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The Economics of Decarbonizing the Energy System – Results and Insights from the RECIPE Model Intercomparison

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Abstract. This paper synthesizes the results from the model intercomparison exercise among regionalized global energy-economy models conducted in the context of the RECIPE project. The economic adjustment effects of long-term climate policy are investigated based on the cross-comparison of the intertemporal optimization models ReMIND-R and WITCH as well as the recursive dynamic computable general equilibrium model IMACLIM-R. A number of robust findings emerge. If the international community takes immediate action to mitigate climate change, the costs of stabilizing atmospheric CO_2 concentrations at 450 ppm (roughly 530-550 ppm-e) discounted at 3% are estimated to be 1.4% or lower of global consumption over the 21st century. Second best settings with either a delay in climate policy or restrictions to the deployment of low-carbon technologies can result in substantial increases of mitigation costs. A delay of global climate policy until 2030 would render the 450 ppm target unachievable. Renewables and CCS are found to be the most critical mitigation technologies, and all models project a rapid switch of investments away from freely emitting energy conversion technologies towards renewables, CCS and nuclear. Concerning end use sectors, the models consistently show an almost full scale decarbonization of the electricity sector by the middle of the 21st century, while the decarbonization of non-electric energy demand, in particular in the transport sector remains incomplete in all mitigation scenarios. The results suggest that assumptions about low-carbon alternatives for non-electric energy demand are of key importance for the costs and achievability of very low stabilization scenarios.

Keywords: Climate Change Economics, Climate Change Mitigation, Integrated Assessment Modeling

CES : Constant Elasticity of Substitution production function

EMF : Stanford Energy Modeling Forum

IAM : Integrated Assessment Model

IPCC : Intergovernmental Panel on Climate Change

RECIPE : Report on Energy and Climate Policy in Europe

1. Introduction

The evidence that the earth's climate is changing is widely recognized, and its scientific basis has also become increasingly robust (IPCC 2007a). If climate change remains unmitigated, global warming due to the anthropogenic greenhouse effect could become as high as 5°C or more, relative to pre-industrial levels (IPCC 2007a). Despite this daunting prospect, so far very little progress has been made in reducing emissions. Emission growth has even accelerated over the largest stretch of the past decade, mostly due to rapid economic growth in emerging economies (Raupach et al. 2007). Despite the discontinued growth in global emission in 2009 resulting from the financial crisis (Olivier and Peters 2010), scenarios of future development in a world without climate policy project significant increases of CO_2 emissions, largely driven by further economic growth (IPCC 2007b).

Integrated assessment modeling has been the method of choice for assessing costs of climate change mitigation and the associated transformation of economic systems. In its Fourth Assessment Report (AR4), Working Group III of the IPCC surveyed a total of 177 climate mitigation scenarios from the recent literature (Fisher et al. 2007). Coordinated model comparison studies considered in the AR4 include the 21^{st} Stanford Energy Modeling Forum (EMF-21, Weyant et al. 2006) and the Innovation Modeling Comparison Project (IMCP, Edenhofer et al. 2006). The focus of the EMF-21 was on the assessment of multigas climate stabilization pathways. IMCP focused on the role of endogenous technological change for the costs of climate change mitigation. Further coordinated studies that were conducted after the AR4 include EMF-22 and ADAM. In EMF-22, a total of 10 IAMs were used to study the impact of international climate policy architectures on the achievability of climate targets of 550ppm CO_2-eq and 450 ppm CO_2-eq (Clarke et al. 2009). The focus of the ADAM project was on costs and achievability of very low stabilization targets and their dependence on technology availability (Edenhofer et al. 2010; Knopf et al. 2009).

While model intercomparison projects such as the EMF exercises with a large number of participating models provide a good representation of the breadth of pertinent IAM approaches and results, they are inevitably limited in the possibility to explore differences between results from individual models in detail. For the present RECIPE study, three state-of-the-art quantitative energy-economy models were used to run a variety of scenarios for which baselines were harmonized with respect to socio-economic parameters and assumptions on fossil-fuel availability. In addition to the default scenarios which assumed an optimal policy setting, so called ‘second-best scenarios’ with either limited availability of low carbon technologies or a delay in the setup of a global climate regime are explored. The dedicated papers by Tavoni et al. (this issue) and Jakob et al. (this issue) explore these second-best scenarios in detail. A special focus of the study is on the attribution of differences in model results to model-specific structural differences, the analysis of transformation processes by energy end-use sector, and the consequences of climate policies for investment decisions.

The paper is structured as follows. In Section 2, the three participating energy-economy-climate models are described and the RECIPE model comparison framework is introduced. Section 3 presents results, both in terms of energy system dynamics and macro-economic effects in response to climate policy. Moreover, sectoral results are shown and interpreted. A concluding discussion follows in Section 4.

2. The RECIPE model comparison

2.1. Three Energy-Economy-Climate Models

We used the three state-of-the-art numerical energy-economy models IMACLIM-R (Sassi et al. 2010; Waisman et al. this issue), ReMIND-R (Leimbach et al. 2010; Bauer et al., this issue) and WITCH (Bosetti et al. 2006; DeCian et al., this issue) to analyze economic and technological implications of ambitious climate mitigation policy. These hybrid models are characterized by a comprehensive top-down representation of the macro-economic processes complemented by a technologically explicit bottom-up representation of energy systems.

An overview of the model characteristics is provided in Table 1. IMACLIM-R (Sassi et al. 2010) is a recursive computable general equilibrium model capturing explicitly the underlying mechanisms driving the dynamics of technical parameters, structural change in demand for goods and services and micro- as well as macro-economic behavioral parameters. The model considers open economies with international trade of all goods and CO_2 permits. A major feature of IMACLIM-R is the partial use of production factors (underused capacities, unemployment) due to sub-optimal investment decisions resulting from the interplay between inertia, imperfect foresight and 'routine' behaviors. Thus it is possible to distinguish between potential and realized economic growth, and, more specifically, to capture the transitory costs resulting from unexpected shocks affecting the economy. In IMACLIM-R, climate policies can be a means of remedying market failures and implementing no-regret options which are profitable in the long term but which would not be taken in the absence of policy intervention due to myopic behavior. This property can also result in 'bi-stability' in the sense that (a) initially large efforts are required to move the system from its current path (i.e. fossil based) to an alternative one (i.e. low-carbon) but (b) little extra effort is required once it is located on this new trajectory thanks to the long-term economic benefits of climate policy in terms of lower dependence on fossil fuels.

The global multi-region model ReMIND-R as introduced by Leimbach et al. (2010) represents an inter-temporal energy-economy-environment model which maximizes global welfare based on nested regional macro-economic production functions. ReMIND-R incorporates a detailed description of energy carriers and conversion technologies (including a wide range of carbon free energy sources), and allows for unrestricted inter-temporal trade relations and capital movements between regions. Energy system costs are based on technological opportunities and constraints in the development of new energy technologies. By embedding technological change in the energy sector into a representation of the macroeconomic environment, ReMIND-R combines the major strengths of bottom-up and top-down models. Economic dynamics are calculated through inter-temporal optimization, assuming perfect foresight by economic agents. This implies that technological options with large up-front investments and long pay-back times (e.g. via technological learning) are taken into account in determining the optimal solution.

The WITCH model (Bosetti et al. 2006; Bosetti et al. 2007; DeCian et al. this issue) is a regional model in which the non-cooperative nature of international relationships is explicitly accounted for. The regional and intertemporal dimensions of the model make it possible to differentiate climate policies across regions and over time. In this way, several policy scenarios can be considered. WITCH is an intertemporal optimization model, in which perfect foresight prevails over a long term horizon covering the whole century. The model includes a wide range of energy technology options,with different assumptions on their future development, which is also related to the level of innovation effort undertaken by countries. Special emphasis is placed on the emergence of carbon-free backstop energy technologies in the electricity as well as the non-electricity sectors[1] and on endogenous improvements in energy efficiency triggered by dedicated R&D investments contributing to a stock of energy efficiency knowledge.

[Table 1 about here]

2.2 The model comparison framework

There is substantial variance between model results as to the costs and achievability of ambitious climate policy targets (IPCC 2007b; Clarke et al. 2009). For integrated assessment models (IAMs), the uncertainty about the properties of the energy-economic system becomes manifest both with respect to the choice of parameters that are exogenous to the models (e.g. incomplete knowledge with regards to economic and technology parameters used to calibrate the models), and with respect to model structure (i.e. representations of interactions between model-endogenous variables, and conceptual theory applied). Carrying out model comparison exercises in order to explore and reduce model uncertainty is an often-used concept in climate economics (see e.g. Edenhofer et al. 2006; Weyant et al. 2006; Clarke et al. 2009; Edenhofer et al. 2010). In this context, one should be clearly aware that models are representations of key relationships between quantitative phenomena that are endogenous to the model and other phenomena taken to be outside the domain of the model. Models are intended to generate plausible, self-consistent scenarios, which are always conditional to the assumptions. These scenarios, in turn, are a useful way for scientists and policymakers to explore the scope of possible developments,

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[1] The backstop technologies are characterized by unlimited resource potential. Their costs are very high initially.

discuss the plausibility of underlying assumptions, and derive appropriate courses of action.

In order to improve the comparability of the model results, the three models employed here were harmonized to represent similar assumptions with regard to socio-economic developments. Over the course of this century, global population is assumed to peak at around 9.5 billion in 2070 and stabilize at roughly 9 billion in 2100. Models were calibrated such that they project world GDP to grow at an average rate of 2.1% to 2.4%, resulting in year 2100 income levels which are between 8 and 10 times their 2005 value[2]. Although to a lesser extent, regional growth rates of GDP were also aligned. Also, short and medium term cost development of fossil fuels was harmonized under the assumption of large and cheap abundance of coal and relative scarcity of oil and gas. The long-term development of fossil fuel prices, however, depends strongly on technology pathways and therefore deviations between models were allowed.

[Table 2 about here]

While macroeconomic drivers were largely harmonized, different visions of development and diffusion of new technologies as well as different structural assumptions about the economic system remain across the three models. A substantial number of common scenarios were generated (Table 2). The baseline scenario represents the business-as-usual development (i.e. projections of future emissions if no climate policy measures are implemented). For the climate policy scenarios, the models were run in a cost-effectiveness mode, i.e. models were forced to meet the prescribed climate target. Damages from climate change, by contrast, were not included in the analysis.

A target of stabilizing atmospheric CO_2 concentrations at 450 ppm was considered for the default policy scenarios. As a sensitivity study, each model performed a scenario run with a climate mitigation target of 410 ppm CO_2-only . In terms of total greenhouse gas concentration, the 450 ppm CO_2 target

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[2] These underlying assumptions are very similar to those employed in CCSP (2007) which (depending on the model) assumes a world population between 8.6 and 9.9 bn in 2100 and average annual GDP growth between 2.3% and 2.5% over the 21st century. WEO (2008) assumes population growth of 1% per year and annual GDP growth of 3.3% for the period 2006-2030, whereas in RECIPE the world population grows at 1% and global GDP at between 3.1% and 3.4% in the respective time period. See Jakob et al. (2009) for more detailed information

corresponds to about 530-550 ppm CO_2-eq, and the 410 ppm CO_2 target to about 490-510 ppm (Fisher et al. 2007). While the CO_2-Emissions from fossil fuel combustion are calculated endogenously, exogenous assumptions on emissions from land-use change and forestry were made. For all models, emissions from deforestation were assumed to follow those of the IPCC SRES A2 marker scenario (Nakicenovic et al. 2001).

