously determined global emission reduction path represents the world-wide available amount of emission rights.

4.1.1 Contraction and Convergence (Policy Scenario A)

As of 2050, the same per capita emission rights are allocated in this scenario. By determining these allocations between 2010 and 2050, there is a smooth transition of the regional shares between grandfathering and equal per capita emissions. 2000 is assumed to become the reference year for grandfathering.

4.1.2 Intensity Target (Policy Scenario B)

In this policy scenario, the shares of the regions on the globally available emission rights correspond to their shares in the world-wide gross product, i.e., each region receives the same emission rights per unit GDP. In this policy scenario, the developed countries are apparently provided with more emission rights than in the other two policy scenarios.

4.1.3 Multi-stage Approach (Policy Scenario C)

We selected a form of multi-stage approach in which the quantitative reduction obligations of the individual regions depend upon their per capita incomes. The following four stages are distinguished:

1st stage:	up to 2,000 $US per capita and year
2nd stage:	up to 4,000 $US per capita and year
3rd stage:	up to 8,000 $US per capita and year
4th stage:	more than 8,000 $US per capita and year

Regions of the first stage are practically not obliged to any reductions. They can, however, participate in the emission trade and will be provided with certificates to the amount of their reference case emissions. This is in contrast to alternative definitions of the multi-stage approach (cf. [10]). Regions of the second stage will be provided with emission rights to the amount of

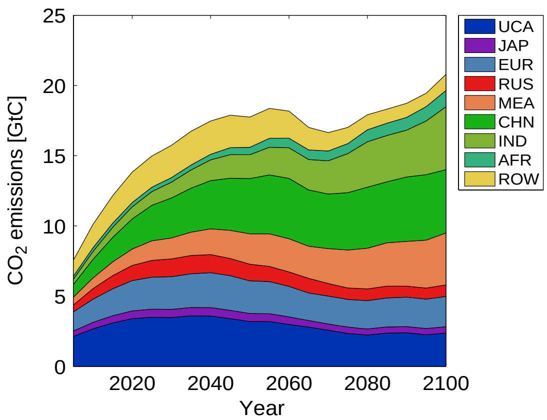


Fig. 6 World-wide emissions (energy-related) in the reference scenario

0.15 GtC per one trillion $US gross product (GDP). Since a growth of the GDP can be expected as a rule, this stage comprehends an increase of emission rights for the respective regions. Regions of the third stage are obliged to stabilize their emissions, i.e., the certificate amount last allocated in stage 2 is frozen on its level. Regions of the fourth stage have to contribute significantly to the emissions reduction. Their share of emission rights results from deducting the number of certificates used for the regions of stages 1 to 3 from the global amount of certificates. The internal allocation between the regions of stage 4 again follows the above-described contraction and convergence approach.

In the base year, the industrial countries UCA, EUR, and Japan are in stage 4. They are presumably quite promptly followed by Russia and China, while China is initially only in stage 2. MEA is initially also in stage 2, ROW is in stage 3, and India and Africa are in stage 1.

4.2 Technology Development and Mitigation Strategies

Drastic changes in the energy system are induced by climate policy. The fundamental changes compared to the reference scenario can be summarized in five options for action:

1. Reduction of the entire energy consumption
2. Immediate expansion of renewable energy technologies for the production of high-value energy sources; expansion of nuclear energy
3. Application of CO_2 capturing and sequestration (CCS) for the conversion of gas and coal into electricity, as well as biomass into hydrogen and fuels
4. Reducing the production of fuels and gases, since technical mitigation options are less efficient here
5. Reducing the production of low-value energy sources solids and other liquids

The technological development is the same in all policy scenarios. This is due to the separability of efficiency and distribution, which applies to models of the general equilibrium type in the absence of market imperfections. This separability can be derived from the Second Fundamental Theorem of Welfare Economics (cf. [28, p. 522]) or for the case of externalities from the Coase Theorem (cf. [35]). In general, there exists a market price and a trade opportunity that provide an efficient outcome no matter how the property rights are allocated. In our case, due to emissions trading, all regions will be enabled to follow a unique region-specific optimal technological development path. We renounce to present repeatedly similar development patterns and focus on the results from policy scenario A. This also applies for the trade patterns in the next section.

Figure 7 shows the global consumption of primary and the production of secondary energy. Both will be reduced in relation to the reference scenario. The primary energy consumption reaches approx. 1,250 EJ at the end of the century, whereas 1,430 EJ was reached in the reference scenario. Secondary energy production increases to roughly 770 EJ in 2100 compared to around 910 EJ in the reference scenario. The most obvious change in the primary energy mix (compared to the reference scenario) is the strong restriction in the use of fossil energy sources and the stronger and earlier expansion in the use of renewable energy sources and nuclear energy. As of 2040, solar energy will also play a role now. The increase of coal consumption in the second half of the century is based on the use of CCS technologies.

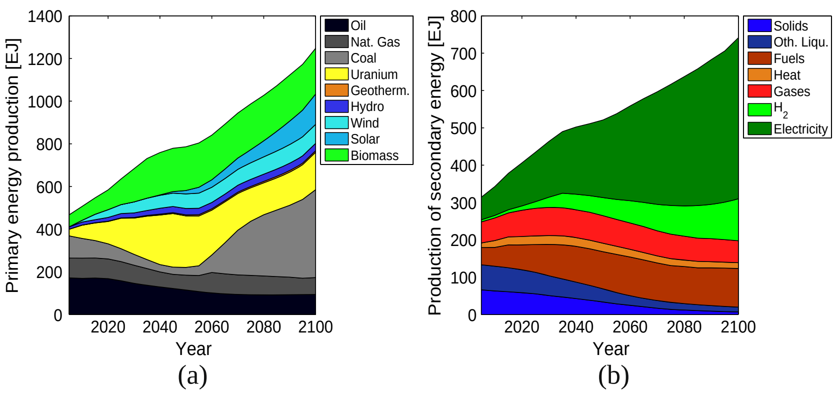


Fig. 7 Global consumption of primary and production of secondary energy sources in policy scenario A. **a** Primary energy. **b** Secondary energy

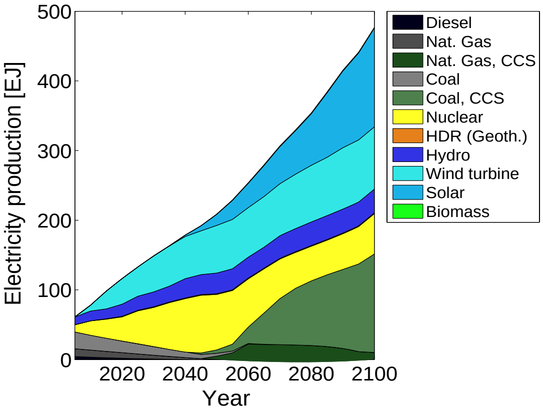


Fig. 8 Global electricity production in policy scenario A

Solids and other liquids will already have been taken out in secondary energy production. Gas, heat, and fuels will be produced to a minor degree. The production of hydrogen and electricity, however, will even increase compared to the reference scenario. Electricity production will reach 480 EJ in 2100. Similar results can be found in [40, p. 514]. The energy mix in global power generation is shown in Fig. 8. Wind and nuclear technologies are dominating in the mid term, while the CCS technology options and renewable energies (in particular solar energy) are dominating in the long run.

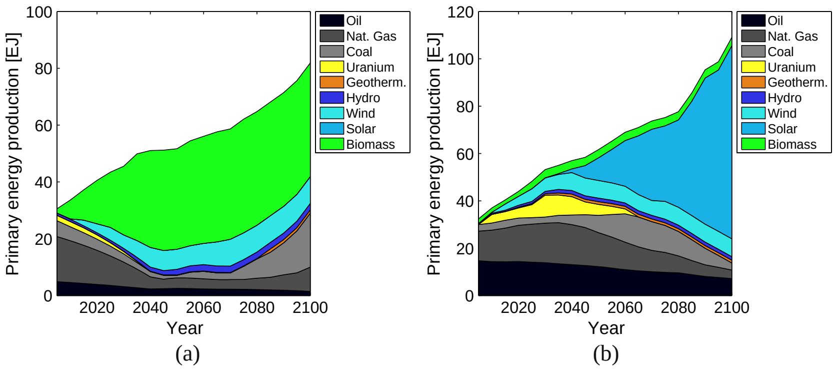
When focussing on the regional energy strategies, it turns out that, in the short term, the increase in primary energy consumption is lower in the developed regions, and it is even followed by a decrease in Japan and EUR. The developed regions have in common that the share of fossil fuels is decreasing in the first half of the century, while the share of renewables and nuclear energy increases. While Japan relies on nuclear energy, UCA substitutes nuclear energy technologies as of 2050 by converting coal into electricity with CO_2 capturing. The decrease in the consumption of oil and natural gas can partially be compensated in the developed regions by the use of biomass. This is especially obvious in UCA.

While there are some differences in the energy mix of the developed regions, differences are more pronounced when comparing China and India on the one side and Russia, Africa, ROW, and MEA on the other side. The latter have high potentials in renewable energy sources that they are going to exploit to a high degree. The largest deviation from the global pattern of energy consumption can be observed for Russia and MEA (see Fig. 9). MEA will employ its huge potential of solar energy. Russia has high potentials in biomass, which actually allows them to discontinue the use of natural gas and to export it instead. Biomass is also the dominating primary energy source in Africa.

The development of the energy mix in China and India resembles the global pattern by using nuclear energy technologies and CO_2 capturing in coal-fired power plants. CO_2 capturing will, in addition, already be used in gas-fired power plants as of 2040 in China. Substantial shares of necessary gas and coal resources will be imported.

On a regional level, results on technological development cannot be compared because there is hardly any literature that provides insights in this detail. Nevertheless, the huge differences in the regional energy mixes are quite remarkable. Results on technological development on a regional level are, in general, less robust than those on the global level. Shifts in resource trade patterns might change the energy mix (in particular in resource-importing regions) without a significant change in regional welfare. If comparing the results on

Fig. 9 Regional primary energy consumption in policy scenario A. **a** RUS. **b** MEA



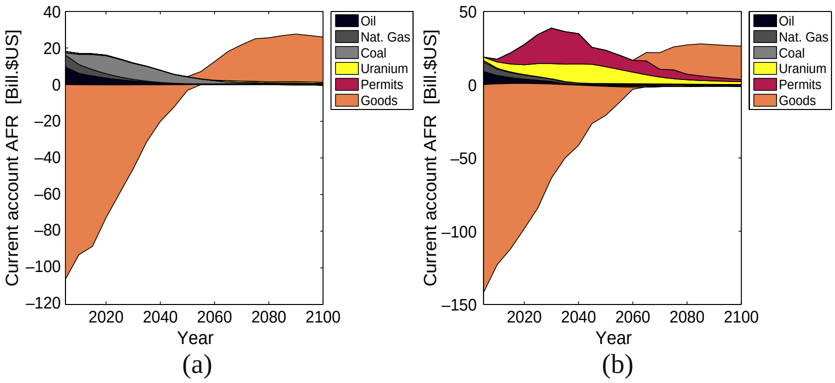


Fig. 10 Current account in Africa. **a** Reference scenario. **b** Policy scenario A

a global level, taking model results from the Innovation Modeling Comparison Project [7] as benchmark, the total energy consumption is in line with MESSAGE results. Like MESSAGE, REMIND-R simulates less reduction of energy consumption in the policy scenario compared to the reference scenario than most other models. While the share of renewables is comparable with the share simulated by other models, the high share of biomass is striking. This applies even in the reference scenario and results from the representation of second generation biomass technologies based on the most recent findings (e.g., [15, 37]). While there are plenty of options to decarbonize the production of electricity, few options exist for the production of fuels and gases. Biomass becomes a serious alternative in this field. Furthermore, REMIND-R exhibits higher shares of nuclear in the short to mid term and of coal (combined with CCS) in the long term. Gas and oil are, however, used less compared to most of the other models of the Comparison Project.

4.3 Trade

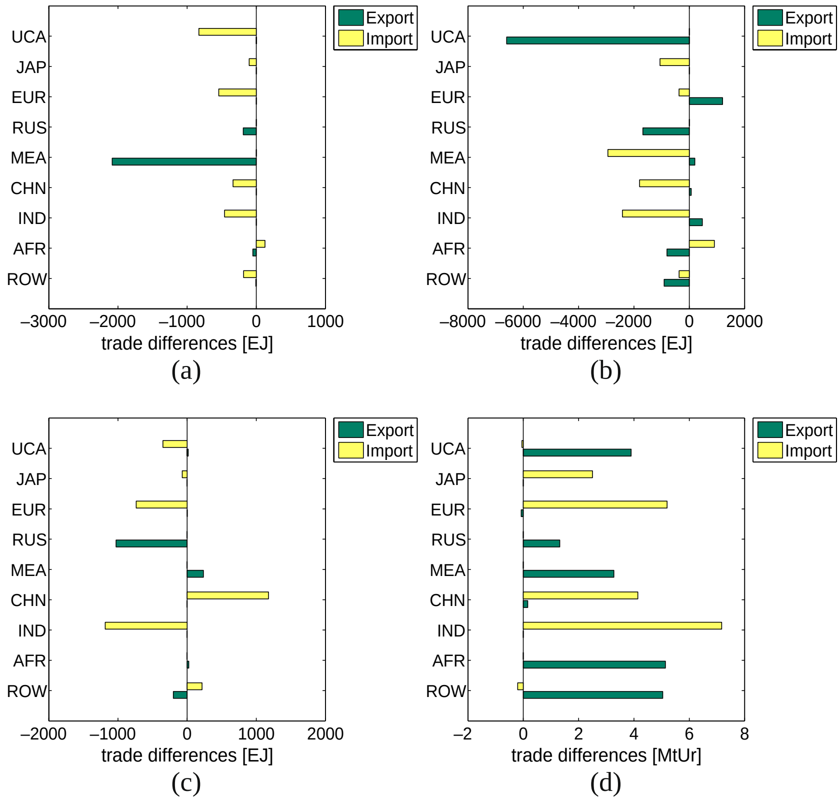
The overall trade structure changes only slightly compared to the reference development in all regions. However, significant changes occur on the energy resource market and the carbon market.

The developed countries use the option of emissions trade and buy permits in considerable amounts. This import, however, is, on a value basis, hardly visible in the current account. The basis for the current accounts is the present value price of permits, which is in a range between 40$US/tC and 80$US/tC. The nominal values, however, rise quite impressively to a level of more than 500$US/tC in 2050 and even more than 6,000$US/tC in 2100.[8] This indicates a very restrictive carbon constraint. The macroeconomic effect of emissions trading is slightly higher for the big sellers of emission rights—ROW and, above all, Africa. This is indicated by Fig. 10, which compares the current accounts of Africa in the reference scenario and the policy scenario A. In return to the sale of permits, the import of goods is expanded in Africa. In addition, Africa produces significant export revenues from the trade of uranium. In contrast to the prices of fossil fuels, the price of uranium increases in the policy scenario compared to the reference scenario (by more than 200% even in the short run).

In Fig. 11, resource trade differences (in physical units cumulated over the century) between the policy scenario and the reference scenario are shown. Negative values represent less trade (either imports or exports) in the policy scenario. In general, trade in fossil resources decreases and trade in uranium increases. Trade with oil decreases significantly (up to more than 30 EJ per year in 2050). Major importers like UCA, EUR, China, and India reduce their demands to the account of MEA's exports. Likewise, the trade of coal is substantially reduced. In the reference scenario, coal trade increases quickly. As of 2040, trade volumes in the coal market are even higher than in the oil market. In contrast, there is no increase at all in coal trade in the policy scenario until 2050. Exports from UCA decrease drastically, while China, the major coal importer, shifts some parts of its imports into the second half of the

[8]While for the year 2050, the carbon price here is of the same order of magnitude as the carbon prices simulated for the less ambitious 450 ppm CO_2 stabilization scenario within the Innovation Modeling Comparison Project (cf. [7, p. 96]), it is significantly higher for the year 2100.

Fig. 11 Differences in trade between policy scenario A and reference scenario. **a** Oil. **b** Coal. **c** Gas. **d** Uranium



century. The diffusion of CCS technologies in the policy scenario revitalizes the use and the international trade of coal as of 2050.

Due to the better CO_2 balance, compared to the other fossil energy sources, the short-term downturn and the overall decrease is significantly smaller in the trade of gas. However, major shifts in the regional shares can be found in the gas market. EUR, UCA, and, above all, India import less, while China increases its imports substantially in the long run. The overall net reduction in gas trading is at the expense of Russia. MEA exports less in the mid term but more in the long term.

In line with demand changes on the resource markets, we see changes in prices. The oil price in the policy scenario is significantly lower than in the reference scenario (see Fig. 12). The difference is somewhat lower for gas and somewhat higher for coal, while the price difference is reversed for uranium.

Worsened terms-of-trade can clearly be expected for the exporters of fossil fuels—MEA, UCA, and Russia. Less export revenues have to be compensated by less imports of goods, which limits consumption. MEA and Russia are probably more strongly affected than UCA, as resource exports bear a higher share in their current accounts.

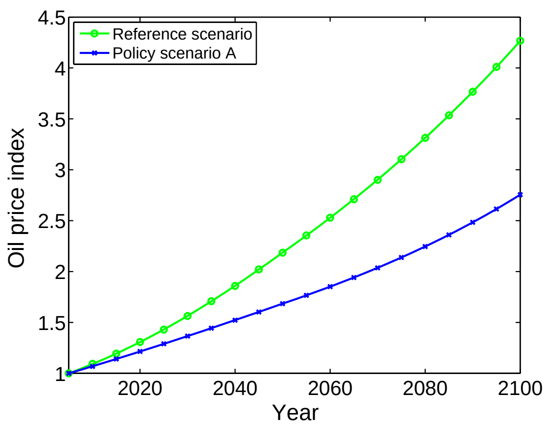


Fig. 12 Oil price index in the reference and policy scenario A ($2005 = 1$)

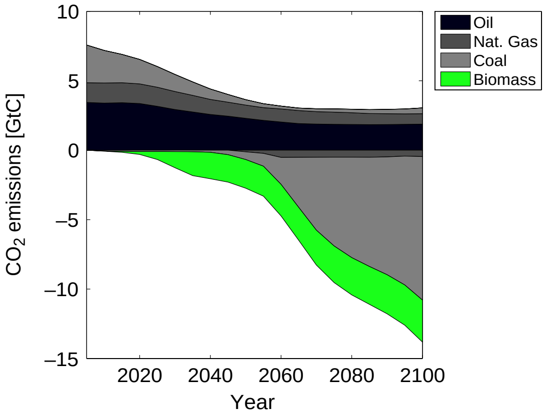


Fig. 13 CO_2 emissions in policy scenario A differentiated by the use of primary energy sources

Gains and losses from emissions trading, changes in the energy resource market, and price-induced terms-of-trade effects have a substantial impact on the mitigation costs (see Subsection 4.5). In contrast to the effects from emissions trading, changes in the resource market represent first-order impacts that depend on the stabilization target but not on the allocation of permits.

4.4 Emissions and Emissions Trading

The pursued stabilization scenario requires a fast and drastic decrease of emissions. Figure 13 shows (exemplarily for policy scenario A) the emissions on the positive side and CO_2 capturing on the negative side. It can quickly be seen that the share of oil in the entire remaining emissions is highest. Total emissions from fossil fuels stay above 3 GtC until the end of the century. Most of these emissions are neutralized by CCS technologies in combination with the use of biomass (green area in Fig. 13). The emissions are most rapidly decreasing in electricity production. In this area, a lot of CO_2 capturing is done, especially when using coal. More than 10 GtC would be captured in 2100.

4.4.1 Contraction and Convergence (Policy Scenario A)

Figure 14a shows the permit allocation. The global sum corresponds to the global emission trajectory. Reductions are most drastic between 2025 and 2050. The permit share of the developing world regions and ROW increases drastically. In the case of a missing emissions trading market, the industrialized world regions would need to decrease their per capita emissions to around 5% of today's level by 2050, MEA, China, and ROW to 20–25%, while India and Africa could still increase their per capita emissions. For both regions, it is, however, obviously more favorable not to increase their own emissions but to sell the allocated emission rights profitably. Taking emissions trading into consideration, the reductions are lower in the developed regions. The respective per capita emissions would need to be reduced by approx. 20–35% in 2025 and by approx. 70–80% in 2050. Moreover, all regions need to reach per capita emissions of less than 1.2 tC per year in 2050, and even less than 0.2 tC in 2100.

The trade of emissions as presented in Fig. 14b divides the big sellers (ROW, India, China, and Africa) and the big buyers (EUR, UCA, and MEA). Initially, permit trading is concentrated on China, ROW, EUR, and UCA. The entire trade volume increases to more than 1.4 GtC until 2040 and decreases then to approx.

Fig. 14 Permit allocation and permit trade in policy scenario A differentiated by regions. **a** Permit allocation. **b** Permit trade

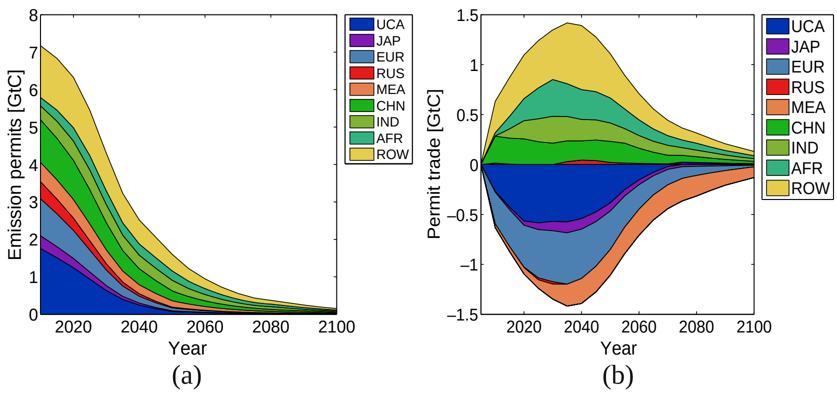
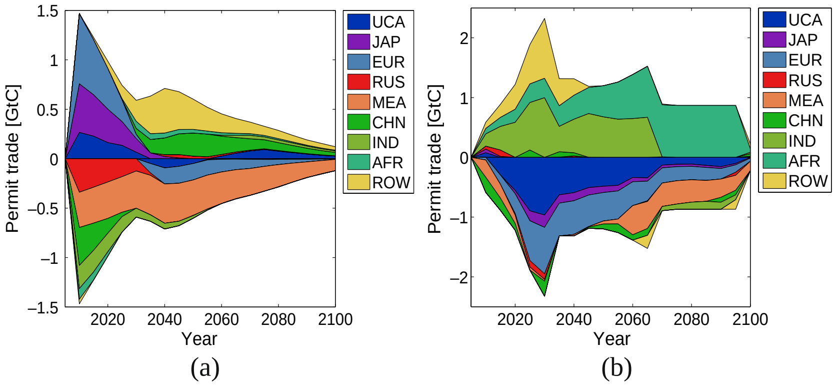


Fig. 15 Permit trade in policy scenarios B and C. **a** Policy scenario B. **b** Policy scenario C



0.15 GtC until 2100. With a permit price of more than 300$US/tC, transfers in the order of nearly 500 billion $US are simulated for the year 2040. As of 2030, the developing regions will sell more than 50% of the emissions rights allocated to them. This share will, in fact, rise up to 100% in Africa, and later, also in India and Russia. The developed regions will increasingly cover their emissions by buying additional emission rights. Already in 2030, in all industrialized countries, more than half of the emissions will be covered by buying additional permits (in UCA even more than 75%). In the second half of the century, this share will even further increase; the world-wide available amount of emission rights, however, will decrease to a level of less than 1 GtC, and thus, the entire trade volume will also decrease.

4.4.2 Policy Scenarios B and C

In contrast to the other policy scenarios, the distribution of emission rights according to GDP enables the industrialized countries not only to reduce the share of imported carbon certificates but even to sell their emission rights in a significant magnitude. Initially, Japan, EUR, and UCA represent big sellers in the permit market (see Fig. 15a). In return, all developing regions (in particular, MEA and China) and Russia are buying permits. MEA remains the largest importer of emission permits, while China and ROW become major sellers of permits in the mid and long terms. The peak in emissions trading of nearly 1.5 GtC already appears in 2010. The yearly trade volume decreases fast to 0.5 GtC in 2030, and thereafter more slowly to 0.15 GtC in 2100.

In policy scenario C, the distribution of roles between emission right purchasers and sellers is similar to policy scenario A. However, there is a considerable shift of shares on the sellers' side. In policy scenario C, China's export shares are negligible. Since Africa will raise its per capita income quite slowly (true for all scenarios), it will not reach the stage where substantial emission reductions will become necessary. This is also true for India until 2070. The resultant amount of emission rights for India and Africa restricts, on the one hand, the allocation of emission rights to other regions and results, on the other hand, in a quasi-monopolistic position of Africa in the sale of emission rights after 2070. In the short to mid term, India dominates the export of emission rights. ROW plays its role as major exporter of permits until 2050 only.

4.5 Mitigation Costs

All policy scenarios pursue the same stabilization target. Regarding ecological efficiency (i.e., its contribution to climate stabilization), they are almost equal. They are also similar with respect to global mitigation costs, which is due to the above-mentioned separability of efficiency and allocation. Global average mitigation costs, measured as consumption losses relating to the reference scenario, are between 1.4% and 1.5%. Global GDP losses are of the same magnitude.[9]

Regional mitigation costs, however, are quite different. Figure 16 provides an overview of the average regional mitigation costs for the three investigated scenarios. Policy scenarios A and C have similar cost structures for UCA, JAP, EUR, MEA, and ROW. While the contraction and convergence scenario is more beneficial for Russia and China, Africa and India benefit significantly from the multi-stage scenario. Policy scenario B has the smallest range in regional mitigation costs. However, at the same time, it is also a scenario of extremes. For many regions, it is either the most

[9] In general, regional GDP losses differ from regional consumption losses. This is due to the effects of international trade.

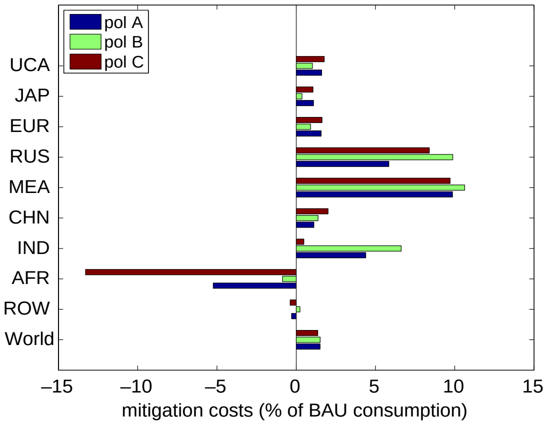


Fig. 16 Average mitigation costs in policy scenarios A, B and C (pol A, pol B and pol C)

favorable or the worst scenario. It is most favorable for industrialized countries. The developing regions, on the other hand, need to bear significant mitigation costs. In the light of the distribution of the historical responsibility for the climate problem, this could be a heavy burden in future climate negotiations.

