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Summary

This paper presents results from a 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 aiming at stabilization of atmospheric CO2 concentrations at 450 ppm 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. The models applied in the project differ in several respects and the comparison exercise tracks differences in the business as usual forecasts as well as in the mitigation scenarios to conceptual differences in the model structures and assumptions. In particular, the models have different representation of the sectoral structure of the energy system. A detailed sectoral analysis conducted as part of this study reveals that the sectoral representation is a crucial determinant of the mitigation strategy and costs. While all models project that the electricity sector can be decarbonized readily, emissions abatement in the non-electric sectors, particularly transport, is much more challenging. Mitigation costs and carbon prices were found to depend strongly on the availability of low-carbon options in the non-electric sectors.

Keywords: Decarbonization, Energy and Climate Policy

JEL Classification: Q48, Q58

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1. Introduction

The evidence that climate is warming is widely recognized and the scientific basis has also become more robust. If emissions keep following a business-as-usual trajectory the global warming due to the anthropogenic greenhouse effect could be as high as 5°C or more, relative to pre-industrial levels (IPCC, 2007a). It is generally accepted that global warming above 2°C is very likely to be associated with increasingly severe impacts not only on natural systems, but also on human systems and thus, the economy. Working group II of the IPCC has quantified climate damages associated with unabated global warming between 1-5% of GDP (IPCC, 2007b), while the Stern Review concludes that consumption losses could be even as high as 20% if non-market impacts are included. Much of that loss could be avoided by strong mitigation policy.

Despite this daunting prospect, so far very little progress has been made in reducing emissions. Emission growth has even accelerated in recent years, mostly due to rapid economic growth in emerging economies (Raupach et al. 2007). Scenarios of the future development in a business-as-usual world project significant increases of CO_2 emissions, largely driven by sustained 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.

We used the three state-of-the-art numerical energy-economy models IMACLIM-R (Crassous et al., 2006), REMIND-R (Leimbach et al., 2009) and WITCH (Bosetti et al., 2006; 2007) to analyze economic and technological implications of ambitious climate mitigation policy. These hybrid models are characterized by a combination of a realistic and complete top-down representation of the macro-economic growth process and a technologically explicit bottom-up representation of the energy-system.

We present results from the RECIPE model intercomparison project (Edenhofer et al. 2009; Jakob et al., 2009; Luderer et al., 2009) for business-as-usual and a policy scenario aiming at a stabilization of atmospheric CO_2 concentrations at 450ppm. Based on an in-depth analysis of model outputs this paper aims at identifying the key determinants for differences in mitigation costs, timing and technology portfolios. It 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 structure and macro-economic effects of 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

As part of the RECIPE project, three energy-economy-climate models were employed.

IMACLIM-R, developed by CIRED (see Crassous et al., 2006), 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. This allows distinguishing between potential and real 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 implement no-regret options which are profitable in the long term but which are not taken under normal conditions due to myopic behavior. This property can also result in some kind of 'bi-stability' in the sense that 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 little extra effort is required once it is located on this new trajectory.

The global multi-region model REMIND-R as introduced by Leimbach et al. (2009) from PIK 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. Mitigation costs estimates 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 actors. This implies that technological options requiring large up-front investments that have long pay-back times (e.g. via technological learning) are taken into account in determining the optimal solution.

The WITCH model developed by the climate change group at FEEM (Bosetti et al., 2006; Bosetti et al., 2007) 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 a truly 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 put on the emergence of carbon-free backstop energy technologies in the electricity as well as the non-electricity sectors and on endogenous improvements in energy efficiency triggered by dedicated R&D investments contributing to a stock of energy efficiency knowledge.

2.2 The model comparison framework

The economic analysis of climate change is concerned with two types of major uncertainties: firstly, parameter uncertainty (i.e. incomplete knowledge with regards to economic and technology parameters used to calibrate the models), and, secondly, model uncertainty (i.e. having several plausible model structures without a clear indication to prefer one structure over the others). Carrying out model comparisons in order to reduce model uncertainty is an often used concept in climate economics (see e.g. Edenhofer et al, 2006; Knopf et al., 2009). In this context, one should be clearly aware that models are not intended to predict the future, but to generate plausible, self-consistent scenarios. These scenarios, in turn, constitute useful tools for scientists and policymakers to explore the scope of possible developments, discuss the plausibility of underlying assumptions, and derive appropriate courses of action.

The three models employed in this model comparison were harmonized to represent very similar assumption with regards 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 income levels which are between 8 and 10 times their 2005 value (i.e. population growth and world GDP). Also, the cost development of fossil fuels was harmonized under the assumption of large and cheap abundance of coal and relative scarcity of oil and gas. By contrast, different visions of development and diffusion of new technologies as well as of economic mechanisms remain across the three models. Comparing the results obtained for the baseline as well as stabilization scenarios with these three models will hence help to shed some light on how different assumptions on technologies and economic dynamics translate into differences in mitigation costs, investment patterns, and optimal emissions reduction trajectories.

For these reason, various scenarios were generated. The baseline scenario represents the business-as-usual development (i.e. projections of future emissions if no climate policy measures are implemented), against which all stabilization scenarios are evaluated. The policy scenarios assess the costs of stabilizing GHG concentrations at 450 ppm CO_2 only, a target that is a minimum requirement to avoid dangerous climate change[2].