The climate policy target was prescribed for the year 2100, but can be exceeded during the century (i.e., overshoot). For ReMIND-R the overshoot for the 450 scenarios was limited to 470 ppm in until 2065 and prescribed to decline linearly to 450 ppm in 2100. A reduced-form climate model based on Petschel-Held et al. (1999) is used in ReMIND-R to simulate how CO_2-emissions translate to increases in atmospheric CO_2 concentrations and changes in global mean temperature. WITCH employs MAGICC 3-box layers climate model as described in Nordhaus and Boyer (2000), where parameters have been updated to Nordhaus DICE 2007[3]. For IMACLIM-R, which is not an optimization model, a carbon price path is determined such as to match closely the emission trajectory of the WITCH model.

The default 450 ppm policy scenarios as well as the 410 ppm sensitivity study can be considered first-best climate policy scenarios since the full portfolio of low-carbon technologies was assumed to be available, and the existence of a fully functional global carbon market by 2010 was assumed. In addition two groups of so-called second-best scenarios are explored (Table 2), both of which consider the same 450 ppm CO_2 mitigation target as the default policy scenario. In the first set, deployment of key low-carbon energy technologies is restricted to the baseline level (Tavoni et al., this issue). In the fixRET scenario, deployment of all energy conversion technologies based on renewable energies, including biomass and the generic backstop technologies considered in WITCH, is constrained to the baseline level. In order to isolate the respective role of biomass, the fixBIO scenario assumes biomass availability to be constrained to the baseline level. In the fixNUC scenario it is assumed that nuclear energy cannot be expanded beyond baseline level. The noCCS scenario explores climate policy in absence of carbon capture and storage. Finally, the noCCS/fixNUC scenario combines the restrictions of the latter two scenarios: CCS is assumed to be unavailable, and nuclear energy is restricted to baseline levels. The setup of the fixRET, fixNUC and noCCS scenarios is similar to that of scenarios conducted in the context of the ADAM project (Edenhofer et al. 2010). All five technology-constrained scenarios follow the same logic: By restricting their deployment to the baseline level, the marginal contribution of technology options or groups of technology options to climate change mitigation can be explored. The increase in mitigation costs induced by these restrictions can be interpreted as "option values" of these technologies, and provide an indication of their importance for achieving the prescribed mitigation target.

The second set of constrained scenarios considers the 450 ppm climate mitigation target under a delay in the setup of an international climate policy regime (Jakob et al., this issue). The first scenario explores a delay of climate policy in all world regions until 2020[4]. All regions are assumed to follow the baseline development until 2020 myopically, i.e. without anticipating the future climate target. In a second scenario, Europe is assumed to act unilaterally until 2020, with myopic business-as-usual trajectories for all other regions. In the third scenario, Europe is assumed to be joined by the other industrialized countries. In the final scenario all industrialized countries along with China and India start climate policy immediately, while other developing non-Annex-I countries join in 2020. The scenarios chosen allow us to explore how global and regional costs of climate change mitigation evolve in stylized fragmented regimes, and to analyze the consequences of inaction.

The objective of the current analysis is to provide the broad picture of the variability of climate policy costs under a wide range of assumptions. Comparing the results obtained for the baseline as well as stabilization scenarios with these three models hence helps to shed some light on how different assumptions on technologies and economic dynamics translate into differences in mitigation costs, carbon prices, and investment patterns.

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[3] http://nordhaus.econ.yale.edu/DICE2007.htm

[4] Delay until 2030 was also considered but no model was able to find a solution given the steep path of reduction required to comply with the stabilization goal.

3. Results

3.1 Socio-economic drivers of emission growth

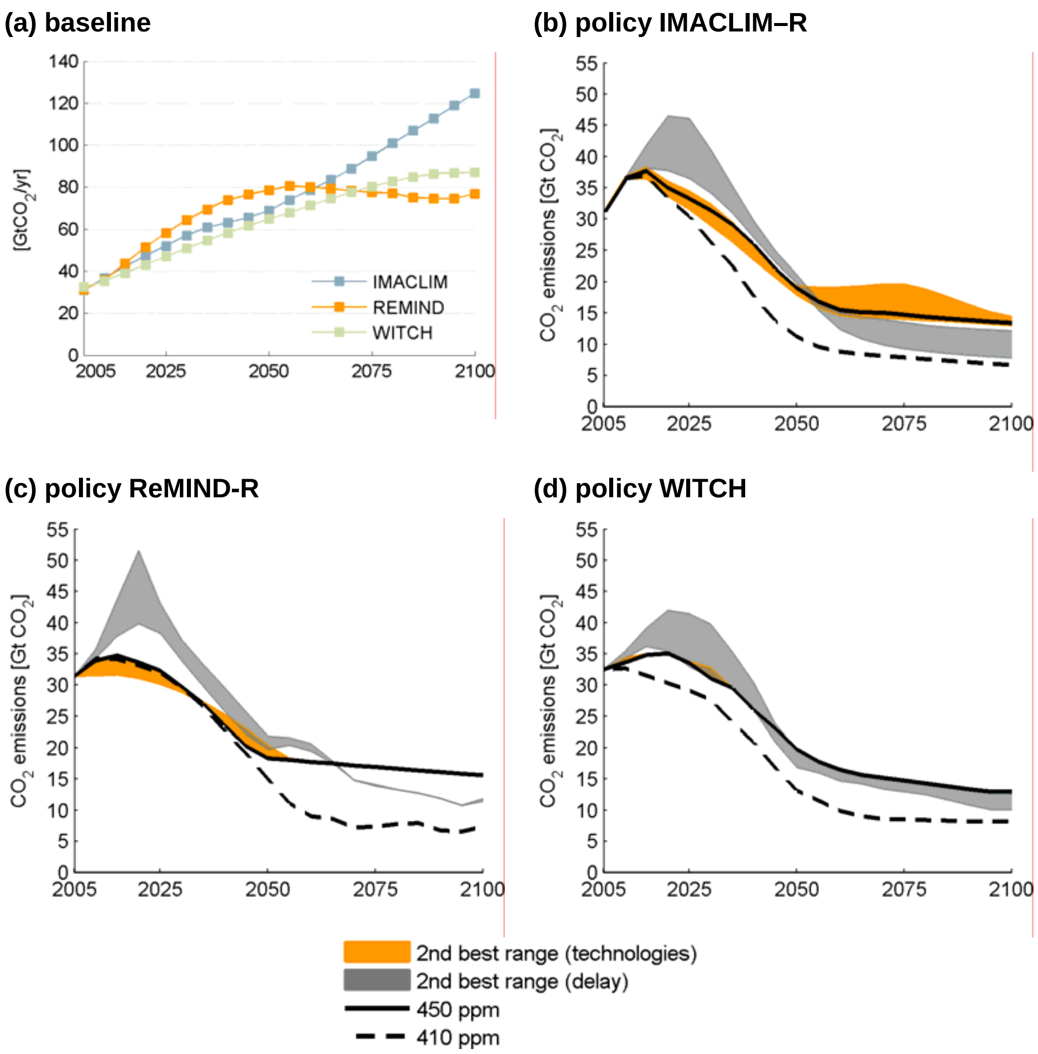

Figure 1 shows pathways of CO_2 emissions from fossil fuel use for the baseline as well as the 450 and 410 ppm policy scenarios.

The IMACLIM-R baseline has the highest long term CO_2 emissions, which reach 125 Gt CO_2 per year in 2100. This emission-intensive baseline is largely due to large-scale deployment of coal liquefaction in response to increasing scarcity of oil. The ReMIND-R baseline is characterized by strong, fossil-based expansion of the energy system until 2050 followed by a period of energy intensity reductions and phase-in of carbon-free energy carriers in response to increasing scarcity of fossils. As a consequence, emissions increase steeply over the course of the first half of the century and stabilize afterwards at around 80 Gt CO_2 per year. The primary energy demand in the WITCH baseline is slightly lower than in the other two models and continues to be based on fossils throughout the century, with only marginal contributions of carbon-free energy carriers to the primary energy supply. Emissions increase monotonically over the 21st century and reach 87 Gt CO_2 by 2100.

For the default scenarios, the mitigation pathways of the RECIPE models toward the 450 ppm target have a peak in emissions between 2015 and 2020 and a 39-42% reduction of CO_2 emissions compared to 2005 levels by 2050. Due to the inertia of the energy-economic system caused by imperfect foresight, IMACLIM-R projects the highest peaking level of all three models. Emissions in 2100 are projected at 13.0-15.6 Gt CO_2 per year. The more ambitious 410 ppm target requires much higher reductions, particularly on the long term. In this scenario, emissions decrease to 7.2-8.2 Gt CO_2 by 2100, about 25% of 2005 levels. While some differences in the stabilization pathways exist across models, the cumulative amount of emissions over the time span from 2005 to 2100 is equal at about 2180 Gt CO_2 for the 450 ppm default stabilization scenario, and about 1700 Gt CO_2 in the case of the 410 ppm scenario. This corresponds to an overall emissions reduction over the century of 3900 to 4850 Gt CO_2 for the 450 ppm scenario, and 4400 to 5350 Gt CO_2 for the 410 ppm scenario compared to the baseline case.

A delay of climate policy results in higher peaking, and makes steeper emission reductions necessary after 2020 to meet the climate policy target. By contrast, in IMACLIM-R and ReMIND-R restrictions in technology availability tend to result in earlier decline of emissions initially in order to compensate for higher emissions at later stages.

[Figure 1 about here]

The comparison of historic CO_2 growth patterns with the emission trajectories required for climate stabilization illustrates the scale of the challenge. The development of energy-related emissions can be interpreted in terms of the driving forces population, per capita GDP, energy intensity of economic output, and carbon intensity of primary energy consumption (Kaya 1990). Such decompositions of the rates of change of CO_2 emissions are depicted in Figure 2[5].

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[5] Several methods are commonly used to decompose CO2 emissions, see Ang (2004) for a review of options. We have used a complete Laspeyres Index method (i.e. including residuals),

The upper row shows decompositions for the baseline scenario, while the results for the policy scenario are depicted in the lower row. Policymakers do not consider reducing population growth nor the reduction of economic output as a way to reduce greenhouse gas emissions, hence the focus of climate change mitigation is on achieving emissions cuts by reducing the energy intensity and carbon intensity of the economic system. Emissions can be reduced by switching from carbon-intensive energy carriers such as coal to low-carbon or carbon-free energy carriers such as renewables. Alternatively, or in addition to carbon intensity reductions, production processes can be optimized or changed as to generate more output for a given amount of energy input. Historical energy efficiency improvements since 1980 averaged about 1% per year, while carbon intensity decreased by a few tenths of a percent on average. This was by far insufficient to compensate for increases in population and per capita GDP, resulting in substantial increases in CO_2 emissions.

