The Economics of Decarbonization – Results from the RECIPE model intercomparison

Background Paper

RECIPE

THE ECONOMICS OF DECARBONIZATION

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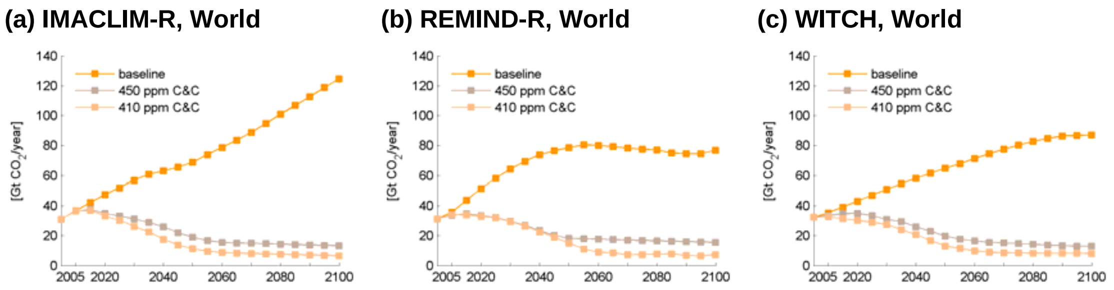
1. A Stabilized World

- **This section describes the model results for the default policy scenarios assessing energy system structure and global welfare effects for climate policy aiming at a stabilization level of 450 ppm CO2.**
- **All models show that stabilization of CO2 concentrations at 450 ppm is possible at costs ranging from 1.4% in the WITCH model to 0.6% in REMIND-R and 0.1% in IMACLIM-R. These values are expressed in consumption losses relative to baseline discounted at 3%.**
- **The IMACLIM-R model, characterized by imperfect foresight and technological inertia, projects highest short to medium term welfare losses induced by climate policy. After 2040, once the structural transformation is achieved, mitigation costs are offset by gains related to efficiency improvements and decreased dependence on fossil fuels. Decarbonization and energy efficiency improvements contribute equally to the mitigation effort.**
- **REMIND-R, which is characterized by high flexibility in terms of low-carbon technologies as well as international and intertemporal trade, projects relatively low consumption losses of well under 1%.**
- **The WITCH model, which is less optimistic about the availability of technology options and assumes higher rigidities in the energy system, projects higher mitigation costs. Due to the barriers to decarbonization within the energy sector, a relatively large share of the mitigation effort must be accomplished by the reduction of the macro-economic energy demand.**
- **The models project an almost full-scale decarbonization of the electricity sector. The decarbonization of the non-electricity sectors, particularly transport, is more challenging and plays a pivotal role for the overall mitigation costs.**
- **Energy systems are characterized by significant inertia and long transition timescales and the long economic life time of installations. An immediate change of investments is required in order to induce a structural change energy system consistent with ambitious mitigation targets.**
- **The explicit simulation of the dynamics related to research and development (R&D) performed by the WITCH model exhibits the need for significant up-scaling of energy-related R&D, both for energy efficiency and decarbonization technologies in order to achieve the stabilization targets in a cost-effective way.**
- **In addition, an analysis of a more ambitious target of stabilization of CO2 concentrations at 410 ppm by 2100 has been undertaken. According to IMACLIM-R and REMIND-R, this scenario entails a moderate increase in mitigation costs, while WITCH projects GWP losses in excess of 5% for this scenario.**

The evidence that climate is warming is widely recognized and the scientific basis has also become more robust. If emissions keep growing along a business-as-usual trajectory, global warming due to the anthropogenic greenhouse effect could become as high as 5°C or more, relative to pre-industrial levels (IPCC, 2007a; Jakob, 2009a). 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, 2007c; Jakob et al., 2009a).

The three models used in the project, IMACLIM-R, REMIND-R and WITCH (all described in detail in Jakob et al., 2009b), are employed to assess the costs of stabilizing CO_2 concentrations at levels of 450 ppm. A stabilization level of 450 ppm CO_2 only (corresponding to about 525 ppm CO_2 eq., depending on assumptions regarding non-CO_2CO_2 gases) would result in a temperature increase of about 2.5-3.0°C relative to pre-industrial levels, depending on the value of climate sensitivity. For this reason, although the main focus of the analysis and of robustness tests is on the 450 scenario, a more ambitious scenario has been also considered. In particular the models were employed to simulate a stabilization scenario to 410 ppm CO_2 only (corresponding to about 460 ppm CO2 eq.), which would yield a medium likelihood of reaching the EU's target of limiting global warming to no more than 2°C above pre-industrial levels (Meinshausen, 2006).



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

Figure 1: 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 the 410 ppm only as projected by the three models IMACLIM-R, REMIND-R and WITCH.

The 450 ppm target will require a peak in emissions between 2015 and 2025 and approximately a 50% reduction of global GHG emissions compared to current levels by 2050 (Figure 1). Today, CO_2 is at a globally averaged concentration of approximately 387 ppm, therefore the more stringent 410 ppm emissions scenario, entails some overshooting in all the three models, although each projects a different trajectory for emissions. WITCH projects an immediate decline in global emissions and an eventual stabilization of CO_2-emissions at 7 Gt CO_2, about a quarter of current emissions. Due to the inertia caused by imperfect foresight, global emissions in IMACLIM-R continue to increase until 2015, but subsequently decline to a long-term stabilization level of 7 Gt CO_2 which is reached by 2060. REMIND-R includes the option to combine biomass and CCS, a technology that results in negative emissions. Its availability allows for deep emission reductions in the second half of the century in REMIND-R, thus providing headroom for higher emissions compared to IMACLIM-R and WITCH until in the earlier decades. The differences in the emission pathways associated with the three models are mainly driven by (a) different assumptions on low-carbon technology availability and the flexibility of investments, and (b) differences in the climate modules. While the stabilization pathways differ, the cumulative amount of emissions over the time span from 2005 to 2100 is equal at about 2180 Gt CO_2 in the case of the 450 ppm 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 between 3900 and 4850 Gt CO_2 for the 450 ppm scenario and 4400 and 5350 Gt CO_2 for the 410 ppm scenario compared to the business-as-usual case.