3. Results

3.1 The Energy System Transformation

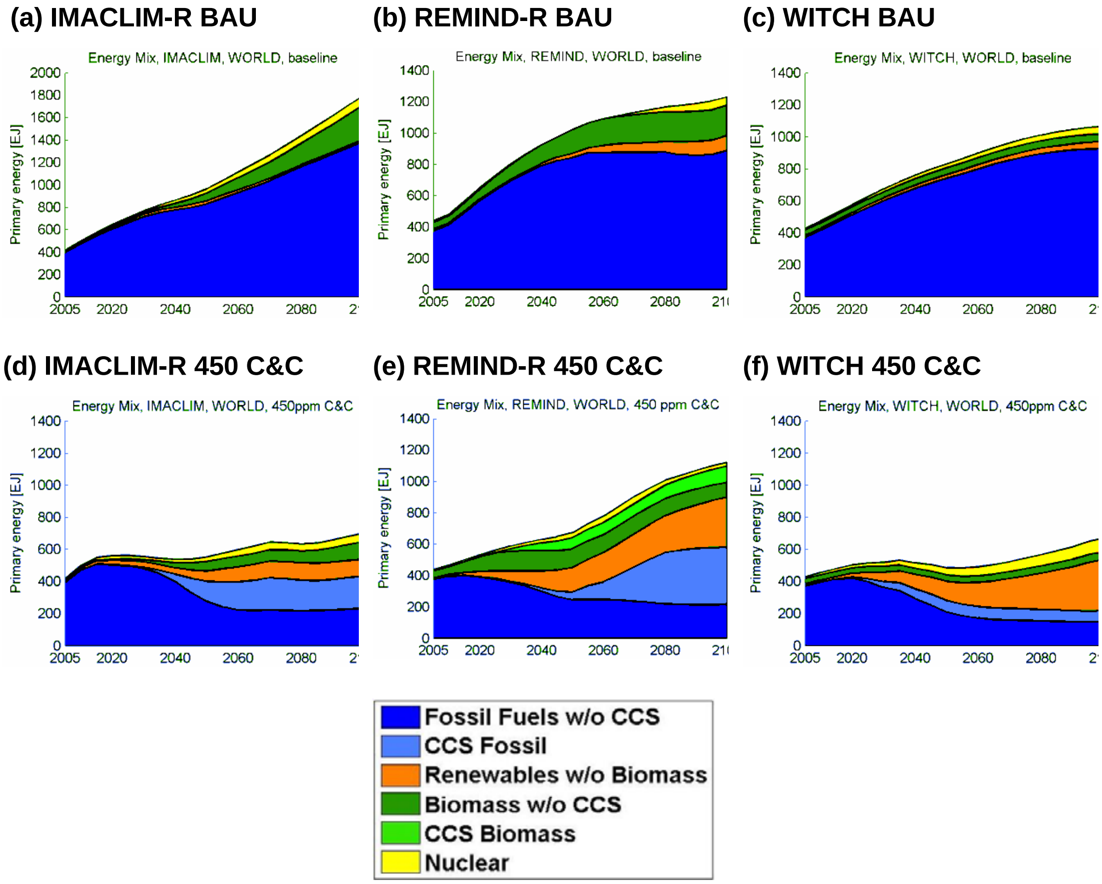

Figure 1: Primary Energy Supply in IMACLIM-R, REMIND-R and WITCH for the baseline case, the default policy scenario with stabilization of atmospheric CO_2 concentrations at 450 ppm. Note different scale for IMACLIM-R BAU scenario.

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[2] As part of RECIPE, also a policy target aiming at stabilization 410 ppm was considered (Luderer et al., 2009). This paper, however, focuses on the 450 ppm target.

The baseline scenarios describe a world in which no climate change mitigation policy occurs. Since the RECIPE models assume abundant availability of cheap coal, the energy systems in the baseline scenarios are highly carbon intensive (Figure 1). A distinguishing feature of the IMACLIM-R model is the large use of coal-to-liquid in the business-as-usual case. 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. Thus, in the baseline scenario, CO_2 emissions continue to rise significantly throughout the 21st century, giving rise to the highest BAU emissions of all three models and implying a larger reduction effort to reach climate stabilization (Figure 2). In contrast to the "black" baseline given by IMACLIM, the REMIND-R baseline can be characterized as a "green" baseline. After a high growth up to 2040, emissions decline after 2050, reaching 77 Gt CO_2 in 2100. This can be explained by a decreasing growth rate of energy demand in REMIND and a higher penetration of carbon-free energy technologies (biomass and other renewable energies) due to resource constraints. The aggregated WITCH baseline is comparable to the REMIND-R one; reaching 86 Gt CO_2 emissions in 2100 with a decreasing emission growth rate in the second half of the century. It can be classified as a less energy-intensive 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. Largely due to constraints in the availability of fossil fuels other than coal, REMIND features an increasing share of renewables in the baseline. By contrast, the supply of energy from renewable energy is small in IMACLIM-R and WITCH.

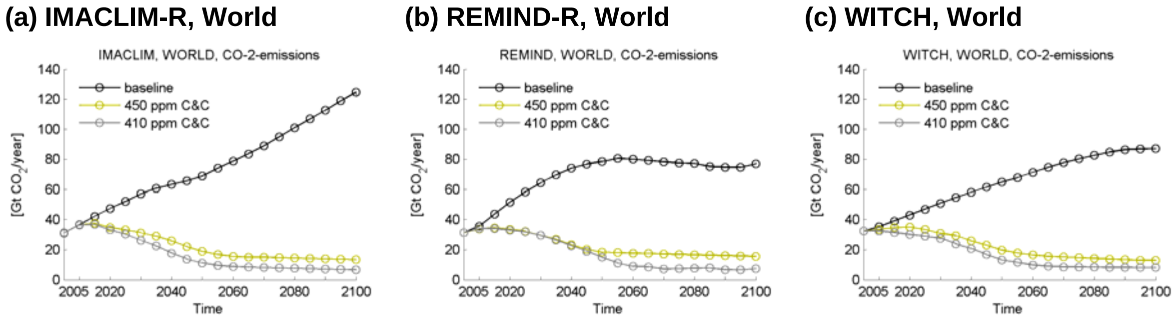

(a) IMACLIM-R, World **(b) REMIND-R, World** **(c) WITCH, World**

Figure 2: Global pathways for CO_2 emissions from fossil fuel combustion for the baseline scenario as well as policy scenarios aiming at stabilization of atmospheric CO_2 concentrations at 450 ppm and 410 ppm only calculated by IMACLIM-R, REMIND-R and WITCH.