[Figure 2 about here]

As described in Section 2.1, the models were harmonized with respect to population and economic growth. Consequently, all scenarios show the same pattern of population growth until 2070 with subsequent decline, and global GDP growth rates (corresponding to the sum of the orange and the purple bar) that decline from more than 3% in 2010 to below 2% in 2100. In line with the historic trends, energy efficiency improvements in the baseline remain too small to offset GDP growth. All models envisage a medium-term increase in carbon intensity in the baseline, a pattern that relates to the assumption of cheap coal (cf. Section 3.3) and which is in accordance with the developments of the recent past (Raupach et al. 2007). Stabilization of atmospheric CO_2 concentrations requires a transformation effort in terms of combined reductions of energy and carbon intensity that is without precedence in history. Figure 2 suggests that models can be characterized in terms of the division between energy efficiency improvements and reductions in carbon intensity of energy: in IMACLIM-R and WITCH, the mitigation target is met by a balanced strategy of energy efficiency improvements, and reductions of carbon intensity. In ReMIND-R, by contrast, the bulk of the

decomposing emission changes every 5 years into the components population, GDP per capita, energy intensity of GDP and carbon intensity of energy.

mitigation effort is met by reduction of carbon intensity, while cumulated energy efficiency improvements are comparable to those in the baseline.

3.2 Macro-economic effects of mitigation policy

This section focuses on the global macro-economic effects of climate policy. A thorough analysis of the regional distribution of mitigation costs in the RECIPE scenarios is provided in Luderer et al. (this issue); a detailed discussion of second best policy scenarios both in term of technology availability (Tavoni et al., this issue) or international climate architectures (Jakob et al., this issue) are discussed in separate papers. The objective of the current analysis is to provide the broad picture of the variability of climate policy costs under a wide range of assumptions.

[Table 3 about here]

There is considerable variation in model results on the economic effects of climate policy. An overview of mitigation costs for different climate policy scenarios is provided in Table 3. To make costs that arise in different points in time comparable, all costs are converted to net present values with a constant discount rate of 3%. The analysis presented here is a cost-effectiveness study, thus damages caused by climate change are not considered. For the default 450 ppm climate policy scenario, the aggregated mitigation costs in terms of consumption losses relative to the baseline aggregated over the period to 2100 and discounted at 3% amount to 0.1% (IMACLIM-R), 0.6% (ReMIND-R), and 1.4% (WITCH). The temporal evolution of mitigation costs and the carbon price are shown in Figure 3. The differences in model approaches are reflected in the structural differences of carbon price trajectories. In ReMIND-R and WITCH, carbon prices increase approximately exponentially over the first half of the century, roughly following a Hotelling path (Hotelling 1931). In ReMIND-R, the CO_2 price of the default 450 ppm scenario does not continue to increase after 2050 due to the prescribed limit on the overshooting of the long-term climate target results. Moreover, for both ReMIND-R and WITCH, (a) endogenous technological progress (i.e., learning effects) in key mitigation technologies, and (b) non-linearities in the carbon cycle (i.e., changes in the airborne fraction of CO_2 emitted to the atmosphere) result in deviations from the idealized exponential price path after 2050.

In IMACLIM-R very high carbon prices are required initially to create a sufficiently strong signal to trigger a transition to a low-carbon energy system (Figure 3a). This dynamic is caused by imperfect foresight in combination with (a) inertias that limit the short-term substitutability between production factors, and (b) endogenous technological change due to which short-term investments have a critical effect on long-term availability and cost of mitigation options. The high prices result in very high transitional mitigation costs and welfare losses in the first 30 years of the modeled period. Once this transition is accomplished, IMACLIM-R projects negative mitigation costs due to additional technical change that is induced by climate policies allowing economies to be more efficient than in the sub-optimal baseline. Conversely to what happens with the other two models, this cost profile would result in higher discounted policy costs if the discount rate used was higher. The flat profile of the carbon price in IMACLIM-R after 2030 can be attributed to (a) the learning processes in carbon saving energy technologies that increase the reduction potentials available at a given carbon price and by (b) climate-friendly infrastructure policies that avoid a costly lock-in into carbon-intensive transportation systems, thus removing a critical obstacle to stabilization in the long run.

[Figure 3 about here]

Increasing the level of ambition of climate policy results in a substantial increase of mitigation costs in IMACLIM-R and WITCH (Figure 4 and Table 3). Global aggregated consumption losses for the 410 ppm climate target amount to 1.3% for IMACLIM-R compared to 0.1% in the default policy scenario. For WITCH, costs almost triple from 1.4% to 4.0%. Also, carbon prices under the 410 ppm target increase drastically to levels of several thousand US$ in the second half of the century, indicating the steepness of the abatement cost curve at this level of ambition. For both models, the 410 ppm mitigation target is close to the feasibility frontier, i.e. mitigation targets of 400 ppm or below are unattainable under the assumptions of these models. ReMIND-R, by contrast, embodies more optimistic assumptions about technology availability and flexibility within the energy system. Therefore, the 410 ppm target is met at a moderate cost markup (0.8% aggregated losses compared to 0.6% in the default policy scenario) and a moderate increase of carbon prices.

A delay in climate policy has a strong effect on the economics of mitigation. All models find that the 450 ppm target becomes unattainable if the world follows the baseline trajectory until 2030[6]. The explanation is twofold: first, substantial emissions would occur in the baseline until 2030, and second, following the baseline until 2030 would lead to a lock-in into further emissions implied from the stock of long-lived carbon-intensive infrastructure and energy-conversion technologies.

In case of a delay until 2020, the target remains achievable, albeit at a substantial cost penalty. Global consumption losses over the course of the 21st century increase from 0.1% to 0.8% in IMACLIM-R, from 0.6 to 1.0% in ReMIND-R, and from 1.4% to 2.1% in WITCH (Table 3). Mitigation costs decrease with increasing participation in the group of early movers. All models find that the cost penalty for the delay decreases to less than one third compared to the delay2020 scenario if all industrialized countries take immediate action. If, in addition, China and India join the coalition of early movers, the cost penalty compared to full participation is less than 0.1%. The short term savings due to inaction are more than offset by the substantial increase in long-term mitigation costs (Figure 4).

Our results are complementary to those of the EMF-22 study (Clarke et al. 2009), which found, based on an coordinated study of ten integrated assessment models, that a delay in mitigation action by the large emerging economies until 2030, and other non-Annex I countries until 2050 makes an ambitious 450 ppm CO_2e target virtually impossible to achieve, and raises costs significantly for the intermediate 550 ppm CO_2e target.

Fragmented regimes, in which some country groups adopt mitigation policies while others delay action, have non-trivial impacts on the regional mitigation costs: while the early movers have to stem a higher overall reduction effort, they benefit from early adjustment and the anticipation of the long-term mitigation target. Jakob et al. (this issue) explore these effects in detail and conclude that for industrialized countries the latter effect (early adjustment and anticipation) tends to prevail over the former (higher overall reduction effort), resulting in an incentive for these countries to take early action.

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[6] In ReMIND-R, the only model that accounts for the possibility to generate negative emissions via BECCS, the target can only be achieved if the overshooting constraint is removed. In this case, atmospheric CO_2 concentration peaks at 535 ppm before declining.

Not only the institutional setting, but also the availability of technologies affects mitigation costs and carbon prices (Tavoni et al. this issue). In general, higher carbon prices are required to meet the climate target if the portfolio of mitigation options is restricted, such that technology constraints result in higher mitigation costs. As the three models represent different visions of future technology development and decarbonization strategies, the relative importance of mitigation options differs across models. For ReMIND-R and WITCH, the highest cost increases are found for the fixRET scenario, for which the deployment of renewables is restricted to the baseline level. For WITCH, this is due to the fact that the scenario assumes constraints on the deployment of the generic electric and non-electric backstop technologies, which are the most crucial abatement options. In ReMIND-R, the high option value of renewables can be explained by the significance of wind and solar energy for electricity production in the presence of climate policy, as well as the prominent role of biomass. Restrictions in biomass availability alone result in a 25% increase of mitigation costs in ReMIND-R, but have little effect for the other models. In all three models, unavailability of CCS results in a substantial cost penalty. Fixing nuclear deployment to baseline level, by contrast, has a rather small effect on aggregated costs. This is due to a combination of (a) substantial deployment that occurs already in the baseline, and (b) the ample availability of other low-carbon options for the power sector.

[Figure 4 about here]

The spread of results for the complete set of first-best and second-best policy scenarios explored in RECIPE as shown in Figure 4 and Figure 3 exhibits the degree of uncertainty about the economics of climate change mitigation. For the scenarios considered, aggregated costs vary between 0.1 and 4% of global macro-economic consumption. Also, carbon prices vary by more than a factor of ten across scenarios and models. The differences arise from structural uncertainty about the energy economic system (as represented by different modeling approaches and assumptions), technological developments, and timing of international action on climate change.

The results of the present analysis let us conclude that the costs of climate change mitigation depend critically on (a) the level of ambition, (b) technology availability and the innovative capacity of societies, (c) long-term planning and the ability to stabilize expectations of investors, and (d) the domestic and international climate policy environment.

3.3 The Energy System Transformation

While the preceding section demonstrated macro-economic consequences and costs of climate mitigation policy, we now focus on alternative visions of the future of global energy systems. In order to keep the analysis tractable, this and the following sections focus on a comparison between the baseline and the default policy scenario.

[Figure 5 about here]

Figures 5(a-c) show primary energy supply in a world without climate measures, i.e the baseline scenario. Since the RECIPE models assume abundant availability of cheap coal, the baseline energy systems are highly carbon intensive. A distinguishing feature of the IMACLIM-R model is the large use of coal-to-liquid in response to the growing mobility demand and increasing oil prices. The coal-to-liquid technology is characterized by (a) high primary energy input per unit of final energy, and (b) high CO_2 emissions per unit of primary energy due to the replacement of crude oil by carbon-intensive coal. This is reflected in the steady increase in CO_2 emissions throughout the 21st century (Figure 2a), giving rise to the highest emission profile of all three models. In turn, this also implies that more abatement is required for reaching the mitigation target than in the other two models (as shown in Figure 1). In contrast to the “black” baseline given by IMACLIM, the ReMIND-R baseline can be characterized as a “green” baseline. After a phase of highly energy and carbon-intensive growth until 2040, the decreasing growth rate of energy demand and the higher penetration of carbon-free energy technologies (biomass and other renewable energies) lead to a decline in emissions. Overall, renewables play a larger role in ReMIND-R than in the other two models, even in the baseline. Compared to the other models, the aggregated WITCH baseline (Figure 5c), can be classified as an energy-saver baseline: the energy intensity in 2050 is 17% lower than in IMACLIM and 19% lower than in ReMIND-R, whereas the carbon intensity of its energy mix is 30% higher than in ReMIND-R and 7% higher than in IMACLIM-R. The resulting overall emissions are comparable to those of ReMIND-R, reaching 86 Gt CO_2 in 2100.