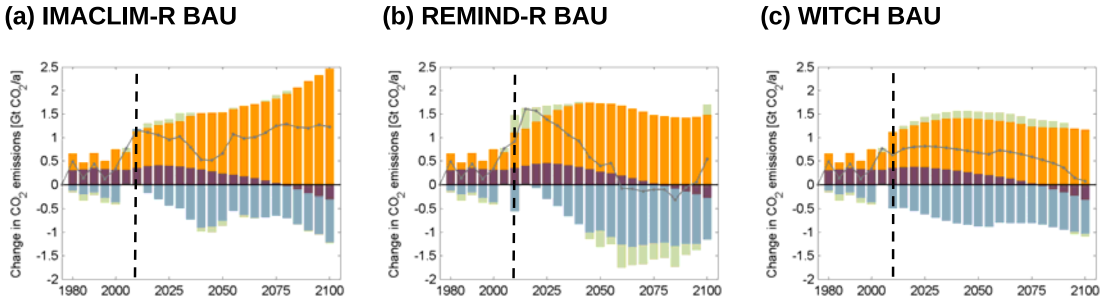
1.1. Macro-economic effects of climate policy

The comparison of historic CO_2 growth patterns with those projected by the models demonstrates the scale of the challenge. Since emissions are influenced by population, per-capita GDP, energy intensity of economic output, and carbon intensity of the primary energy carriers used, the rate of change in energy-related emissions can be attributed to these four driving forces. This approach is called Kaya decomposition (Kaya, 1990).

In Figure 2 historic emission changes are compared to future changes as projected by IMACLIM-R, REMIND-R and WITCH and decomposed along population growth (red), GDP per capita (orange), energy intensity reductions (grey), and decarbonization (green).

Since policymakers have no or little influence on population growth, and reduction of economic output is not an option, the challenge for climate policy is to achieve emission cuts by reducing energy- and carbon intensity of the economic system. Decoupling GDP growth from emission growth requires a reduction of the amount of energy used to produce one unit of GDP (energy intensity), a reduction of CO_2 emissions of primary energy consumption (carbon intensity), or a combination of both strategies.

The three models demonstrate that in order to reduce emissions despite the increase in population and GDP, energy intensity improvements and decarbonization need to be increased substantially compared to historic developments (Figure 3). Thus, in order to achieve the climate target assumed for the basic policy scenario, a large scale transformation of the energy system is required.


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

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

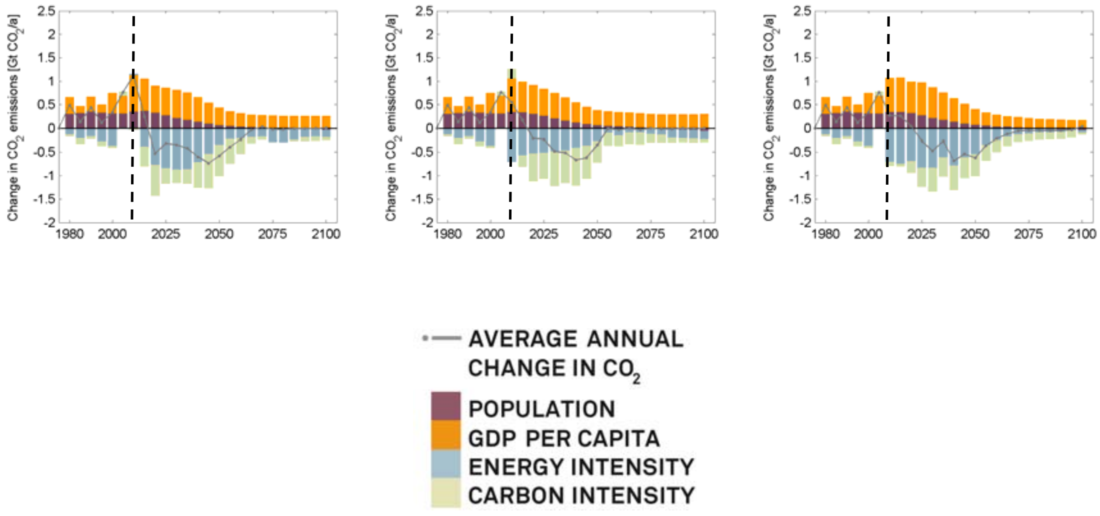
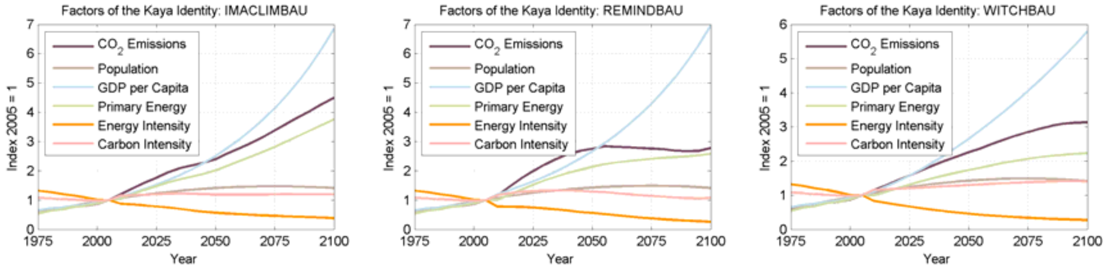


Figure 2: Decomposition of historic CO_2 emission trends and model results for IMACLIM-R, REMIND-R and WITCH for the baseline and the 450 ppm C&C scenario in terms of the driving factors population growth, per capita GDP, energy intensity of economic output, and carbon intensity of primary energy use. The dashed lines indicate the transition from historic data (IEA) to modeled data (RECIPE models). Note different scales between BAU and policy scenarios.

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



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

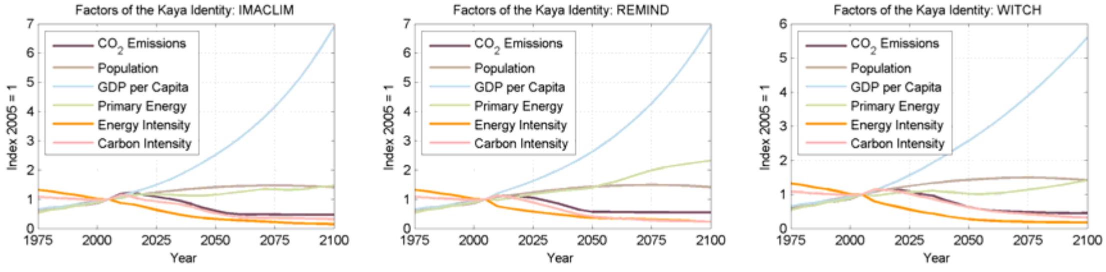
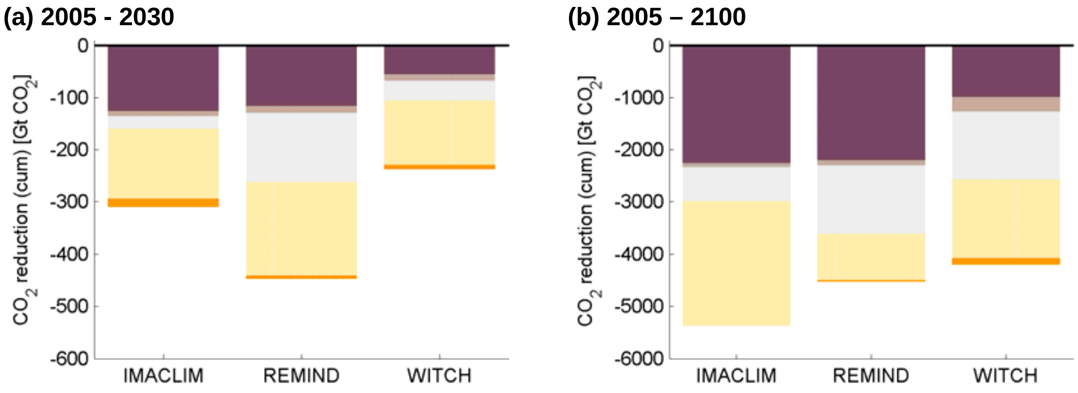