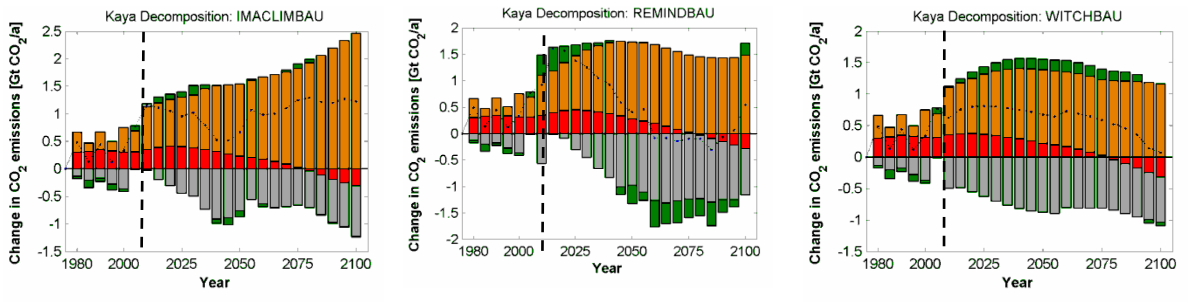
The gap between business-as-usual CO_2 emissions and emission trajectories required to achieve the stabilization targets as illustrated in Figure 2 demonstrates the scale of the climate stabilization challenge. A climate policy aimed at stabilizing CO_2 concentration results in a substantial reduction of energy demand in the WITCH and IMACLIM-R models. In REMIND-R, by contrast, energy demand keeps increasing even in the presence of a climate target because additional 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). Since the carbon is absorbed from the atmosphere by plants during their growth, but ends up – at least partially – stored underground, bioenergy in combination with CCS has the potential to generate negative emissions and thus becomes an important mitigation option. 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 stabilization scenario illustrates how inertia and rigidities of the energy sector are represented in the WITCH model, mimicking durability of capital. Moreover, the possibilities of replacing traditional carbon-based technologies with carbon-free options are limited, because of assumptions on CCS capture rate and on biomass penetration are more conservative than in the 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 price.

3.2 Macro-economic effects of climate policy

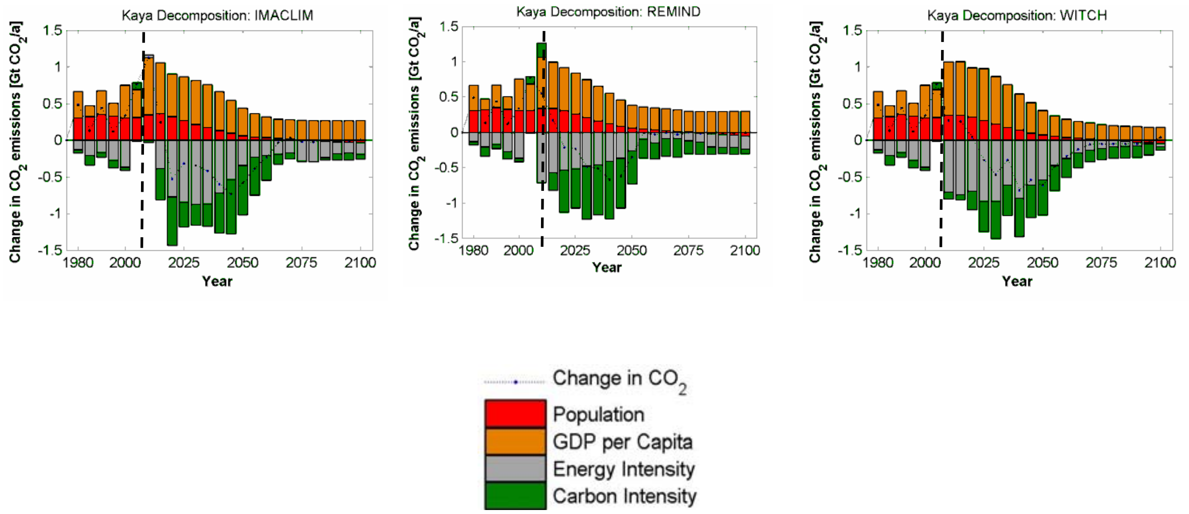
Energy-related emissions are driven by population, per capita GDP, energy intensity of economic output, and the amount of CO_2 emitted per unit of primary energy consumption. These developments are shown in Figure 3. Since policymakers have no or only little influence on population growth and the reduction of economic output is usually not considered an option, the focus of climate change mitigation is on achieving emissions cuts by reducing the energy 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. Figure 2.3 also illustrates that in the low-carbon scenarios improved energy efficiency and lower carbon intensity of fuels reduces the impact on GDP growth on CO_2 emissions.