The gap between baseline CO_2 emissions and emission trajectories required to achieve the stabilization targets, as illustrated in Figure 1, demonstrates the scale of the climate stabilization challenge. As shown in Figure 5(d-f), a climate policy aimed at stabilizing CO_2 concentration results in a substantial reduction of energy demand in the WITCH and IMACLIM-R models. In ReMIND-R, by contrast, energy demand keeps increasing steeply even in the presence of a climate target because energy demand can be satisfied readily with low-carbon technologies. ReMIND-R features high flexibility in energy system investments (e.g. rapid expansion of renewables). Moreover, ReMIND-R includes the option of combining bioenergy with CCS (BECCS). This technology has the potential to generate negative net emissions to the atmosphere and thus may become an important mitigation option (e.g. Van Vuuren et al. 2010). Due to the ample availability of low-carbon energy carriers, decarbonization of energy supply is preferred over energy efficiency improvements.

The omission of coal-to-liquid in the IMACLIM-R policy scenario results in a strong reduction of primary energy supply from coal. In addition to efficiency improvements, the emission reductions are achieved by introducing renewables and CCS as well as expanding nuclear energy. The energy mix in the WITCH scenario reflects inertia and rigidities of the energy sector as represented in this model. Moreover, the possibilities of replacing traditional carbon-based technologies with carbon-free options are limited, because assumptions on CCS capture rate and on biomass penetration are more conservative than in both other models. These features, together with the presence of endogenous energy-saving technical change explain why climate policy induces a significant reduction in energy supply in the WITCH model. Energy saving technical change allows saving energy per unit of output produced, leading to significant energy efficiency improvements. Endogenous technical change is driven by energy R&D investments which become particularly profitable at higher carbon prices. These results point to an important role of savings on the demand side of the energy balance equation.

All models emphasize the role of innovation and technological learning in carbon free or low-carbon technologies, be it in the form of performance improvements of CCS technologies, or of progress in already available renewable energy technologies, such as wind and solar. Additional innovation occurs as a result of a ramp-up in energy R&D investments to the levels that were reached in the 1980s. In particular, total energy R&D should rise from the current level, roughly 0.02% as a share of gross world product, to around 0.09%; an amount in the order of USD 60-80 billions. This is emphasized by the results of the WITCH model where not only experience learning but also R&D is modeled as an endogenous process. One of the effects of energy R&D in the WITCH model is to increase the competitiveness of backstop technologies, which are, for the analyses presented here, aggregated with other sources of renewable energy.

The different structure of energy supply in the three models, which is evident in the baseline scenario and even more pronounced in the stabilization scenario, hinges on five main factors: (a) the availability and future development of technological options; (b) assumptions about resources for exhaustible energy carriers as well as renewable potentials; (c) the presence and the nature (exogenous or endogenous) of innovation and technical change; (d) the degree of flexibility in the models; as well as (e) the durability of capital stocks and the inertia of the energy sector. Other important determinants include macroeconomic substitution processes and the representation of the decision process, assumptions about foresight and intertemporal strategic planning embodied in different models, macro-economic parameters characterizing the substitutability of energy with other production factors and the substitutability between different energy carriers and trade opportunities.

3.4 Energy system investments

The transformation of the energy system induced by climate policy becomes particularly evident in the energy system investments. Figure 6 shows the mix of investments in energy technologies in the baseline scenario as well as in the 450 ppm stabilization scenario. All models consistently project a fundamental change in investment patterns compared to business-as-usual in order to achieve the stabilization target. According to the models, ambitious and cost-effective mitigation requires a rapid switch of investments away from conventional fossil towards low-carbon energy systems. Investments in fossil energy capacity without CCS are phased out almost immediately (ReMIND-R), within 15 years (IMACLIM-R) or reduced by more than a factor of ten (WITCH). All models project massive investments in CCS and an up-scaling of investments in renewables. The WITCH model simulates explicitly R&D investments in energy efficiency improvements as well as carbon-free backstop technologies. R&D investments for energy decarbonization are projected to be in the order of USD 40 billions per year whereas R&D investments for energy efficiency roughly double in the presence of a stabilization policy. ReMIND-R shows a substantial increase of energy system investments compared to the baseline. This is largely due to a switch away from fuel-intensive fossil technologies towards capital-intensive technologies, in particular wind, solar and nuclear. In the policy scenario, overall investments in ReMIND-R are about one trillion dollars higher than in WITCH and IMACLIM-R by the end of the 21st century. For WITCH and IMACLIM-R overall investments are only slightly higher than in the baseline because the increased capital expenditure for low-carbon technologies is offset by the contraction in overall energy demand.

A striking result of the IMACLIM-R model is the transitory contraction of energy investments between 2015 and 2040, which has two causes. First, this period corresponds to substantial transitory losses in terms of economic activity which strongly reduces the total availability of investment capital. Secondly, energy producers take initial investment decisions under imperfect foresight, which prevents them from anticipating the decrease of energy demand after the onset of climate policy. As a consequence, at a time when climate policy results in substantial increases in energy efficiency, idle capacities are high in the energy sector and investments are redirect towards tighter markets. The combination of these two effects explains the sudden drop in energy investments.

[Figure 6 about here]

The investment structure of ReMIND-R reflects the model's flexibility in switching between technologies. Figure 6 (b) shows how renewable energy gains importance in ReMIND-R already in the baseline scenario. In particular, wind energy already competes with investments in the fossil energy sector in the first half of the century. In the policy scenarios, investments in nuclear energy and investments in solar energy are scaled up substantially compared to the baseline scenario. Investments in CCS technologies account for a major share of total investments from 2030 onwards. Overall and in contrast to both other models, investments in the energy system are significantly increased compared to the baseline scenario, indicating that technological changes within the energy system dominate over macro-economic adjustments.

3.5 Sectoral results

An important focus of the RECIPE model intercomparison project is to provide insights on differences and robust findings with respect to sectoral mitigation strategies. This section describes sectoral representation of the models and analyses the results by energy end use sectors.

The representation of energy-consuming sectors varies across the three models. IMACLIM-R, as a recursive CGE model, features the highest sectoral detail among the three models considered. Overall, 12 productive sectors are represented. For the analysis presented here, consumption of primary and final energy as well as greenhouse gas emissions are aggregated to four source sectors: electricity, industry, residential, and transport.

In ReMIND-R, the macro-economic demand for final energy is split into stationary (electricity and non-electricity) and transport applications. These two sectors are supplied by various types of secondary energy carriers such as electricity and liquid fuels, which in turn are products of conversions from primary energy carriers. ReMIND-R is characterized by a large number of conversion technologies within the energy system, resulting in comparatively high flexibility for the shift between primary energy carriers. Since the supply of the stationary sector with electricity as well as several other non-electric secondary energy carriers is represented explicitly, energy demand is shown for the three source categories electricity production (including combined heat and power), non-electric stationary applications, and transport.

On the level of macro-economic energy demand, WITCH distinguishes between electricity and the non-electric sector. The supply of electric and non-electric energy is represented by a hierarchical nest of CES production functions, substitutability between different energy carriers is limited. The primary energy carriers available for electricity production are coal (both conventional and in combination with CCS), gas, oil, nuclear, wind and solar, hydro, and a generic backstop technology for electricity production. For the non-electric sector, biomass (both traditional and advanced), coal and oil are used as primary energy carriers as well as a generic backstop technology for non-electric energy. The limited substitutability induced by the CES-structure as well as the less optimistic supply of energy conversion technologies results in significantly lower energy system flexibility compared to the ReMIND-R model.

[Figure 7 about here]

The electricity mixes as projected by the three models for the baseline as well as the 450 ppm scenario are depicted in Figure 7. In 2005, power production accounted for roughly 40% of the overall global primary energy consumption. According to IMACLIM-R and ReMIND-R, electricity demand will increase six-fold until 2100. WITCH has slightly lower growth rates. In the baseline projections, the electricity generation mix is dominated by fossil fuels. All models project, however, substantial penetration of non-fossil energy carriers in the second half of the century, with combined shares of 24-37% by 2100. IMACLIM-R and WITCH project lower shares of renewables, while nuclear energy plays a more important role. In ReMIND-R, the non-fossil share of power production is dominated by renewables. Nuclear capacity declines until 2040, but expands afterwards.

In a climate-constrained world, a variety of low-carbon or even carbon-free technologies are available for electricity production: renewables, nuclear and CCS. Consequently, for the 450 ppm policy scenario, the decarbonization proceeds most rapidly in the electricity sector. All models feature a steep decline of conventional fossil power generation capacity, while electricity production form renewables is expanded substantially. CCS becomes deployed in considerable scale around 2030 in IMACLIM-R and from 2050 on in ReMIND-R. For both models, this technology contributes substantially to the reduction of CO_2 emissions to the atmosphere, while it plays a less important role in WITCH.

All three models project a significant expansion of nuclear energy use over the course of the 21st century. In the baseline scenario, nuclear electricity production in 2100 exceeds current levels by a factor of four (ReMIND-R, WITCH) to nine (IMACLIM-R). In the climate stabilization scenarios, the increase of power production from nuclear is particularly strong in the WITCH model. In ReMIND-R, nuclear contributes significantly to electricity production during a transition period.

In IMACLIM-R the period from 2015 through 2035 is characterized by a substantial contraction of electricity demand. This coincides with the period during which the bulk of the economic burden induced by the low-carbon transition is borne. Afterwards, a pronounced increase in electricity demand occurs, largely induced by a switch from non-electric to electric energy sources in the industry sector. In WITCH electricity demand until 2050 is considerably lower than in the baseline. Once the carbon-free backstop technology is available, growth in power generation accelerates, thus yielding similar demand in baseline and policy scenarios by 2100.

The primary energy mixes used for the transport sector are depicted in Figure 8. According to ReMIND-R and IMACLIM-R, energy demand for transport will grow by a factor of 4.5 to 6, respectively, over the course of the 21st century if no climate policy is in place. Currently, transportation energy is almost entirely provided from fossil fuels. As oil will become increasingly scarce, both models project that alternatives fuels will play an important role already in the baseline. In the IMACLIM-R baseline, the transport sector relies heavily on coal-liquefaction. Biomass is also projected to assume an increasing share of primary energy supply from 2020 (IMACLIM-R) or 2030 (ReMIND-R) onwards.

In IMACLIM-R mitigation in the transport sector relies on a combination of fuel switching (increase of market share of biofuels and electric cars) and the reduction of energy demand. For the 450 ppm scenario, primary energy consumption in 2040 is 25% lower than in the baseline. The decrease of energy demand is a result of both energy efficiency improvements in the vehicle fleet, in particular the penetration of plug-in hybrid technology, and infrastructure policy introduced as complementary measures of carbon pricing to decrease the transport intensity of the economy.

Electrification is often considered one of the most promising technology options for decarbonization of the transport sector (e.g. IEA 2009). In ReMIND-R and WITCH, electrification is only represented implicitly via substitution within the macro-economic system. IMACLIM-R makes plug-in hybrid vehicles explicitly available in the technology portfolio, thus including electrification of the transport sector. However, under the parameter assumptions used, competitive margins remain for the internal combustion engine. Thus the penetration of electric vehicles remains small and accounts only for a marginal fraction of the transport sector’s energy consumption.