Figure 3: Kaya factors for the baseline and the 450 ppm C&C as projected by the RECIPE models (2005-2100). For comparison, historic trends based on IEA (2007) are depicted for 1975-2005.

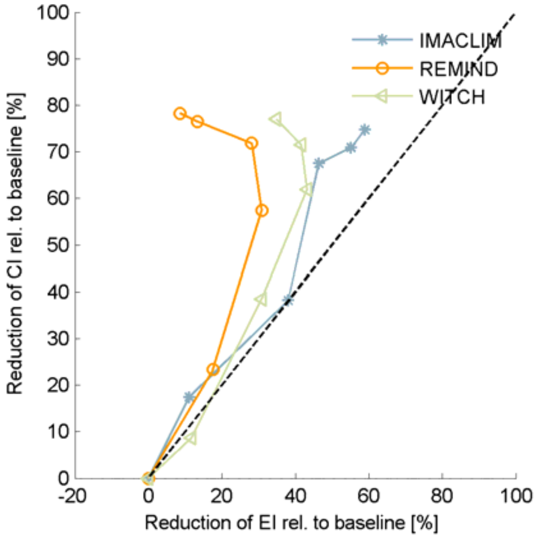
The basic policy scenario discussed in this section combines a global cap on CO_2 concentrations (450 ppm) with an emissions trading scheme. The mitigation burden is allocated across countries using a contraction & convergence allocation rule (Meyer, 2004). According to this scheme, emission allowances are initially grandfathered according to status quo emissions. A long-term equal-per-capita emission target is defined (here we used 2050), and the share of allocations of each region then converges linearly towards this target in a transition phase.

The relative contribution of energy efficiency improvements and carbon intensity reduction to the necessary decline of energy-related CO_2 emissions is depicted in Figure 4. Efficiency improvements refer to a decrease of energy intensity, i.e. the amount of primary energy required for a given amount of economic output. Carbon intensity reductions are achieved by a switch towards primary energy carriers with lower (e.g. natural gas in lieu of coal) or zero (e.g. renewables) carbon content, or by capture and sequestration of CO_2 emissions (CCS). Due to the higher baseline emissions in IMACLIM-R, the cumulative reduction effort is significantly larger than in the other two models, particularly in the second half of the century. In all three models, CCS, expansion of renewables and nuclear contribute to emission reductions. The relative importance of efficiency improvements and decarbonization is, however, different among models. It stands out in particular that the IMACLIM-R and WITCH models impute a comparable contribution to the decarbonization effect and the improvement in energy efficiency, while REMIND-R puts a much stronger emphasis on decarbonization. This is also evident from Figure 4 (c), which describes the reductions in energy and carbon intensity relative to BAU for five points in time from 2020 through 2100. Along the dotted line, the two types of improvements contribute equally to emissions reduction, whereas points above this line indicate larger improvements in carbon intensity compared to energy intensity. The path for the REMIND-R model is located far above the other two, which, by contrast, are very close to the 45 degree line, especially in the first half of the century. Carbon reduction becomes increasingly more important in the second half of the century.


(a) 2005 - 2030

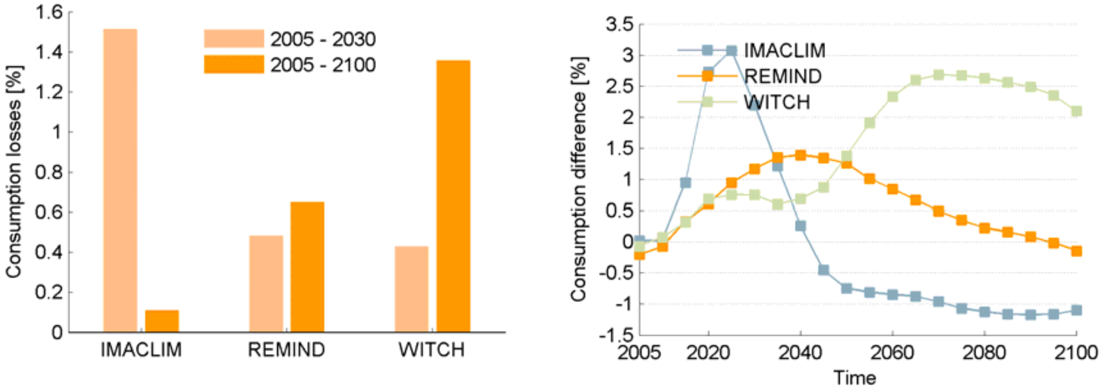
(b) 2005 – 2100

(c) Strategy trajectories 450 ppm C&C scenario

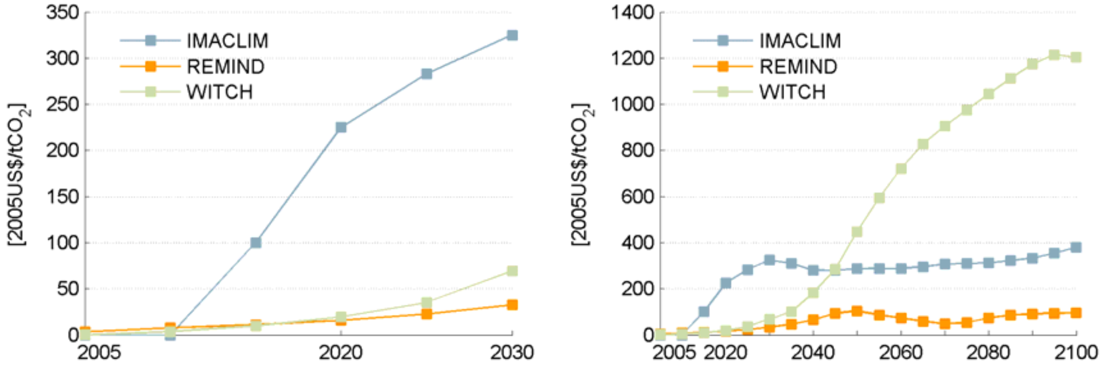


🟪 CI fossil
🟫 CI nuclear
⬜ CI renew
🟨 EI
🟧 GDP

Figure 4: Relative contribution of energy and carbon intensity reduction to the required reduction in energy-related CO_2-emissions for (a) 2005-2030 for the 450ppm C&C scenario, (b) the entire simulation period 2005-2100 for the 450ppm C&C scenario (c) the temporal evolution of carbon and energy intensity relative to baseline for the years 2005, 2020, 2040, 2060, 2080, and 2100 for the 450ppm C&C scenario.