(a) IMACLIM-R BAU

(b) REMIND-R BAU

(c) WITCH BAU



(d) IMACLIM-R 450 ppm C&C

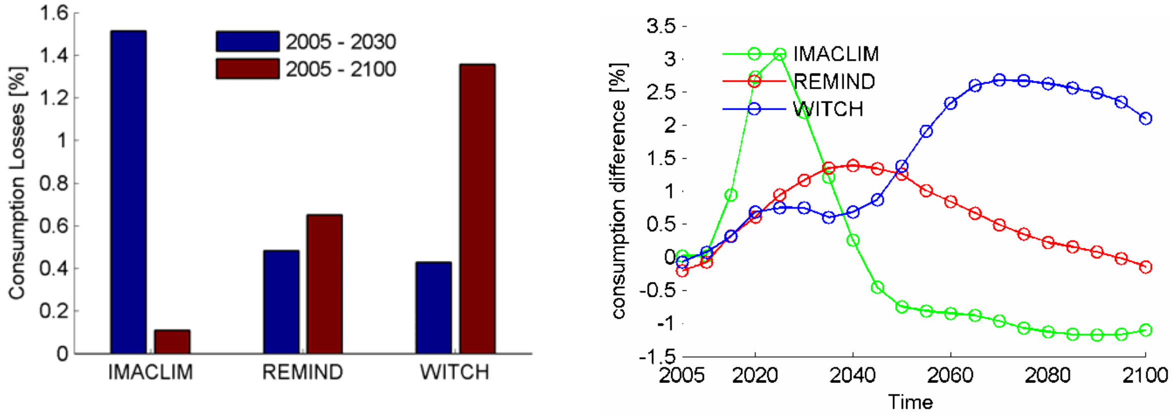
(e) REMIND-R 450 ppm C&C

(f) WITCH 450 ppm C&C

Figure 3: Decomposition of historic CO_2 emission trends and model projections for IMACLIM-R, REMIND-R and WITCH for the baseline and the 450 ppm. 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 absolute annual change in CO_2 emissions. Note the different scales between BAU and policy scenarios.

For the business-as-usual (BAU) development path, the models project that energy efficiency improvements (grey bars) can only partly offset the increases resulting from growth in per capita GDP. The increasing consumption of coal results in a medium-term increase in carbon intensity, a pattern that is in line with recent trends (Raupach et al., 2007). Stabilization of atmospheric CO_2 concentrations requires a transformation effort in terms of energy and carbon intensity that is huge and without precedence in history given the differences to the business-as-usual development. Models can be characterized in terms of the division of labor between energy efficiency improvements and reductions in carbon intensity. While for REMIND-R the bulk of the mitigation effort is achieved via decarbonization, IMACLIM-R and WITCH assume a more balanced strategy with efficiency and decarbonization contributing approximately equally.

Due to their structural differences and different representations of the energy system, the models project different economic effects of climate policy. The aggregated mitigation costs in terms of consumption losses relative to the baseline discounted over the period to 2100 accrue to 0.1% (IMACLIM-R), 0.6% (REMIND-R), and 1.4% (WITCH). The size and temporal evolution of mitigation costs and the carbon price are shown in Figure 4. The differences in model approaches are reflected in the structural differences of carbon price trajectories. In IMACLIM-R, due to the assumptions on imperfect foresight, very high carbon prices are required initially to create a sufficiently strong signal to trigger a transition to a low-carbon energy system (Figure 4c). These 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. For Europe, mitigation costs also peak in 2030, but remain positive afterwards. Aggregated European consumption losses are thus considerably higher than on the global level and are projected to be highest among the three models. The flat profile of the carbon price in IMACLIM-R after 2030 can be attributed to (1) the learning processes in carbon saving energy technologies that increase the reduction potentials available at a given carbon price and by (2) climate-friendly infrastructure policies that avoid a costly lock-in to carbon-intensive transportation systems, thus removing a critical obstacle to stabilization in the long run.



(a) Aggregated global consumption losses 450 ppm

(b) Global consumption losses 450 ppm

(c) Carbon price 450 ppm 2005 – 2030

(d) Carbon price 450 ppm 2005 – 2100

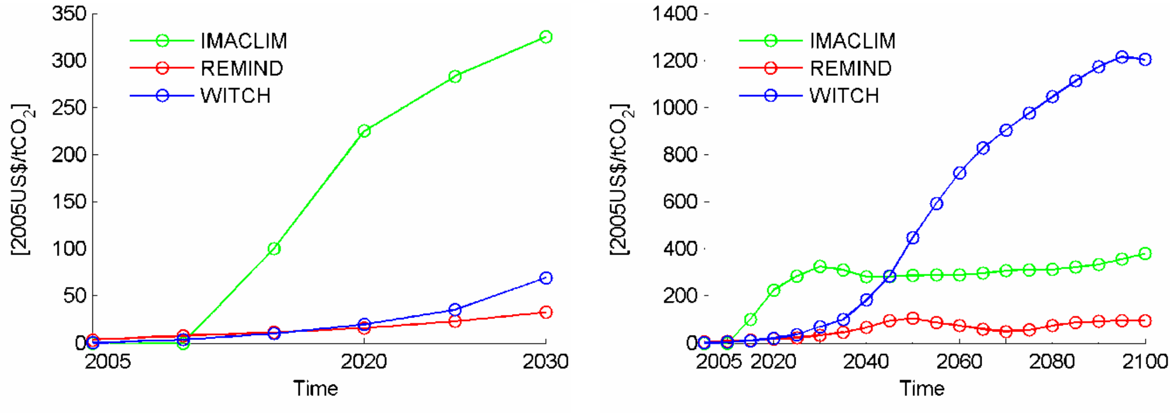


Figure 4: Global (a,b) welfare losses as consumption differences relative to baseline as well as the global carbon price (e,f) for the 450 ppm scenario. Aggregated consumption losses (a) are discounted at 3%.