As a robust result, it turns out that the variance of mitigation costs is higher between the different regions than between the different policy scenarios. Obviously, first-order impacts prevail regardless of the design of the policy regime. MEA has to bear the highest costs in all scenarios (always more than 9%). The reconstruction of the global energy system reduces part of the possible rents of this region, whose revenues are, to a large part, derived from selling fossil resources. This is, in a slightly milder form, also true for Russia (mitigation costs of always more than 5%). For the three developed regions UCA, Japan, and EUR, the costs over the different scenarios develop according to a fixed pattern. The highest mitigation costs among this group can be found in UCA, they are slightly lower in Europe, and they are lowest in Japan. Besides the different base level (highest per capita emissions in UCA), the growth pattern is also reflected in this relation. In general, it holds: the higher economic growth, the higher the mitigation costs. For all three regions, policy scenario B is the most favorable one (average mitigation costs amount to 1% or less). For China, the lowest costs arise in policy scenario A; however, variance of costs between the scenarios is relatively small. The contrary holds for India, where all scenarios but the multi-stage scenario C are quite expensive. Africa benefits in all policy scenarios, most remarkably in the multi-stage scenario (more than 10% consumption gains), which is mainly due to the fact that, for a long time span, Africa is provided with an amount of permits according to its baseline emissions.

The cost differences between the policy scenarios are clearly linked to the transfers on the carbon market. Revenues increase consumption directly, but do not change investment decisions. Emissions trading evens out any changes in relative prices between the different policy scenarios. The fact that mitigation cost differences are relatively low, given the huge differences in permit allocation, may reduce conflicts in the international negotiation process.

4.6 Climate Sensitivity

While a comprehensive sensitivity analysis is beyond the scope of the paper, we provide some additional insights with respect to the impact of the climate sensitivity parameter. This parameter is considered as one of the most uncertain parameters in integrated assessment models. Departing from the default value of 2.8°C, we run model experiments (exemplarly for policy scenario A) by assuming the climate sensitivity to amount to 2.0°C (scenario var 1) and 3.5°C (scenario var 2).

Figure 17 shows the sensitivity of the global emissions on this assumption. Whereas a low climate sensitivity allows emissions to stay above the current level until 2050, a high climate sensitivity demands for a more drastic reduction of emissions than the default policy scenario A (cf. Fig. 14). Within the current setting, REMIND-R is not able to find a feasible solution with a climate sensitivity of 3.6°C and higher. Achieving a feasible solution in some of these cases, which requests for an even faster reduction of CO_2 emissions than in

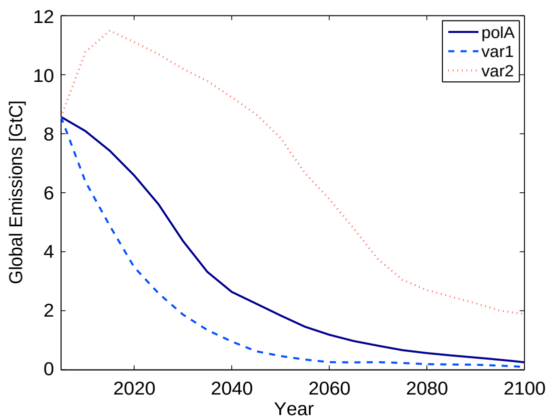


Fig. 17 Global emissions for policy scenario A with different climate sensitivities

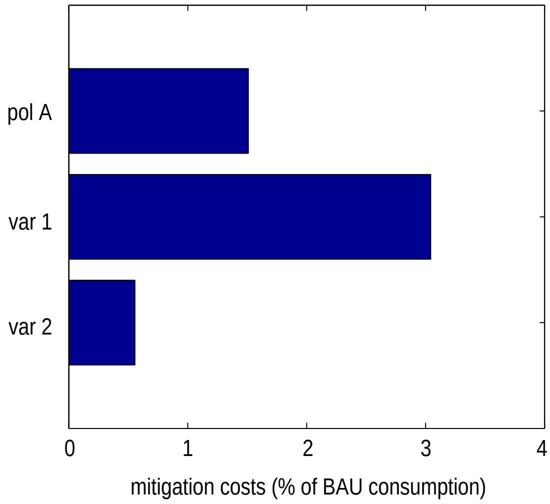


Fig. 18 Average mitigation costs for policy scenario A with different climate sensitivities

scenario var 1, will be possible if we allow for idle capacities and negative emissions.

The drastic emission reduction in the 3.5°C climate sensitivity scenario results in an increasing share of solar energy and a complete fade out of coal technologies—even with the CCS option—due to the remaining emissions. Most significantly, the total amount of primary energy consumption is reduced—on a global level from around 1,250 EJ in 2100 in the default policy scenario A to around 950 EJ in the high climate sensitivity scenario.

The sensitivity of mitigation costs is shown in Fig. 18. Mitigation costs more than halve for the low climate sensitivity scenario and more than double for the high climate sensitivity scenario. Both changes indicate a dominant impact of this parameter. The carbon price increases by an order of magnitude in the high climate sensitivity scenario. This would extremely benefit the permit seller and requests for an additional compensation scheme.

5 Conclusions

This study analyzes climate policy implications in the context of globalization by means of the energy–economy–climate model REMIND-R. In determining regional mitigation costs and the technological development in the energy sector, REMIND-R considers the feedbacks of investment and trade decisions of regions that are linked by global markets. The analyzed policy regimes are primarily differentiated by their allocation of emission rights. Moreover, they represent alternative designs of an international cap and trade system that is geared to meet the 2°C climate target. The following conclusions can be drawn:

- Ambitious climate targets that meet the 2°C climate target with high likelihood can be reached with costs amounting to approx. 1.5% of the global gross product; this roughly confirms cost estimates of low stabilization scenarios from earlier studies based on global models [7]. This number, however, can halve or double within quite a narrow range of climate sensitivity variation.
- The regional burden of emission reductions considerably varies with the particular designs of a post-2012 climate policy regime; however, the variance of mitigation costs between the regions is higher than between the policy regimes.
- Regions with high shares in trade of fossil resources (MEA and Russia) bear the highest costs, while Africa can considerably benefit from an integration into a global emissions trading system.

The present study analyzes ambitious climate protection scenarios that require drastic reduction policies (reductions of 70–80% globally until 2050). Immediate and multilateral action is needed in such scenarios. Given the rather small variance of mitigation costs in major regions like UCA, Europe, MEA, and China, a policy regime should be chosen that provides high incentives to join an international agreement for the remaining regions. From this perspective, either the contraction and convergence scenario (incentive for Russia) or the multi-stage approach (incentive for Africa and India) is preferable.

As usual, all results are only valid within the framework of the assumptions made. In the current context, we in particular assume perfect markets and perfect intertemporal foresight. Both slightly tend to decrease the mitigation costs by optimally investing in most promising long-term mitigation measures based on optimal trade flows. However, for the regions with high shares in resource trade, mitigation costs could be overestimated by the model due to the fact that the reference scenario accounts for too optimistic trade volumes. Trade losses in the fossil-constrained policy scenario rise consequently. Additional experiments furthermore show that, with the assumption of lower fossil resource availability, mitigation costs decrease significantly.

From the analysis of the technology development in the energy sector, it turns out that the regions follow quite different strategies. However, while the mitigation cost estimates are robust against variations of input parameters, the regional energy mix is sensitive. More research is needed to integrate further technologies (e.g., electric vehicles in the transport sector) and to systematically investigate to which degree and which costs major carbon-free technologies can be substituted by each other. First experiments in this direction indicate that doing without nuclear energy is not costly, but forgoing the CCS option will increase the mitigation costs substantially.

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Chapter 4

The REMIND-R Model: The Role of Renewables in the Low-Carbon Transformation *

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The REMIND-R model: the role of renewables in the low-carbon transformation—first-best vs. second-best worlds

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Abstract Can near-term public support of renewable energy technologies contain the increase of mitigation costs due to delays of implementing emission caps at the global level? To answer this question we design a set of first and second best scenarios to analyze the impact of early deployment of renewable energy technologies on welfare and emission timing to achieve atmospheric carbon stabilization by 2100. We use the global multiregional energy–economy–climate hybrid model REMIND-R as a tool for this analysis. An important design feature of the policy scenarios is the timing of climate policy. Immediate climate policy contains the mitigation costs at less than 1% even if the CO_2 concentration target is 410 ppm by 2100. Delayed climate policy increases the costs significantly because the absence of a strong carbon price signal continues the carbon intensive growth path. The additional costs can be decreased by early technology policies supporting renewable energy technologies because emissions grow less, alternative energy technologies are increased in capacity and their costs are reduced through learning by doing. The effects of early technology policy are different in scenarios with immediate carbon pricing. In the case of delayed climate policy, the emission path can be brought closer to the first-best solution, whereas in the case of immediate climate policy additional technology policy would lead to deviations from the optimal emission path. Hence, technology policy in the delayed climate policy case reduces costs, but in the case of immediate climate policy they increase. However, the near-term emission reductions are smaller in the case of delayed climate policies. At the regional level the effects on mitigation costs are heterogeneously distributed. For the USA and Europe early technology policy has a

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positive welfare effect for immediate and delayed climate policies. In contrast, India looses in both cases. China loses in the case of immediate climate policy, but profits in the delayed case. Early support of renewable energy technologies devalues the stock of emission allowances, and this effect is considerable for delayed climate policies. In combination with the initial allocation rule of contraction and convergence a relatively well-endowed country like India loses and potential importers like the EU gain from early renewable deployment.

1 Introduction

The transformation of the global energy system towards de-carbonization is identified as a key challenge for the 21st century. Following historical trends of de-carbonization is not sufficient to meet stringent climate change mitigation targets as well as major objectives related to environmental protection and economic development, see e.g. Nakicenovic and Riahi (2002). Renewable energy technologies have been identified as an essential option for the transformation of the energy system to meet climate change mitigation. The main driver triggering the recent deployment of renewable energy technologies has not been carbon pricing but dedicated support for renewable energy technologies. May convert the logical relationship into the opposite direction: high renewable deployment contains the costs for achieving stringent climate policies and, hence, increases the social acceptability and economic affordability of such long-term goals. The present paper aims at gaining insight on the role of renewable energy technologies in the transformation of the global energy system and on how they interact with global and regional mitigation costs, if climate policy is delayed.

The issues of climate change mitigation and renewable energy technology (RET) deployment are high on the political agenda. An international agreement on binding caps on greenhouse gas (GHG) emissions is yet not implemented and it is expected that it will take some years before such agreement will enter into force at the global level. The fifteenth Conference of the Parties (COP) 2009 to the UN Framework Convention on Climate Change (UNFCCC) in Copenhagen was expected to make a great step into this direction, but it failed to meet these expectations. However, the Copenhagen Accord called for long-term co-operative action, recognizing the scientific view that the increase of global mean temperature should not exceed 2°C. This is an important outcome in making Art. 2 of the UNFCCC more operational that formulated the ultimate objective of stabilizing GHG concentrations at a level that prevents dangerous interference with the climate system. Though the international negotiation process arrived at a more concrete long-term target, there is no internationally binding agreement on how to deal with emissions in the short-term. Rogelj et al. (2010) reviewed the pledges to the Copenhagen Accord and concluded that according to the pessimistic interpretation the emission cap in 2020 "is nearly equal to the business-as-usual [emissions]."

The growth of CO_2 emissions during the last decade was the highest ever reported, which was mainly triggered by the increasing use of coal. This trend is expected to continue over the next decades, if no effective climate policies are implemented. The global economic crisis of 2008 is not expected to make a huge difference; see e.g. IEA-WEO (2010).

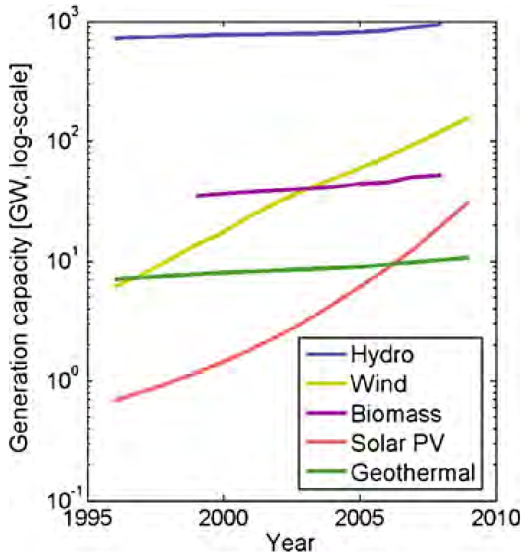


Fig. 1 Global generation capacities of RETs in the electricity sector 1996 to 2009. Sources: GWEC (2010), IEA WEO various issues, REN 21 various issues, Jäger-Waldau (2009)

At the same time, RET deployment is pushed forward by many national governments, for a number of reasons, including climate change mitigation. Feed-in tariffs, renewable energy quotas and other measures triggered a boom of RET, especially in the electricity sector. The recent recession did not interrupt the development. Green Recovery Programs—see e.g. Edenhofer et al. (2009)—are accelerating the development. Jäger-Waldau (2009, p. 10) notes that the major part of the various national fiscal stimuli for renewable energies have not yet been spent, but are going to become effective in 2010 and 2011.

Figure 1 reports the global generation capacities of electricity producing RETs in log-scale. The global cumulative capacity for Wind has been increasing at an annual rate between 21% and 37%; for solar PV the cumulative capacity has been growing at 20% p.a. in the late nineties and by more than 40% p.a. in the period 2005 to 2008. Jäger-Waldau (2009, p. 103) concludes that “the photovoltaic industry is developing into a fully-fledged mass-producing industry.” Hydro, geothermal, and biomass were only slowly increasing, but started at relatively high levels in the 1990s. It should be noted that the capacity additions of hydro in 2008 are reported at 35GW, which is still larger than the sum of wind and solar, amounting to 32.5GW. The capacity additions of wind and solar are rapidly growing and, hence, are expected to exceed the new installations of the more traditional renewable electricity technologies within the next few years.

The recent boom of RET over the first decade of the 21st century outpaced all earlier expectations.[1] Policies already in place and recent observations of market developments confirm the expectation that RET deployment will keep on rapidly growing in the near-term future, see e.g. GWEC (2010, p. 15), Jäger-Waldau (2009, p. 17).

[1]For example, IEA-WEO (2002, p. 412) expected the wind power capacity in 2010 at 55GW. The realized value in 2009, however, is 159GW.

In summary, the present situation is ambivalent. The need for limiting climate change is accepted but no emission limitations are implemented at the global level, and renewable energy sources as well as coal use grow at very high rates. From an economic point of view these ambivalent developments raise two sets of research questions:

1. Assume the implementation of global climate policy is delayed until 2020. Is the near-term RET deployment reducing or increasing the mitigation costs of delayed climate change mitigation policies? How is this related to the global CO_2 emissions in 2020? What are the mitigation cost impacts for different regions?
2. For comparison, assume that RET deployment is varied and a global cap-and-trade system for CO_2 emissions is implemented immediately. How do deviations from the optimal RET deployment scenario change the time path and the regional distribution of mitigation cost? What is the impact on global CO_2 emissions?

To answer the first set of questions is the main objective of the present study. The complex interplay of climate and technology policies leads to various effects. To provide a clear understanding of the forces at work, the second set of questions is elaborated.

The methodological approach addressing these questions is to design and to analyze a set of first- and second-best scenarios using the energy–economy–climate model REMIND-R. This is in line with the general philosophy of the RECIPE project; see Luderer et al. (2011, this issue). Previous contributions to the economics of climate change mitigation have intensively applied this methodology for designing scenarios to assess mitigation costs. Manne and Richels (2004) discuss the impact of endogenous technology learning-by-doing on the optimal emission path and the costs for achieving a given stabilization target. They find that technology learning has little impact on the optimal emission path, but significantly reduces the costs for achieving the stabilization target. The International Model Comparison Project assessed the contribution of induced technological change to meeting atmospheric stabilization of GHGs at the lowest possible costs; see Edenhofer et al. (2006). The EU ADAM project mainly focused on the significance of having available specific low-carbon technologies; see Edenhofer et al. (2010). The 22nd round of the Stanford Energy Modeling Forum focused on the impact of delayed mitigation policies and the significance of temporary over-shooting of the stabilization targets; see Clarke et al. (2009).

We extend the methodology in two directions focusing especially on the timing of climate and technology policies. The first set of questions suggests the comparison of two different second-best scenarios: delayed climate policy and early RET deployment are combined. Up to our knowledge the comparison of two second-best scenarios is an innovation to the methodology and extends the debate on the economics of climate change mitigation and technology deployment. The resulting impact of early technology deployment on the mitigation costs is considerable. For improving our understanding we formulate the second set of scenarios which analyze the impact of weaker versus stronger technology development in combination with immediate climate policy. This is also different to common technology second-best scenarios, where the availability of technologies is limited below the optimal case. In the present study the deployment of RET is constrained to deviate negatively as well as positively from the first-best solution.

The analysis of second-best scenarios is related to the discussion about the optimal timing and coordination of policies in the context of climate change mitigation; see Sorrell and Sijm (2003). Böhringer et al. (2009) evaluate the simultaneous application of a cap-and-trade system and renewable penetration targets in the EU using a computable general equilibrium model. They find that the additional costs of the technology policy are small and the CO_2 permit price is decreased. Kverndokk and Rosendahl (2007) discuss the optimal choice of emission taxes and technology subsidies for limiting cumulative emissions in the presence of spill-over effects due technology learning-by-doing. The highly stylized partial model covers the electricity sector of a single region. The study analyzes delays in choosing carbon taxes and technology subsidies. The paper finds that delaying the optimal carbon emissions tax has little impact on welfare. In addition, its effect is smaller than delaying the optimal technology subsidy. Similar studies on first- and second-best policies with explicit representation of policy instruments to address multiple and interlinked externality problems have been undertaken on the coordination of technology R&D and emission taxing policies; see e.g. Gerlagh et al. (2009). Also other market failures could be considered, but like the issue of technology R&D this is not the focus of this paper.

The present study applies a multi-regional model covering the total energy system, the macro-economy and the climate system. It computes first- and second-best scenarios to quantify the economic, technological, and environmental effects of climate and technology policy. The first- and second-best scenarios are implemented by imposing constraints on environmental variables (i.e. atmospheric CO_2 concentration) and on technology related control variables (i.e. investments). The approach to design second-best scenarios by constraining investment variables is different to the second-best policy analysis as has been studied by Kverndokk and Rosendahl (2007), who imposed constraints on policy variables that aim at changing the investment decisions of autonomous private agents.

The remainder of the paper is organized as follows. Section 2 introduces the REMIND-R model that is the numerical tool for assessing the research questions. Section 3 introduces the design of the scenarios and how they are related to the research questions. Section 4 presents and discusses the results. Section 5 concludes and points to promising fields for future research.

2 The REMIND-R model

The Refined Model of Investment and Technological Development (REMIND) is used as the numerical tool to address the research questions raised above. The model is documented in literature; see Bauer et al. (2009) and Leimbach et al. (2010). In the following the general structure of the model and the role of renewable energy is elaborated as it is important for the sake of this paper.

Figure 2 provides a generic overview on the model structure. REMIND-R is an inter-temporal, general equilibrium, multi-regional energy–economy–climate model.

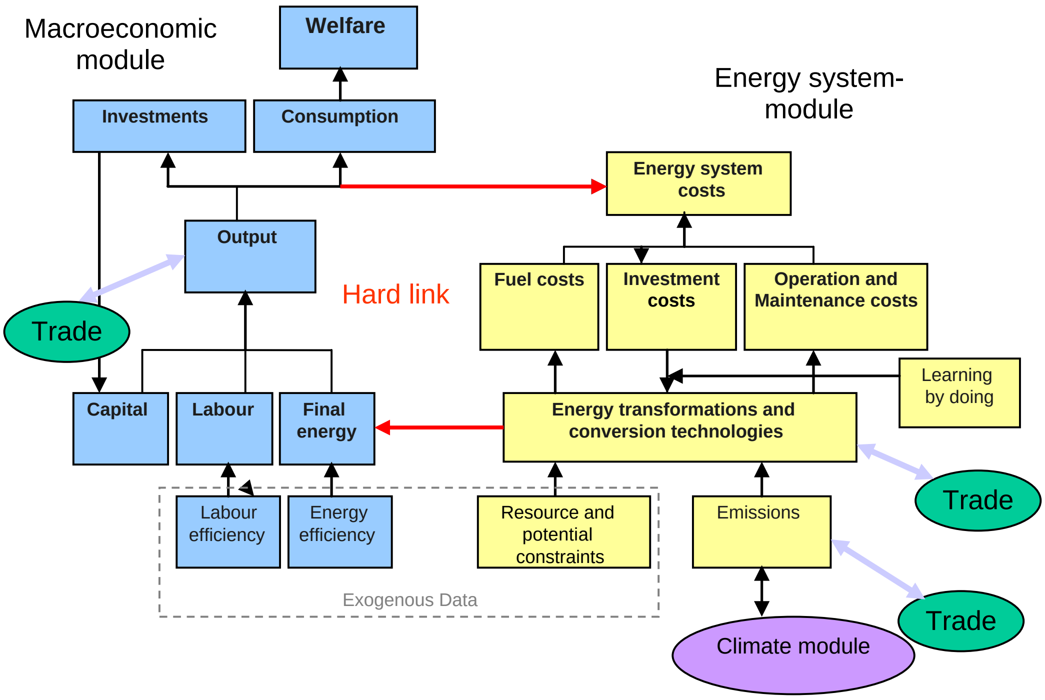


Fig. 2 Overview of the REMIND-R model framework. *Blue boxes on the left* are related to the macroeconomic growth model, *yellow boxes on the right* denote elements of the energy system model. The *red arrows* highlight the hard-links between models. The *light-colored arrows* indicate trade relationships

In each of the eleven world regions[2] a Ramsey-type growth model represents the macro-economy. The energy sector model is embedded into the macro-economic growth model. Both models interact by financial and energy trade flows. A social optimum for each region is computed by maximizing the inter-temporal, social welfare subject to economic and technological constraints as well as prices for internationally traded goods. In each region a hard-link between the macro-economy and the energy system guarantees simultaneous equilibrium on all markets for final goods, capital, labor and energy; see Bauer et al. (2008). The Negishi-approach is applied to compute the Pareto-equilibrium of trade between the regions; see Manne and Rutherford (1994) and Leimbach and Toth (2003). International trade comprises the generic macro-economic good, coal, oil, gas, uranium and emission permits.

Climate policy is imposed by setting a constraint on the atmospheric CO_2 concentration. The resulting CO_2 emission path minimizes the mitigation costs for the world economy by fully exploring 'when'- and 'where'-flexibility of mitigation measures given the full tradability of emission permits and inter-temporal equilibrium of the international capital market. The emission permits are distributed to the regions according to an allocation rule, based on the contraction and convergence scheme.

[2]In the present study we have focus on the US (USA), Europe (EUR), China (CHN), and India (IND). The other countries are summarized in the two aggregates Rest of Annex-1 (RAI), which comprise those countries committed to reduce emissions under the Kyoto Protocol and Rest of Non-Annex-1 (RNAI), which are all the other countries that have not agreed on reducing emissions.

The allocation to the regions follows a two step approach. First, the global emission path is optimized. Second, each region receives a share of this aggregate according to the allocation scheme.

The energy sector represents the conversion of energy carriers by various linear production technologies. Each technology is described by a set of techno-economic characteristics. Energy conversion requires the availability of capacities that are extended by specific investments and decreased by technical depreciation. Table 1 gives an overview of all available technologies and conversion routes from primary to secondary energy. Primary energy is distinguished in exhaustible and renewable energy carriers. The former are subject to extraction costs that increase in cumulative extraction. The tradable endowments are owned by the region where they are located. The latter are non-tradable and subject to potentials that are differentiated by grades that capture the decreasing quality of different locations. Secondary energy carriers are delivered to the macro-economic sector that uses them in combination with capital and labor to generate macro-economic output using a nested CES production function.

Renewable energy carriers are an option to supply the rapidly growing demand for electricity. The renewable energy technologies solar PV and wind turbines are learning technologies with learning rates of 20% and 12%, respectively. Learning-by-doing can reduce the investment costs of wind turbines from 1200$US per kW to a minimum of 883$US per kW. The assumptions for solar PV are 4900$US per kW and 600$US per kW, respectively. The fluctuating nature of both primary energy sources is addressed by imposing constraints that imply the need of storage facilities and excess capacities, both, depending on the technologies' share in the generation mix; see Pietzcker et al. (2009) based on techno-economic assumptions from Chen et al. (2009).

Biomass is notable for the supply of other secondary energy carriers. Currently biomass is mainly used in solid form for satisfying basic needs using traditional biomass technologies. With growing income and growing demand for modern energy carriers traditional biomass utilization fades out of the system. The supply for modern ligno-cellulosic biomass utilization is growing to a maximum of 200EJ p.a. in 2050; see van Vuuren et al. (2009) for an assessment of this assumption. Biomass can also be utilized in combination with carbon capture and sequestration (CCS) for the production of electricity, hydrogen and transportation fuels. Hydrogen could be produced from low-carbon electricity sources like renewables or nuclear vie electrolysis (not shown in Table 1). More direct conversion routes for hydrogen production from renewables and nuclear are discussed in Magné et al. (2010).

3 Scenarios

The development of the scenario set-up in this study follows a five step approach. Table 2 summarizes the scenario assumptions that are elaborated in more detailed next. The first step is to compute a case without climate policy constraints, denoted as the BASELINE scenario.