(a) Aggregated consumption losses

(b) Consumption losses


(c) Carbon Price 450ppm 2005 – 2030

(d) Carbon Price 450ppm 2005 – 2100

Figure 5: Global mitigation costs as global welfare losses as consumption differences relative to baseline (a,b), as well as the global carbon price (c,d) for the 450ppm scenario.

Due to their structural differences and different representations of the energy system, the models project different economic effects of climate policy. The size and temporal evolution of mitigation costs and the carbon price are represented in Figure 5.

The differences in the model approaches become evident in the carbon prices. In IMACLIM-R, due to the assumptions on imperfect foresight and the inertias in the energy system, very high carbon prices are required initially to create a signal credible enough to trigger a transition to a low-carbon energy system (Figure 5c,d). These high prices especially impact emerging economies at a stage of their development in which they are particularly vulnerable, and result in very high transitional mitigation costs and welfare losses in the first 30 year of the modeled time period. Once this transition is accomplished, IMACLIM-R projects negative mitigation costs thanks to structural adjustments and technical change that is induced by climate policies and allows economies to be more efficient than in the sub-optimal baseline. The flat profile of the carbon price in IMACLIM-R after 2030 is explained by (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 carbon intensive transportation system and thus remove a critical obstacle to stabilization in the long run.

The perfect foresight intertemporal optimization models REMIND-R and WITCH, by contrast, envisage much smoother development of the carbon price with a continuous increases until the mid of the 21st century. The mitigation costs in WITCH are much higher than in the other two models, as shown in Figure 5 (a,b). Due to the relatively more conservative assumptions concerning technology substitution within the energy sector, a larger share of the emissions reductions have to be performed by curbing the economy’s energy demand, which is, at the required scale, a rather costly option that drives up CO_2 prices and mitigation costs. In REMIND-R, the carbon price remains on a rather moderate level. Once the experience curves of learning technologies (wind and solar) are passed through, the availability of cheap alternative energy sources reduces CO_2 abatement costs. The free international trade of goods and emissions certificates effectively gives rise to a frictionless capital market. As regions can invest at the expense of a trade deficit that is paid back at later times, it also introduces intertemporal flexibility. Therefore, it can be expected to have a significant impact on economic dynamics, especially for emerging economies which can borrow and pay back their debts relatively easily in the future as they are growing quickly but who, given their low current incomes, are unlikely to shift large amounts of spending from consumption to investment activities. It is yet to be clarified in which way allowing for inter-temporal trade impacts on costs to mitigate carbon emissions, a question that should be subject to further research.

		2020	**2040**	**2060**	**2080**	**2100**
RECIPE	WITCH	1.1%	1.7%	3.8%	4.0%	3.2%
	REMIND-R	0.7%	1.3%	1%	0.5%	0.2%
	IMACLIM-R	2.5%	0.2%	-0.4%	-0.6%	-0.7%
CCSP	IGSM (EPPA)	2.1%	4.1%	6.7%	10.1%	16.1%
	MERGE	0.6%	1.4%	2.2%	1.8%	1.4%
	MiniCAM	0.2%	1.2%	1.9%	1.9%	1.4%

Table 1: Global mitigation costs (percentage deviation from baseline GDP) for 450 ppm C&C stabilization scenarios in RECIPE and the US Climate Change Science Program.

		2020	2040	2060	2080	2100
RECIPE 450 ppm	WITCH	0.61%	0.70%	2.3%	2.6%	2.1%
	REMIND-R	0.6%	1.4%	0.8%	0.2%	-0.14%
	IMACLIM-R	2.7%	0.26%	-0.85%	-1.1%	-0.11%

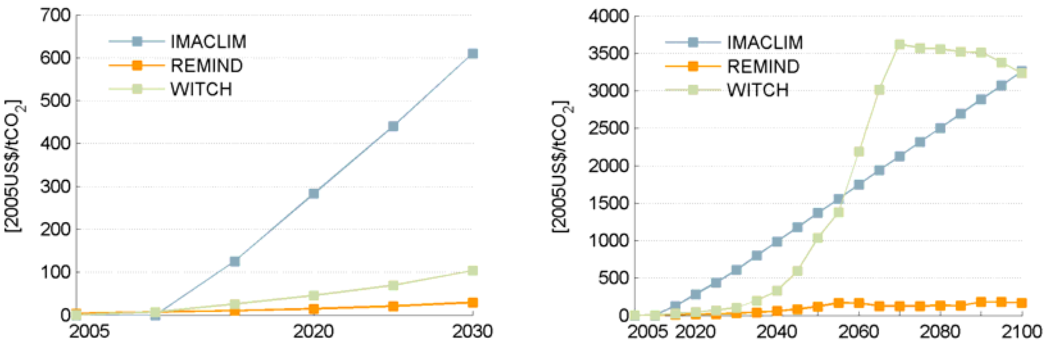
Table 2: Global consumption losses (percentage deviation from baseline) for 450 ppm stabilization scenarios in RECIPE.

Mitigation costs in terms of deviation from BAU GDP are reported in Table 1. In order to put our analysis in perspective, the lower part of Table 1 considers cost figures of the US Climate Change Science Program model comparison exercise that used three different models (CCSP, 2007). The range of costs estimated by that comparison project is also quite broad largely because of structural differences and different assumptions in the three models. The results obtained in the RECIPE project for REMIND and WITCH are roughly comparable to the results produced by the MERGE and MiniCAM models.

Table 2 reports welfare effects measured in terms of consumption losses with respect to the baseline scenario. In line with GDP costs, the WITCH model is associated with a higher cost profile, while REMIND-R has a more optimistic path. The IMACLIM-R model finds the highest losses for the first 20 years, but losses decrease subsequently and turn into welfare gains in the long-term. This result is linked to a baseline that includes some imperfect foresight and lead to sub-optimal investment decisions. Climate policies accelerate technical change and help correcting this sub-optimality through a reorientation of capital flows.