In ReMIND-R, coal-to-liquid and biomass-to-liquid technologies play an important role in the policy scenarios. The CO_2 produced in the liquefaction process can be captured and stored. While power generation with CCS becomes only relevant after 2040, ReMIND projects coal liquefaction in combination with CCS to be deployed at significant scale in the near-term. In ReMIND, biomass liquefaction in combination with CCS is the key long-term mitigation option for transport. For this pathway, 50% of the carbon stored in the biomass can be captured and stored, thus resulting in negative net emissions. In contrast to the other models, energy-demand in the transport sector under climate policy is almost equal to that in the baseline: The bulk of the demand-side reductions of final energy are offset by efficiency losses due the large-scale deployment of CCS. It is important to note that the share of bioenergy used for transport versus that for electricity generation and other stationary uses will depend critically on techno-economic assumptions, as well as the availability of fossils and other sources of primary energy. This is subject to current research (e.g. Klein et al. 2010; Luckow et al 2010).

WITCH does not represent the transportation sector separately, but a composite of all non-electric forms of final energy demand. In the baseline scenario, energy demand in the non-electric sector is almost entirely supplied by fossil fuels, complemented by an about 10% share of traditional biomass. Although a significant contraction of fossil fuel consumption is achieved, fossils still account for a large share of primary energy supply in the policy scenarios. The carbon-free backstop technology is introduced between 2020 and 2025, and it contributes increasingly to non-electric energy. The amount of biomass consumed in the 450 ppm scenario is similar to that in the baseline. Overall, WITCH projects low-carbon alternatives in the non-electric sector to penetrate slowly, thus limiting the decarbonization of the sector. Consequently, a significant decline of primary energy demand is required to meet the mitigation target. The primary energy demand in the non-electric sector is 40% lower in the 450 ppm policy scenario compared to the baseline. This contraction of non-electric energy supply gives rise to a substantial decrease in macro-economic output.

Figure 9 displays the non-electric energy demand in the stationary sectors. For WITCH, this component is included in the non-electric sector. IMACLIM-R explicitly represents the industry and domestic sectors. The increase of primary energy demand for the industry sector in the baseline scenario is moderate compared to that in the power and transport sectors. The energy mix is dominated by fossil fuels with an increasing share of coal. Biomass plays a marginal role. The non-electric energy demand for industry for the 450 ppm stabilization scenario deviates sharply from the baseline after 2040, and subsequently declines by 85% within 20 years. This happens as a result of a switch in the energy mix from fossil fuels to electricity in the new capital vintages in the presence of a carbon price. The delay in the transformation of the energy mix is due to fossil-fuel intensive capacities that are installed in the initial phase and replaced only progressively.

On the global scale, non-electric energy demand in the residential sector is rather small, currently accounting for less than 10% of the overall primary energy. In the baseline, the energy mix of this sector is dominated by natural gas. IMACLIM-R projects large potential for energy efficiency improvements. For the policy scenarios, non-electric residential energy demand decreases by 50% by 2050 and more than 95% by 2100. This results from high potential of very efficient buildings, which rely mainly on electricity for their residual energy demand.

[Figure 8 about here]

[Figure 9 about here]

In ReMIND-R, biomass accounts for a significant share of 20-25% of stationary non-electric primary energy supply already in the baseline, where it is used both in the form of traditional biomass and for the production of synthetic natural gas. Due to initial cost advantages, coal is projected to replace oil and gas in stationary, non-electric applications. After 2050, by contrast, gas becomes more competitive and gradually crowds out coal. The overall primary energy demand is projected to increase by 60% between 2005 and 2050 and to decline in the second half of the century. In the policy scenarios, the energy demand is projected to be rather stable. Coal plays a less important role, while the share of gas increases. In the stabilization scenario, an increasing share of biomass is projected to be used in combination with CCS, both for the production of liquid fuels and for hydrogen.

The contribution of various sectors to the overall mitigation effort is depicted in Figure 10. In line with the full scale decarbonization of the power sector, the bulk of the mitigation effort is performed in electricity production. This is due to the fact that there is a broad portfolio of economically feasible decarbonization options available in the power sector – including renewables, CCS and nuclear. All models show that the residual emissions in the mitigation scenarios are dominated by the emissions from transport and other non-electric energy demand, since these sectors are most difficult to decarbonize. IMACLIM-R features the highest baseline-emissions of all three models, largely because of the extensive use of coal-to-liquid in the transport sector. In the policy scenario, infrastructure improvements, as well as the introduction of biomass and electric vehicles results in a considerable decrease of fossil fuel use for transport. In ReMIND-R, the dominant mitigation option for transport is to generate fuels from biomass in combination with CCS. As this technology results in negative CO_2 emissions, it enables additional headroom for emissions from remaining fossil fuel use for transport and non-electric stationary energy demand.

[Figure 10 about here]

Since more technologies are available for the decarbonization of power supply, a very robust finding across all three models is an increase of the share of electricity, while non-electric energy demand contracts significantly.

4. Discussion and Conclusions

Emissions from the combustion of fossil fuels account for the bulk of anthropogenic greenhouse gas emissions. The transformation of the energy system thus lies in the heart of the global effort to curb global warming.

We used three structurally different models to explore decarbonization scenarios of the energy system. The three models were harmonized to represent similar assumptions with regard to socio-economic developments (i.e. population growth and world GDP) and availability of fossil resources, but represent different visions of the development and diffusion of new technologies. Comparing the results obtained for the baseline as well as stabilization scenarios with these three models hence helps to shed light on how different assumptions on technologies and economic dynamics translate into differences in mitigation costs, investment patterns, and optimal emission reduction trajectories.

The findings of the study can be summarized as follows:

(1) In a first-best setting, that is if the international community agrees to start climate mitigation policy immediately, and if the full portfolio of low-carbon technologies represented in the models is available, stabilizing

global CO_2 emissions at 450 ppm by 2100 can be achieved at costs of 0.1% to1.4% of aggregated global macro-economic consumption.

(2) A delay in global climate policy efforts until 2020 results in a considerable cost increase compared the default policy scenario. The larger the group of nations that delay climate policy, the higher are the costs.

(3) If key low-carbon technologies are unavailable or restricted to the deployment level in the baseline scenario, costs increase substantially. A comparison of mitigation scenarios with all technologies available with scenarios in which deployment of low-technologies is restricted allows ranking technologies according to their relative importance for the mitigation effort. The IMACLIM-R, ReMIND-R and WITCH results suggest that renewables including biomass, as well as CCS are the most crucial technology options, while the option to expand nuclear beyond baseline levels is somewhat less important.

(4) A robust finding across all three models, as well as across the different assumptions on climate policy regime and technology availability is that emissions peak by 2020 at the latest.

(5) A rapid adjustment of investment portfolios required to achieve the climate target in a cost-efficient way. For the climate policy scenarios, all models find a decrease of investments into conventional, non-CCS fossil energy conversion technologies by at least a factor of ten relative to baseline level by 2020. By contrast, investments into low-carbon technologies, particularly renewables, is up-scaled markedly.

(6) The models agree in projecting an almost full-scale decarbonization of the electricity sector. In the default 450 ppm policy scenario less than 10% of global electricity supply is provided from freely emitting installations after 2050.

(7) Emission reductions outside the power sector are found to be more challenging. Long-term mitigation costs strongly depend on energy efficiency improvements and the availability of abatement options in the transport sector. The absence of mature alternative technologies for transport underlines the paramount importance of technological innovations to overcome the dependence of this sector on fossil fuels.

Given the complexity of the problem, our analysis necessarily remains stylized. Many important issues need further exploration. Future research needs to analyze the effect of second-best settings for a much wider range of scenario settings. For example, it will be of key importance to improve our understanding of how cost and achievability of stabilization targets with different levels of ambition are affected by imperfect technology portfolios or institutional frameworks. Moreover, a systematic exploration of second-best scenarios across different assumptions about uncertain parameters and global socio-economic developments should be conducted. Crucial uncertainty arises from the dynamics of innovation and technological development, and the commercialization of innovative technologies. To a large extent, the dynamics of innovation are endogenous, i.e. they depend on policies and investment decisions, but are difficult to fully capture. Last but not least, taking an integrated perspective on mitigation strategies across different regions, sectors, and time steps, while maintaining a high degree of technological explicitness, remains a major challenge. Further research to address these issues will be crucial to inform decision-makers about robust strategies towards a more climate-friendly, low-carbon future.

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Tables

	IMACLIM	ReMIND-R	WITCH
Macro-economic core	Recursive-dynamic CGE	Intertemporal optimization (Ramsey-type growth model)	Intertemporal optimization (Ramsey-type growth model)
Expectations/Foresight	Imperfect foresight based on the extrapolation of past trends	Perfect foresight	Perfect foresight
Substitution possibilities within the macro-economy / sectoral coverage	12 sectors: 5 energy supply + 3 transport + 4 production sectors Leontieff short-term production functions in all intermediate inputs (including energy) and labor.	CES function for production of generic industrial good from primary inputs capital and labor and intermediate input energy	CES production function of generic final good from primary inputs capital and labor and intermediate input energy
Link between energy system and macro-economy	Energy demand results from households' energy services demand and intermediate consumptions for production. Investments into energy sectors are included in the investment-saving equilibrium.	Economic activity determines demand; energy system costs are included in macro-economic budget constraint. Hard link, i.e. energy system and macro-economy are optimized jointly.	Economic activity determines demand; energy system costs are included in macro-economic budget constraint. Hard link, i.e. energy system and macro-economy are optimized jointly.
Production function in the energy system / substitution possibilities	Electricity sector: explicit cost-competing technologies with merit order. Liquid Fuels produced from oil (production capacities, see below) + biomass (supply curves for biofuels)+ coal	Linear substitution between competing technologies for secondary energy production. Supply curves for exhaustibles (cumulative extraction cost curves) as well as renewables (grades with different capacity factors).	Limited substitutability between technologies for provision of final energy modelled with CES production functions. Breakthrough technologies are modeled as linearly substituting nuclear in the electricity sector and oil in the non electricity sector. Transaction costs and diffusion rates introduce convexities.
Supply of primary energy carriers	Coal, gas: Cumulative extraction cost curves. Oil: bell-shaped production curves. Strategic behavior and market power by Middle-East producers.	Exhaustibles: Cumulative extraction cost curves for each region Renewables: Different potential grades characterized by decreasing capacity factor	Supply curves for exhaustible resources.
Trade	International trade for each sector through a pool. Trade balance depends on the endogenous terms of trade.	Single market for all commodities (exhaustible fuels, final good, permits)	Trade of emission permits
Interaction between regions	International trade for goods and capital. International technology spillovers through worldwide learning curves.	Pareto-optimum that corresponds to the market solution (Negishi Equilibrium). Learning spilloveres are implicitly internalized.	Nash equilibrium with forced cooperation on climate. Technology spillovers between regions.
Implementation of climate policy targets	Exogenous emission constraint + allocation rules for distribution of emission permits among regions. Endogenous carbon price as well as auxiliary policies and measures	Pareto-optimal achievement of CO_2 concentration target under full intertemporal flexibility.	Exogenous constraints on emissions, concentration, forcing or temperature can be imposed.
Technological Change / Learning	Learning curves inducing a decrease of capital costs for technologies in electricity and private cars.	Learning by doing (LbD) for wind and solar. A global learning curve is assumed.	Learning-by-Doing for wind and solar, energy R&D investments
Representation of end-use sectors	Electricity, Transport (distinguished by mode) Residential, Industry	Three end-use sectors: Electric, stationary non-electric, transport	Electric, non-electric
Investment dynamics	Capital allocation driven by investment needs for building production capacities. Capital vintage for productive sectors. Capital depreciation	Capital motion equations, vintages for energy supply technologies	Capital motion equations, no vintage, capital depreciation.