The second step is to compute three first-best climate change mitigation scenarios. The scenarios are constrained to stabilize CO_2 concentrations at 410, 450, and 490 ppm by 2100 with temporary over-shoot. In each scenario the CO_2 concentration

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

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

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 methane 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

[a]These technologies are also available with carbon capture

Climatic Change

Table 2 Overview of scenarios

	Climate policy (CO_2 only)	RET deployment	Comment
Baseline	None	Optimal	
POL^{x}	Starting in 2010 × indicates the stabilization at 410, 450, 490 ppm by 2100	Optimal	First-best scenarios
POL^{DEL}	Delayed (**DEL**) until 2020 450 ppm by 2100	Optimal subject to delayed climate policy	Second-best: Delayed climate policy
$POL^{D\&R}$ (s/m/w)	Delayed (**D**) until 2020 450 ppm by 2100	**R**ET deployment is strong (**s**), medium (**m**) or weak (**w**) Until 2020	Second-best: Delayed climate policy and exogenous RET deployment
POL^{RET} (s/w,20/30)	Starting in 2010 450 ppm by 2100	**RET** support strong (**s**) or weak (**w**) Until 2020 or 2030	Second-best: Immediate climate policy with exogenous RET deployment

is allowed to exceed the target by a maximum of 4.5%.[3] Non-energy CO_2 emissions are assumed to follow an exogenous path; see Luderer et al. (2011, this issue). The emission permits are consistent with the optimal emission path and distributed among regions according to the convergence and contraction scheme achieving equal per-capita allocation in 2050; see Den Elzen et al. (2008) and Leimbach et al. (2010). The scenarios are denoted POL^{x}, where x indicates the stabilization target.[4]

In the third step climate policy is delayed. The climate policy starts in 2020. Until the beginning of climate policy all investment paths are constrained to the BASELINE scenario. This scenario is denoted POL^{DEL}.[5]

In the fourth step the delayed climate policy is combined with early RET deployment constraints. For this purpose in all regions the RET deployments of the three POL^{x} scenarios until 2050 are given as exogenous constraints in a scenario without any climate policy. The resulting three scenarios provide different development paths for the entire energy–economy system. These three developments until 2020 are used as exogenous constraints for all stock variables, i.e. until the period, when climate policy becomes active. Hence, the delayed climate policy is combined with weak, medium and strong scenarios for early deployment renewables. These scenarios are denoted $POL^{D\&R}$. The three deployment scenarios (**w**eak, **m**edium, **s**trong) are indicated in parentheses. The three scenarios are compared with the POL^{450} and the POL^{DEL} scenarios to address the first set of questions raised above.

In the fifth step immediate climate policy is combined with four non-optimal RET deployment paths to achieve the 450 ppm stabilization level; i.e. the capacity values

[3]This degree of overshooting is the same as assumed in A1_CC_Overshoot in Luderer et al. (2011, this issue). To maintain consistency across scenarios the same overshooting is allowed for the scenarios POL^{410} and POL^{490}.

[4]The scenario POL^{450} is the same as the scenario A1_CC_Overshoot in Luderer et al. (2011, this issue). The scenario POL^{410}, however, is stricter than the scenario A1_CC_410 because the permissible overshoot is smaller.

[5]This scenario is the same as the scenario C8_DELAY2020 in Luderer et al. (2011, this issue).

of all technologies as given in the renewable columns of Table 1. For this purpose **s**(trong) and **w**(eak) RET deployments are considered as exogenous scenarios. The assumptions for the exogenous RET deployment pathways are taken from POL^{410} for the scenario strong scenario and from POL^{490} for the weak scenario. Furthermore, the deployment assumptions are fixed for two time horizons until (20)**20** and (20)**30**. This set of second-best scenarios is denoted POL^{RET}. A specification in parentheses distinguishes the intensity and the duration of the exogenous RET deployment assumptions. The benchmark for comparison is the first-best POL^{450} scenario. The analysis addresses the second set of questions raised above.

The design of the $POL^{D\&R}$ scenarios is based on model outcomes for the period 2010 to 2020 because this approach provides different levels of RET deployment. The alternative would be to base the assumptions on deployment targets announced by governments. It is, however, not the aim of the present study to assess the various renewable policy targets, but to assess the significance of a range of RET deployment assumptions. Deriving the assumptions from scenarios computed by the same optimization model implies that the deployment paths are implicitly tailor-made for the model. The technology policy assumptions are, thus, not subject to the critique of failing to 'picking the winner', which means that the portfolio of the technology policy is not a mis-allocation, but suits the needs of the energy sector represented in the model.

4 Results

4.1 First best solutions—BASELINE and POL^x

The BASELINE and the POL^x scenarios are the starting point for the analysis. The POL^{450} scenario serves as a point of reference for the second-best scenarios introduced in the following sub-sections. Furthermore, the POL^x scenarios provide RET deployment paths that are used as constraints for second-best scenarios below.

Figure 3 shows the global CO_2 emissions from the energy sector for the four scenarios. BASELINE emissions increase to 21GtC p.a. in 2050 and remain approximately at this level. The rapid increase of CO_2 emissions is mainly triggered

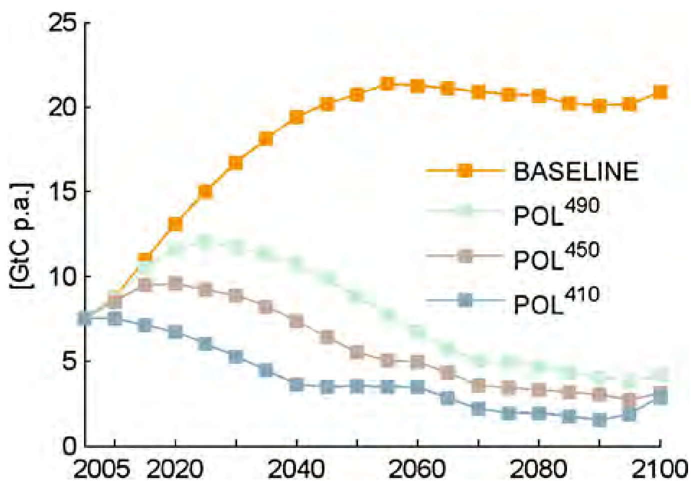


Fig. 3 Global CO_2 emissions 2005 to 2100 from the energy sector for the scenarios BASELINE and POL^x

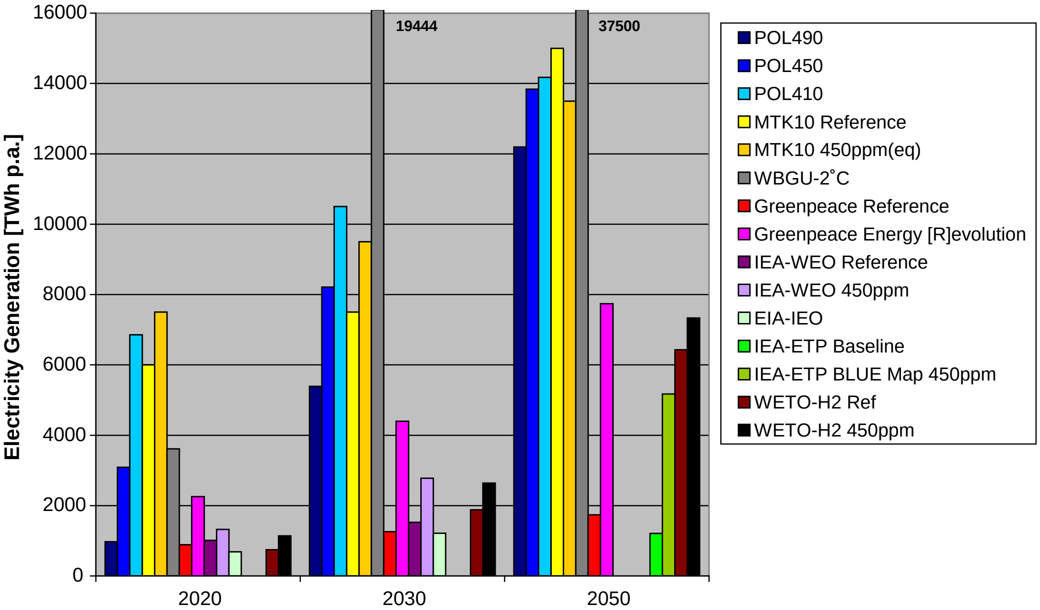


Fig. 4 Electricity generation from wind power turbines in the three POL^x scenarios computed with REMIND-R and results from other publications. Sources: WBGU (2003, p. 138), Magne et al. (2010, p. 93), Greenpeace (2008, p. 190 and 191), IEA (2009, p. 229 and 623), IEA (2008 p. 85), EIA (2009, p. 67), WETO is EC (2006, p. 120 and 129). IEA-WEO and EIA-IEO consider only a time horizon until 2030; IEA-ETP reported numbers only for the year 2050

by the supply of huge amounts of cheap coal. The three POL^x scenarios cover a wide range of different emission pathways. To achieve the 450 ppm target, CO_2 emissions deviate from the BASELINE immediately, peak in 2020 below 10GtC p.a. and decrease to 3.6GtC p.a. in 2070 to stay at this level afterwards. The less ambitious 490 ppm target allows the emissions to peak in 2025 at a much higher level (12GtC p.a.). The emissions start to deviate from the BASELINE path after 2015. In the longer run emissions stabilize at 5GtC p.a. To achieve the much more ambitious 410 ppm target emissions need to decrease immediately and stabilize at 2GtC p.a. in 2070.

The deployment of RET in the three POL^x scenarios also varies over a large range. In the following, the deployment of wind and solar for electricity production are analyzed in depth and compared with scenarios from the literature. The choice for these two technologies is due to the significant deployment computed with REMIND-R and the rapid growth experienced in recent past.[6] Finally, remarks on other RET that are subject to the technology deployment policies will be added.

Figure 4 shows the electricity generation from wind power turbines in the years 2020, 2030 and 2050. The three POL^x scenarios computed for this study show significant sensitivity regarding timing of deployment of wind power turbines. The largest relative differences are observed in 2020, but in 2050 all three paths converge

[6] It is worth to note that only few studies provide results on differentiated global renewable electricity generation. It is common practice to report figures that contain an aggregate on "Other Renewables", which does not give insight into the contribution of wind, solar, etc.

to quite similar levels. For the scenario POL^{410} the growth is most significant in the coming decades, whereas for the POL^{490} scenario growth accelerates significantly after 2030.

The future wind electricity production of the three scenarios can be compared with simple extrapolation of the historical time series given in Fig. 1 above. Assuming a constant growth rate of installed capacity until 2020 would result in a capacity of 3000GW. Assuming an annual average of 2000 full load hours, which is a relatively low number, would result in an output of electricity of 6000TWh p.a. Comparing this number with the results in Fig. 4 indicates that for the scenario POL^{450} future growth rates could even decrease from their historical levels. For the case POL^{410} the growth rate of installed wind turbine capacity might need to increase above historical rates.

For the comparison with other studies it is useful to distinguish two groups. The first group comprises modeling studies that are similar to the present REMIND-R study. They apply inter-temporal energy-economy models with optimization under perfect foresight. Magne et al. (2010) use the model MERGE-ETL (denoted MTK10) and WBGU (2003) uses the model MESSAGE (denoted WBGU-2°C). Both studies show—like the REMIND-R scenarios—high wind power generation. MTK10 provides two scenarios: the reference case does not consider any climate policy and the 450 ppm scenario[7] considers all GHGs and, thus, is more stringent than the POL^{450} scenario of the present study. In the near-term wind power generation is higher in the 450 ppm scenario than in the reference scenario, but in 2050 the ranking is reversed. This can be explained with the absorptive capacity for fluctuating electricity sources that decreases in the policy scenario because the total electricity generation decreases. The WBGU scenario is supposed to limit the increase of global mean temperature to not more than 2°C above pre-industrial levels. Wind power generation is the highest of all scenarios.[8]

The second group of scenarios is mainly motivated by energy issues and the underlying models are not using inter-temporal optimization with perfect foresight. The scenarios show much lower deployment of wind power. Even the Greenpeace Energy [R]evolution scenario is much lower in 2050 than the scenarios belonging to the first group.[9] The lowest scenario is provided by the US Energy Information Administration (EIA) that does, however, not consider a climate stabilization target. The smallest difference between the reference case and the climate policy case is provided by the WETO-H2 study.

Figure 5 shows the corresponding graph for electricity production from solar sources in log-scale. For all scenarios solar electricity generation in 2030 is less than for wind. In 2050 this ranking is reversed in some of the scenarios. Solar electricity production increases by two orders of magnitude—and even more for few scenarios—within three decades. Regarding the timing of deployment the three

[7]The scenario allows for over-shooting the concentration target.

[8]It should be noted that this scenario is subject to limited possibilities for using alternative technologies in the power sector. Nakicenovic and Riahi (2002) provide an in-depth analysis of the MESSAGE model. For a broad range of scenarios wind power generation is significantly lower than in the present scenario. However, the figures for electricity production are not reported.

[9]It should be noted that the Energy [R]evolution scenario assumes considerably higher increases of energy efficiency than the other scenarios, hence, electricity demand is lower. Therefore, the share of wind power in the overall generation mix is higher than for the other scenarios.

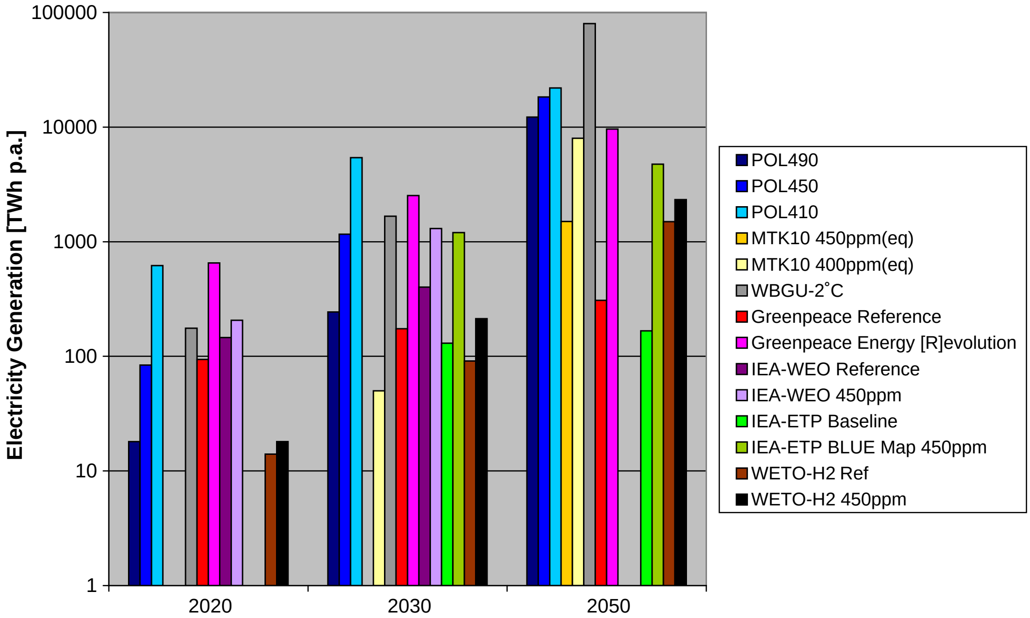


Fig. 5 Electricity generation from solar technologies in the three POL^x scenarios computed with REMIND-R and results from other publications. Note the log-scale. Sources: WBGU (2003, p. 138), Magne et al. (2010, p. 93), Greenpeace (2008, pp. 190 and 191), IEA (2009, pp. 229 and 623), IEA (2008 p. 85 and 367), EIA (2009, p. 67), WETO is EC (2006, p. 120 and 129). IEA-WEO and EIA-IEO consider only a time horizon until 2030; IEA-ETP do not report numbers only for the year 2020

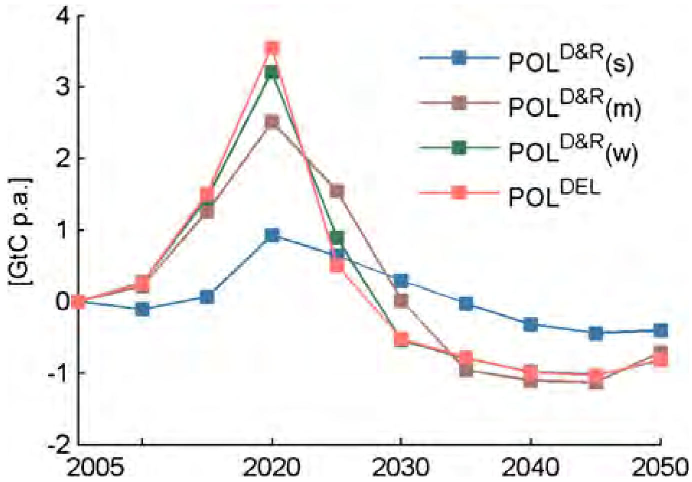
POL^x scenarios show a similar behavior as in the case for wind power production. MTK10 shows lower deployment for solar power. Also the same sensitivity as for the REMIND-R model can be observed regarding timing of deployment as the stabilization target is tightened from 450 ppm(eq) to 400 ppm(eq). The WBGU-2°C scenario again shows much higher figures than REMIND-R. The scenarios of the second group exhibit relatively small differences compared with the first group in 2030. For example, the POL^{450} scenario shows nearly the same solar electricity production as the WEO 450 ppm scenario and the ETP BLUE map scenario. Only in the longer term in 2050 the POL^x scenarios are much higher than the Greenpeace, the ETP and the WETO-H_2 scenarios.

The four scenarios imply different investment costs in the year 2020 as they depend on technology deployment according to the dynamics of learning by doing. Table 3 presents the investment costs in 2020 for the wind and solar PV technology. The lower investment costs for the stricter climate policy targets are a direct consequence of the social optimal deployment of technologies shown above. This result is important for the analysis below.

Table 3 Investment costs of wind and solar PV technologies in 2020 for the four scenarios BAU and POL^x

Technology	Unit	Scenario			
		BAU	POL^{490}	POL^{450}	POL^{410}
Wind	$US/kW	1144	960	917	901
Solar PV	$US/kW	4900	3823	2548	1543

Fig. 6 Impact of delayed climate policy and different assumptions of near-term RET deployment on annual global CO_2 emissions from the energy sector from 2005 to 2050. The lines indicate absolute differences of the POL^{DEL} and the three $POL^{D\&R}$ scenarios with respect to the POL^{450} scenario



Biomass is the most important other RET that is used in the POL^x scenarios. In all three scenarios the maximum potential of 200EJ p.a. is utilized in 2050. It is mainly converted into synthetic natural gas and transportation fuels—the latter partly with CCS. In the scenario POL^{450} biomass with CCS is deployed from 2030 on.

Finally, the mitigation costs of the three POL^x cases are assessed. Mitigation costs are measured as the cumulative discounted consumption losses for the 21st century relative to the BASELINE case. For discounting we used the interest rate that is computed endogenously in the REMIND-R model.[10] For the medium case POL^{450} the losses are 0.5%. For the less ambitious POL^{490} the losses are only 0.3%, but increase to 0.8% as the stabilization target is tightened in the POL^{410} case.

4.2 Delayed climate policy and early RET deployment—POL^{DEL} and $POL^{D\&R}$

The assumption of an immediately established global cap-and-trade system is flawed because the international negotiations take more time. The POL^{DEL} scenario analyses delayed climate policies by freezing the development of all stock variables until 2020 on BASELINE levels. Measures to support renewable energies are not reflected in this near term development. This design feature is added in the $POL^{D\&R}$ scenarios, which combine delayed climate policies and early RET deployment. The design of $POL^{D\&R}$ scenarios captures the current situation with large renewable deployment initiatives but missing global climate policy.

Figure 6 shows the impact on global CO_2 emissions from the energy sector. The graph depicts the absolute differences compared with the POL^{450} case (see Fig. 3 above) until 2050. In the year 2020 the emissions in the POL^{DEL} case are 3.5GtC p.a. higher. This difference can be significantly reduced by imposing the RET

[10]The interest rate in REMIND is time-variable. The steady state value is 5.5% that is approached starting from 8%. It is common practice to apply a constant discount rate to compute net present values of consumption and GDP differences. In the present case the differences between the policy scenarios and the BAU scenario are non-trivial because of multiple intersections. This implies that a fixed discount rate can lead to counter-intuitive rankings of the scenarios; i.e. a second best scenario performs better than a first best scenario. If we apply the endogenous time variable interest rate, the rankings of scenarios are sound.

deployment. If the deployment from the original POL^{450} scenario is assumed until 2020, the difference in emissions reduces to 2.5GtC p.a. During the following decades the differences change sign because the 450 ppm concentration target has to be met in all scenarios. In the scenario POL^{DEL} the rapid and enormous decreases of emissions after 2020 are mainly achieved by abandoning new fossil investments and heavily investing into biomass with CCS. Higher deployments of RET reduce the emission level in 2020 and therefore do not require such massive changes after 2020 because the peak is lower and, hence, this reduces the need to go quickly below the optimal emission path of the POL^{450}. These smoothed changes reduce the mitigation costs.

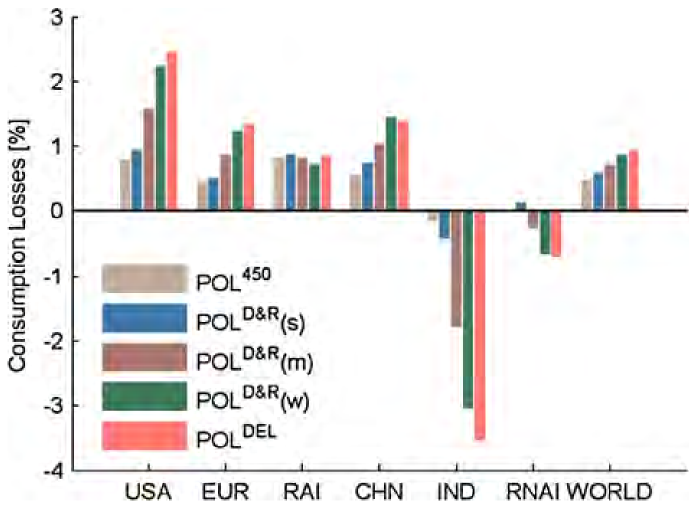
The mitigation costs for the different scenarios are of particular interest because *a-priori* it is unclear whether the costs of delayed climate policy increase or decrease, if early RET deployment is additionally assumed. It is valid to say that the POL^{450} scenario implies the lowest mitigation costs of the five scenarios considered here. The costs of the POL^{DEL} scenario are expected to be higher, because the energy–economy system can not choose the cost-minimal timing of mitigation measures. The key question is, whether political measures for early deployment of renewables are justified as long as the global climate cap-and-trade system has not yet entered into force to achieve a common CO_2 concentration target.

Figure 7 shows the global and regional mitigation costs measured as the cumulative discounted consumption differences relative to the BASELINE scenario. At the global level it turns out that early RET deployment reduces the additional mitigation costs of delayed climate policy. The additional costs of the POL^{DEL} case can be reduced by 0.23%-points, if RET deployment that originally was optimal in the POL^{450} scenario is triggered by support measures; i.e. the scenario $POL^{D\&R}$(m). However, the cost reducing effect is bound by the mitigation costs of the POL^{450} case.

The distributional effects are heterogeneous among regions. For the US and the EU the cost reducing effect of early RET deployment is in the same direction as at the global level. The same is also true for China, if only the medium and strong deployment scenarios are considered. For India and the RNAI region the effect is of the opposite sign.

The net effect of the mitigation costs for the different regions can be explained by analyzing the different components. The differences of mitigation costs are

Fig. 7 Global and regional mitigation costs for the POL^{450}, the $POL^{D\&R}$ and the POL^{DEL} scenarios. Mitigation costs are measured as the cumulative discounted consumption losses relative to the BASELINE case for the time horizon 2005 to 2100. The indices in the parenthesis indicate **s**(trong), **m**(edium) and **w**(eak) of RET deployment. The time varying endogenously computed interest rate is used as the discounting rate



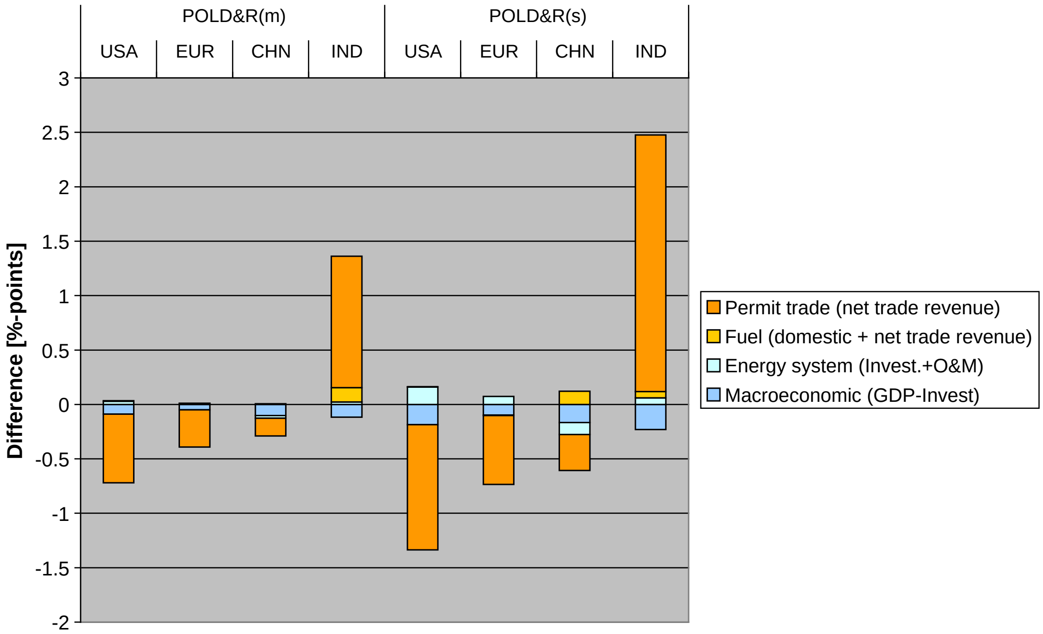


Fig. 8 Impact of various effects on the mitigation costs of the US, Europe, China and India for the $\mathrm{POL}^{\mathrm{D\&R}}$(m) and $\mathrm{POL}^{\mathrm{D\&R}}$(s) scenarios compared with the $\mathrm{POL}^{\mathrm{DEL}}$ scenario. Negative (positive) values indicate mitigation cost reductions compared with the $\mathrm{POL}^{\mathrm{DEL}}$ scenario. Note: the relative differences are relative to changes of GDP, whereas mitigation costs are relative to consumption differences

explained by changes in (a) macroeconomic variables of GDP and investments in the macroeconomic capital stock (b) non-fuel energy system costs consisting of investment and O&M costs, (c) fuel costs including net export revenues and (d) permit trade. The methodology for deriving the single components from the results of the optimal inter-temporal solution is provided by Lüken et al. (2009).

Figure 8 shows the differences with respect to the $\mathrm{POL}^{\mathrm{DEL}}$ scenario. Negative (positive) values indicate cost reduction (increases) with respect to the $\mathrm{POL}^{\mathrm{DEL}}$ scenario. The sum of positive and negative components equal the difference that can be observed in Fig. 7 above. By far the most prominent influence is the emission permit component. For the net permit importers US, Europe and China early deployment of renewables is profitable because the cost escalating influence of emission permits in the delayed climate policy scenario can be reduced. The opposite line of argumentation works for the net permit exporter India. The redistribution effect is stronger the more ambitious the RET deployment scenario is.[11]

The other three components are negligible compared with the permit effect. Hence, early RET deployment in case of delayed climate policy is mainly affecting the value of tradable emission permits, which in turn affects the redistribution among regions related to the permit effect proportionally. The reason is that early RET

[11] Moreover, the regional redistribution of the value of permits scales almost linearly with the total value of permits. For example, the total permit value of the $\mathrm{POL}^{\mathrm{D\&R}}$(m) scenario is 40% less than in the $\mathrm{POL}^{\mathrm{DEL}}$ scenario. This reduces the permit effect in each region by about 40%. This result is independent of the sign of the permit effect.

deployment decreases the CO_2 permit price in 2020. In the case POL^{DEL} the price amounts to 92\$US/tCO_2, which is reduced to 53\$US/tCO_2 for the medium RET deployment scenario.