3.4 Sectoral results

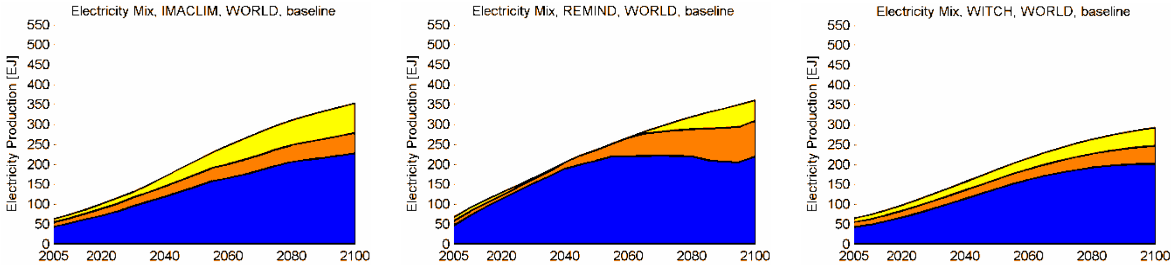
Mitigation potentials and strategies vary strongly across source sectors. Also, the representation of energy-consuming sectors differs across the three models. It is therefore an important focus of the RECIPE model intercomparison project to provide insights on differences and robust findings with respect to sectoral mitigation strategies.

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. It explicitly represents the energy system structure in the electricity, transport, residential and industry sectors.

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 sectors, resulting in comparatively high flexibility for the shift between primary energy carriers. In particular, REMIND-R has various technological options to combine fossils and biomass with CCS. 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 the electricity and the non-electricity sectors. The supply of electric and non-electric energy is represented by a hierarchical nest of CES -type production functions. 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-electricity sector, biomass (both traditional and advanced), coal and oil are used as primary energy carriers as well as a generic backstop technology for non electricity production. 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.

(a) IMACLIM-R BAU **(b) REMIND-R BAU** **(c) WITCH BAU**



(d) IMACLIM-R 450 ppm **(e) REMIND-R 450 ppm** **(f) WITCH 450 ppm**

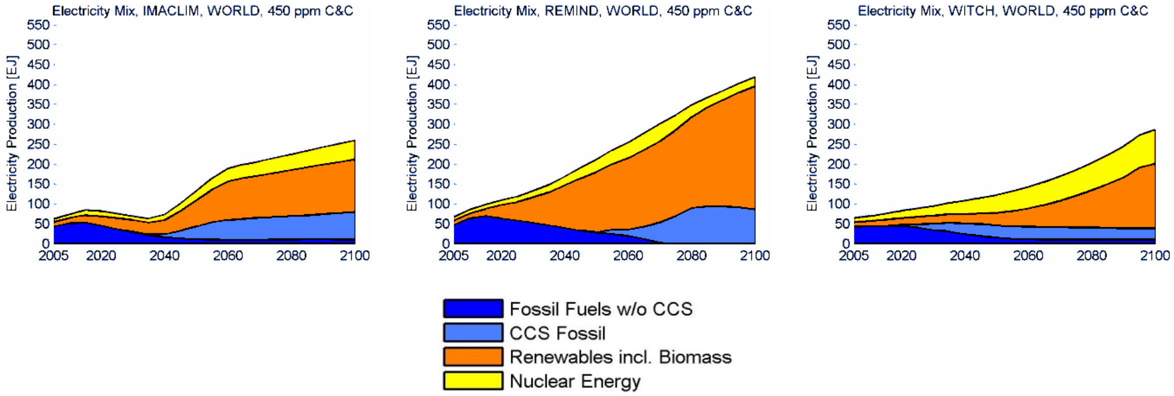


Figure 5: Electricity mix for the European power sector (IMACLIM-R and WITCH) as well as power and heat for REMIND-R.

The electricity mixes as projected by the three models for the baseline as well as the 450 ppm scenarios are depicted in Figure 5. 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 sixfold until 2100. WITCH projects slightly lower growth rates. In the baseline projections, the electricity generation mix is dominated by fossil fuels. REMIND-R, however, projects substantial penetration of renewables already in the baseline scenario, with a contribution of 20% to the electricity production in 2050. IMACLIM-R and WITCH project lower shares of renewables, while nuclear energy plays a more important role. In REMIND-R, nuclear capacity declines until 2040 but is expanded afterwards.

A variety of low-carbon or even carbon-free technologies are available for electricity production: renewables, nuclear and CCS. Consequently, all models project that the decarbonization proceeds most rapidly in the electricity sector. All models project a steep decline of conventional fossil power generation capacity, while electricity production form renewables is expanded substantially. CCS is projected to become available around 2030. In IMACLIM-R and REMIND-

R 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 is projected to exceed current levels by a factor of four (REMIND-R, WITCH) to nine (IMACLIM-R). In the climate stabilization scenarios, WITCH projects a pronounced increase of nuclear power in the electricity mix. Similarly, REMIND-R projects that nuclear contributes significantly to electricity production during a transition period. The total installed capacity projected for the 450 ppm scenario in 2050 corresponds to about 900 (REMIND-R) to 1200 (WITCH) reactors of 1.5 GW capacity. After 2020, IMACLIM-R projects nuclear energy production for the policy scenario to be smaller than in the baseline.