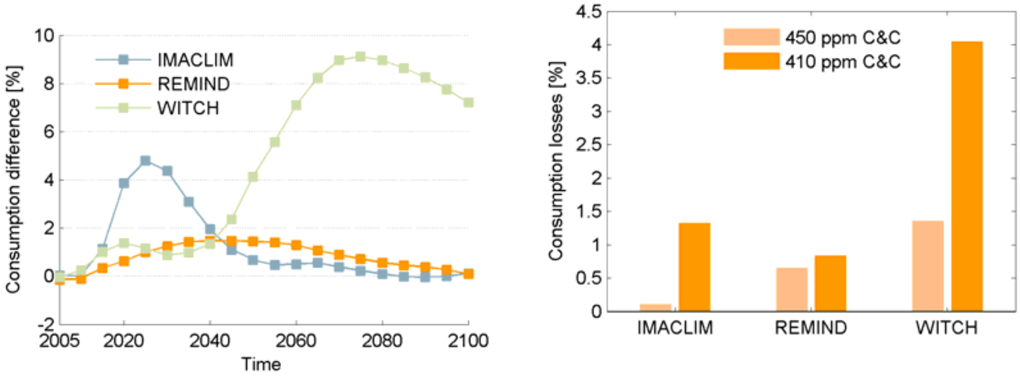
Box 1: The challenge of low stabilization

The EU has established a climate protection target of limiting globally averaged warming to no more than 2°C relative to pre-industrial levels. Recent research results confirm that such ambitious stabilization is required to avoid severe impacts on natural and anthropogenic systems (Smith et al., 2009) and to prevent triggering large-scale discontinuities in the climate system (Lenton et al., 2009). In order to ensure medium to high likelihood of limiting global warming to 2°C, stabilization of atmospheric CO_2 concentration well below 450 ppm, which was used for the default policy scenario, is required (Meinshausen, 2006). Against this background, we assess the feasibility of stabilization of atmospheric CO_2 concentrations at 410 ppm.



(a) Carbon Price 2005-2030

(b) Carbon Price 2005-2100



(c) Consumption losses

(d) Aggregated cons. losses 2005-2100

Figure 6: Carbon price (a,b), global consumption losses (c) for the 410 ppm stabilization scenario and comparison of aggregated consumption losses for the 410 and 450 ppm scenarios (d). Aggregated consumption losses are discounted by 3%.

From the perspective of energy economics, this target is very demanding as it would require substantially stronger reduction efforts than 450 ppm stabilization. According to all models, low stabilization at 410 ppm CO$_2$ is feasible. The economic impacts of climate policy, however, are projected to increase significantly with the level of ambition. Both WITCH and IMACLIM-R project carbon prices in excess of 1000 USD/t CO$_2$ for this scenario by 2050 (Figure 6b). Aggregated global consumption losses are projected to more than triple compared to the 450 ppm scenario in WITCH (Figure 6d). In IMACLIM-R, aggregated consumption losses are projected to increase by almost one percentage point. REMIND-R is more optimistic than the other two models concerning macro-economic flexibility and the availability of technological alternatives. In particular, it includes the option of generating negative emissions by combining biomass with CCS, thus creating the potential for deeper overall emission reductions. Consequently, REMIND-R projects consumption losses to increase only moderately in the low stabilization scenario compared to the 450 ppm scenario.

It is important to note that costs and feasibility of low stabilization are particularly sensitive to the representation of the macro-economy and assumptions on technologies. Therefore, further dedicated modelling studies such as those presented by Knopf et al. (2009) are required to enhance our understanding of the economics of low stabilization.

1.2. Three visions of the energy sector

While the three models were harmonized in particular with respect to the macroeconomic dimension, namely projections for regional GDP growth rates, fossil fuel prices and population (Jakob et al., 2009a), they reflect three different representations of the energy sector. Figure 7 shows the structural differences in primary energy supply in the three models for the business-as-usual scenario (BAU) and the 450 ppm default policy scenario. For comparison, also the results for the more ambitious 410 ppm stabilization scenario are shown as well (cf. Box 1).

The BAU composition of energy supply of the three models is characterized by a predominance of fossil fuels. The second most important source of energy supply is biomass (Jakob et al., 2009a). Already in the BAU scenario, in the absence of any climate policy, the WITCH and REMIND-R models feature an increasing share of renewables in the energy mix. This is largely due to resource constraints for fossil fuels. The supply of energy from renewable energy such as wind and solar is, however, negligible in IMACLIM-R.

The three models embody three different visions of future evolution of conventional fossils and low-carbon technologies and make different assumptions on the role of technical change in improving energy efficiency and enhancing de-carbonization.

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. 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. According to the REMIND-R model, almost half of the cumulative reduction burden is met by CCS (Figure 4b). Due to the ample availability of low-carbon energy carriers, decarbonization of energy supply is preferred over energy efficiency improvements.

A distinguishing feature of the IMACLIM-R model is the large use of coal-to-liquid in the business-as-usual case (Jakob et al., 2009a). 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 than in REMIND-R and WITCH (see also Jakob et al., 2009a). The omission of coal-to-liquid in the 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 WITCH model is characterized by inertias and rigidities due to the assumption of imperfect substitutability between different energy carriers. Moreover, the possibilities of replacing traditional carbon-based technologies with carbon-free options are limited, because of assumptions on CCS capture rate and because of more conservative assumptions on biomass penetration. These characteristics are reflected in the WITCH energy mix in the stabilization scenario. Together with the presence of endogenous energy-saving technical change, they also 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.