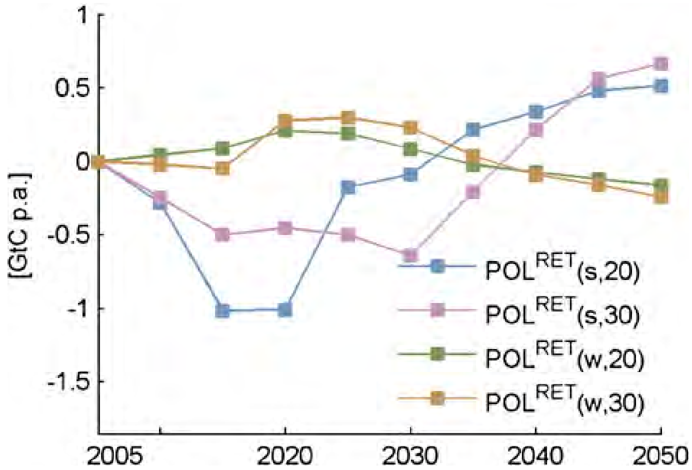
In summary, the increase of mitigation costs due to delayed climate policies can be decreased by early RET deployment. The most important factor that decreases the mitigation costs is the devaluation of emission permits that is explained by three reasons. First near-term emissions are decreased and therefore less of the cumulative emissions are consumed and the emissions must be decreased from less than the baseline level; see Fig. 6. Second, early deployment of renewables increases the capacity of carbon free energy technologies; see Figs. 4 and 5. Third, learning-by-doing decreases the costs of additional deployment of renewable energy technologies; see Table 3. The regional distribution impact of the devaluation of emission permits, however, is very different and depends on the difference between the initial and the market allocation; i.e. the closer the initial allocation of permits matches the efficient market allocation the less emphasized would be the permit trade effect.

4.3 Early renewable deployment and immediate climate policy—POL^{RET}

For understanding the factors better that led to the huge cost decrease in the previous section, we also provide another set of scenarios. In these scenarios deviations from the optimal RET deployment are assessed for achieving the 450 ppm CO_2 stabilization target. The exogenous variation of RET deployment shed light on the impact on emissions and mitigation costs, if the renewables penetration is weaker or stronger relative to the first best POL^{450} case. The deviation from the optimal deployment path *a-priori* implies higher global mitigation costs and changes in the emission time path. The open questions are whether on the global level early or deferred RET is worse, what the effect on the regional distribution of mitigation costs is and how the time-path of mitigation costs varies as the renewable deployment is changed?

Figure 9 shows the impact on CO_2 emissions for the four POL^{RET} scenarios with strong and weak RET deployment until the years 2020 and 2030. The graph depicts the absolute differences with respect to the POL^{450} scenario until 2050. The graph shows that deviations from the optimal path of renewable deployment to achieve the 450 ppm target imply near and long-term changes in CO_2 emissions. The variation of RET deployment leads to an intuitive temporal reallocation of CO_2 emissions. For the scenarios with stronger than optimal RET deployment—i.e. POL^{RET}(s,20) and POL^{RET}(s,30)—coal use in the electricity sector is partially replaced in the near term that allows higher emissions in the longer term; *et vice versa* for the scenarios with weaker than optimal RET deployment. The pattern of deviations is more distinct for the short-term deviations of RET deployment and levels out for the longer-term deviations, since the stabilization target is the same. In general, the deviations from the optimal CO_2 emission path of the POL^{450} scenario are assessed to be small compared with the changes in the effects observed in the POL$^{D\&R}$ scenarios. The maximum deviation of -1GtC p.a. in 2020 for the scenario POL^{RET}(s,20) is relatively small compared with the differences of emissions reductions between the POL^{410} and the POL^{450} cases; see Fig. 3 above. Hence, high penetration levels of RET are not expected to replace fossil energy carriers on a one-to-one basis in a climate policy

Fig. 9 Impact of deviations from the optimal RET deployment path on annual global CO_2 emissions from the energy sector from 2005 to 2050. The lines indicate absolute differences of the four POL^{RET} scenarios with respect to the POL^{450} scenario



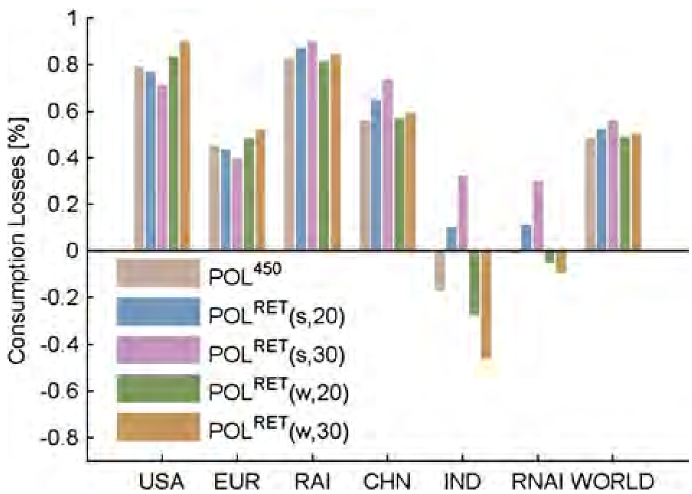
regime, which is due to an emission rebound effect in the energy sector, see also Bauer et al. (2010).

The impact of non-optimal RET deployment on mitigation costs is shown in Fig. 10. The graph depicts the mitigation costs in the optimal POL^{450} scenario as a reference and the mitigation costs of the four POL^{RET} scenarios. The results confirm the a-priori expectation that deviations from the optimal RET deployment path increase mitigation costs, though the differences are quite small. The penalty on mitigation cost is little higher for the two cases with RET deployment stronger than the optimal path. Thus, at least on the global level the timing of RET deployment is of minor importance for the mitigation costs.

Figure 11 presents the components that explain the difference between the POL^{450} and the two second-best scenarios that fix the RET deployment until 2030. The methodology is the same as for Fig. 8 given in the previous sub-section.

In all regions the positive (or negative) effect of strong (or weak) renewable deployment on the macroeconomic component is offset by higher (or lower) energy system expenditures. In the scenario POL^{RET}(s,30) the negative effect of non-fuel energy system costs exceeds the positive macroeconomic effect. In the scenario

Fig. 10 Global and regional mitigation costs for the POL^{450} and the POL^{RET} scenarios. Mitigation costs are measured as the cumulative discounted consumption losses relative to the BASELINE case for the time horizon 2005 to 2100. The indices in the parenthesis indicate the deviation from the optimal RET deployment path: the intensity **s**(trong) and **w**(eak) and the duration (20)**20** and (20)**30**. The time varying endogenously computed interest rate is used as the discounting rate



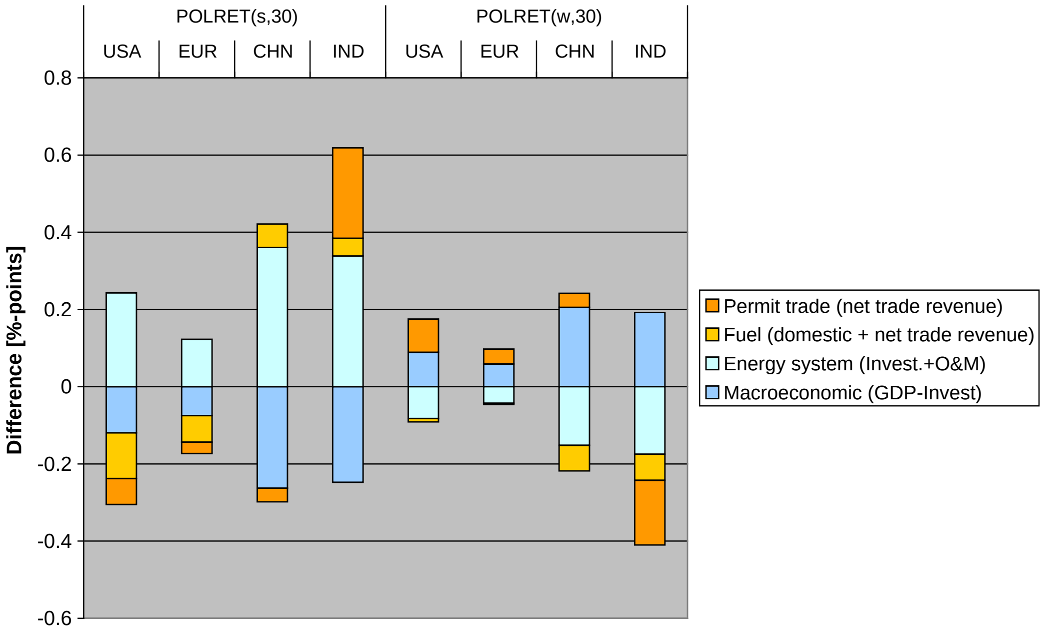


Fig. 11 Impact of various effects on the mitigation costs of the US, Europe, China and India for the $\mathrm{POL}^{\mathrm{RET}}$(s,30) and $\mathrm{POL}^{\mathrm{RET}}$(w,30) scenarios compared with the POL^{450} scenario. Note: the relative differences are relative to changes of GDP, whereas mitigation costs are relative to consumption differences

$\mathrm{POL}^{\mathrm{RET}}$(w,30) the signs of these two effects is reversed. In the US and Europe the fuel cost effect in the scenario with stronger (or weaker) than optimal RET deployment reduces (or increases) the mitigation costs because less fuels are produced domestically and imported. The opposite holds for China and India.[12] The permit effect is most important in the case of India, where strong RET deployment leads to smaller permit export revenues because of a smaller export at lower prices *et vice versa* in the case of weak RET deployment. The other regions however profit from this effect, though the importance is smaller as they have a larger overall GDP.

The small differences of mitigation costs between the first-best and the four $\mathrm{POL}^{\mathrm{RET}}$ second-best scenarios are mainly the net effects of larger redistribution between economic activity and de-valuation of emission permits as well as energy trade. The de-valuation effect, however, is much smaller than in the case of delayed climate policy. The macro-economic and non-fuel energy system effects are the same for all regions because the economy is supplied with more energy, but the fuel cost and permit trade effect vary between the regions. Whether a region suffers or gains from deviations from the optimal RET deployment depends on the direction and magnitude of the latter two effects. The differences in the permit trade effect, which is much smaller in the $\mathrm{POL}^{\mathrm{RET}}$ than in the $\mathrm{POL}^{\mathrm{D\&R}}$ scenarios, is due to the relatively smaller impacts on the CO_2 prices because the renewable mitigation option substitutes alternative options leading to only small CO_2 price changes. Also the impact on the CO_2 emission path is smaller in the $\mathrm{POL}^{\mathrm{RET}}$ than in the $\mathrm{POL}^{\mathrm{D\&R}}$

[12] We do not elaborate the energy trade effect more here, because the complex interplay of prices and quantities for the various energy carriers is not the focus of this study.

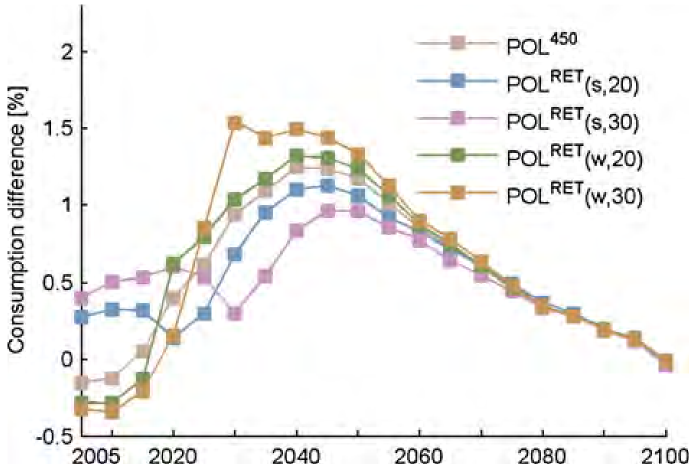


Fig. 12 Time paths of consumption differences 2005 to 2100 relative to the BASELINE case for the POL^{450} and the POL^{RET} scenarios. The indices in the parenthesis indicate **s**(trong) and **w**(eak) and the duration of RET deployment; i.e. (20)**20** and (20)**30**

scenarios shown in Figs. 6 and 9. Hence, the price and the quantity effect lead to a decrease of the overall permit trade effect.

Since the transformation of the energy system is a challenge for the present as well as the following generations, the time paths of mitigation costs of the scenarios are analyzed next. Figure 12 depicts the time paths of consumption differences of the POL^{450} as well as the four POL^{RET} scenarios relative to the BASELINE case. The optimal case POL^{450} shows a path that increases until 2040 peaking at 1.24% p.a. and decreases towards zero afterwards.[13] The four POL^{RET} scenarios show significant deviations from this path. Strong RET deployment until 2030 (POL^{RET}(s,30)) leads to an even flatter time path that already starts at 0.4% p.a. but does never exceed 1% p.a.. The two low deployment scenarios instead exhibit a much more emphasized peaking behavior. They start with some moderate gains, which are due to lower overall investments allocated to the energy system, but the maximum is higher. This is especially the case for the POL^{RET}(w,30) scenario, in which the weaker than optimal RET deployment lasts until 2030 peaking at 1.5% p.a. in 2035.

The comparison of the first-best climate mitigation scenario with the second-best scenarios shows that deviations from the optimal RET deployment paths only imply small changes in the optimal emission time paths and the global cumulative discounted mitigation costs. The regional distribution of the mitigation costs is heterogeneous and depends on the intensity of the RET deployment scenario as well as the contribution of various economic influences affecting the regions. Also the time path of mitigation costs is changed significantly for the different RET deployment scenarios. The cumulative discounted mitigation costs do not reflect the shape of these time paths.

5 Discussion and further research

Early deployment of renewable energy technologies reduces the global costs for achieving a 450 ppm CO_2 concentration target, if climate policy measures are

[13]The shape is not unusual for climate change mitigation assessments with stabilization targets; see Edenhofer et al. (2010, p. 32).

delayed. The cost reduction is due to the devaluation of emission permit that can be explained by three effects. First, early RET deployment replaces some fossil fuel utilization and leaves more emissions for the rest of the 21st century. Second, if large capacities of RET are available in 2020 the negative effect of significantly reducing new fossil fuel investments and increasing the utilization of biomass with CCS is contained. Finally, additional investments in RET will be cheaper post-2020 as early deployment will reduce the investment costs due to learning-by-doing. The global mitigation costs, however, cannot be reduced below the first-best scenario with optimal timing of all mitigation measures.

Similar results can be expected for other energy–economy models since Jakob et al. (2011, this issue) and Clarke et al. (2009, p. S77) report significant increases of carbon prices and mitigation costs as climate policy is delayed. The effectiveness of technology policies for reducing the emissions in the near term and triggering improvements of low carbon technologies is the crucial link to reduce the costs of delaying climate policies. Emission rebound effects can turn out to be serious obstacles to the positive impact of technology policies. Bauer et al. (2010) quantified the emission rebound effects of various mitigation options. The debate about the Green Paradox is even more pessimistic about technology policies, because fossil fuel extraction is expected to increase in the near term as fossil fuel owners anticipate future devaluation of their resources; see e.g. Sinn (2008).

Deviations from the optimal RET deployment path in the case of immediate climate policy increase the global mitigation costs compared with the first-best solution. The impacts on global emissions and discounted global mitigation costs are quite small, which confirms the finding of Böhringer et al. (2009) in the context of European climate and energy policy. Hence, the optimal timing of renewable investments is of minor importance from a global point of view. The impact on the time path of mitigation costs over the entire century, however, is significant. The optimal time path of mitigation costs follows an inverted U-shape with a peak around the middle of the century. Higher than optimal deployment of RET flattens the curve, but less than optimal deployment increases the peak of mitigation costs. This inter-temporal reallocation is not reflected in the discounted mitigation costs. The intergenerational re-distribution of mitigation costs due to different renewable energy investments is not discussed so far in the scientific literature. This issue is not addressed in the present paper and left to future research. An additional argument for stronger RET deployment (scenario $POL^{RET}(s)$) is that it serves as a hedging strategy against the case that in the future it might become necessary to achieve a lower stabilization target than initially chosen, e.g. decreasing the CO_2 stabilization level from 450 to 410 ppm. The significance of technology policies for hedging against climate risks has not been explored yet and seems an interesting field of future research.[14]

The impact of variations of RET deployment on global mitigation costs is larger in the case of delayed than in the case immediate climate policy. This result is in contrast with the finding of Kverndokk and Rosendahl (2007), who stated that the delay of carbon pricing is less significant than the delay of technology subsidies. The difference of results can be related to a number of factors. Kverndokk and

[14]The authors would like to thank an anonymous reviewer for this suggestion.

Rosendahl (2007) only reflect the electricity sector, in which learning technologies are very important, but the present study deals with the total energy sector, where learning technologies are less important. Moreover, Kverndokk and Rosendahl (2007) allow for optimal adjustment of the subsidy in case of delayed climate policy, but the present study only considers exogenous variations of RET deployment paths. Moreover, in case of a delayed technology subsidy the carbon tax in Kverndokk and Rosendahl (2007) would need to increase significantly to achieve any emission reduction (beyond demand responses) because besides two carbon-free learning technologies there is only one fossil generation technology considered. The REMIND model instead considers a large variety of different electricity generating technologies and renewables are differentiated by quality grades, which implies a smoothed transition.

The interregional distribution of mitigation costs is heterogeneous in both cases of immediate and delayed climate policies. At the regional level the US and Europe would gain from strong worldwide deployment of RET in both climate policy regimes. China would gain from strong and medium early deployment, if climate policies are delayed, but in case of immediate climate policy China would lose from strong RET deployment. India and all other non-Annex 1 regions lose from early RET deployment in both climate policy regimes.

In case of delayed climate policy variations of early RET deployment have significant impact on the global mitigation costs as well as the regional distribution. The main factor is that the total value of emission permits allocated to the regions decreases as early RET deployment is imposed on the system. This has a negative effect on regions, which receive relatively plentiful assignments and export these permits. Conversely, net importers gain from early RET deployment.

The main conclusion for policy making from this study is that early deployment of renewable energy technologies can reduce additional global costs of delayed climate policy. High income regions and China can reduce the costs of delayed climate policy by inducing this transformation of the global energy system. Especially the US and Europe would also profit from strong world-wide renewable deployment in case of immediate climate policy, thus, making this option a robust strategy for these regions. Low-income regions may not experience this cost reducing effect. In both cases of immediate and delayed climate policy low-income countries are found to lose from ambitious renewable deployment policies.

The present study only analyzed the influence of early RET deployment, but also other technology related policies should be studied. Most promising to us seem energy efficiency, fossil CCS, gas for coal substitution, and nuclear. The present study also showed that it is important to study the factors that determine the mitigation costs. As the value of carbon permits appears to have a significant influence on the results, future research should aim at identifying the reasons for changing mitigation costs as technology policy is imposed in case of delayed climate policy. Furthermore, the scenario space may also be extended to the land-use sector asking for scenario assumptions that reduce GHG emissions other than CO_2 from the energy sector. Following this line of research would broaden the perspective on alternative scenarios limiting and reducing GHG emissions by different policies.

The method of developing second-best scenarios is appropriate to explore the range of alternative future developments and the implications on costs providing guidance to policy makers and supporting international negotiations. However, the major interest of policy makers is the assessment of international agreements, optimal policy instruments and their coordination in a policy mix. The contributions of Kverndokk and Rosendahl (2007) and Gerlagh et al. (2009) address this challenge, but need much more improvement. The extension towards higher technological resolution and multi-regional frameworks requires additional theoretical foundation and more powerful numerical algorithms to solve these models.

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Chapter 5

The Dimensions of Technological Change and Their Impacts on Climate Change Mitigation.*

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The Dimensions of Technological Change and Their Impacts on Climate Change Mitigation

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March 29, 2011

Abstract

In climate policy analysis, mitigation costs and strategies are key variables. This study explores the impact of two dimensions (i.e. dynamics and direction) of technological change on these variables based on the climate policy model REMIND-RS that links a macroeconomic model and an energy system model. Results of a sensitivity analysis show that mitigation costs and strategies are quite sensitive to the dynamics and especially the direction of technological change represented by changes of production factors' efficiency. For example the higher the labour efficiency, the higher are the mitigation costs. Higher energy-related efficiencies can more than compensate this increase of mitigation costs. Moreover, it turns out that energy efficiency improvements in the electricity and transport sector have a much higher impact on the mitigation costs than those in the stationary non-electric sector. The question arises whether the impact of technological change varies in a world with different structural assumptions. The latter is emulated by modifying the elasticity of substitution and by restricting the use of some technologies. It turns out that the sign and intensity of the impacts of technological change are influenced by the scenario world assumed.

JEL classification: E27, O11, O30, Q43, Q54

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1 Introduction

The IPCC Third Assessment Report (AR3) highlights the importance of baseline assumptions of economic development like GDP growth, energy intensity and emissions in determining the economic costs and strategies of climate policies. However, there are only a few studies (Manne [22], Böhringer [3]) that analyse this issue in a systematic way. This paper contributes to fill this research gap. By exploring different scenarios of efficiency growth, the impact of the dynamics and direction of technological change on the costs and strategies of climate change mitigation is qualified and quantified. This investigation is conducted within a scenario framework of alternative assumptions about possibilities of substitution and availability of technologies.

Technological change studied in this paper is characterized by two dimensions - dynamics and direction. The dynamics of technological change represented by overall efficiency improvements determine the economic growth path. While this influences the baseline results of a model, the question arises whether the dynamics also influence the costs and/or strategies of climate policies. This question also applies with respect to the impact of the direction of technological change. In this study, the sensitivity of mitigation costs and strategies is analysed with a particular focus on the impacts of the relationship between labour and energy efficiency improvements.

Mitigation costs describe the costs of countries, regions and the whole world for keeping a given climate stabilization goal and can be measured as consumption losses compared to a baseline scenario without climate policy measures. In intertemporal growth models, these costs are on the one hand driven by the general growth path. If a region grows fast in a baseline scenario, it will have to reduce a huge amount of emissions and might face high mitigation costs in a policy scenario (see Löschel [21]). On the other hand, mitigation costs depend on the innovation capacity and flexibility of the energy system. Assumptions on the growth path of production factors' efficiency affect both drivers of mitigation costs: general macroeconomic growth and technological evolution of the energy system.
Within this study, which analyses the sensitivity of mitigation strategies on the

variation of the dimension of technological change, the primary energy mix of a region is used as an indicator for the chosen strategy. If the whole economy of a region is growing fast, the total energy demand will increase. It is expected that more and also gradually more expensive carbon-free technologies show up in the optimal energy mix of a climate policy scenario (Dowlatabadi [8]). Such changes in the mitigation strategy will be explored in some detail in this paper as well as changes in response to technological change that result in a more labour-intensive or energy-intensive production structure.

Regarding energy specific technological progress, this study explores the impact of exogenous efficiency growth on the mitigation costs and strategies based on a climate policy model that links a macroeconomic model and an energy system model. In climate policy models, improvements in energy efficiency are often represented by aggregated parameters, for example AEEI - the Autonomous Energy Efficiency Improvement (see for example Sanstad [30]). Gerlagh and van der Zwaan [14] included the parameter autonomous energy service efficiency improvement (AESEI) in their sensitivity analysis of mitigation costs. By going a step further, the present paper analyses the influence of variations of exogenous growth and technological change in a model framework that assigns efficiency parameters to each factor of a nested CES production function. Some of these production factors represent end-use energy sectors. Exogenous growth that affects each production factor in a different way mimics biased and directed technological change. In this context, it is of interest, whether an increase of factor productivity results in factor savings or rather in an extended use of the production factor (Nordhaus [27]).
With the exogenous growth assumption explored in this paper, a more or a less energy efficient world can be simulated. This exogenous mechanism of technological change is simple, transparent and ready for sensitivity analysis (Gillingham [15]). All model results depend on basic assumptions about structural elements. The question arises whether the sensitivity on parameter variations changes in a world with different baseline assumptions. A general structural change can be emulated by switching to a value of the elasticity of substitution that shifts the whole model behaviour. This study investigates whether the efficiency of a production factor will play a significant role for mitigation cost estimates and whether this influence depends on the elasticity of substitution. It is also analysed how mitigation cost

impacts of productivity changes vary and how the strategies to achieve a climate target have to be adapted in scenario worlds that differ with respect to the available portfolio of energy technologies.

The structure of this paper is as follows: Within section 2, the applied model REMIND-RS is described. Section 3 explains the dynamics and directions of technological change. Numerical results of a sensitivity analysis on the dimensions of technological change will be discussed. Section 4 highlights the findings from a rerun sensitivity analysis within different scenario worlds. In the first part, the interaction between elasticities of substitution and efficiency growth changes is analysed, while the second part studies the role of technological restrictions. Short conclusions and possible further model developments are discussed in section 5.

2 Model and Scenario Set-up

2.1 REMIND-RS

The model REMIND-RS, which is used for the analysis of this paper, is based on the model REMIND-R. The multi-regional hybrid model REMIND-R[1] couples a macro-economic model, an energy system model and a simple climate model. By maximizing a global welfare function, REMIND-R computes a social planner solution. For a detailed description of the model see Leimbach [20]. For this type of analysis, a fast and flexible model named REMIND-RS has been developed; it includes the complete energy system module and climate module of REMIND-R but has been scaled down from 11 to 5 regions. These world regions are:

- USA - USA
- EUR - EU27
- CHN - China
- INA - Developing regions, less resources
- ROW - Mainly resource exporting regions

[1]The equations are explained at http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/esm-group/remind-code

The region INA includes India, Sub-Saharan Africa, Latin America and Other Asia (Central and South East Asia), while Middle East and North Africa, Japan, Russia and the rest of the world (Canada, Australia, etc.) are part of the region ROW. The parameterisation of REMIND-RS is based on the version REMIND-R 1.3 used in the project RECIPE ([11]).