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 is projected, largely induced by a switch from non-electric to electric energy sources in the industry sector. WITCH projects lower growth in electricity demand until 2050 compared to the baseline. Once the low-carbon breakthrough 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 10. According to REMIND-R and IMACLIM-R, the transport sector 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. IMACLIM-R projects that the transport sector heavily relies on coal-liquefaction. Biomass is also projected to assume an increasing share of primary energy supply from 2020 (IMACLIM-R) or 2030 (REMIND-R).

Electrification is regarded one of the most promising technology options for decarbonization of the transport sector. In REMIND-R and WITCH, electrification is only represented implicitly via substitution within the macro-economic system. IMACLIM-R represents the deployment of plug-in hybrid vehicles, thus explicitly including electrification of the transport sector. Including this option might facilitate the use of carbon free technologies in the transportation sector. However, according to IMACLIM-R, despite the availability of plug-in hybrid vehicles, electricity accounts only for a minute 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 (corresponding to 67 % of the carbon contained in the raw material) is captured and stored. Coal liquefaction in combination with CCS is projected to become available as early as 2010. As the carbon contained in the biomass was removed from the atmosphere during plant growth, the biomass plus CCS conversion pathway results in negative net emissions. As long-term energy-demand in the transport sector is almost equal to that projected for the baseline, efficiency only plays a minor role in REMIND-R.

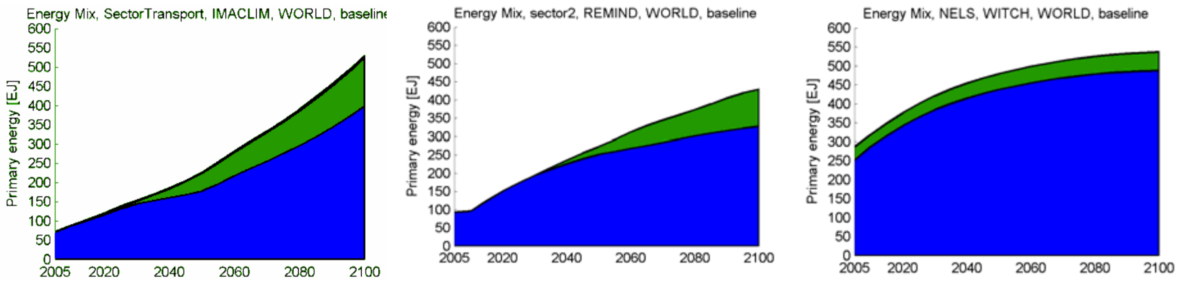
According to IMACLIM-R, an increase of biogenic fuels and the reduction of energy demand are the most important mitigation options for the transport sector. A decrease of primary energy consumption of 25% for the 450 ppm scenario compared to the baseline is projected for 2040. This results from (a) energy efficiency improvements in the vehicles fleet, (b) the penetration of plug-in hybrid technology, and (c) infrastructure policy introduced as complementary measures of carbon pricing to decrease the transport intensity of the economy.

WITCH does not report the transportation sector separately, but simulates a composite of all non-electricity forms of final energy demand. In the baseline scenario, energy demand in the non-electricity sector is projected to be 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 projected to become introduced between 2020 and 2025 and to contribute 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-electricity sector to penetrate slowly, thus limiting the decarbonization of the sector. Consequently, a significant decline of primary energy demand is required. The 450 ppm policy scenario projects a reduction by 40% relative to BAU. This contraction of non-electric energy supply gives rise to a substantial decrease in macro-economic productivity.

Figure 7 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 in primary energy demand in the industry sector for the baseline scenario is projected to be moderate compared to that in the electricity and transport sectors. The energy mix is dominated by fossil fuels with an increasing share of coal. Biomass is projected to play a very marginal role. For the 450 ppm stabilization scenario, IMACLIM-R projects a sharp deviation from business-as-usual after 2040 and a subsequent decline of non-electric energy demand 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 when after the introduction 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, a decrease in non-electric energy demand of 50% by 2050 and more than 95% by 2100 is projected. This results from high potential of very efficient buildings, which rely mainly on electricity for their residual energy demand.