Table 1: Overview of key characteristics of models.

Scenario name	Description of change over default
default 450ppm	Start of climate policy in 2010, stabilization of CO_2 concentrations at 450 ppm by 2100
410ppm	stabilization of CO_2 concentrations at 410 ppm by 2100
Baseline	No climate policy
fixNUC	deployment of nuclear fixed to baseline levels
fixRET	deployment of renewables incl. biomass and backstop (WITCH) fixed to baseline level
noCCS	No CCS technologies available
fixBIO	biomass deployment fixed to baseline
noCCS/fixNUC	No CCS technologies *and* nuclear deployment fixed to baseline
delay2030	No climate policy, no anticipation of future climate target until 2030
delay2020	No climate policy, no anticipation of future climate target until 2020
EUonly	Climate policy in EU from 2010, no climate policy, no anticipation of future climate target until 2020 by all others
IC[REDACTED]only	Climate policy in all industrialized countries (Annex I of the UNFCCC) from 2010; no climate policy, no anticipation of future climate target until 2020 by all others
IC+CHN+IND	Climate policy in all industrialized countries, China and India from 2010; no climate policy, no anticipation of future climate target until 2020 by all others

Table 2: Overview of first and second best scenarios considered. The two first best climate policy scenarios consider climate targets of 450 ppm and 410 ppm. The first group of second-best scenarios (orange shading) considers limits on the availability of technologies (Tavoni et al., this issue). The second group of scenarios (grey shading) considers delay in establishing an international climate policy regime (Jakob et al., this issue). For all second best scenarios, a stabilization of atmospheric CO_2-concentrations at 450 ppm is used as climate policy target.

Scenario name	Mitigation costs [% losses relative to baseline]		
	IMACLIM-R	ReMIND-R	WITCH
Default 450ppm	0.1	0.6	1.4
fixNUC	0.2	0.7	1.3
fixRET	0.2	1.5	3.3
noCCS	1.0	0.8	1.9
fixBIO	0.2	0.8	1.5
noCCS/fixNUC	1.4	0.9	3.3
delay2030	infeasible	Infeasible	infeasible
delay2020	0.8	1.0	2.1
EUonly	0.7	0.8	1.9
ICOnly	0.3	0.6	1.6
IC+CHN+IND	0.1	0.6	1.4
410ppm	1.3	0.8	4.0

Table 3: Global mitigation costs expressed in terms of consumption losses relative to the baseline scenario discounted at 3%. The 450 ppm climate policy target was found to be infeasible in the delay2030 scenario

Figures

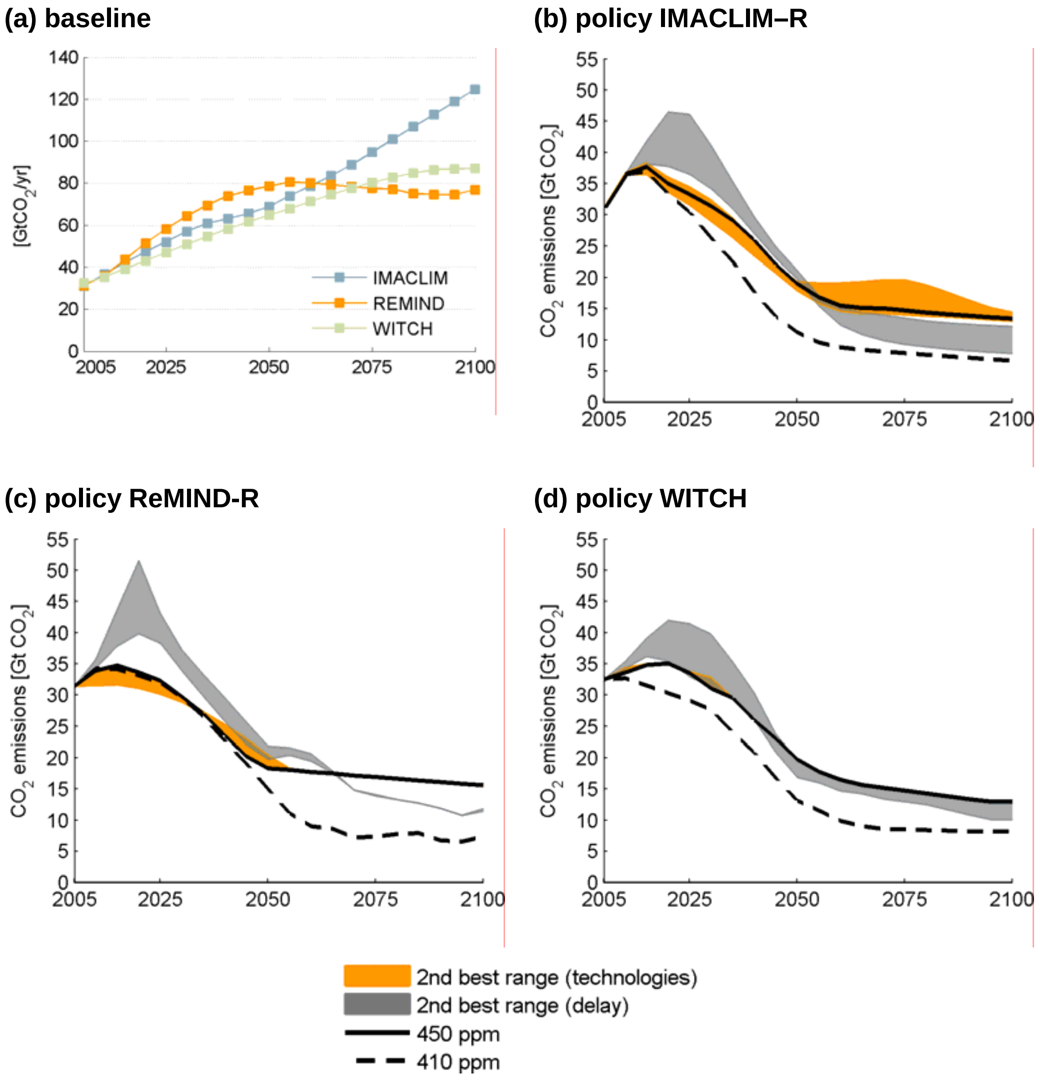

Figure 1: Global pathways for CO_2 emissions from fossil fuel combustion for (a) the baseline scenario, and (b-d) climate policy scenarios. In (b-d), the solid line indicates the default scenario 450 ppm scenario. Shaded areas indicate technology-constrained scenarios (orange), and delay of climate policy (grey). Emission reduction pathways for stabilization at 410 ppm CO2 are shown in dashed.

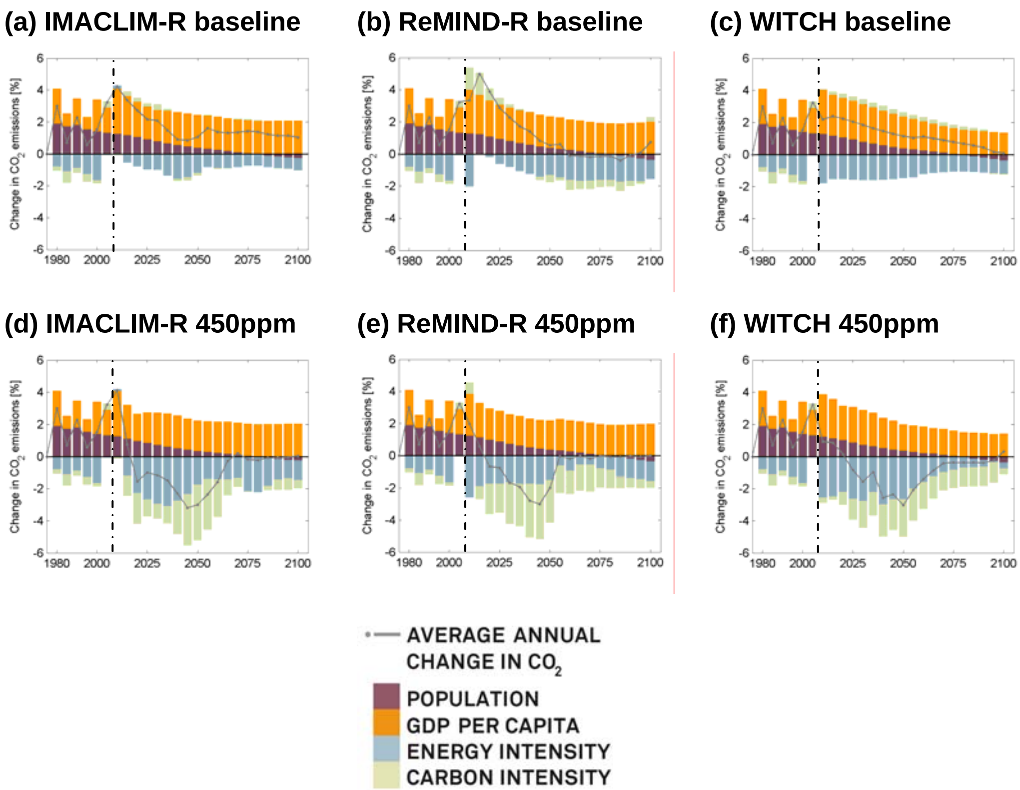

Figure 2: Decomposition of historic CO_2 emission trends and model projections for IMACLIM-R, ReMIND-R and WITCH for the baseline and the default 450 ppm scenario. The figures show the annual contribution of changes in the driving factors population growth, per capita GDP, energy intensity of economic output, and carbon intensity of primary energy use on global CO_2 emissions. The vertical dashed lines indicate the transition from historic data (IEA) to modeled data (RECIPE models). Horizontal lines indicate the percentage annual change in CO_2 emissions.