The production function of REMIND-RS is represented by a nested CES function of the general structure

$$OUT_{t,r} = \left(\sum_{i \epsilon CES} (A_{IN_i,t,r} \cdot IN_{i,t,r})^{\rho_{OUT,r}} \right)^{1/\rho_{OUT,r}} . \tag{1}$$

The output OUT for each region r by each time step t is the sum of the production factor inputs IN multiplied by the associated efficiency parameter A_{IN} to the power of $\rho_{OUT} = (\sigma_{OUT} - 1)/\sigma_{OUT}$, where σ_{OUT} is the elasticity of substitution to produce the output OUT. The list CES assigns the associated inputs IN to each output OUT. The first CES-level combines capital, labour and total final energy. This total final energy is produced by stationary and transport energy which in turn are the result of a CES production function. The whole CES production tree is shown in Figure 1. The elasticities of substitution σ_{OUT} are lower than one in the first two CES-levels, while the production factors of the lower CES-levels are assumed to be complements (i.e. $\sigma_{OUT} > 1$). These values are comparable to the values assumed by Gerlagh ([14]). The default REMIND model applies an exogenous growth path of labour efficiency and energy efficiency change rates which are defined in relation to labour productivity changes. This general exogenously driven growth assumption is in common with many other growth models (for example Nordhaus[26], Manne [23]), thus providing additional relevance to this analysis for the interpretation of other mitigation cost studies.

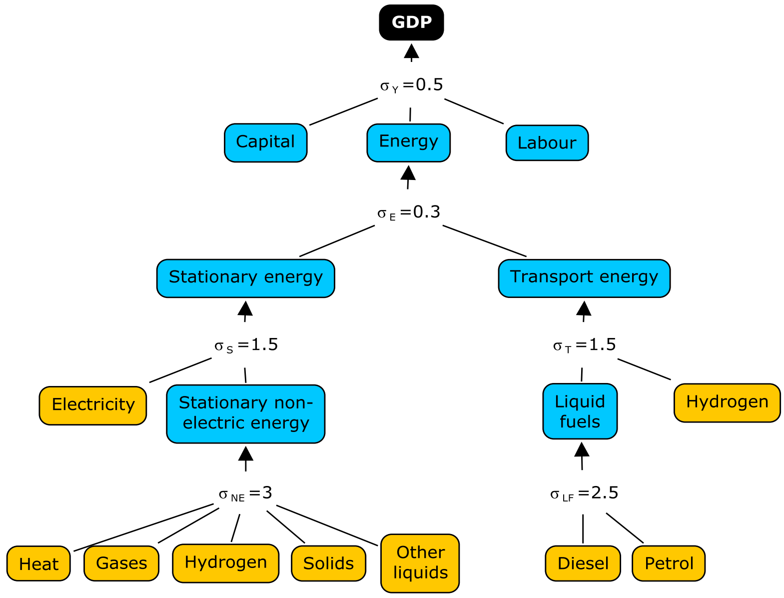
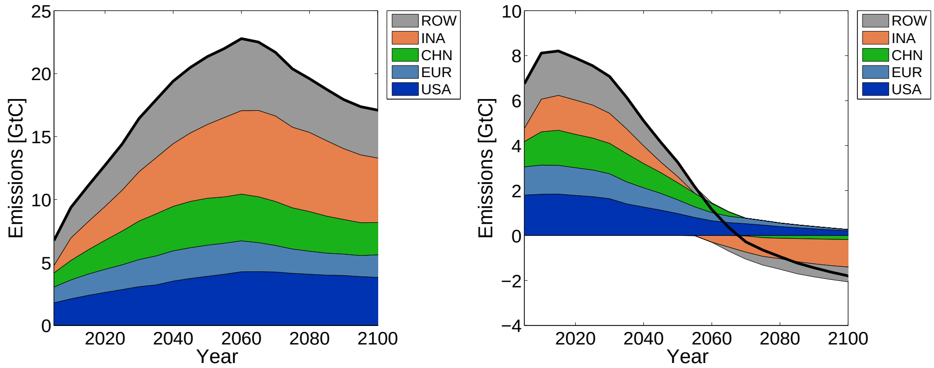


Figure 1: Nested CES structure of the macro-economic module of REMIND-RS

2.2 Default Scenarios

In running a climate policy scenario, REMIND-RS simulates a cap-and-trade climate policy regime that applies a cumulative emission budget as a basis for determining regional caps. A global budget of 300 GtC for 2000-2100 is divided between the regions by the Contraction and Convergence approach (Meyer [25]). Following Meinshausen [24], a global carbon budget is always linked to a likelihood to keep a specific temperature goal.

The regional emissions which sum up to an optimal emission path that holds the emission budget of a baseline scenario without any climate mitigation policy are shown in Figure 2(a), those of a policy scenario in Figure 2(b). This stabilization scenario implies negative global emissions (black line in Figure 2(b)) from 2070 on. This negative emissions are mainly realized by the use of technologies with biomass and CCS.



(a) Baseline scenario

(b) Policy scenario

Figure 2: Emissions of the default baseline and policy scenario

The global GDP grows from 48 trill. \$US [2] in 2005 to 521 trill. \$US in 2100, which classifies the baseline scenario as a high growth scenario.

The applied emissions trading regime (Contraction and Convergence[3]) which implies equal per capita permit allocation from 2050 on provides INA due to its high share of global population with a huge amount of global emission rights. INA can sell parts of these permits profitably to the developed regions.

3 Dimensions of Technology Change - Impacts on Mitigation Costs and Strategies

The model REMIND-RS reflects technological change in the macro-economic production part mainly due to the exogenous growth of the efficiency parameters A_{IN}. In the first part of this section, the impact of the dynamics of overall technological change is analysed. This is represented by a proportional change of all efficiency parameters in the macro and energy demand sector. Within these experiments, the relationship between the different efficiency parameters is kept constant.

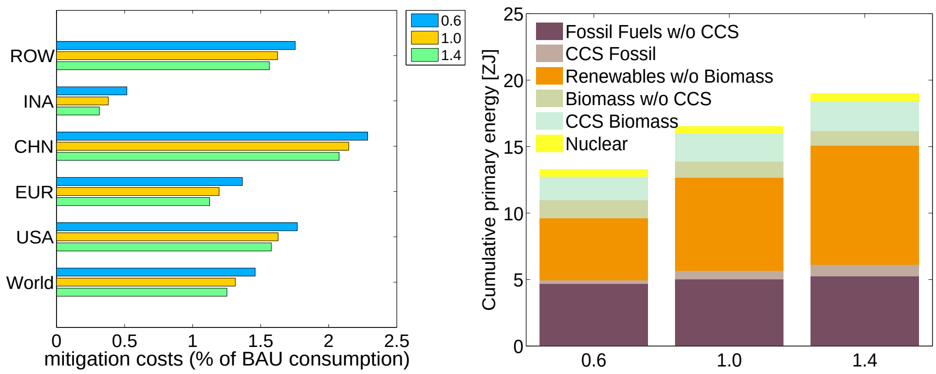
[2] All macro economic values are measured in constant international \$US 2005 (market exchange rate)

[3] First, the emission permits are allocated relative to grandfather emissions and via a linear transition equal per capita emissions for each region assumed from 2050 on.

In contrast, if the efficiency of only one production factor is varied, the relationship of the growth path will change and differently directed technological change can be analysed. The sensitivity of mitigation costs and strategies on this dimension of technological change is studied in the second part of this section.

3.1 Dynamics of Technological Change

To simulate an alternative dynamic of technological change with generally higher or lower growth, all efficiency parameters but the efficiency of capital are multiplied by 0.6, 0.8, 1.0, 1.2, 1.4. Within all these experiments of the sensitivity analysis, the ratio between all efficiency growth parameters is the same as in the default scenario.



(a) Mitigation costs (b) Mitigation strategies

Figure 3: Dynamics variation

Figure 3(a) shows the mitigation costs for the default scenarios (1.0) and an increased/decreased level of technological change - varied by 40% (1.4/0.6). Mitigation costs within this study are defined as the percental consumption difference between a baseline (BAU) and a policy scenario averaged over time. The higher the overall growth, the lower are the costs for all regions to keep the climate target. The cost difference, however, is moderate. The relationship between labour efficiency and total energy efficiency, which remains unchanged, is crucial. The sign of the change of mitigation costs indicate that it is more important for the regions

to be efficient in the energy sectors than it is worse that an increased growth path means a higher amount of emissions to be reduced in the policy scenario.
The higher the (efficiency) growth path, the more primary energy is used. Figure 3(b) shows the global cumulative (over time) primary energy mix for the default policy scenario and the two extreme variations, i.e. 0.6 and 1.4. The high efficiency scenario is associated with a higher share of renewable energies in the energy mix, while the total amount of fossil fuels, biomass and nuclear are nearly the same in all scenarios. Due to the increased carbon price and the level of consumption already reached, it becomes increasingly expensive to use more of these technologies. However, the variation of the dynamics of technological change has a moderate impact on mitigation strategies, mainly increasing the use of renewable energy when assuming a faster growth path.

3.2 Direction of Technological Change

Within the sensitivity analysis, sub-sets of efficiency growth parameters are varied to mimic different directions of technological change. In detail, the efficiency parameters of the following production factors are multiplied by 0.6, 0.8, 1.0, 1.2, 1.4:

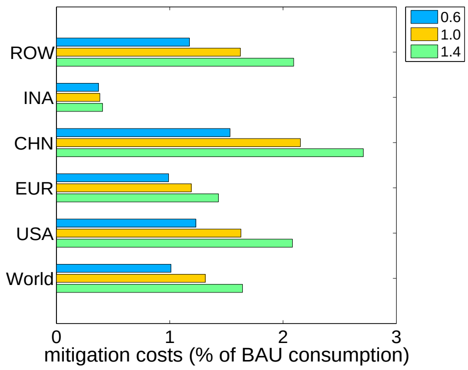
1. Labour
2. Total energy
3. Transport energy
4. Electricity
5. Stationary non-electric energy

The variation of the efficiency of any energy type, which is not at the lower end of the CES-tree, is achieved by varying all related end-use energy types of the lowest CES-level. For example, for the variation of the efficiency of transport energy, the efficiencies of hydro, diesel and petrol are changed (see figure 1).
Since REMIND-RS is a hybrid model, the impact of efficiencies in the macroeconomy and some energy production sectors can be studied simultaneously. It turns out that the variation of all parameters but the efficiency of stationary non-electric energy show a huge impact on mitigation costs. The impact on mitigation

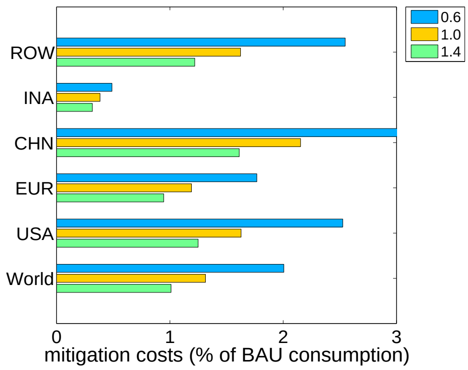
strategies depends on the analysed/changed sector.

3.2.1 Labour and Total Energy

This part focuses on the impacts of the variation of efficiency parameters from the macro-economic part of REMIND-RS, i.e. the first CES-level.



(a) Labour efficiency variation



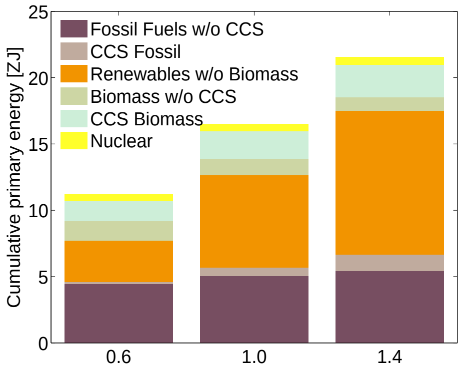
(b) Total energy efficiency variation

Figure 4: Mitigation costs for labour and total energy efficiency variation

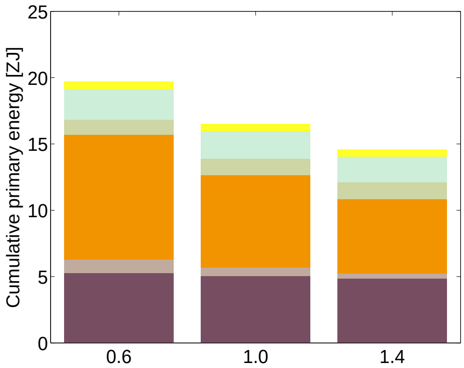
The higher the labour efficiency growth, the higher are mitigation costs for the whole world (see Figure 4(a)). The main reason for this effect is the higher baseline growth and because of this the higher mitigation gap to keep a budget target. When increasing labour efficiency growth, the use of all other production factors is increasing, more capital and total energy (see figure 5(a)) are used. This results in higher consumption, including higher consumption of energy and fossil fuels and because of this in higher emissions in the baseline scenario. The emission gap, which has to be reduced in the policy scenario, develops in correlation with the efficiency of labour. All but the region INA faces additional mitigation costs when multiplying the labour efficiency growth with 1.2 and 1.4 compared to the default experiments. INA gains from the higher demand for emission permits from the other regions and from a higher permit price. The default permit price starts from 50 $US/tC in 2010 and increases to 460 $US/tC in 2050, while the permit price for the high labour efficiency (1.4) scenario starts from 80 $US/tC in 2010 and increases to 810 $US/tC in 2050.

Figure 4(b) shows the impact of the variation of total energy efficiency growth. The higher the total energy efficiency, the lower are the mitigation costs. This is in contrast to the results of labour efficiency variations but these findings are in line with Edenhofer [10]. The impact of higher total energy efficiency can be explained by less energy that is needed to produce the baseline GDP. Because of this and the fact that in the baseline energy is mainly produced based on fossil fuels, the amount of emissions to be reduced in the policy scenario is lower. The increase of total energy efficiency does not induce a general production increasing effect but reduces the use of the production factor total energy. This reaction occurs because of the low elasticity of substitution in the first CES-level and is known as factor saving technological change (Fellner [13]). Given an exogenous population (production factor labour) path to get an optimal share of production factors, the total energy use is reduced. This lower demand for total energy can be met by the use of cheap technologies. In contrast, a reduced productivity of the production factor total energy increases the pressure on the energy system when trying to keep the budget target. The share of renewable and CCS technologies on the cumulative energy mix is increased (see figure5(b)). Technology possibilities and capacities become limited, and it is more efficient to reduce general growth before investing into very expensive low-carbon technologies.

Although the impact of changes in labour efficiency on the emission gap is higher than the variation based on the same percentage variation of total energy efficiency, the latter parameter shows the highest impact on global mitigation costs. The efficiency of energy use seems to be more important for the mitigation costs than the mitigation gap of the emissions. Lowering the total energy efficiency to 60% results in a 52% increase of mitigation costs (see Table 1), while the same reduction of labour efficiency lowers mitigation costs by 23%.



(a) Labour efficiency variation



(b) Total energy efficiency variation

Figure 5: Mitigation strategies of policy scenarios subject to labour and total energy efficiency variation

3.2.2 Energy-related Production Factors

In a simpler way as demonstrated for the impact of efficiency variation of total energy, increasing efficiency of the energy-related production factors from the lower CES-levels reduces the global mitigation costs. As shown in Table 1, only the variation of the efficiency of stationary non-electric energy has a minor impact on the global mitigation costs. All other energy-related production factors are as important as labour efficiency and total energy efficiency for the level of mitigation costs, thus showing the prominent role of the energy efficiency growth path in many production sectors for climate change mitigation.

The small impact of the efficiency parameter of stationary non-electric energy can be explained by the fact that this production factor can be easily substituted ($\sigma_S = 1.5$) by an increase of electricity, which can be produced less carbon intensively. But the other way around, a reduced efficiency of electricity cannot be compensated by a higher use of stationary non-electric energy because of the carbon intensity of this sector. Consequently, it results in significantly higher mitigation costs compared to the default scenarios. Thus, the possibility to decarbonize influences the intensity of the impact of efficiency variations of production factors in the same CES-level on mitigation costs changes.

Table 1: Percentage change of global mitigation costs depending on the variation of the following efficiency parameter

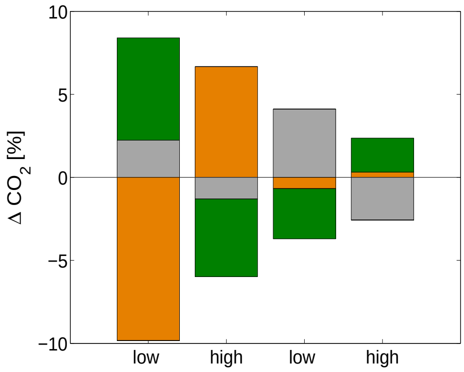
Parameter	0.6	0.8	1.2	1.4
Dynamic	+11.04	+4.26	-2.38	-4.71
Labour efficiency	-23.10	-12.36	+13.14	+25.02
Total energy efficiency	+52.65	+20.61	-13.64	-23.12
Efficiency of transport energy	+27.01	+10.46	-6.37	-10.66
Efficiency of electricity	+23.40	+9.68	-6.74	-11.97
Efficiency of stat. non-elec. energy	+1.58	+0.68	-0.58	-1.13

The reactions of the regional mitigation costs on the parameter variation are in general in line with the global results. Yet INA, in contrast to the other regions, faces higher mitigation costs when increasing the efficiency of transport energy. In REMIND-RS, the transport sector is most difficult to decarbonize. As a result, INA loses its gains from permit exports when the use of transport energy is reduced because of a higher efficiency in this sector.

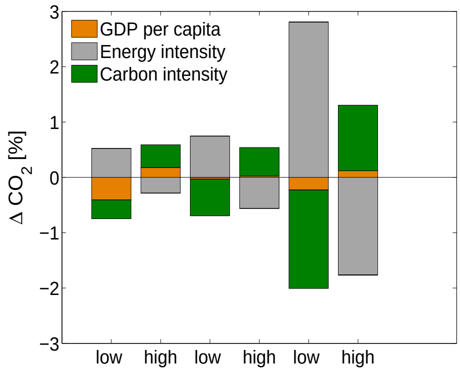
Mitigation cost changes caused by the explored efficiency parameter variations range on the upper end of changes that literature identifies for other kinds of changes in model assumptions and within scenario analysis, e.g. technology availability, climate target (cf. Edenhofer et al. [12]). Comparably high percentage mitigation cost differences are shown by Riahi [28] between SRES scenarios that represent a complex of baseline assumptions and between different climate stabilization targets.

In analysing how strong the mitigation strategies are influenced by the variation of the direction of technological change, a Kaya decomposition (Steckel[31], Kaya[18]) is used. It represents a common tool for studying emission dynamics (e.g. Rogner [29]).
Within the Kaya decomposition, carbon emissions F are split into four terms: Population L, GDP per capita (Y/L), energy intensity of GDP (E/Y), carbon intensity of energy (F/E). It holds the equation

$$F = L\left(\frac{Y}{L}\right)\left(\frac{E}{Y}\right)\left(\frac{F}{E}\right). \tag{2}$$



(a) Left panel labour, right panel total energy



(b) Left panel transport energy, middle panel stationary non-electric energy, right panel electricity

Figure 6: Kaya decomposition of emission differences between policy scenarios with efficiency variation and default policy scenario

Each bar in figure 6 stands for the Kaya decomposition of the difference of cumulative carbon emissions between a default policy scenario and a policy scenario with efficiency variation. Because of the exogenous population path, which is always the same in all scenarios, the contribution of the factor population L is always zero. In a world with high (1.4) labour efficiency mainly an increased GDP per capita causes the increased carbon emissions. However, the carbon intensity is lowered due to an increased use of renewable energies. The other way around, the GDP-effect will mainly reduce emissions, if labour efficiency is lowered. For all the efficiencies of energy-related sectors GDP per capita plays a minor role for the amount of emissions but energy and carbon intensity are important. A low (0.6) total energy efficiency results in an increased total energy use (grey bar) but also an increased share of renewable energy and thereby a lower carbon intensity (green negative bar). So there are two effects influencing the emissions in the opposite direction. This indicates a change of the mitigation strategies: more but less carbon intensive energy. In principle, these results also hold for the variation of the efficiency parameters of the lower CES-levels: the lower the energy related efficiency, the higher the energy intensity and the lower the carbon intensity because of a higher share of renewable technologies in the primary energy mix.

4 Different Worlds - Impacts on Mitigation Costs and Strategies

Two other aspects that determine state and perspectives of technological change will be analysed in the following. This applies first to the elasticity of substitution and second to the availability of energy technologies. As these elements are related to basic model assumptions, changes in these aspects are denoted as different worlds. If such basic assumptions change, what will this mean for the impacts of dimensions of technological change on mitigation costs and strategies? In a world with another elasticity of substitution between some production factors or with reduced availability of some technologies, certain production factors might play a different role in a policy scenario. Because of this, the impact of the variation of the efficiency of production factors on mitigation costs and strategies might change.

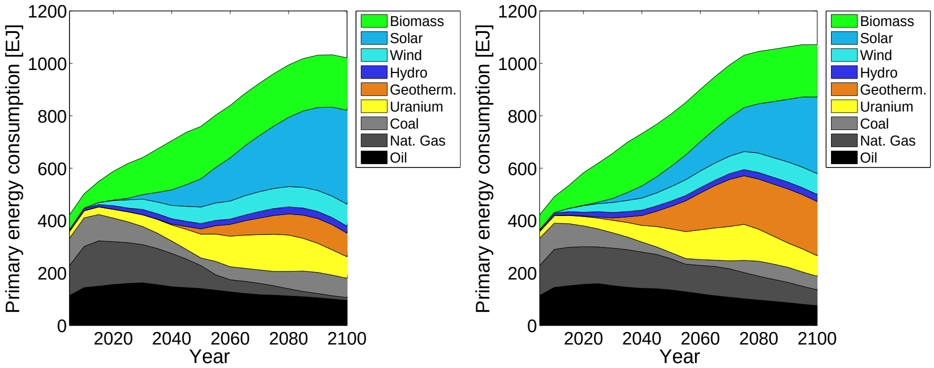
4.1 Elasticity of Substitution

4.1.1 Reference Scenario Setting

This section focusses on the impact of the elasticity of substitution without changing the dimensions of technological change. The assumptions about these parameters influence the whole model behaviour - macro-economic and energy system related. Within this paper, two elasticities of substitution in key CES-levels are changed, i.e. σ_Y and σ_S (see figure1).

The first example is the elasticity of substitution of the first CES-level σ_Y. In literature, there are a lot of empirical analyses which try to estimate this parameter. Most authors indicate an elasticity of substitution less than one (Kemfert [19]), what is in line with the default assumption of REMIND-RS of $\sigma_Y = 0.5$. Burniaux [6] outlines that in the long-run the elasticity between capital and energy is ranging from 0.4 to 1.6. Some authors (Chang [7], Hazilla [17], Watanabe [33]) tend to assume that energy and capital/labour are very good substitutes with an elasticity of substitution greater than one. To analyse the impact of a drastically change, experiments with $\sigma_Y = 1.2$ are run with REMIND-RS.

The elasticity of substitution of the first CES-level has a huge impact on mitigation costs. The higher the elasticity of substitution between labour, capital and energy, the higher the mitigation costs. For $\sigma_Y = 1.2$, mitigation cost amount to 3.1% compared to 1.3% for the default scenarios. With increased elasticity of substitution in the first CES-level capital, labour and energy become very good substitutes. Because of this, the use of total energy (and capital) is increased to overcome the fix labour growth path and create a faster growing economy. This results in the baseline scenario in an increased amount of carbon which has to be reduced in the policy scenario.



(a) $\sigma_S = 1.5$ (b) $\sigma_S = 0.8$

Figure 7: Global primary energy consumption for a default ($\sigma_S = 1.5$) and alternative ($\sigma_S = 0.8$) policy scenario

The second example for a changed elasticity of substitution focuses on the flexibility of the energy demand sector. Literature (e.g. Acemoglu [1]) constitutes that the impact of efficiency variations depends on the elasticity of substitution of all related CES-levels. This effect gets more important when some sectors are based on completely different technologies and energy sources and hence the possibility to substitute production factors by each other is restricted. Even worse, if there are lock-in-effects or path dependencies, fast changes of these technologies will not be possible (Weyant[34], Arthur[2]). This yields in a low elasticity of substitution.

To analyse the impact of a lower flexibility of the energy demand sector due to a reduced elasticity of substitution, additional experiments are run where the elasticity of substitution between electricity and stationary non-electric energy $\sigma_S = 0.8$

instead of $\sigma_S = 1.5$. A low elasticity of substitution between these production factors is in line with other hybrid models like WITCH ($\sigma_S = 0.5$) (see Bosetti[4]). Especially in the stationary energy sector, lock-in-effects are a plausible scenario because of the complex infrastructure of this sector (Unruh[32]).

The elasticity of substitution of the stationary energy sector shows a huge impact on mitigation costs (2.1% instead of 1.3% for the default scenarios). This effect can be explained due to significant changes in the energy mix. Figure 7(b) shows the global primary energy consumption for the policy scenario with reduced elasticity of substitution compared to the default policy scenario (see Figure 7(a)). Because of the limited possibility of substituting stationary non-electric energy by electricity, more expensive technologies like geothermal and natural gas with CCS are used in a more intensive way for the production of low carbon energy in the stationary non-electric energy sector, if $\sigma_S = 0.8$.

4.1.2 Dimensions of Technological Change and Elasticity of Substitution

As shown, the elasticity of substitution plays an important role for the technology choice and therefore the production factor use. The question arises what are the impacts of the dimensions of technological change (dynamics, directions) within an alternative scenario world which assumes different elasticities of substitution? Within this subsection, the sensitivity analysis about the impact of efficiency parameters is rerun for the previous two examples of alternative elasticities of substitution ($\sigma_Y = 1.2$ instead of 0.5 and $\sigma_S = 0.8$ instead of 1.5).
Table 2 shows the percentage change of mitigation costs between the reference scenarios and the scenarios with efficiency variation of total energy, of labour and of all production factors simultaneously (i.e. dynamics' variation). In contrast to the results with $\sigma_Y = 0.5$, changes in the efficiency of labour and total energy affect the mitigation costs in the same direction, if $\sigma_Y = 1.2$: The more efficient the production factors, the higher is the general growth path, the more emissions have to be reduced and the higher are the mitigation costs. The role of total energy efficiency changes because in a world where total energy, labour and capital are

good substitutes, an increased total energy efficiency results in an increased use of this production factor. The exogenous labour growth path is no longer a limiting factor.

Table 2: Percentage change of global mitigation costs depending on the variation of the following efficiency parameter if $\sigma_Y = 1.2$

Parameter	0.6	0.8	1.2	1.4
Dynamics	-23.20	-11.75	+11.42	+23.02
Total energy efficiency	-16.58	-8.17	+6.38	+12.84
Labour efficiency	-9.17	-4.10	+3.76	+8.18

Table 3 shows the percentage change of mitigation costs for the variation of the efficiency of electricity and stationary non-electric energy. The impact of efficiency in electricity use is lowered while the formerly meaningless efficiency of stationary non-electric energy becomes nearly as important as the other energy related efficiency variations. Because electricity is not intensively used for substituting stationary non-electric energy, if $\sigma_S = 0.8$, the efficiency of electricity use is no longer a key parameter for influencing mitigation costs. On the contrary, a decrease of the efficiency of stationary non-electric energy increases mitigation costs substantially, e.g. by 21% for a 40% efficiency growth reduction.