(a) IMACLIM-R BAU **(b) REMIND-R BAU** **(c) WITCH BAU**



(d) IMACLIM-R 450 ppm **(e) REMIND-R 450 ppm** **(f) WITCH 450 ppm**

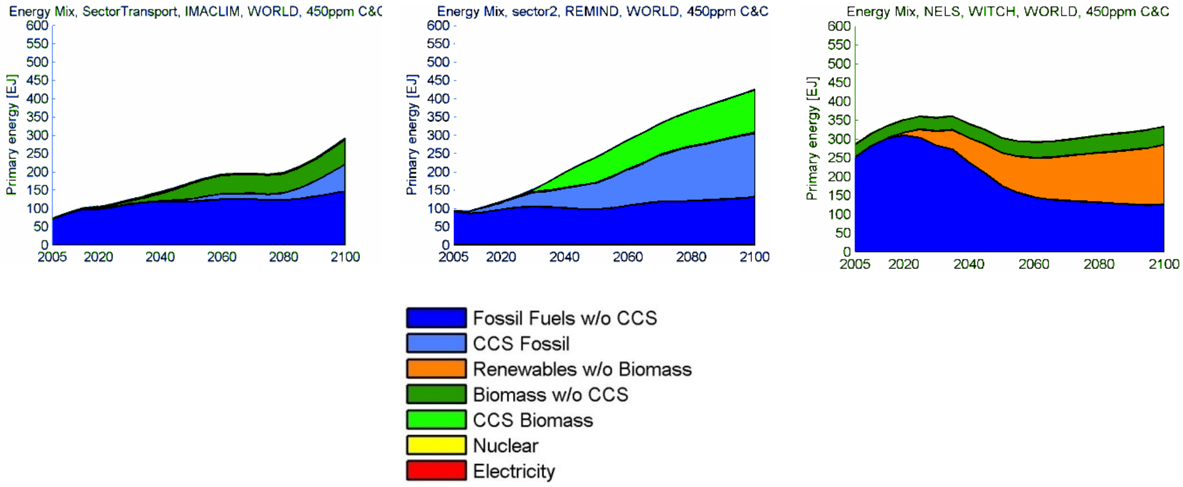
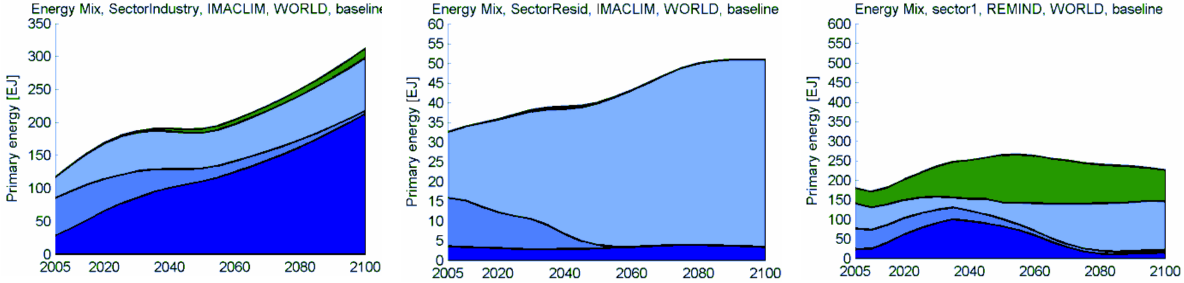


Figure 6: Primary energy mix for the transport sector (IMACLIM-R and REMIND-R) and non-electricity sector (WITCH), in the baseline as well as the 450 ppm. For IMACLIM-R, primary energy consumption related to electricity used by plug-in hybrids is included in red. In its current version, REMIND-R does not consider electrification in the transport sector.

According to 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.


(a) IMACLIM-R BAU Ind. (b) IMACLIM-R BAU Res. (c) REMIND-R BAU Stat.

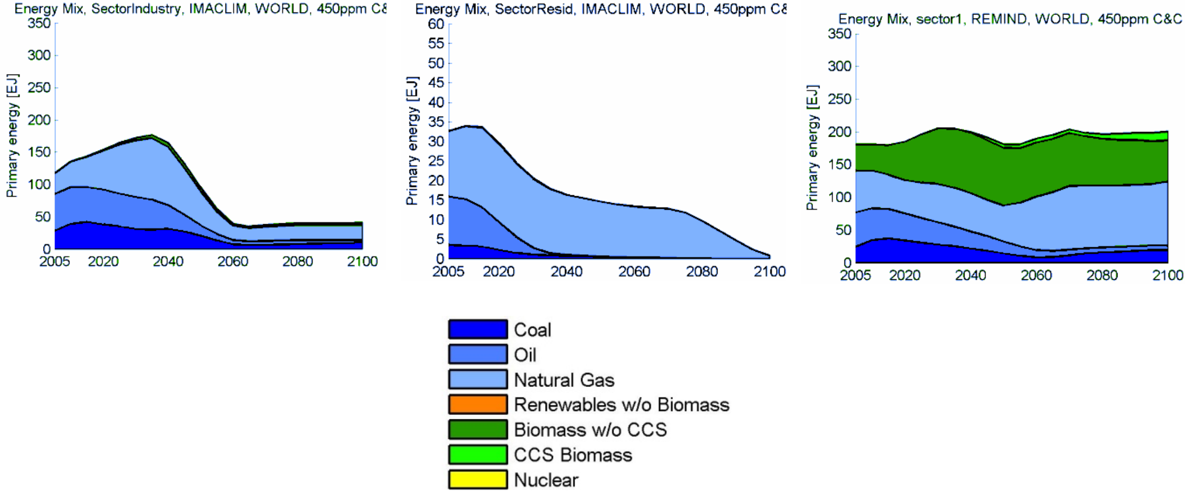
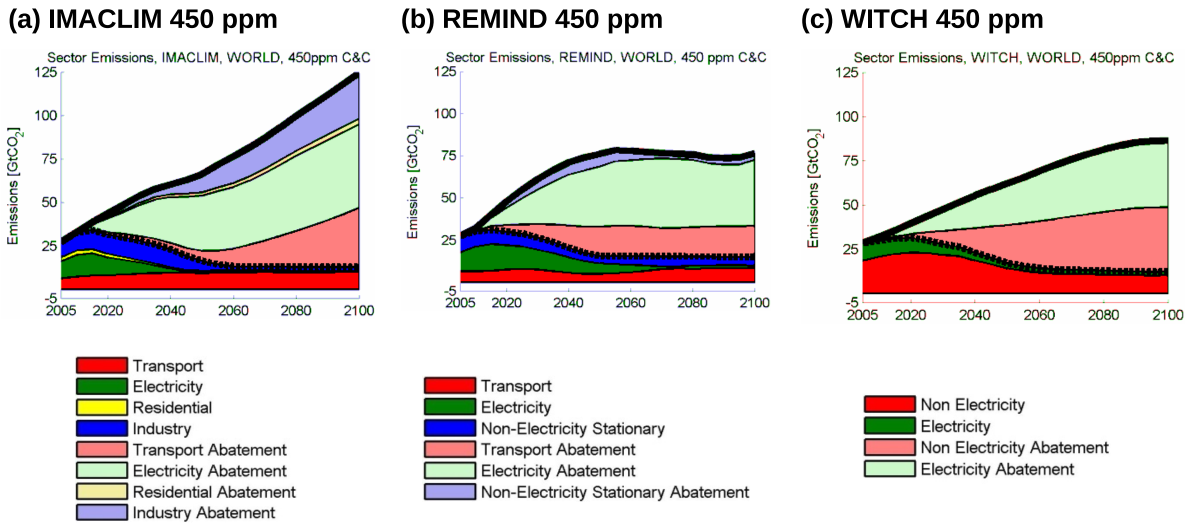

(d) IMACLIM-R 450ppm Ind. (e) IMACLIM-R 450ppm Res. (f) REMIND-R 450ppm Stat.