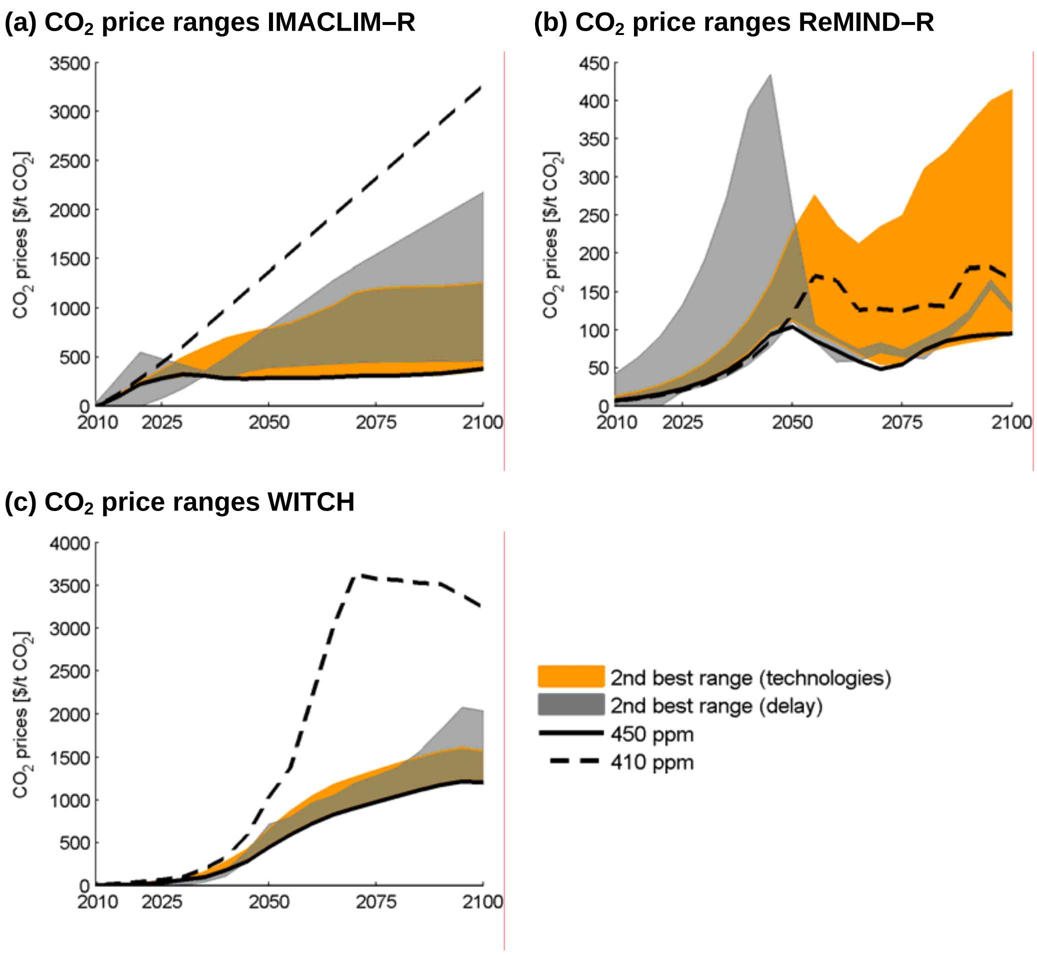

Figure 3: Global carbon price ranges for the models IMACLIM-R, ReMIND-R and WITCH. Note that scales differ for the three models.

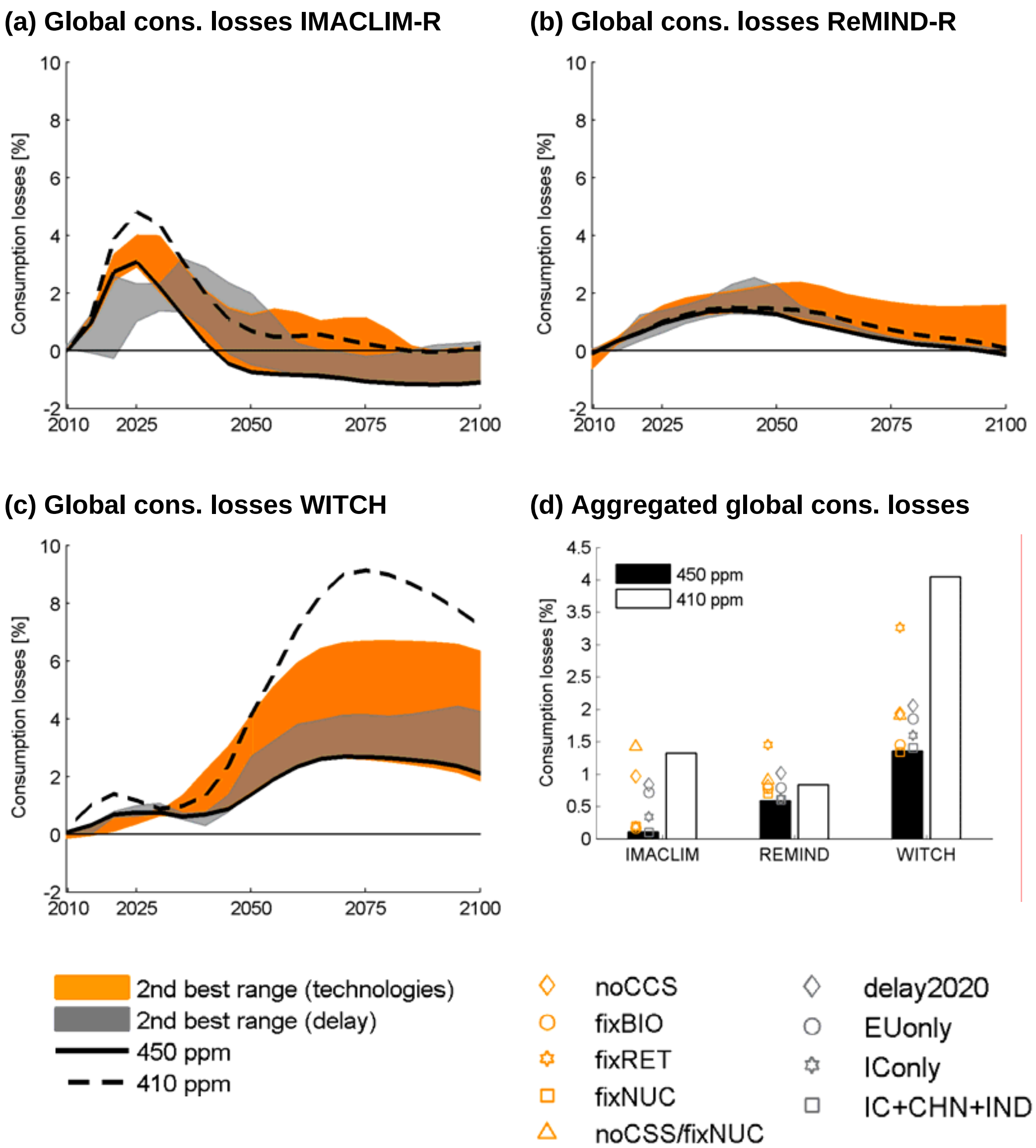

Figure 4: Global welfare losses as consumption differences relative to baseline for the first-best default 450 ppm (solid), the 410 ppm (dashed) as well as ranges for second best scenarios with limited availability of technologies (orange shading) or delayed climate policy (grey shading). Aggregated consumption losses (d) are discounted at 3%.

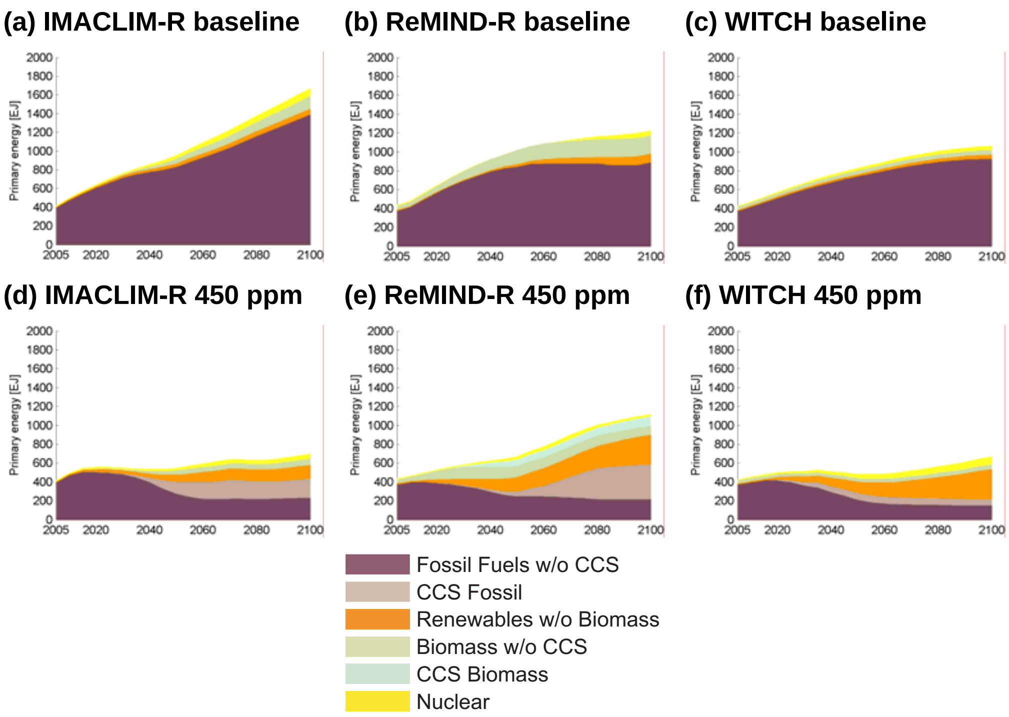

Figure 5: Primary Energy Supply in IMACLIM-R, ReMIND-R and WITCH for the baseline case (a-c) and the default policy scenario with stabilization of atmospheric CO_2 concentrations at 450 ppm (d-f).

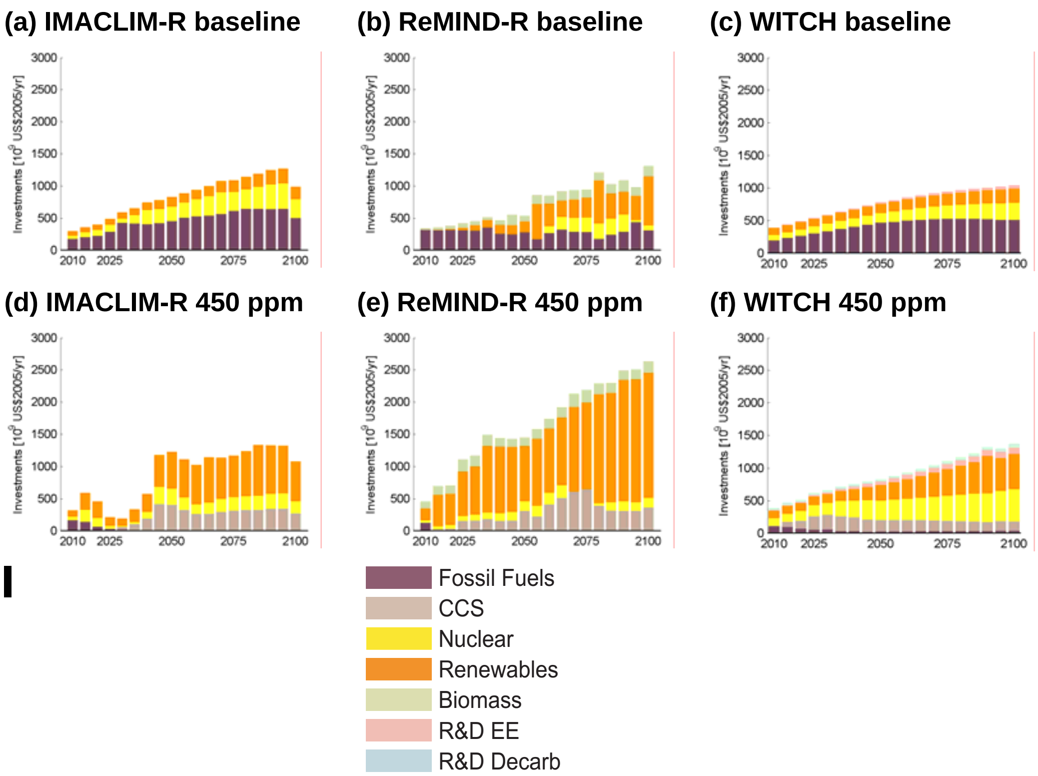

Figure 6: Investments in the energy system for the baseline (a-c) and the default 450 ppm scenario (d-f). For WITCH: R&D EE – investments in energy efficiency R&D; R&D Decarb – investments in carbon free backstop technologies.