Table 3: Percentage change of global mitigation costs depending on the variation of the following efficiency parameter if $\sigma_S = 0.8$

Parameter	0.6	0.8	1.2	1.4
Efficiency of electricity	+13.23	+5.47	-4.13	-7.37
Efficiency of stat. non-elec. energy	+21.54	+8.76	-6.44	-11.25

These results show that in general the flexibility of the energy use is one of the most important aspects for low mitigation costs. This flexibility might be realized due to a high elasticity of substitution or high energy efficiencies, especially for sectors which can hardly be decarbonized. To create the basic conditions for such a flexible world with low mitigation costs is a challenge for climate change mitigation policies.

4.2 Technology Options

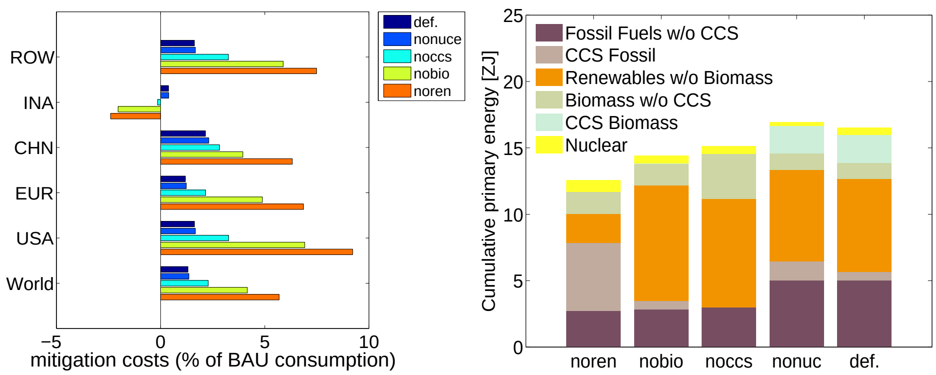
4.2.1 Reference Scenario Setting

The following part of this study looks at another kind of alternative worlds - policy scenarios where the use of some technologies is restricted. The flexibility of the energy system is represented by the availability of technologies.

First, the question is answered what are the most important technologies to meet the emission budget constraint? A few experiments are run in which the supply from the following technologies is restricted to the baseline use:

- nonuc - nuclear energy
- noccs - all technologies with CCS
- nobio - all biomass technologies
- noren - all renewable energies

Within the default parameter, setting the use of renewable energies seems to be the most important technology in a stabilization scenario. The restriction of nuclear energy results only in a small increase of mitigation costs. The whole ranking of technologies (see figure 8(a)), beginning with the least important one, is: nuclear energy, technologies with CCS, biomass technologies and renewable energy technologies.



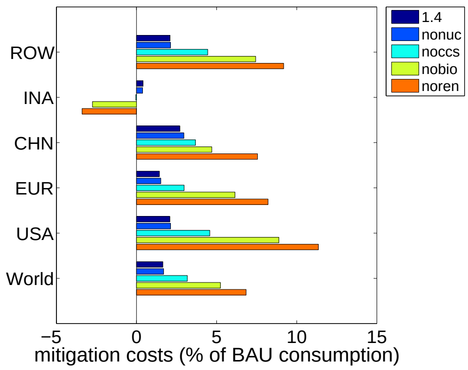
(a) Mitigation costs (b) Mitigation strategies

Figure 8: Technology options default

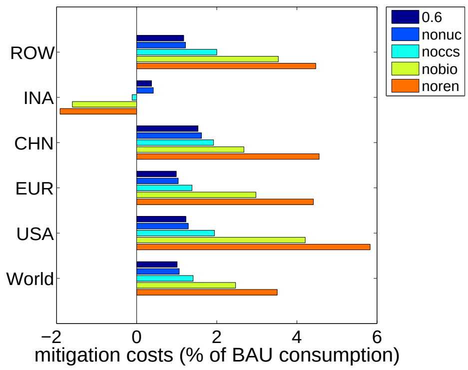
Figure 8(b) shows the cumulative primary energy mix for the default policy scenario and the policy scenarios with restricted use of some technologies. The most drastically impact on the mitigation strategies has the norenew scenario where a big share of energy based on CCS technologies is needed to achieve the climate target.

4.2.2 Dimensions of Technological Change and Technology Options

Within this subsection, the question is addressed whether the impact of the dimensions of technological change will vary, if the use of technologies is restricted to baseline use. If the production structure of a sector mainly depends on a single carbon-free technology and the availability of this technology is restricted, the efficiency parameter of this sector will likely play a key role for climate policies.
The most important technologies for low mitigation costs are based on renewable energies. Figure 9 shows the results for labour efficiency growth multiplied by 1.4 on the left side and multiplied by 0.6 on the right side. Apart from renewable technologies, technologies which use CCS or biomass are highly cost-relevant. This also holds for the variation of the energy-related efficiency parameters.



(a) Labour efficiency high (1.4)



(b) Labour efficiency low (0.6)

Figure 9: Technology options for labour efficiency variation

While it is shown that the world-wide ranking of technologies remains the same as in the default scenario for the variation of the dimensions of technological change, the question will be answered in the following whether mitigation costs and strategies change due to efficiency growth variation depending on the world scenario assumed.

The percentage differences between the reference mitigation costs for the different technology worlds (i.e. default, nonuc, noccs, nobio, norenew) and the mitigation costs within these worlds with an additional variation in the dimensions of technological change are presented in table 4.

Table 4: Percentage change of global mitigation costs depending on the variation of technological change dimensions compared to the corresponding reference scenarios of technological change

Dimension	default	nonuc	noccs	nobio	norenew
1.) Dynamics high	-4.71	-5.22	+1.10	-4.41	-5.22
2.) Dynamics low	11.04	12.01	-1.58	-1.49	+0.79
3.) Labour efficiency high	+25.02	+24.65	+38.86	+25.78	+20.24
4.) Labour efficiency low	-23.10	-21.79	-38.29	-40.70	-38.29
5.) Total energy efficiency high	-23.12	-23.11	-27.68	-26.66	-25.29
6.) Total energy efficiency low	+52.65	+52.53	+61.51	+50.44	45.14
7.) Eff. of transport energy high	-10.66	-10.46	-19.57	-29.37	-25.96
8.) Eff. of transport energy low	+27.01	+26.61	+54.84	+45.90	+32.93
9.) Eff. of electricity high	-11.97	-11.68	-6.76	-6.42	-8.21
10.) Eff. of electricity low	+23.40	+23.26	+14.78	+0.12	+3.34

Although the sign of the change of mitigation costs for each type of efficiency variation stays the same in each technology world (one line in table 4), the impact intensity of variation of technological change dimensions on mitigation costs depends on the technology portfolio.

In a world without using of CCS technologies, the efficiency in the transport sector plays a major role. A reduction of this efficiency to 60% results in an increase of mitigation costs of +55% instead of 27% in a default reference world. If the use of biomass is restricted, a reduced efficiency of electricity will have a minor impact (+0.12%) on mitigation costs in contrast to the default reference world. There are modest differences between default first best scenarios and nonuc scenarios for all dimensions of technological change (first and second column). The impact of total energy efficiency is huge but nearly constant over default and technology scenarios (line five and six).

5 Conclusions

This paper shows that mitigation costs and strategies are quite sensitive to the dynamics and especially the direction of technological change represented by changes of production factors' efficiency. Most essential is the ratio between growth assumed for labour efficiency and some energy efficiencies. As the impact of both types of efficiency is in opposite direction, a simultaneous increase/decrease of both has a moderate effect only. Increasing/decreasing the efficiency parameter of only one type of these production factors, however, changes the costs substantially. A decrease of labour efficiency to 60% of the default value reduces the mitigation costs by 23%, while a decrease of energy-related efficiency parameters reduces the mitigation costs by 2-53%. This impact is at the upper range of what is reported in literature for other variations in model assumptions (e.g. variation of technology availability or climate target).
The mitigation strategies are subject to moderate changes when varying the direction of technological change. Mainly in scenarios with an increased total energy demand, the share of renewable technologies is increased in climate policy scenarios.

In follow-up experiments, the sensitivity analysis was rerun within alternative scenario worlds characterized by modified elasticities of substitution or restricted availability of energy technologies. It turns out that the sign and intensity of the impacts of technological change are influenced by the scenario world assumed. If the macro-economic production factors of the first CES-level are very good substitutes, the impact of both total energy efficiency variation and the dynamics of technological change will affect mitigation costs in the opposite direction as in the default scenarios. The higher the labour efficiency and/or total energy efficiency, the higher are the mitigation costs.
Mitigation cost estimates and mitigation strategies also depend on the elasticity of substitution between the production factors in the energy end-use sector. In scenarios with a lowered elasticity of substitution in the stationary energy sector, more

expensive low carbon technologies are used. The rerun sensitivity analysis shows that the formerly meaningless efficiency variation of stationary non-electric energy becomes more important for mitigation costs. This demonstrates the prominent role of flexibility of the energy demand sector, indicated either by high efficiency or by high elasticity of substitution.
It is finally shown that the impact intensity of parameter variations on mitigation costs depends on the set of available technologies. In a world with restricted use of technologies which use biomass, the efficiency of electricity plays a minor role than in a world without any technology restrictions. The efficiency of the transport sector becomes more important when neglecting the use of CCS technologies.
For climate policies, given the findings of this study, it is essential to support investments in energy efficiency improvements and facilitate structural changes that result in higher substitution possibilities between end-use energy technologies. To avoid high mitigation costs, also a diversification of technologies in the energy production sector is essential.

While this study focuses on the impact of exogenous technological change, its findings detected further research questions. The identified huge sensitivity of mitigation costs estimates to the level and especially the direction of technology improvements requests for an endogenous formulation of technological change. First results of modeling the impact of endogenous technological change on climate policies are presented for example by Griffith [16], Edenhofer [9] and Bosetti [5]. With endogenous growth, for instance based on R&D investments, new framework conditions are set up and new findings might be generated. In such a framework applied to REMIND-RS, the costs for efficiency increase have to be paid by the regions, while the social planner can decide where to increase productivity.

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Chapter 6

Endogenous Sector-specific R&D Investments into Energy Efficiency as Mitigation Option.*

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Endogenous Sector-specific R&D Investments into Energy Efficiency as Mitigation Option

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Abstract

In climate change mitigation analysis the influence of technological change is strongly discussed. This paper deals with the question, when and where energy efficiency enhancing R&D investments play an important role as mitigation option. Therefor the hybrid model REMIND-RS is extended by a new formulation of endogenous sector-specific technological change. Simulation results show that mainly efficiency improvements in the transport and electricity sector play an important role for climate change mitigation. Reallocation of investments form labour efficiency into the efficiency of energy related production factors helps significantly to reduce climate change mitigation costs, especially if the amount of technological options is reduced.

JEL classification: E27, O11, O33, O41, Q43, Q54
keywords: climate change mitigation, endogenous efficiency improvements, R&D investments, endogenous growth

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1 Introduction

Climate change is one of the main challenges to deal with in the next century. In order to avoid dramatic damages due to significantly increased global mean temperature, global carbon emissions have to be reduced. In the literature there are discussed a few mitigation options to meet this task: (i) restructuring the energy production, (ii) creating a carbon free backstop-technology, (iii) production factor substitution, (iv) energy efficiency improvements. Many paper analyse the possibilities and conditions of the first three options. Fischer ([12]) find that an optimal portfolio of policies for reducing CO_2 emissions will include an emissions price and subsidies for technology R&D and learning.
This paper focuses on the fourth option: efficiency improvements, in particular due to R&D investments. As Himmelberg [23] and Weyant [42] indicate, R&D investments have a large impact on energy efficiency development. A mechanism for endogenous efficiency development is introduced in an Integrated Assessment Model to analyse the impacts and constraints of investments into production factor efficiencies, . Thus the question can be answered how to allocate R&D investment when carbon emissions have to be reduced in a climate policy regime. It is expected to be helpful to redirect investments from total factor productivity or labour efficiency to energy related efficiencies, because with a higher efficiency a reduced energy input helps lowering carbon emissions. Gillingham [14] names it as a feature of multi-sector models, to provide insights on the effects of interactions between sectors, such as spillovers - or crowding out - from R&D.
Implementing R&D investments into labour productivity allows to model endogenous economic growth. Most of the models of endogenous growth described in the literature represent macro-economic models which ignore the production factor energy or use a simple formulation of it. For a detailed analysis of climate change mitigation options it is important to look at the interaction between restructuring the energy production and increasing production factor efficiency due to R&D investments. Therefore a model with a detailed energy system and macro-economic part is necessary to answer the question if and when energy improvements triggered by R&D investments represent a key climate change mitigation option. This paper applies such a model - REMIND-RS - which provides the possibility of en-

dogenous R&D investments into the efficiency of labour and as well as different end-use energy types.

This paper is structured as follows: Section 2 describes endogenous technological change as growth factor and how energy efficiency is modeled in the literature. The overall structure and the calibration of the R&D function of REMIND-RS are explained in section 3, while the results of reference scenarios are shown in section 4. Experiments with restricted investments into energy sectors and technology restrictions are discussed in section 5. After a sensitivity analysis in section 6, section 7 concludes the paper.

2 Endogenous Technological Change

2.1 Endogenous Growth

In contrast to the classical growth theory, endogenous growth theory tries to explain technical innovation endogenously. Important literature like Romer [39] and Grossman and Helpman [20] analyses the crucial question about the key drivers for regionally differentiated economic growth and about an adequate design of endogenous growth within a macro-economic model. The main challenge is to find a functional form to describe the impact of knowledge/human capital on the productivity of a related economy. Within the literature, mainly two ways of implementing endogenous growth into macroeconomic models are described. On the one hand the increase of total factor productivity may be interpreted as a result of investments in the knowledge pool of a country. Translating this to the productivity of one production factor means increasing factor efficiency due to R&D investments. On the other hand an additional production factor ”knowledge stock/human capital” may be introduced. Then the investment decisions determine the amount of this production factor (knowledge stock).

There are a few economic models, that implement endogenous growth and technological change by introducing an additional production factor that represents knowledge. ENTICE [36] is an advanced version of the model DICE with the same production function. Technological change comes through changes in the total factor productivity. In addition, effective energy input is modeled as a combination of carbon based fossil fuels and energy related human capital. A scaling factor determines the level of energy savings resulting from new energy knowledge.

The paper from Bosetti et all. [5] about the hybrid model WITCH deals with international energy R&D spillover. Following Popp [36], technological advances are captured by a stock of knowledge and combined with energy in a CES function. This new production formulation simulates the production of energy services demanded by the final good production sector.

The model REMIND-RS, used for the analysis of this paper, is based on the alternative way of modeling endogenous growth via production efficiency instead of introducing a new production factor. Investments can be spent to improve the efficiency of labour or end-use energy sectors. Due to policy interventions, these investments may be directed into different sectors.

Some empirical paper tried to identify evidence for variables (e.g. trade liberalization) explaining growth. Therefore endogenous productivity change is introduced into a model via defining a parameter *A* for total factor productivity in the production function $Y = A \cdot F(L,T)$. The output *Y* is produced by the production factors *L* and *T*, e.g. labour and land. Grossman and Helpman [19] consider a two-sector, two-factor economy and interpret *A* as the stock of knowledge capital.

In trying to explain why some low-income countries show convergence whereas others do not, Greiner and Semmler [16] analysed a growth model with a Coub-Douglas production function where the knowledge capital raises the labour productivity and itself is affected by education efforts.

Within the Integrated Assessment model MIND [8] investments into a R&D sector increase efficiency parameters. In an additional paper Edenhofer et.al. [9] run a sensitivity analysis of the labour and energy efficiency among other important parameter. They find evidence for the influence of R&D investments on macro economic growth as well as the mix of mitigation options.

Griffith et.al.[17] discuss the theoretical literature on Schumpeterian endogenous growth and the empirical literature on R&D. Within a theoretical multi-regional

model with three sectors, the authors analyze the impact of absorptive capacity on R&D investments. The production function of the final good is a Cobb-Douglas function of intermediate inputs and sector specific capital. A multiplied parameter denotes the productivity or quality of intermediate inputs. Productivity changes of intermediate inputs depend on the ratio between the most advanced regional productivity and the regional productivity in the initial time step.
Bosetti et. al. [4] extended a version of RICE 99 by a formulation of the relationship between technological change and both Learning-by-Researching and Learning-by-Doing named FEEM-RICE v.3. They introduce an Energy Technical Change Index (ETCI) which is defined as a convex combination of the stocks of knowledge and abatement.

2.2 Energy Efficiency Improvements

Looking at climate change mitigation from a perspective of an energy system model, the focus lies on technological change. Löschel [30] differentiates between bottom-up and top-down models and an exogenous vs. endogenous formulation of technological change. The exogenous formulation is often represented by aggregated parameters, for example AEEI - the Autonomous Energy Efficiency Improvement- as described by Sanstad [40]. Gerlagh and van der Zwaan [13] included the parameter autonomous energy service efficiency improvement (AESEI) in their sensitivity analysis of mitigation costs.
There are only a few models that represent energy efficiency development endogenously. Das Gopal and Powell [15] model energy efficiency improvements based on embodied technological spillover in the CGE model GTAP. Therefor the authors build on the production technology tree in the GTAP model. Each production level is described as a CES function with a technological progress parameter.
Crassous et.al. [6] envisage endogenous technological change in the recursive dynamic general equilibrium model Imaclim-R to study how modeling induced technological change affects costs of CO_2 stabilization. In this model energy efficiency is a function of historical investments as well as variations of relative prices.
When focussing on technological development, often learning curves are used for

representing technological change. First Arrow [3] described learning by doing as a feature that decreases investment costs due to increasing installed capacity of a technology. Especially in energy system models this approach is used (see Grübler [21] and Rao [38]) and sometimes extended by a learning by research factor in the learning curves as described by Kypreos [28] [1]. Within this paper, the impact of R&D investment into the efficiency of end-use energy efficiency is analysed based on REMIND-RS. These investments do not represent the R&D investments into a single conversion technology but include the whole portfolio of spending into efficiency, which sum up to the efficiency increase of the end-use energy.

3 The Model REMIND-RS

3.1 Overall Structure

For this study the integrated assessment model REMIND-R is used and upgraded by implementing new features of endogenous technological change. This hybrid model couples a macro-economic model, a detailed energy system model and a simple climate model and is based on the multi-regional model REMIND-R[2]. For a detailed description of the model see Leimbach [29]. REMIND-RS includes the complete energy system module and climate module of REMIND-R but has been scaled down from 11 to 5 regions. These world regions are:

- USA - USA
- EUR - EU27
- CHN - China
- INA - Developing regions, less resources
- ROW - Mainly resource exporting regions.

The region INA includes India, Sub-Saharan Africa, Latin America and Other Asia (Central and South East Asia), while Middle East and North Africa, Japan, Russia and the rest of the world (Canada, Australia, etc.) are part of the region ROW.

[1] REMIND-RS assumes learning by doing for wind and solar.

[2] The equations are explained at http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/esm-group/remind-code.

REMIND-RS maximizes a global welfare function and computes an intertemporal optimal regional social planner solution for the time span 2005-2100. The parameterisation of REMIND-RS is based on the version REMIND-R 1.3 used in the project RECIPE ([10]), but with updated data for the solar and wind potential and including adjustment costs for fast extension of technologies.

The production function of REMIND-RS is represented by a nested CES (constant elasticity of substitution) function of the general structure

$$OUT_{t,r} = \left(\sum_{i \epsilon CES} (A_{IN_i,t,r} \cdot IN_{i,t,r})^{\rho_{OUT,r}} \right)^{1/\rho_{OUT,r}} . \quad (1)$$

The output OUT for each region r by each time step t is the sum of the production factor inputs IN multiplied by the associated efficiency parameter A_{IN_i} to the power of $\rho_{OUT} = (\sigma_{OUT} - 1)/\sigma_{OUT}$, where σ_{OUT} is the elasticity of substitution to produce the output OUT. The list CES assigns the associated inputs IN to each output OUT. The whole nested CES tree is shown in Figure 1. All outputs (intermediate outputs and GDP) in the CES-tree represent monetary values. In the first level GDP is the output of a CES function of the production factors capital, total energy and labour. The total energy itself is produced by a CES function, whose input factors are CES function outputs again (i.e. stationary and transport energy). Stationary energy is the result of a CES production function of electricity and stationary non-electric energy while transport energy is a combination of liquid fuels and hydrogen. Sector-specific final energy types represent the bottom end of the 'CES-tree'.The elasticities of substitution σ_{OUT} are lower than one in the first two CES-levels, while the production factors of the lower CES-levels are assumed to be substitutes (i.e. $\sigma_{OUT} > 1$). These values are comparable to the values assumed by Gerlagh [13].

In the new formulation of REMIND-RS, used in this paper, the efficiency development of the following production factors is modeled endogenously and depends on the decision of R&D investments of the social planner: labour L, transport energy T, electricity EL and stationary non-electric energy SNE. The productivities of the other production factors are assumed to keep constant to the calibrated value in

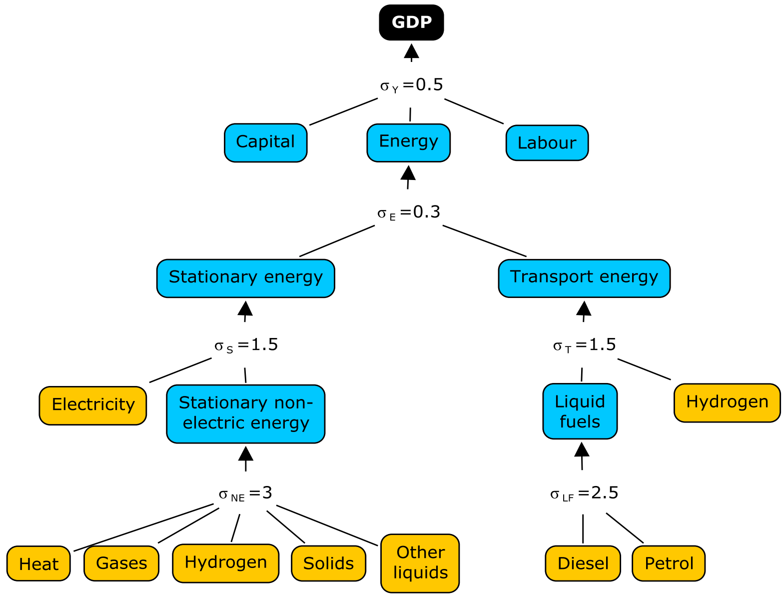


Figure 1: Nested CES structure of the macro-economic module of REMIND-RS

2005. These factor productivities in the first period of the model are calculated to balance the input- and output-values from empirical data.

Beside the endogenous efficiency improvements, REMIND-RS has a second channel for endogenous technological change: global learning-by-doing. The more capacity of solar and wind is installed, the lower are the investment costs.

3.1.1 The R&D Function used in REMIND-RS

The efficiency variables $A_{IN,t,r}$ are subject to R&D investments $RD_{IN,t,r}$ described by

$$A_{IN,t+1,r} = \left(1 + \gamma_{IN,r} \left(\frac{RD_{IN,t,r}}{Y_{t,r}}\right)^{\alpha_{IN,r}}\right) A_{IN,t,r} \tag{2}$$

where $\alpha_{IN,r}$ represents the elasticity of productivity growth on R&D investments and $\gamma_{IN,r}$ is the efficiency of R&D investments for each region r and production

sector IN. This formulation is similar to the R&D function, described by Jones and Williams [27]. For REMIND-RS, it is assumed, that there are no innovation clusters but a complete intertemporal knowledge spillover. Hübler [24] argues that this formulation also follows the Schumpeterian view based on the description by Aghion and Howitt [2]. In addition, the R&D investments in REMIND-RS are normalized by the GDP. Such a R&D function is used in the global model MIND ([8]) for labour and total energy efficiency. This formulation guarantees in a regionalized model that the same share of R&D investments on GDP results in the same productivity increase in each region for the same parameter set of $\gamma_{IN,r}$ and $\alpha_{IN,r}$. Zachariadis [45] refers to Aghion and Howitt [1], who suggest that R&D intensity (per GDP) is the proper empirical measure for the R&D input of the innovation function in the context of endogenous growth models without scale effects.
The sum of all investments into production factor efficiency is financed by the produced output $Y_{t,r}$ and hence part of the budget equation $Y_r + M_r = C_r + I_r + ESM_r + \sum_{in} RD_{in,r}$ that holds for each time step t. The sum of the regional consumption C_r, investments I_r into capital stock, energy system costs EMS_r and all R&D investments equal the output Y_r plus the net import of the composite good M_r.

3.2 Calibration and Data

The literature about the influence of R&D investments on GDP growth finds that R&D investment has a significant positive effect on the growth rate of total factor productivity (Griliches [18]). However, calibration and initialization of the parameter of the R&D function is a key challenge.
In the model REMIND-RS, it is assumed that the parameter $\alpha_{IN,r}$ is not constant over time as it is common in other models, but depends on the level of efficiency of a region $A_{IN,t,r}$. Popp [35] finds that the quality of existing knowledge have strong effects on innovation and Doraszelski ([7]) argues, that in most cases the impact of current R&D on future productivity depends crucially on current productivity. The long-run elasticity of labour related R&D investments is assumed to be $\alpha_{L,r} = 0.1$ in REMIND-RS. This is in line with empirical findings, e.g. Guellec [22] gets a long-term elasticity of business R&D of 0.132. But the elasticity is not constant

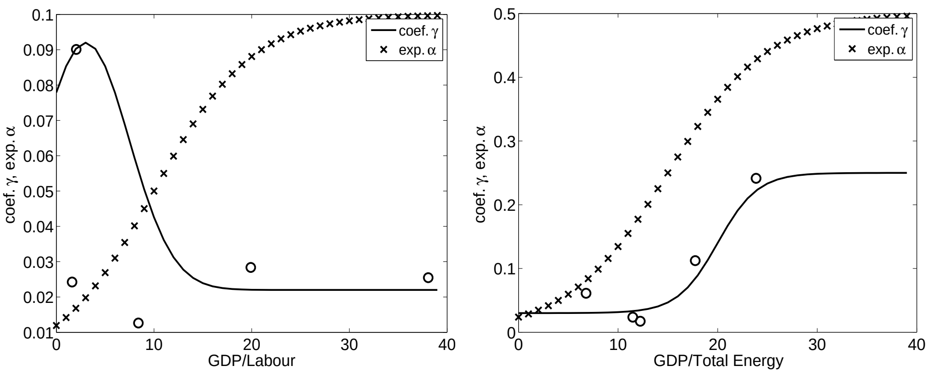
over time. In a region, which is on a very low technological level, R&D investments beyond the optimal level are expected to have a low marginal value, i.e. the absorbtion capacity to employ additional R&D investments has still to be build up. To emulate this situation, for less developed regions the elasticity of R&D investments is assumed to be small and increases with the level of labour efficiency. This is supported by Wieser [43], who finds indication that the elasticity of R&D increases over time. The assumed functional form of $\alpha_{L,r}$ in REMIND-RS is shown in figure 2(a).