Figure 7: Residential and industrial sectors for IMACLIM-R and non-electric stationary sector for REMIND-R. In WITCH, the stationary sector is included in the non-electricity sector. As CCS does not play a role for the sector, fossil fuels are further decomposed into coal, oil and natural gas.

The contribution of various sectors to the overall mitigation effort is depicted in Figure 8. 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. IMACLIM-R and WITCH 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. The somewhat lower remaining emissions by the transport sector in REMIND-R underline how different model representations of abatement technologies impact energy system patterns. 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 scenarios, one major mitigation option in the transport sector is the deployment of plug-in hybrid vehicles, resulting in considerable efficiency gains and a shift from non-electric to electric energy demand. In REMIND-R, by contrast, the option to generate transport fuels from biomass in combination with CCS is used extensively. As this technology results in negative CO_2 emissions, it even enables additional headroom for emissions from the stationary sectors.


(a) IMACLIM 450 ppm

(b) REMIND 450 ppm

(c) WITCH 450 ppm

Figure 8: Global CO_2 emissions decomposed by different sectors for the three models IMACLIM, REMIND and WITCH for the 450 ppm. 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.

4. Discussion and Conclusions

The three models employed in the comparison were harmonized to represent very similar assumption with regards to socio-economic developments (i.e. population growth and world GDP) and availability of fossil resources but different visions of 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 emissions reduction trajectories.

The different structure of energy supply in the three models, visible in the baseline scenario but more evident in the stabilization scenario, hinge on four main factors: (a) the availability of technological options which is different across models; (b) assumptions about natural resources; (c) the presence and the nature (exogenous or endogenous) of innovation and technical change, which contributes to determining the degree of flexibility of the three models; (d) the durability of capital stocks and the inertia of the energy sector. Other important elements for the final energy mix include macroeconomic substitution processes and the representation of the decision process, the assumptions on 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.

The fundamental differences in the model designs allow us to extract three self-consistent yet different visions of the nature of the decarbonization process. REMIND-R is the most optimistic of the three participating models. It assumes perfect foresight by all agents and considers a wide variety of mitigation technologies. Moreover, it includes intertemporal trade, thus giving rise to a frictionless international capital market. It does not account for externalities effects other than CO_2 emissions. WITCH, also an optimization model assuming perfect foresight, is distinctly different from REMIND-R in assuming higher stiffness in the macro-economy and fewer technological options in the energy sector. IMACLIM-R is characterized by imperfect foresight and significant inertia. In its baseline scenario, IMACLIM-R projects the most carbon-intensive growth path. IMACLIM-R is characterized by large sectoral detail.

The three pathways outlined by the models demonstrate the implications of different institutional and technological settings for the magnitude, timing and regional distribution of mitigation costs as well as technology portfolios.

In REMIND-R, the flexibility in the energy system and the large number of low-carbon technologies options make it possible to accomplish the mitigation effort almost entirely through decarbonization, while energy efficiency improvements only play a minor role. Aggregated global consumption losses are projected at 0.7% for the 450 ppm stabilization scenario and to be distributed smoothly over time. The option of combining biomass with CCS, which implies negative net emissions, reduces the mitigation burden for sectors that are difficult to decarbonizes, such as transport.

In WITCH, by contrast, the marginal costs of abatement through adjustments within the energy system so high that they need to be complemented with reductions in macro-economic energy demand, thus resulting in reductions of output and higher economic costs. Curbing emissions in the non-electricity sector requires substantial investments in low-carbon innovations and marked contractions in energy demand, resulting in high carbon prices and overall welfare losses that are higher than in the other two models.

According to IMACLIM-R, very high carbon prices are required initially to induce a low-carbon transition. Short to medium term welfare losses are substantially higher than in the models that assume perfect foresight. After 2040, once the low-carbon transformation is accomplished, IMACLIM-R mitigation costs are offset by gains related to efficiency improvements and decreased dependence on fossil fuels. Decarbonization and energy efficiency are projected to contribute equally to the mitigation effort.

Despite the largely different assumptions and representations of macro-economic effects, technologies and the nature of the transformation process, a number of common conclusions can be drawn from the models. Firstly, all models project that ambitious CO_2 reductions yielding atmospheric stabilization of CO_2 concentrations at 450 ppm can be achieved at costs of 1.4% or less of global consumption. However, bold political action, particularly the setup of an international carbon market and investment in low-carbon innovation, is required. The reductions needed for achieving ambitious stabilization targets imply a large scale transformation of the energy system. All models project a rapid decarbonization of the electricity sector and an immediate phase-out of investments in conventional fossil power generation capacity (cf. Luderer et al., 2009). Emissions reductions outside the power sector, particularly transport, are projected to be more challenging. Long-term mitigation costs strongly depend on energy efficiency improvements and the availability of abatement options in transport sector. This underlines the paramount importance of technological innovations to overcome the dependence of this sector on fossil fuels.

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