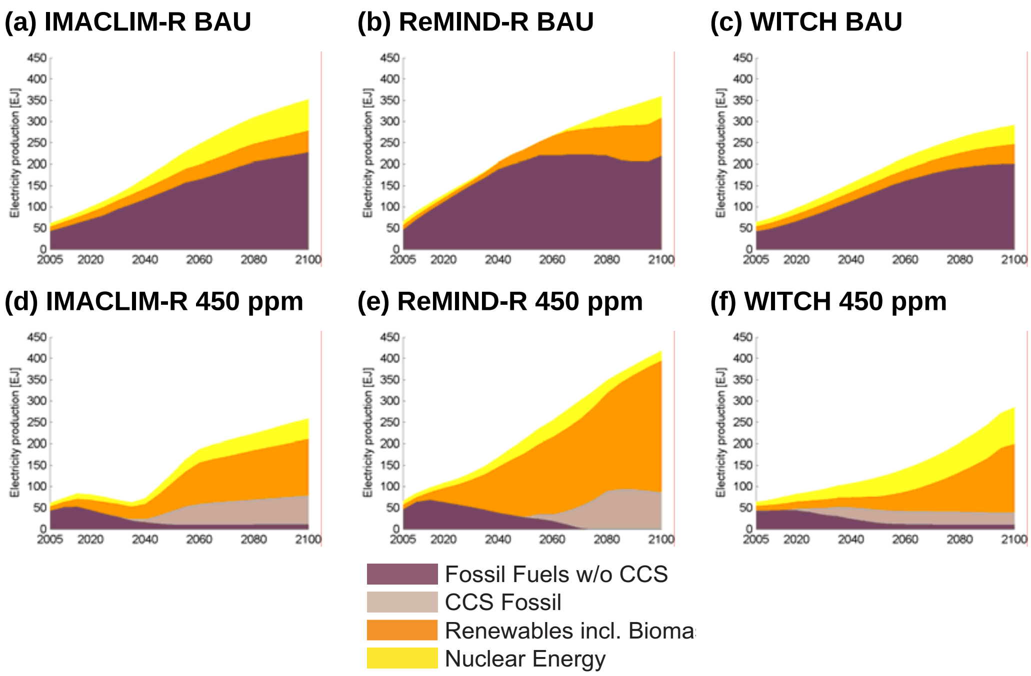

Figure 7: Global electricity production by primary energy source for the baseline (a-c) and the default 450 ppm scenario (d-f).

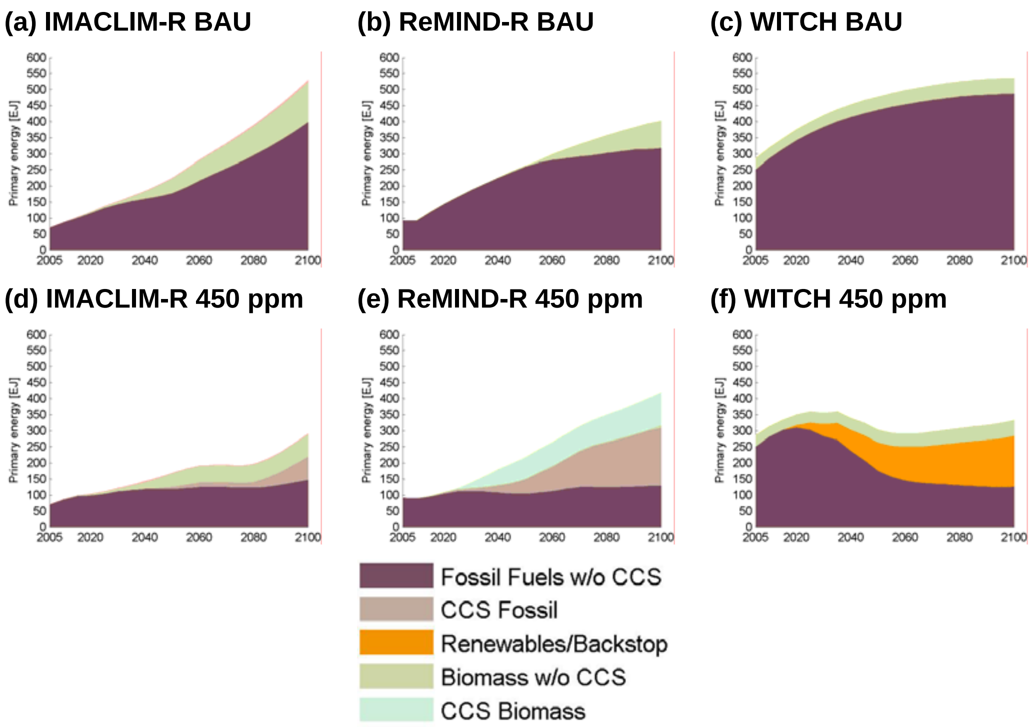

Figure 8: Primary energy mix for the transport sector (IMACLIM-R and ReMIND-R) and non-electricity sector[7] (WITCH), in the baseline (a-c) as well as the default 450 ppm (d-f).

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[7] The WITCH model represents energy demand in terms of electric and non-electric energy use. The transport sector is not represented explicitly. Therefore non-electric energy demand is depicted here.

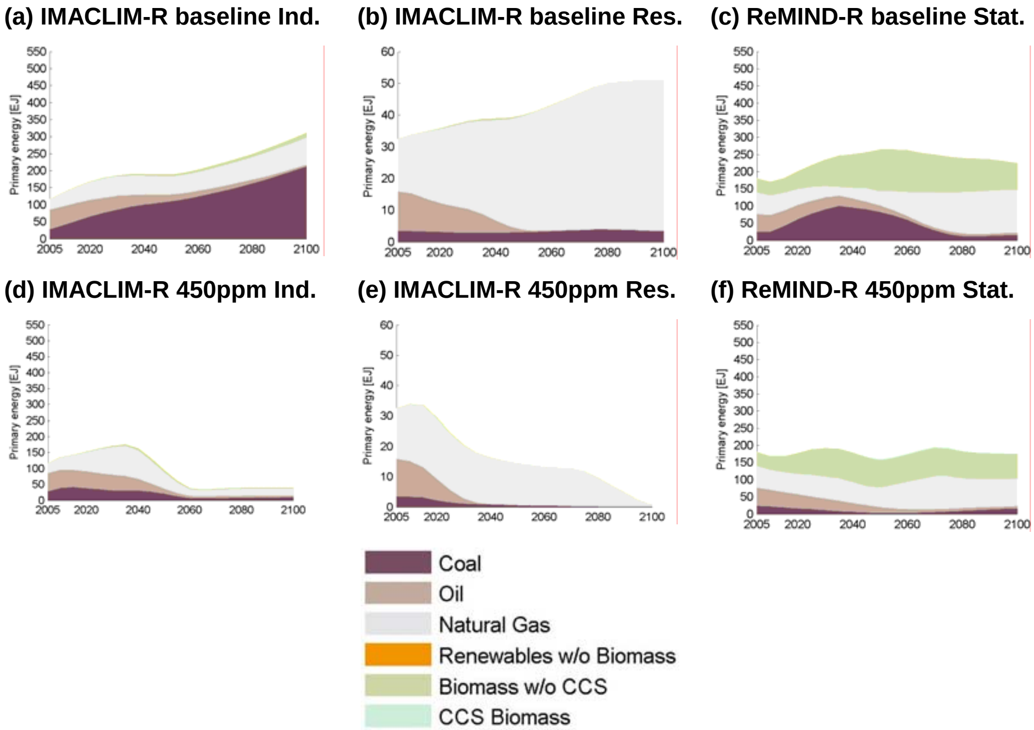

Figure 9: Primary energy consumption in the residential and industry sectors for IMACLIM-R and non-electric stationary sector for ReMIND-R. In WITCH, the stationary sector is included in the non-electricity sector. Fossil fuels are further decomposed by coal, oil and natural gas.

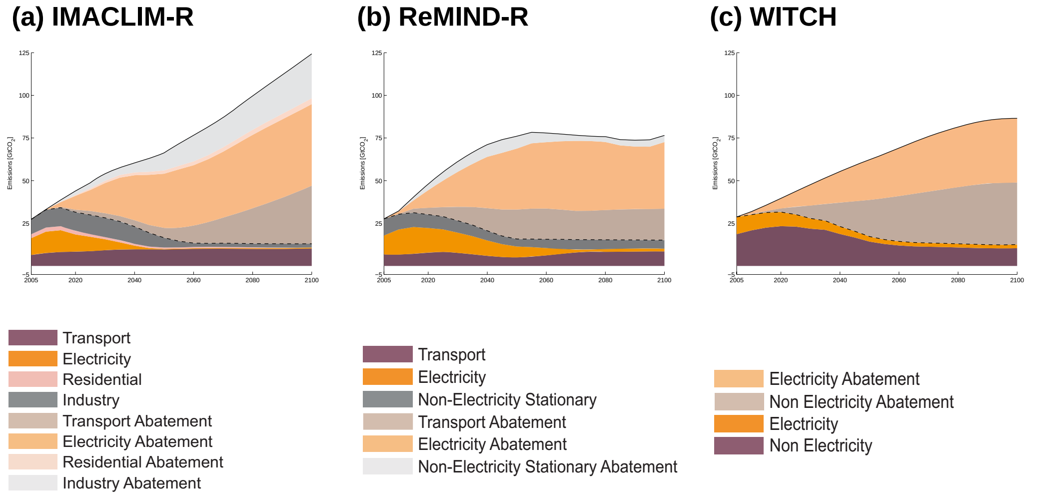

Figure 10: Global CO_2 emissions decomposed by different sectors for the three models IMACLIM, ReMIND and WITCH for the 450 ppm scenario. The upper solid line indicates baseline emissions. The dashed line indicates the emission trajectory in the climate policy scenarios. The emissions abatement – the area between the baseline and policy emissions – can be attributed to the different sectors (light colors). Note that the sectoral breakdown differs between models.