The long-run elasticity of energy related R&D investments in REMIND-RS is assumed to be $\alpha_{E,r} = 0.5$. That is higher than the used/choosen elasticity of labour related R&D investments. Jamasb [26] analysed the elasticity of learning by research and gets values between 0.02 and 0.8, depending on the development stages of technologies. Mainly capital intensive technologies like nuclear, wind and solar show a high R&D elasticity. Popp [35] calculates a long-run energy elasticity of 0.42. A sensitivity analysis about the assumptions on the elasticity of R&D investments is presented in section 6.

The calibration of $\gamma_{IN,r}$ is based on the assumed functional relationship for $\alpha_{IN,r}$ and is described by

$$\gamma_{IN,t,r} = \frac{\left(\frac{A_{IN,t+1,r}}{A_{IN,t,r}}\right) - 1}{\left(\frac{RD_{IN,t,r}}{Y_{t,r}}\right)^{\alpha_{IN,r}}}. \tag{3}$$

$\gamma_{IN,t,r}$ is calculated for the time span 1996-2006 based on empirical data for $A_{IN,t,r}$, $Y_{t,r}$ and $RD_{IN,t,r}$. $\gamma_{IN,r}$ is then the arithmetic mean of $\gamma_{IN,t,r}$. To calculate $\gamma_{IN,t,r}$, the efficiency growth of all modeled sectors for all regions would be used. Because of the definition of the efficiency of a sector as OUT/IN, the GDP (Y), labour (L), transport energy (T), electricity (EL) and stationary non-electric energy (SNE) path is needed for all regions . But there is a lack of data for sector specific energy consumption for some regions of REMIND-RS, so the calibration of the R&D function for transport energy, electricity and stationary non-electric energy is based on total energy efficiency. GDP development, population (labour) and total energy for the last decades are used from WDI2010 ([44]). General R&D expenditures (used within the calibration as representation for labour efficiency R&D) are also documented in WDI2010 ([44]) from 1996 on. Data on energy related R&D investments are rare and mainly available for industrialized regions (IEA2007 [25]).



(a) Labour (b) Total energy

Figure 2: Parameter of the R&D function for labour and total energy efficiency

Calibration results suggest that like $\alpha_{IN,r}$, $\gamma_{IN,r}$ is not constant over time, but can be described for all regions by a function depending on the efficiency level. The function for the efficiency of labour related R&D investments indicate, that the region China is on a catching up process with a high efficiency parameter $\gamma_{IN,r}$, while industrialized regions - like Europe and USA now - have a long-run R&D investment efficiency of 0.022 for labour related R&D investments. The used function $\gamma_{L,r}$ depending on the labour efficiency level is shown in figure 2(a). The circles stand for the calibrated initiative values $\gamma_{L,r}$ for the five regions of REMIND-RS based on the empirical data.

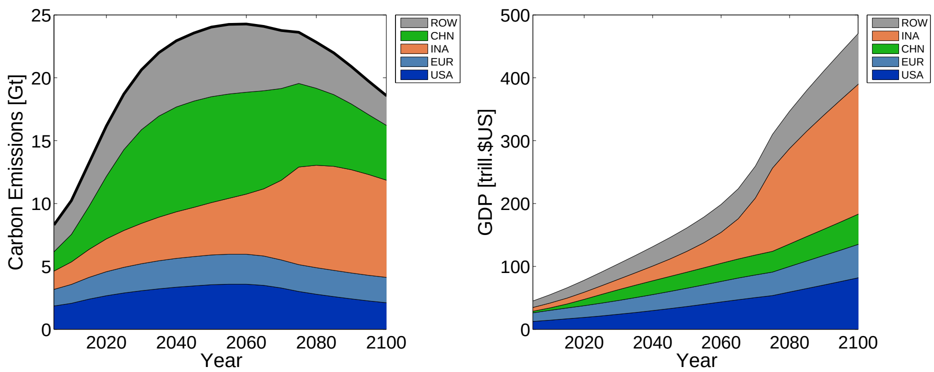
Two functions $\gamma_{IN,r}$ are calculated: one for R&D investments in labour efficiency $\gamma_{L,r}$, and one for all energy related R&D investments $\gamma_{T,r} = \gamma_{EL,r} = \gamma_{SNE,r}$ based on empirical total energy efficiency (i.e. Y/E). In contrast to the function of the efficiency parameter for labour related R&D investments, the efficiency for energy related R&D investments is increasing in the efficiency level and reaches a value of 0.25 in the long-run for industrialized regions. The resulting functional relationship $\gamma_{T/EL/SNE,r}$ depending on the efficiency level is shown in figure 2(b). In the model experiments the same function for the parameters for the energy related sectors are used, but the concrete value depends on the R&D investments of the regions into the respective sector.

In REMIND-RS the region INA plays a special role. It is a heterogenous region, including very low developed countries. It is assumed that INA will not catch up as fast as China do. Therefore all functions for the parameters of the R&D functions are moved to a higher efficiency level. With this transformation, the low R&D shares of the region INA - as shown by empirical data - are met. The resulting growth path in REMIND-RS and the R&D investments into production factor efficiency are discussed in section 4.

4 Reference Scenarios

Within this section, the results of reference scenarios that include endogenous investments into production factor efficiency as described in the former section are shown.

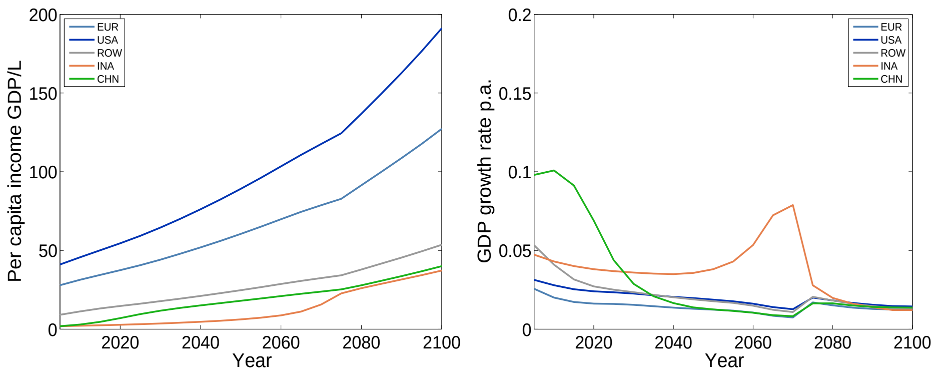
The first reference scenario is a business as usual (BAU) scenario, where the optimal consumption path for all factors and the resulting emissions (see figure 3(a)) are calculated. In such a BAU scenario climate change damage costs are ignored.



(a) Emissions (b) GDP

Figure 3: Carbon emissions and GDP for all regions

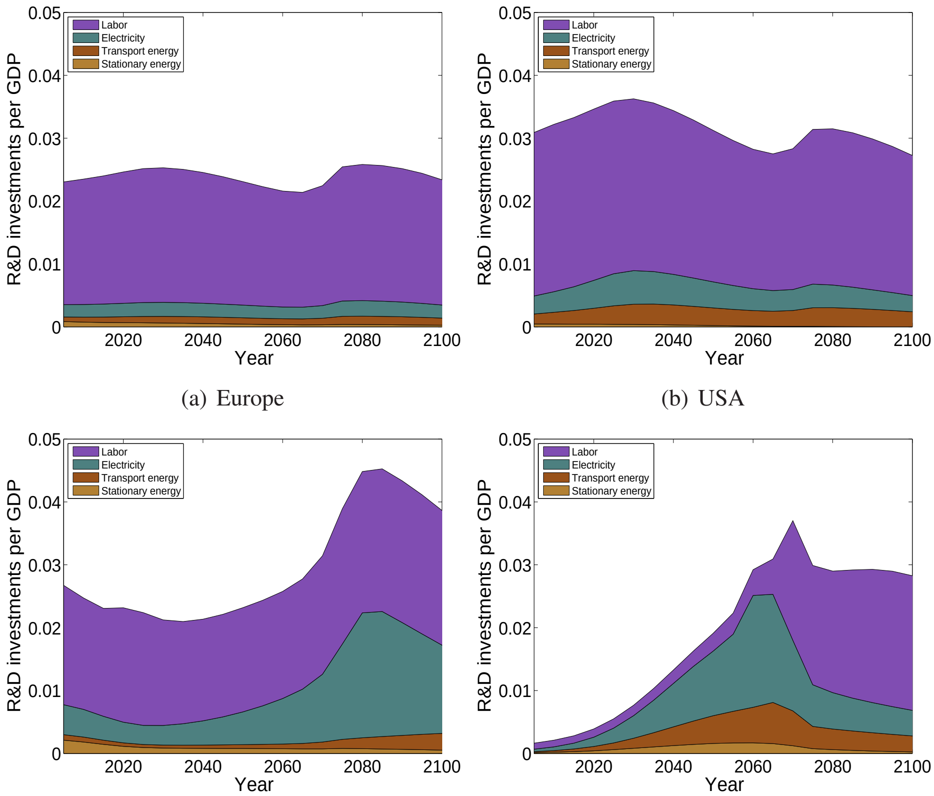
Figure 3(b) shows the GDP path for each modeled region until the year 2100. The global GDP increases from 45 trill.$US in 2005 to 470 trill. $US in 2100. The industrialized regions Europe and USA are growing with a slightly decreasing growth rate o beginning with 3% and ending with 1% in 2100. China starts with a high GDP growth rate of 10%, which falls until 2040 to the level of the industrialized regions (see figure 4(b)). The region INA will realize such a catching up process in the mid of the century. In 2045 the total GDP of INA reaches the GDP of Europe, in 2055 the one of USA. Nevertheless, in terms of per capita GDP, INA is still far behind the industrialized regions. With a delayed increase of GDP growth, it reaches China in 2080 (see figure 4(a)). In the literature about the future GDP development similar growth path are discussed (PWC2011 [37]).



(a) GDP per capita (b) GDP growth rate

Figure 4: GDP per capita and GDP growth rate for all regions

The discontinous GDP growth path for some regions in REMIND-RS is induced by the labour efficiency growth path. This efficiency development depends on the R&D investments and are influenced by the formulation and parameterisation of the R&D functions. Figure 5 shows the R&D investment share per GDP for the regions Europe, USA, China and INA for each sector. The R&D share of the industrialized regions Europe and USA are around 2.5 % of GDP and in line with empirical data (WDI2010 [44]). The R&D investments into the energy related sectors are one-fifth of the investments into labour efficiency. Margolis and Kammen [32] document that the energy sector's R&D intensity is extremely low in comparison to many other sectors. The developing region INA invests a very low R&D share in 2005, similar to the sparse data for developing countries (SEI ([41])), but increases its energy R&D investments to a share of 2.5% in 2065. The R&D share of China is slightly to high in the beginning, compared to empirical data, decreasing until 2030 and increasing again until 2085.



(a) Europe

(b) USA

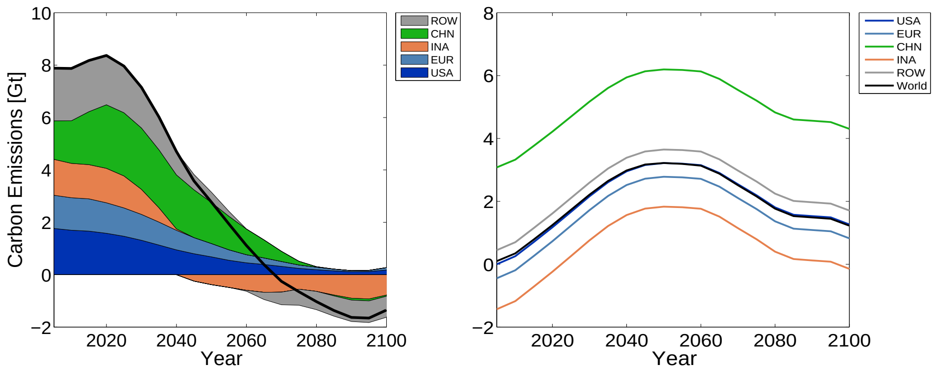
(c) China

(d) INA

Figure 5: R&D investments per GDP, BAU scenario

The second reference scenario is a scenario with a climate policy strategy (POL). The cumulated emissions are not allowed to exceed 300 GtC between 2005 and 2100. Meinshausen [34] showed that each emission budget can be associated with a specific probability to reach a temperature cap. The whole emission budget is allocated in form of tradable permits to the regions via the Contraction and Convergence scheme as described in Meyer [33]. REMIND-RS calculates the optimal use of production factors - especially the regional energy production. Thereby it is guaranteed that CO_2 emissions are reduced first in those regions, where it can be realized at lowest costs. The calculated carbon emissions in the POL scenario are demonstrated in figure 6(a). Keeping the climate target means a steep reduction of emissions as of 2030 and from 2070 on negative emissions.

The costs of climate change mitigation measured as the average percentage dif-



(a) Emissions (b) Mitigation costs

Figure 6: Carbon emissions and mitigation costs for all regions

ference of (regional) consumption between these scenarios amount to 2% of global consumption differences. The costs for the whole time horizon for each region are presented in figure 6(b). China faces the highest mitigation costs of 6.2% consumption losses in 2050, while INA gains from selling emission permits and gets the lowest mitigation costs.

Within a climate policy scenario, energy efficiency plays an important role. To reduce carbon emissions, the energy production has to be restructured based on low carbon/carbon free technologies or the use of final energy has to be optimized by efficiency improvements. In REMIND-RS, climate policy induces investments into renewable, biomass, CCS or nuclear technologies. Moreover, R&D investments into the efficiency of energy related production factors are increased compared to the BAU scenario. Figure 7 shows the difference of R&D investment shares for the regions Europe, USA, China and INA for all production sectors with endogenous efficiency development in the POL scenario. Investments into the efficiency of

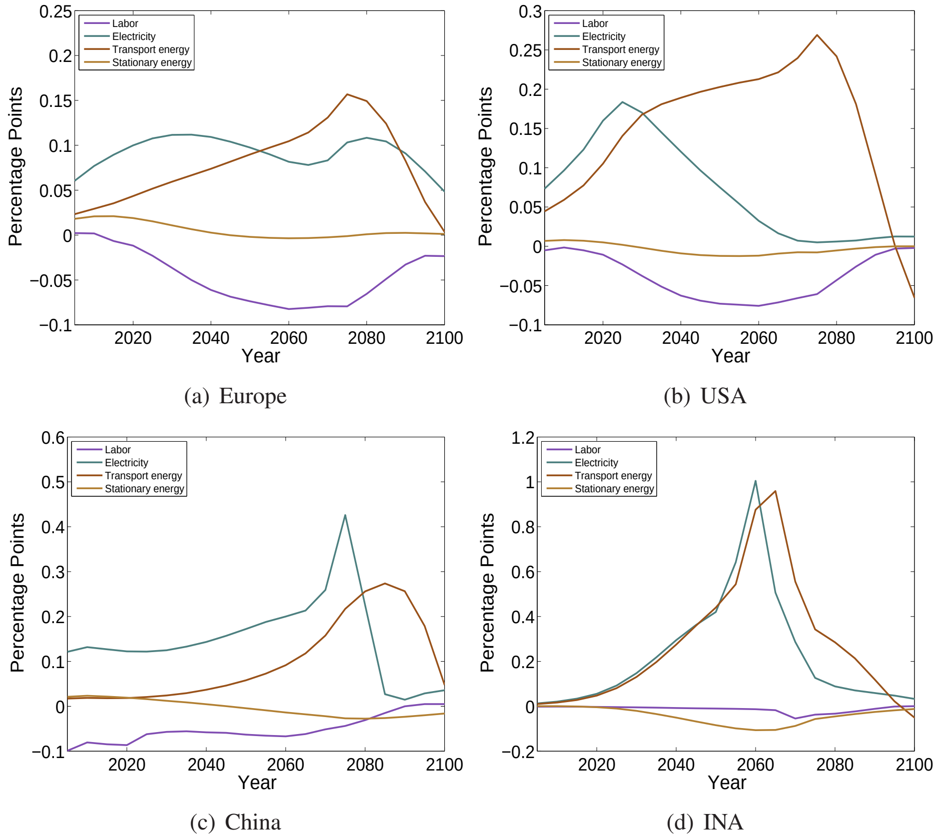


Figure 7: Difference of R&D investment share per GDP in percentage points, POL scenario

electricity and transport energy use are increased in all regions, and especially in INA during the mid of the century. In 2065 the R&D share of these sectors amount to 1.8% compared to 1.2% in the BAU scenario. In the USA around 2020 the investment into the efficiency of electricity consumption is increased and later in the century the R&D investments into the efficiency of the transport sector are intensified.

5 Policy Analysis

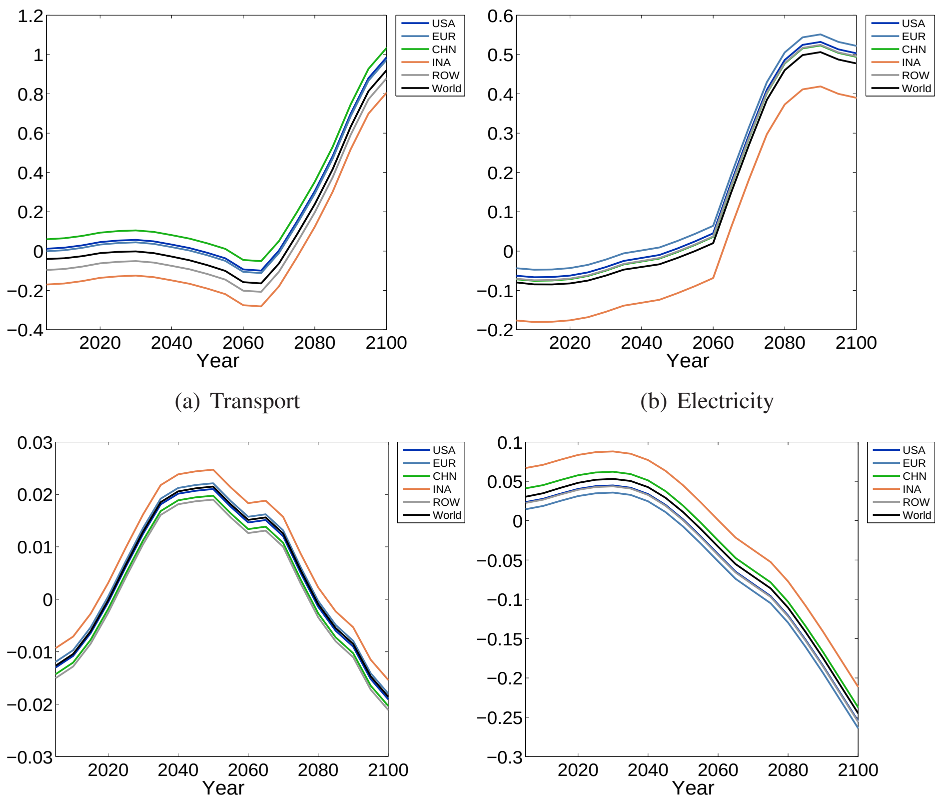
5.1 Energy Sector Experiments

Within the hybrid model REMIND-RS, it is possible to run sector specific experiments. Due to the nested CES production function structure, R&D investments can be directed into different sectors. The question arises, within which sectors R&D investments are most important for climate change mitigation. To figure this out, some experiments are run, where the R&D investments into one sector are fixed to baseline investments within a climate policy scenario. The increase of the mitigation costs denotes the importance of the efficiency of this sector. The R&D sector experiments are labeled as following:

- POL_T - Investments into the efficiency of transport sector are fixed to BAU
- POL_{EL}- Investments into the efficiency of electricity sector are fixed to BAU
- POL_{SNE} - Investments into the efficiency of stationary non-electric energy sector are fixed to BAU
- POL_L - Investments into labour efficiency are fixed to BAU
- POL_E - Investments into all energy sector related efficiencies are fixed to BAU.

The results of the experiments with REMIND-RS show that mainly the R&D investments into the transport sector are important for low mitigation costs. A restriction of the R&D investments into the transport sector increases global costs from 1.99% to 2.11%. The transport sector is the sector, which in REMIND-RS is most difficult to decarbonize by technology options. So the R&D investments in this sector overcome the lack of carbon free technologies.

The R&D investments into the electricity sector also play a key role for low costs of climate change mitigation. In this sector the energy production can be easily generated by low carbon technologies, but electricity is also used to substitute stationary non-electric energy. Therefore the efficiency of the electricity sector is important for climate change mitigation and fixing the investments into this sector increases the costs to 2.12% global consumption losses. Restricting the R&D investments



(a) Transport (b) Electricity

(c) Stat. non-elec. (d) Labour

Figure 8: mitigation costs for the R&D sector experiments

in the stationary non-electric energy sector increases mitigation costs only by 0.01 percentage points. Restricted investments into labour efficiency yield consumption losses of 1.95%.

Figure 8 shows the percentage consumption difference between the reference policy scenario POL and the sector scenarios POL_T, POL_{EL}, POL_{SNE} and POL_L over time. Positive values indicate more consumption in the POL scenario, where all R&D investments are spent in optimal intensity and timing to keep the climate target. If R&D investments in the transport sector are fixed to the investments of the BAU scenario, especially from 2065 on, climate change mitigation policy is more cost-intensive and increase the costs by 1 percent point in 2100 (see figure 8(a)). Restricting the R&D investments into the electricity sector also increases

mitigation costs in the second half of the century. In the first half of the century in a POL_{EL} and POL_T scenario the utility is higher than in the POL scenario, because of less investments into R&D , but in the long-run these early investments are helpful to keep the carbon budget.
Fixing the investments into labour efficiency underlines the substitution effect of these spendings between a BAU and POL scenario. The consumption difference over time is in the opposite direction for labour and energy related sector experiments. In the end of the century the consumption is higher in the POL_L scenario compared to the POL scenario, because in the latter scenario the R&D from labour efficiency is re-allocated into energy related efficiency improvements.

5.2 Technology Experiments

Former studies (Edenhofer [10] [11]) indicated that a broad portfolio of technological options are necessary for moderate mitigation costs especially for low emission stabilization scenarios. In the following the question is analysed, whether R&D investments might compensate the increased mitigation costs if the use of some technologies is restricted. Therefor the following experiments are run:

- $noCCS$ - no technologies with CCS are available
- $noCCS - fixRD$ - no technologies with CCS are available and all investments into efficiency are fixed to BAU
- $noRenew$ - use of renewable technologies restricted to BAU use
- $noRenew - fixRD$ - use of renewable technologies restricted to BAU use and all investments into efficiency are fixed to BAU

Figure 9 concentrates the results of the technological experiments. For most regions R&D investments play an important role for climate change mitigation. This importance is intensified, if the technological options for carbon free energy production are reduced. The global mitigation costs rise by 0.5-3 percentage points if in addition to a technological restriction, the R&D investments are constrained. The noCCS scenario results in global mitigation costs of 3% consumption differences and this is increased to 3.5% for the noCCS-fixRD scenario. Especially restricting the use of all renewable technologies including biomass, wind and solar

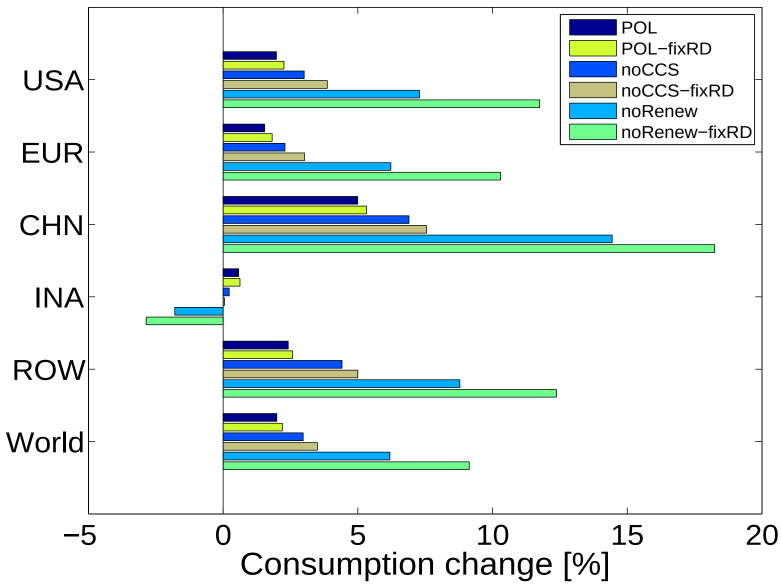
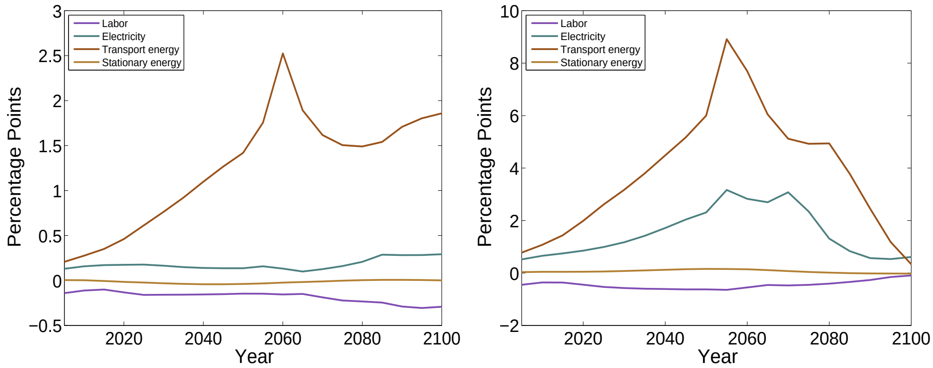


Figure 9: Mitigation costs with restricted technological use and restricted investments into efficiency

results in high mitigation costs. If the R&D investments are fixed to BAU use, the mitigation costs amount to 9.1% global consumption losses. But these costs are lowered by 3 percentage points if endogenous re-allocation of the investments into production factor efficiencies is allowed. These results demonstrate the important role of investments into efficiency in a climate change scenario. The meaning of R&D investments into the efficiency of energy related production sectors increases the more the technological options of the energy system are restricted.

This general pattern holds for all regions but INA. INA is affected in the opposite direction: the higher global mitigation costs, the better for INA. Because of the Contraction and Convergence scheme of the permit allocation, INA is the main permit exporter and gains from a higher permit price due to reduced options in keeping a climate target.