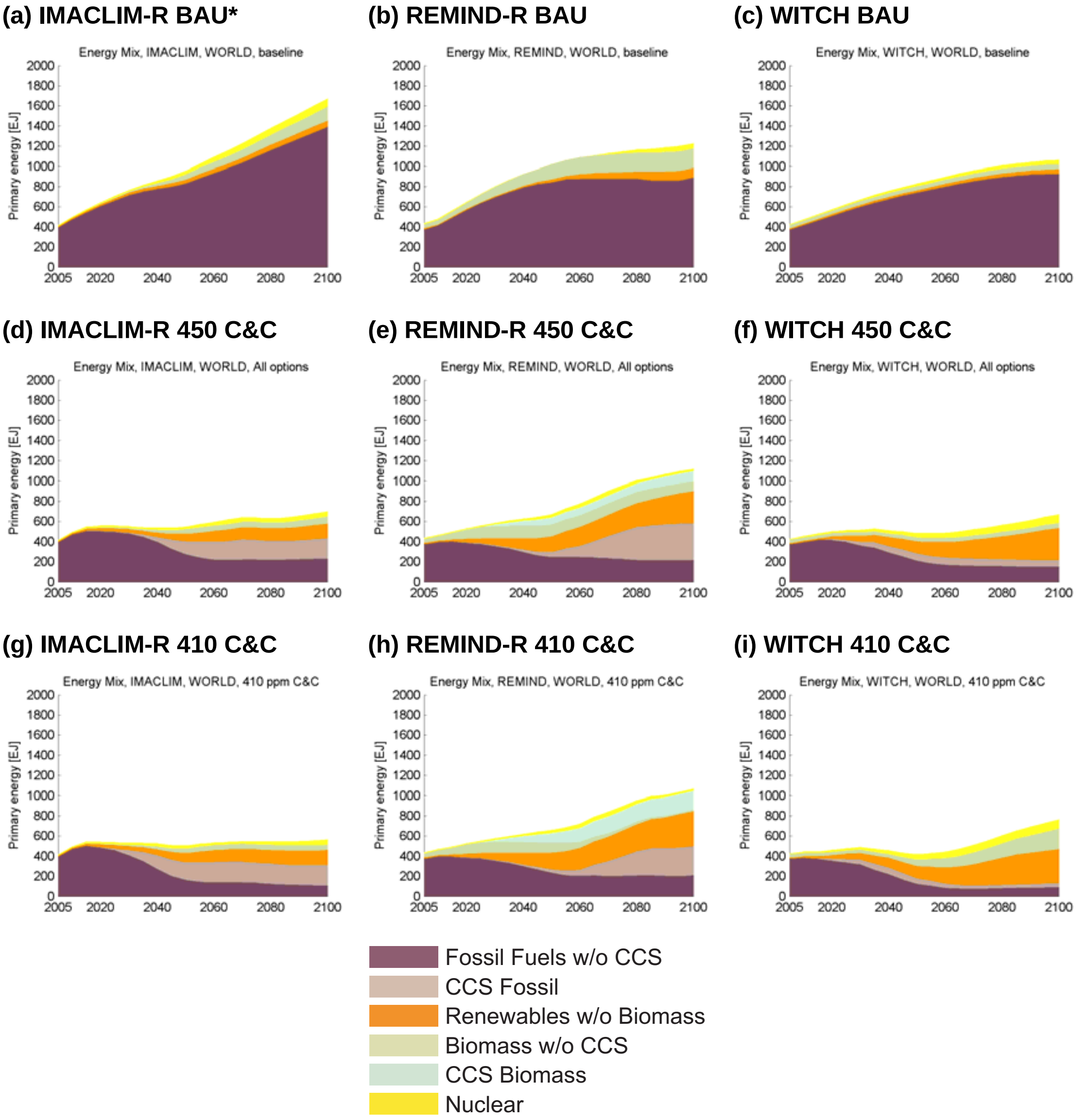

(a) IMACLIM-R BAU*
(b) REMIND-R BAU
(c) WITCH BAU
(d) IMACLIM-R 450 C&C
(e) REMIND-R 450 C&C
(f) WITCH 450 C&C
(g) IMACLIM-R 410 C&C
(h) REMIND-R 410 C&C
(i) WITCH 410 C&C

Figure 7: 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 and the policy scenario with stabilization of atmospheric CO_2 concentrations at 410 ppm.

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) different assumptions on the availability of technological options; (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.

1.3. Energy system investments

Figure 8 shows the mix of investments in energy technologies in the BAU 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 into 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 40 billions USD 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 BAU. In the policy scenarios, overall investments in REMIND-R are almost one trillion dollars higher than in WITCH and IMACLIM-R by the end of the 21st century. This result is consistent with the finding that, in the presence of a stabilization policy, energy supply contacts considerably in WITCH and IMACLIM-R (cf. Section 1.2). REMIND-R, by contrast, is characterized by a strong switch in investments from traditional sources to carbon free options, especially CCS.

A striking feature 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 (Figure 5), which strongly reduces the total availability of investments. Second, 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, 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.