Figure 10 shows the difference of the global R&D investment shares of GDP between the POL and the noCCS and noRenew scenarios. Mainly the investments into the efficiency of the transport sector are increased if technological options are



(a) noCCS (b) noRenew

Figure 10: Difference of the global R&D investments per GDP between technology scenarios and the reference POL scenario

restricted. The share of energy efficiency related investments amount to 4% of the global GDP in 2055 for the noRenew scenario. Such steep increase is feasible and plausible as Nemet and Kammen ([31]) figured out. They analyse data about research and development investments in the energy sector in the U.S. and indicate that a five to ten-fold increase in energy R&D investment is both warranted and feasible. However, the experiments with REMIND-RS simultanously showed that they are also necessary to reduce climate change mitigation costs if technological options are restricted.

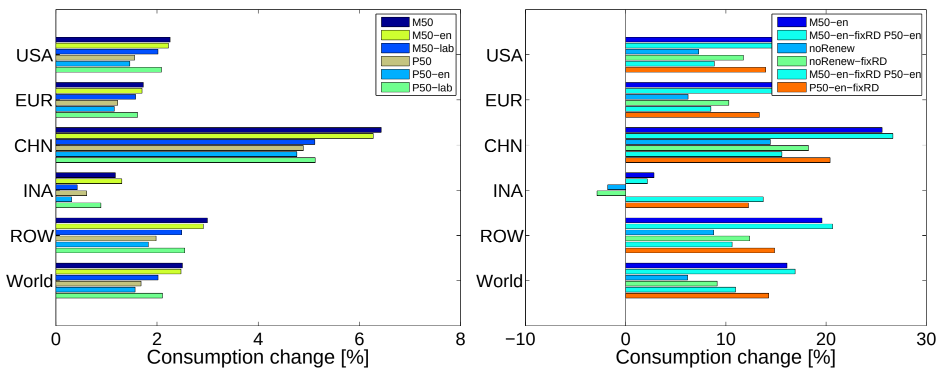
6 Sensitivity Analysis

The calibration routine (see section 4) indicates the long-run elasticity as a crucial paprameter of high uncertainty. Within this section the assumption on the long-run elasticity of the R&D function is varied. The effect of a fifty percentage increase and decrease is analysed. When changing this parameter, also the calibrated function for the second parameter $\gamma_{IN,r}$ has to be adopted. The results indicate that (i) the mitigation costs depend on the parameterisation of the R&D function, (ii) the mitigation costs reducing effect of R&D investments depend on the elasticity of R&D investments and (iii) the R&D share depends on the elasticity of the R&D

investments.

Figure 11(a) shows the consumption difference between the respective BAU and POL scenarios with following changes:

- $M50 - en$ - long-run elasticity of energy related R&D investments lowered by fifty percent
- $M50 - lab$ - long-run elasticity of labour related R&D investments lowered by fifty percent
- $M50$ - long-run elasticity of labour and energy related R&D investments lowered by fifty percent
- $P50 - en$ - long-run elasticity of energy related R&D investments increased by fifty percent
- $P50 - lab$ - long-run elasticity of labour related R&D investments increased by fifty percent
- $P50$ - long-run elasticity of labour and energy related R&D investments increased by fifty percent



(a) Reference (b) noRenew

Figure 11: Sensitivity analysis

The higher the elasticity of energy related R&D investments, the lower are the mitigation cost, while the opposite holds for the R&D function of labour efficiency. The experiments with restricted technological use and fixed R&D investments to BAU use are rerun for a variation of the energy related R&D functions. As demonstrated in Figure 11(b) the effect that due to redirection of investments into efficiency the high mitigation costs can be lowered is smaller. However, R&D investments reduce the global mitigation costs for all parameterizations of the R&D function.

Table 1: R&D share in 2005 in Europe

R&D investments	data	BAU	M50-en	M50-lab	P50-en	P50-lab
labour	1.8	1.9	2.0	1.2	1.9	3.0
energy related	0.4	0.35	0.28	0.38	0.45	0.34

Table 1 compares the R&D shares of Europe in 2005 for the scenario of the sensitivity analysis and the default scenarios with empirical data. The parameterization of the R&D function used for this study are the best fit of the empirical data.

7 Conclusions

This paper uses an Integrated Assessment Model to assess the importance of efficiency improvements induced by R&D investments for climate change mitigation policies. The question is answered, how R&D investments are redirected under a climate change policy regime compared to a BAU scenario.
It is shown that the model of endogenous technological change based on R&D investments in labour efficiency development simulates a plausible scenario of economic growth for industrialized regions, fast growing region like China and developing regions. In scenarios with climate change mitigation policies, aming at keeping a global carbon budget of 300GtC, the R&D investments are re-allocated to further improve the efficiencies of the energy related production factors.
Within sector experiments, where the R&D investments into single sectors are fixed to BAU use, it is figured out, which energy sector gains most from R&D investments. It is found that mainly investments into the efficiency of the transport and electricity sector play a crucial role for lowering mitigation costs, especially in the second part of the century. Without this option the climate change mitigation costs are increased by 0.5-1 percentage points in the end of the century.
If some carbon free/low carbon technologies will not be available in a climate change mitigation scenario, the costs could increase dramatically. If no CCS is available the costs amount to 3% and restricting the use of all renewable technolo-

gies means mitigation costs of 6.2% consumption losses. The technology experiments of this paper indicate that this cost increase is partly compensated by investments into end-use energy efficiency improvements. In comparison with a scenario that fixes R&D investments to BAU scenario use, mitigation costs are reduced by 0.5-3 percentage points.

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Chapter 7

Synthesis and Outlook

This thesis deals with the costs and strategies of climate change mitigation. It investigates the overall research question of what are investment strategies for climate change mitigation. The chapters 2 to 6 answer the questions raised in the introduction of the dissertation (chapter 1.5). Within this chapter the key results are presented and discussed in a comprehensive way. Furthermore, an outlook for further research questions is drawn.

The first part of this synthesis chapter 7.1 presents the results of chapter 2 and 3 of this thesis, which are mainly dealing with investment strategies in an optimal world. Chapter 4 to 6 in addition investigate the investment strategies to reduce GHG emissions in a world with technological or political restrictions. These results are summarized in the second part of this chapter 7.2. In 7.3 all results form chapter 2 to 6 are discussed and an outlook and further research questions are presented.

7.1 Investment Strategies and Technological Spillover in an Optimal World

Technological Spillovers

Chapter 2 focuses on the impacts of technological spillovers and investigates the following questions:

- How do climate change mitigation costs depend on technological spillovers?
- What is the effect of technological spillover bound to bilateral capital trade?
- Are there first-mover advantages or commitment incentives due to technological spillover?

To answer these questions, a multi-regional growth model named MIND-RS is developed. This model adopts a multi-regional extension of MIND with separated investment good sector. It the structure, the energy system and endogenous technological change by R&D

investments from the global Integrated Assessment model MIND (Edenhofer [4]). MIND-RS as well includes technological change by interregional spillovers. These spillovers are bound to bilateral capital trade. Within an iterative algorithm a cooperative solution is calculated.

The model experiments show that in the presence of spillovers that affect labour and energy efficiency, two opposite effects impact climate change mitigation costs. On the one hand, a growth effect increases mitigation costs. On the other hand, mitigation costs are reduced by energy efficiency improvements. The ratio between the spillover intensities that either increase energy or labour efficiency determines the mitigation costs. The higher this ratio, the lower are the costs.

As well, the results indicate that due to the link of energy technological spillover to foreign capital imports, a new climate change mitigation option is introduced. The trade volumes are much higher in spillover scenarios as compared to non-spillover scenarios. Moreover, this results in higher relative capital and carbon prices in a scenario with endogenous technological change. Capital exporting regions like USA and Europe profit from these improved terms-of-trade.

In MIND-RS experiments, energy efficiency advantages pay off in climate policy scenarios, supporting the hypothesis of benefits for forerunners. It turns out that the first-mover advantage increases with an increase in the efficiency of domestic R&D investments into labour efficiency. Thereby, labour-efficiency enhancing capital imports become less attractive, while energy-efficiency enhancing capital imports appear more attractive.
The model results from scenarios with embodied technological spillovers indicate an incentive for single regions to join a climate policy coalition. It turns out that restrictions on technology transfers induce developing regions to take part in a climate policy regime.

MIND-RS is a model with a small energy system part, but models the technological change including spillover in detail. For climate change mitigation, also the investment strategy into single technologies is adopted. Therefore a more complex IA model is developed in chapter 3.

Investment Strategies into Technologies and Impacts of Policy Regimes

The detailed investment decisions in the energy system are the focus of chapter 3 and the following questions are answered:

- What are the optimal long-term investments in the energy system for climate change mitigation?
- How differ mitigation costs and strategies between different world regions?
- What are the mitigation costs under different climate policy regimes?

For the exploration of these questions a multi-regional hybrid model called REMIND-R is developed. It couples a macro-economic growth model, a detailed energy system model and a simple climate model. The nine world regions are linked by trade in goods, resources and emission permits. REMIND-R is run in a cost-effectiveness mode, maximizing global consumption under climate policy restrictions. The energy system module involves more than 50 different transformation technologies. Technologies are bound to capacities, which constrain the production potentials. Primary energy technologies produce secondary energy types, which are transformed into final energy.

The numerical analysis demonstrates that investments into the energy system are adopted for climate change mitigation. In general, the entire energy consumption is reduced while renewable energy technologies are expanded immediately. CCS technologies are used in combination with the conversion of gas and coal into electricity. The production of fuels and gases is lowered and the use of low-value energy sources like solids and other liquids is reduced.

As well, the results show that the different regions follow quite different strategies to reduce carbon emissions. In the short-term, the increase in primary energy consumption is lower in the industrialized regions. In the first half of the century, the share of fossil fuels is decreasing in all developed regions, while the share of renewable and nuclear energy increases. Japan relies on nuclear energy and USA substitutes nuclear energy technologies as of 2050 by converting coal into electricity with CCS. The regions with high potentials in renewable energy sources exploiting them to a high degree. The middle-eastern regions will employ their huge potential of solar energy while Russia has high potentials in biomass. China and India base their future energy production on using nuclear technologies and CCS in coal-fired power plants. Ambitious climate targets can be reached with global costs amounting to approximately 1.5% of the global gross product. Regions with high shares in exports of fossil fuels bear the highest costs. The region named MEA for example faces more than 9% consumption losses. Developing regions like Africa might benefit from a global climate policy regime due to in net benefits under climate regimes compared to buiseness-as-usual scenarios.

In addition, it is underlined that the regional mitigation costs significantly depend on the amount of emissions that have to be reduced in a world region. The regional burden of emission reductions is influenced by the design of the policy regime, i.e. the emission permit allocation scheme. For example, a contraction and convergence scenario gives incentives for Russia to join a climate regime while the developing regions Africa and India gain from a multi-stage approach. For the rest of the modeled regions the variance of mitigation costs is rather small. Moreover, the variance of mitigation costs between the regions is higher than between the policy regimes.

Chapter 2 and 3 analyze investment strategies mostly in first best worlds. Chapter 4 to 6 in addition deal with worlds with political or technological restrictions.

7.2 Second Best Worlds and Investment Strategies

Early Investments into Renewable Energy Technologies

The impacts of early investments into renewable energy technologies in first-best and second-best worlds are studied in chapter 4 and the following questions are answered:

- How do mitigation costs increase due to delays of implementing emission caps at the global level?
- Can near-term public support of renewable energy technologies contain these increases?
- What are the effects of an early support of renewable energy technologies on regional mitigation costs?

To answer these questions, again the multi-regional hybrid model REMIND-R is used. It is extended with some small features. The regional solution in chapter 4 includes eleven world regions. For the analysis a broad portfolio of different policy scenarios is run. Investment strategies into renewable energy technologies are calculated in first-best climate change mitigation scenarios that stabilize at 410, 450 and 490 ppm by 2100. These investment strategies are used in delayed climate policy scenarios to emulate early or late support of renewable energy technologies.

The model experiments show that climate change mitigation costs increase significantly if the climate policy implementation is delayed. After 2020 a rapid and enormous reduction of emissions has to be realized. Therefore, new fossil fuel investments are shifted towards biomass technologies with CCS.

In addition, it is demonstrated that under delayed climate policy, early deployment of renewable energy technologies reduces the global costs for achieving a 450ppm CO_2 concentration target. This can be explained by the devaluation of emission permits due to three effects: (i) some fossil fuels are replaced by renewable energy technologies, (ii) the significant and negative shift of investments from fossil fuels to biomass technologies with CCS in 2020 is contained and (iii) additional investments into renewable energy technologies will get cheaper because of a learning-by-doing effect. However, the global mitigation costs can not be reduced below the first-best scenario.
In a scenario with immediate climate policy, a deviation from the optimal investment strategy into renewable energy technologies increases the global mitigation costs slightly. But the results show a significant effect on the timing of mitigation costs. The less than the optimal deployment of renewable energy technologies, the higher the mitigation costs peak around the mid of the century.

The results indicate that the variation of mitigation costs between regions is high in both cases in immediate and delayed climate policies. The US and Europe always gain from a strong deployment of renewable energy technologies. If climate policies are delayed, China gains from some early deployment of renewable energy technologies. But if immediately a climate policy is introduced, China loses from early investments. The developing regions, e.g. India, Africa, lose from an early renewable energy technologies deployment in both immediate and delayed climate policy scenarios.

The analysis of this section is based on an eleven-region IA model with a very complex energy system module. In the following research study, a numerically faster model version is prefered.

Dimensions of Technological Change

Chapter 5 deals with dynamics and directions of technological change and investigates the following questions:

- What are the impacts of different dynamics and directions of technological change on climate change mitigation costs and strategies?
- How does the impact of technological change vary under different elasticities of substitution between the production factors?
- How does the impact of technological change depend on the availability of energy technologies?

The study presented in chapter 5 is based on the hybrid model REMIND-RS. This is a five-regions version of the hybrid model REMIND-R. It adopts the macro-economic structure, the detailed energy system and the simple climate module. The impacts of the exogenous parameter of efficiency development are analyzed in a comprehensive sensitivity analysis.

The numerical experiments indicate that mitigation costs and strategies are quite sensitive to the dynamics and especially the direction of technological change. The ratio between the growth of labour and some energy efficiencies plays a key role. These efficiency developments influence the mitigation costs in the opposite direction. Simultaneous changes of labour and energy efficiencies have only a moderate effect. But a decrease of the efficiency of the single production factor labour to 60% decreases mitigation costs by 23%. A decrease of energy related efficiency parameters result in a mitigation cost increase by 2 to 53%.

As well, it turns out that the sign and the intensity of the impacts of technological change are influenced by the scenario world assumed. Experiments in which the macro-economic production factors of the first CES-level are very good substitutes in contrast to the assumed default low elasticity of substitution are studied. There is evidence that the dynamics of technological change affect mitigation costs in the opposite direction, i.e. the higher the labour efficiency and/or total energy efficiency, the higher are climate change mitigation costs. Additional experiments with a lowered elasticity of substitution in the stationary energy sector are analyzed. It turns out that this results in more expensive low carbon technologies. Thereby, the meaning of the efficiency of the stationary non-electric energy sector for mitigation cost is increased.

Further experiments indicate that the impact of different dynamics and directions of technological change depend on the set of available technologies. For example the efficiency of electricity plays a minor role in a world with restricted use of biomass technologies compared to a world without any technological restrictions. The efficiency of the transport sector becomes more important if no use of technologies which use CCS are allowed.

These results highlight the importance of the efficiency development of production factors for climate change mitigation costs and strategies rising further research questions on endogenous efficiency improvements.

Endogenous Technological Change

The role of endogenous technological change for climate change mitigation and the following questions are analyzed in chapter 6:

- When and where do R&D investments into production factor efficiency play an important role as climate change mitigation option?
- Can the increased mitigation costs under limited technological options be compensated by a re-allocation of investments into efficiency of energy related production factors?

For the analysis of this questions, an extended version of the REMIND-RS model is used. Into this five-region hybrid model endogenous technological change due to production factor efficiency improvement is introduced. For comparing the impacts of R&D investments into different production factors, the possibility of direct investments into labour efficiency or some end-use energy efficiency sectors is implemented. The change of efficiency depends on the efficiency level of the investing region.

The model experiments demonstrate that endogenous R&D investments into labour efficiency mainly determine the macro-economic growth path. In scenarios with climate change mitigation policies, the R&D investments are re-allocated to further improve the efficiencies of the energy related production factors. Climate policy experiments, in which the R&D investments into labour efficiency or some end-use energy production factors are fixed to baseline spendings show that these investments affect mitigation costs in the opposite direction over time. It is found that mainly investments into the efficiency of the transport and electricity sector play a crucial role for lowering mitigation costs, especially in the second part of the century. The mitigation costs would increase by 0.5 to 1 percentage points, if no re-allocation of R&D investments into end-use energy related productivities in a policy scenario is allowed for.

In a climate change policy scenario, the restricted use of some low carbon technologies increases the mitigation costs significantly. If no CCS is available the costs amount to 3% global consumption differences. Restricting the use of all renewable energy technologies results in global mitigation costs of 6.2%. The experiments in chapter 6 show that these dramatical mitigation costs can be lowered by the re-allocation of R&D investments into end-use energy sector efficiencies. In comparison with a scenario that fixes R&D investments to BAU scenario use, mitigation costs are reduced by 0.5 to 3 percentage points.

All questions identified in the introduction of this thesis are answered within the chapter 2 to 6. The following section summarizes these results and discusses them in a comprehensive way.

7.3 Discussion and Further Research

Within this section, the results of chapter 2 to 6 are discussed. The common features and methods will be highlighted and some limitations of the numerical approach will be presented. Thereby future research question are identified.

Discussion

The answers on the questions investigated in chapter 2 to 6 give a broad picture for the answer on the overall research question: What are possible investment strategies for climate change mitigation? The results of chapter 3, 5 and 6 demonstrate that a rich portfolio of technologies is necessary for low emission reduction costs. Regional mitigation strategies are significantly different and depend on the advantages of technologies and resources of some regions. In addition, regional mitigation costs show drastical differences depending on the assumed permit allocation rule. Chapter 4 highlights that the investments into low carbon technologies, respectively renewable energy technologies like wind, solar and biomass should start early in the century. Especially if no global climate change mitigation regime is installed immediately, early investments into renewable energy technologies avoid dramatic mitigation costs in the second part of the century. Furthermore the development and ratio of labour efficiency and energy efficiency improvements have a high impact on mitigation mitigation costs and strategies. This is pointed out in chapter 5. Chapter 6 shows how important R&D investments into production factor efficiencies are. Especially sectors which are hardly to be decarbonized gain from investments into technological change and thereby climate change mitigation costs are reduced. In addition, this chapter demonstrates that a re-direction of R&D investments from labour efficiency to energy related technological improvements helps to overcome the increased mitigation costs under technological restrictions. Another feature of endogenous technological change is analyzed in chapter 2 of this thesis. Technological spillovers bound to bilateral capital trade shows a significant impact on climate change mitigation costs. As well, this feature provides first mover advantages for some industrialized regions and incentives for developing regions to join a climate policy regime.
Jointly, the findings of this thesis demonstrate the important role of investment strategies for climate change mitigation costs. The world gains from early investments into both a broad portfolio of technologies and into energy efficiencies. Thereby the immediate support and high diversity of investments mainly provide decreased costs of GHG emission reductions.

All models used for the analysis are regional optimization models that maximize a global welfare solution. This type of model provides some advantages and also some limitations. The different models presented in chapter 2, chapter 3 and chapter 5 and 6 focus on different aspects of climate change modeling. Therefore, they are specialized and partly ignore features for answering questions from other chapters. The best model might be one that includes all advantages of the presented models. Yet, until now such a big and heavy model would exceed the numerical capacities. However, the specialized models are constructed to answer the raised research questions. REMIND-R for example is a hybrid model with a highly detailed energy system module. This is important for the analysis of the questions answered in chapter 3 and 4. REMIND-RS includes less world regions than REMIND-R but provides an endogenous formulation of technological change. Nevertheless, an extension of the existing models is part of future research.

The presented models assume perfect markets and perfect intertemporal foresight. Thereby a benchmark solution with benchmark climate change mitigation costs are created. All decisions - including investments into technologies, production factor use, etc. - incorporate the optimal behavior of all regions at each time step. This approach tends to

decrease the mitigation costs by optimally investing in most promising long-term mitigation mechanisms. Chapter 4 to 6 partly leave this perfect world by including exogenous restrictions. However, these experiments still assume perfect foresight and react to the exogenous restrictions in an optimal way. In addition, all used models ignore any strategic behavior of regions, firms or investors. For such investigations usually smaller models based on game theory are used. The hybrid models of this thesis include too many variables, because of the detailed energy system and high regional solution for the analysis of strategic behavior.
As for all models holds that the empirical foundation is sometimes problematic. Key data about capital stocks, investments and capacities of technologies can easily be found for industrialized regions. But for a more detailed regional resolution, sometime different data sources have to be used. Moreover, the empirical foundation of some specific parameters is small. The elasticity of substitution between labour, capital and energy for example has a big impact on mitigation costs but quite impossible to estimate from data. As well, only space data exist for parameters needed for implementations of endogenous technological change (Bosetti [2], Keller [7], Verdolini [13]).
The atmospheric climate change problem is always facing some uncertainties - uncertainties about the radiative forcing, climate sensitivity, and tipping points. The models used in this thesis are run in a cost-effectiveness mode, which ignores all costs of climate change. So the model results provide a benchmark world. The exogenous bound on emissions or a temperature cap is introduced to avoid dramatical climate change. However, a complex climate uncertainty would exceed this thesis. First results about the implications of mid-century targets keeping long-term climate policy targets are presented by O'Neill [10]. Held et.al. [6] investigate the impacts of uncertainty in four key model parameters.

The discussed advantages and limitations indicate further questions for future research analysis. A few examples are presented in the following section.

Outlook and Further Research

The results of this thesis answer different aspects of the overall research question, but as well further questions are identified. Some research questions call for extensions of the used models or need alternative solution algorithms. In the following, a few examples are discussed.

The demonstrated models use a simple transport module but the results indicate that especially this sector plays an important role for the level of mitigation cost. Further research with an extended transport sector including electricity transport is needed. Then, the investment strategies in this sector and the importance of R&D investments into efficiency improvements of this sector can be identified.
As well, a more detailed analysis of the interactions between regional investment strategies into technologies and R&D investments into factor efficiency developments is needed. Therefore, a model with endogenous technological change and a high regional solution should be developed. Research questions dealing with the impacts of high R&D investments for developing regions could be analyzed with such a model. Perhaps climate change mitigation investments are the key variables that result in economic divergence of industrialized and developing regions. Thereby also technological spillovers may show

important effects on climate change mitigation costs. Some IA models for climate change analysis (Bosetti [1], Crassous [3], Kypreos [8]) use a more detailed formulation of the endogenous technological change including absorptive capacities or spendings separated for innovation and imitation. More empirical research is needed for a better foundation of the model formulations for endogenous technological change.

Beside the possibility for installing new features of describing effects in a more detailed formulation, also the solution algorithm might be changed to investigate further questions. Especially if spillovers or other externalities are taken into account in a climate change analysis, an alternative solution algorithms are needed. Further research questions are: When will a region join a climate coalition? What is the regional amount or emission reductions, if no global climate regime is installed? How can a free-rider-effect be overcome? Answering these research questions implies to leave the assumption of a benchmark solution under optimal conditions. The strategic behavior of a country can be calculated if the welfare of each country is maximized independently of global welfare effects. A few studies are dealing with the identified research questions (Lessmann [9], Flachsland [5]).

In addition there is a research domain analyzing uncertainty in climate change models. These experiments might be run in a cost-benefit mode, where the costs of climate change mitigation and climate change damages are compared and the cheapest mitigation level is calculated (e.g. Pizer [11], Tol [12]). Alternatively, a Monte Carlo Analysis can be used to study uncertainty implications. However, in numerical experiments with different solution algorithms, endogenous technological change might play a different role. Further research for example might investigate the question, whether the optimal share of R&D investments depends on the uncertainty about climate sensitivity.

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Statement of Contribution

The chapters of this thesis are the result of collaborations between the author of this thesis and her advisor, Prof. Dr. Ottmar Edenhofer, involving additional colleagues as indicated. In particular, the chapters dealing with technological change (Chapters 2, 5 and 6) were developed in close collaboration with Marian Leimbach.

The author of this thesis has made significant contributions to the contents of all five papers, from conceptual design over technical development to writing. This section details the contribution of the author to the five papers and acknowledges major contributions of others.

Chapter 2 The conceptional design and writing of the article has been undertaken by Marian Leimbach. The author of this thesis contributed to the numerical experiments, their implementation and execution, and processing of model results and their visualization in the graphs of the chapter.

Chapter 3 The model REMIND-R used in this chapter is based on the model MIND, mainly developed by Nico Bauer. Marian Leimbach was responsible for the conceptional design and writing of this article. The author of this thesis contributed to the development of the model, the numerical experiments, their visualization and interpretation. Ottmar Edenhofer contributed by framing the research question and in extensive discussions.

Chapter 4 The conceptual design and writing has been undertaken by Nico Bauer. The author of this thesis contributed to framing the research question and specifying the scenarios. She was responsible for most of the numerical experiments, their implementation and visualization. In addition, the author gave inputs to some sections of the paper. Marian Leimbach was involved in the definition of the research question as well as the editing process.

Chapter 5 The author was responsible for the conceptual design and writing of the article. As well, she developed the used model REMIND-RS based on the REMIND-R model. The model experiments are run by the author. Frequently therefor the multi-run environment SimEnv was used. The author was responsible for the visualization and interpretation of the results. Marian Leimbach contributed to the conceptual design of the article, designing the numerical experiments and provided editing as well as some text inputs.

Chapter 6 The extension of the model was implemented by the author. As well, she was responsible for framing the research question, constructing the numerical experiments, their visualization and writing the article. Marian Leimbach contributed to the conceptual design of the article, designing the numerical experiments and provided editing as well as some text inputs.

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Tools and Resources

This thesis relies mainly on numerical modeling and a number of software tools were used to create and run the model experiments. In addition, tools for the analysis and visualization of the results are used. This section lists these tools.

Modeling All model experiments performed by the author made use of the General Algebraic Modeling System (GAMS), version 22.7.2 [1] and the CONOPT3 solver, version 3.14S [2], for non-linear programs. The multi-run environment SimEnv, versions 1.15–2.01 [3], was used partly.

Data processing Model output was analyzed using The MathWorks' MATLAB, version 2007b [4] and the NetCDF Toolbox for MATLAB by Charles R. Denham.

Typesetting This document was prepared using LaTeX[5], particularly the pdfpages package [6] to include Chapters 2 to 6 in their given layouts.

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