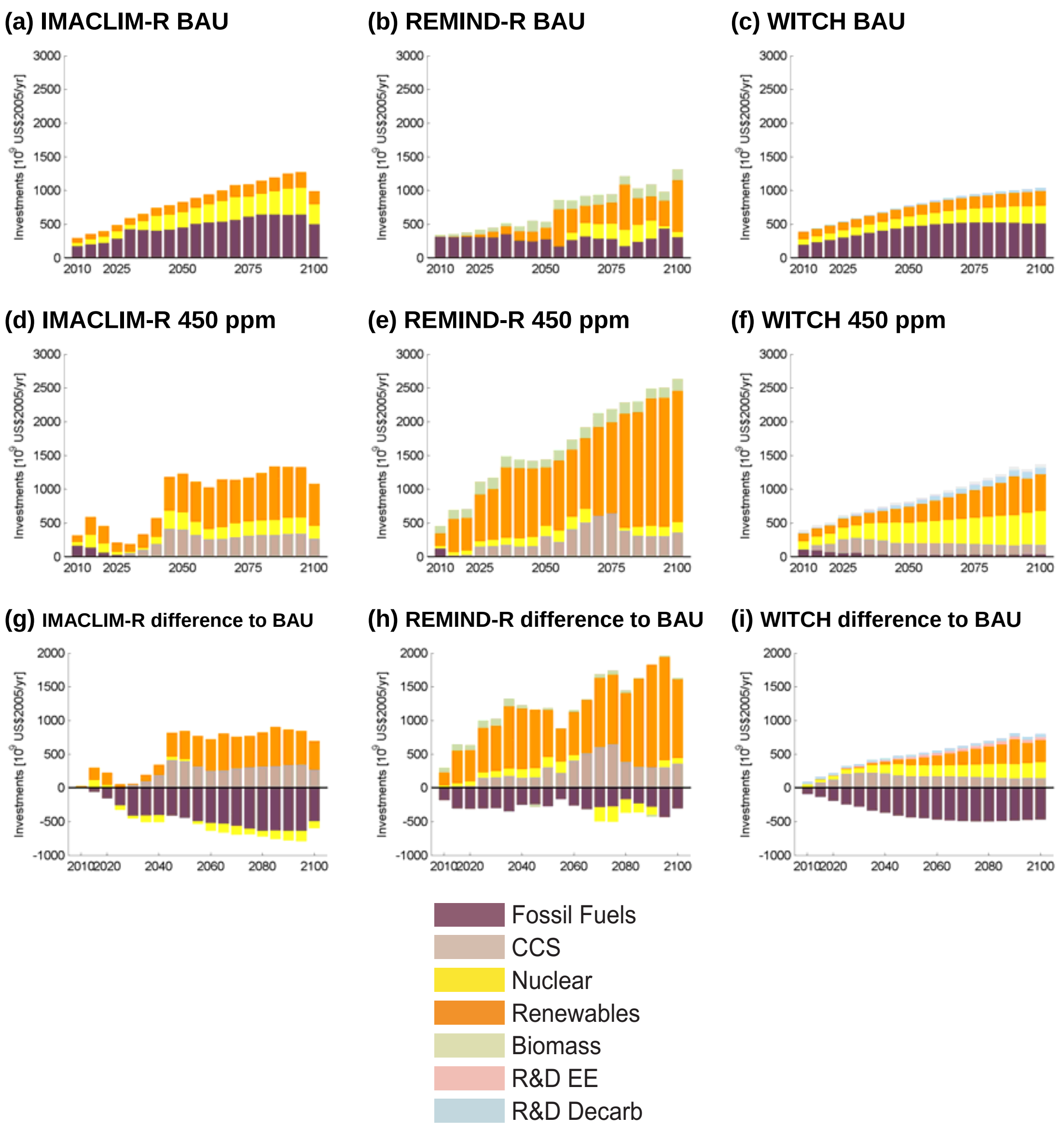


Figure 8: Investments in the energy system in percent of GDP for the baseline (a-c) and the default 450 ppm C&C scenario (d-f), as well as in absolute differences between baseline and policy scenarios (g-i).

The investment structure of REMIND-R demonstrates flexibility in switching between technologies. The grade structure, which applies for all renewable energy technologies, implies discontinuities in the evolution of technological costs. Therefore, investment trajectories from REMIND-R are not as smooth as with both other models. Figure 8 clearly shows how renewable energy gains importance in REMIND-R already within the BAU scenario. In particular, wind energy competes with investments into the fossil energy sector already in the first decades of the simulation time. In the policy scenarios, investments into nuclear energy and investments into solar energy are scaled up substantially compared to the baseline scenario. Investments into CCS technologies account for a major share of total investments from 2030. Overall and in contrast to both other models, investments into the energy system are significantly increased compared to the BAU scenario, indicating that technological changes within the energy system dominate over macro-economic adjustments.

Technology options available today are not sufficient to meet the growing demand for carbon-free energy as it is simulated in the stabilization scenarios. All models emphasize the role of innovation and technological learning in carbon free or low-carbon technologies, be it in the form of a more efficient capturing rate for CCS technologies, or of a substantial improvement in already available renewable energies, such as wind and solar. Additional innovation will occur as a result of a ramp-up in energy R&D investments to the levels that were reached in the 1980s. 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 backstops, which are, for the analyses presented here, aggregated with other sources of renewable energy.

1.4. Sectoral results

The representation of energy-consuming sectors differs across the three models. This section provides insights into the sectoral structure of energy consumption, which strongly influences abatement strategies.

IMACLIM-R, as a recursive CGE model, features the highest sectoral detail among the three models considered. Overall, 12 productive sectors are represented in IMACLIM-R (cf. Jakob et al., 2009b). 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 (Jakob et al., 2009b). 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 (Jakob et al., 2009b). The supply of electric and non-electric energy is represented by a hierarchical nest of CES[1]-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

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[1] Constant elasticity of substitution. Cf. Appendix for details.

traditional and advanced), coal and oil are used as primary energy carriers as well as a generic backstop technology for non-electric energy 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.

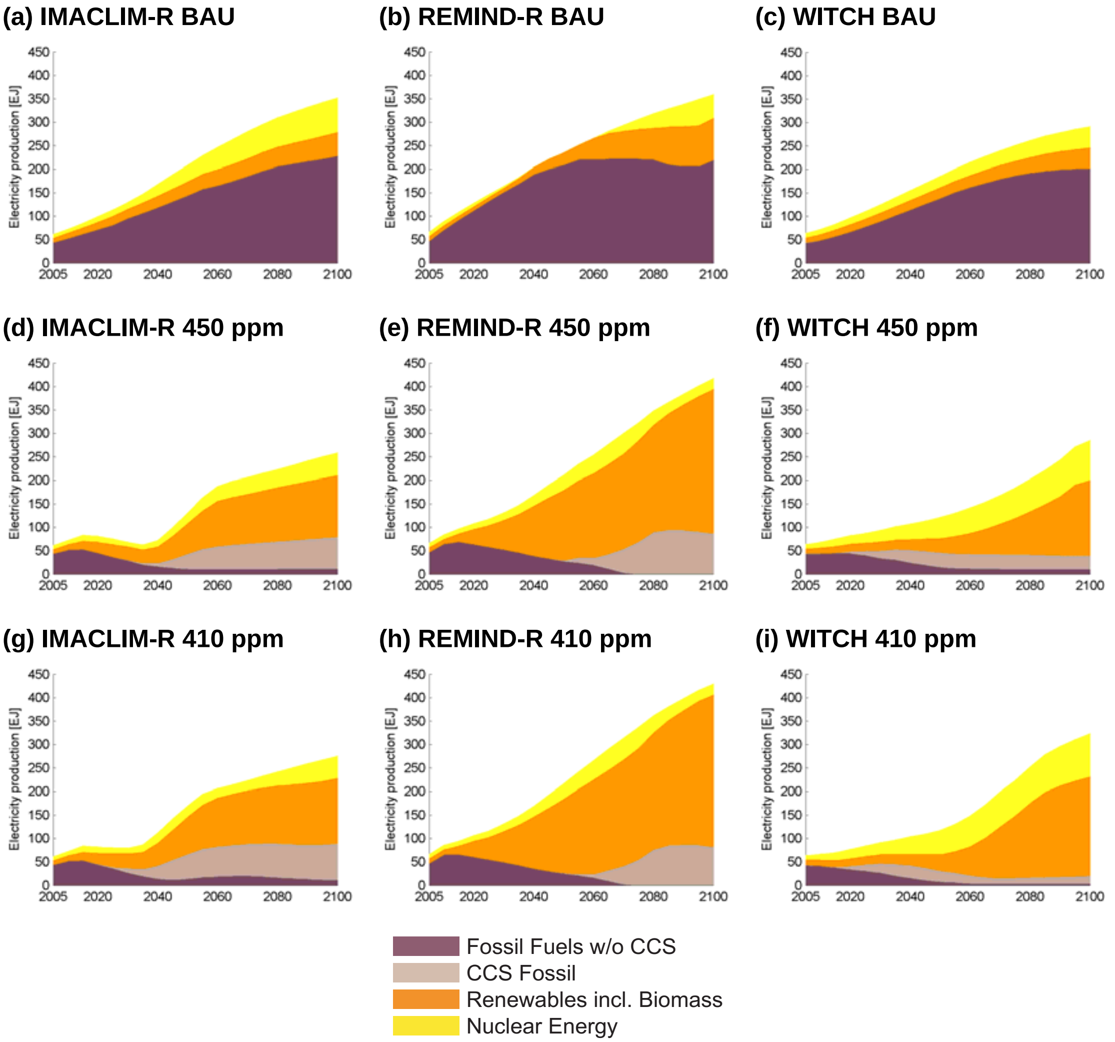


Figure 9: Electritcity mix for the power sector (IMACLIM-R and WITCH) as well as power and heat for REMIND-R in the baseline as well as the 450 ppm and 410 ppm stabilization scenarios. Note that the renewables share includes biomass and biomass plus CCS.

The electricity mix as projected by the three models for the baseline as well as the 450 ppm and 410 ppm stabilization scenarios is depicted in Figure 9. In 2005, power production accounted for roughly 40% of the overall global primary energy consumption. According to IMACLIM-R and RENIND-R, electricity demand will increase six-fold 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.

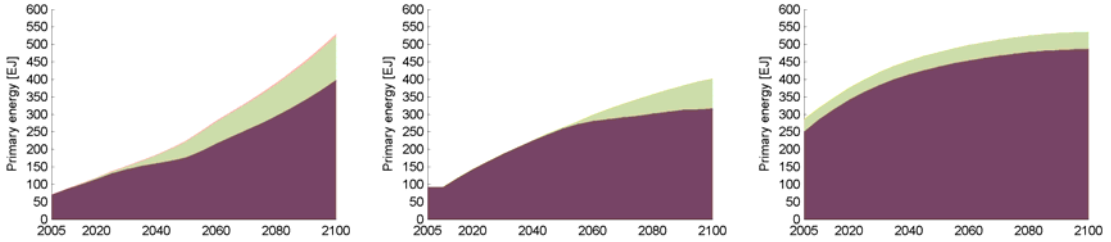
A variety of low-carbon or even carbon-free technologies are available for electricity production: renewables, nuclear and CCS. Consequently, all models project that the decarbonization proceeds most rapidly in the electricity sector. All models project a steep decline of conventional fossil power generation 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.

In all three models, nuclear energy expands significantly 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, WITCH projects a pronounced increase of nuclear power in the electricity mix. Similarly, nuclear contributes significantly to electricity production in REMIND-R 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, nuclear energy production for the policy scenario in IMACLIM-R is smaller than in the baseline.

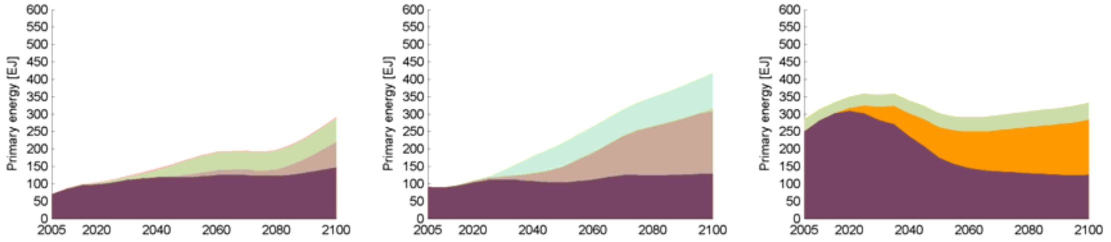
In IMACLIM-R the period from 2015 through 2035 is characterized by a substantial contraction of electricity demand. This coincides with the period during which the bulk of the economic burden induced by the low-carbon transition is borne. Afterwards, a pronounced increase in electricity demand occurs, largely induced by a switch from non-electric to electric energy sources in the industry, domestic and transport sectors. 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. In IMACLIM-R the transport sector heavily relies on coal-liquefaction. Biomass also assumes an increasing share of primary energy supply from 2020 (IMACLIM-R) or 2030 (REMIND-R).

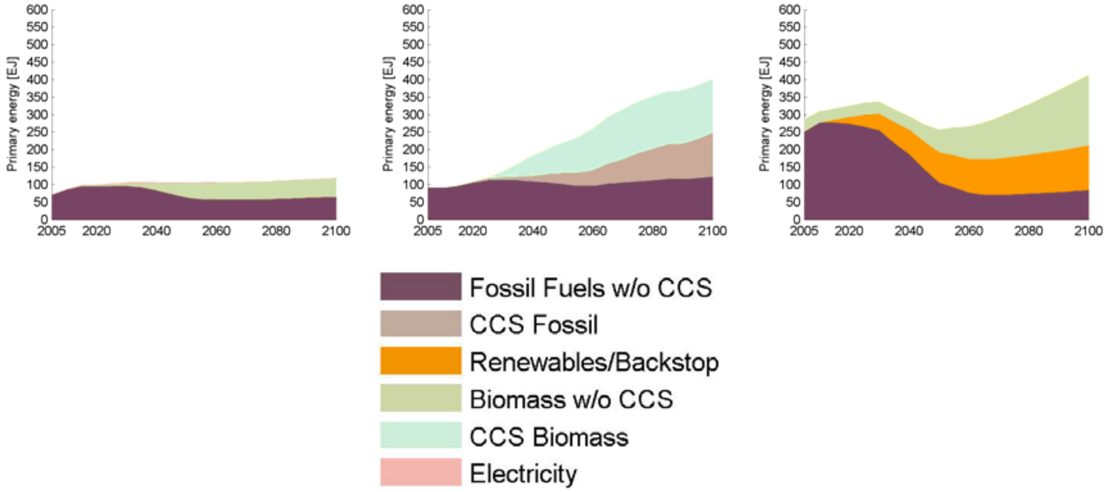
Electrification is one of the most important technology options for decarbonization of the transport sector. In WITCH, electrification is represented implicitly via substitution within the macro-economic system. IMACLIM-R represents the deployment of plug-in hybrid vehicles, thus explicitly including electrification of the transport sector. Including this option might facilitate the use of carbon free technologies in the transportation sector. While the introduction of plug-in hybrid vehicles results in substantial efficiency gains, despite their availability electricity accounts only for a small fraction of the transport sector's overall energy consumption.



(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**



(g) IMACLIM-R 410 ppm **(h) REMIND-R 410 ppm** **(i) WITCH 410 ppm**

Figure 10: 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 and 410 ppm stabilization scenarios. For IMACLIM-R, primary energy consumption related to electricity used by plug-in hybrids is included in red. In the model version usded for the RECIPE project, REMIND-R does not consider electrification in the transport sector.

In REMIND-R, the deployment of biofuels in combination with CCS emerges as the dominant mitigation option for transport. Biomass is used both for the production of liquid fuels and hydrogen. In addition, hydrogen production from coal in combination with CCS plays an important role. Due to the negative emissions generated from the biomass-based process chains, enough headroom remains for a significant remaining share of conventional oil in transport energy supply. In the present version of REMIND-R, electrification of the transport sector is not represented. Results obtained with a REMIND model variant featuring a highly resolved transport sector suggest that electrification of the transport sector remains an insignificant option (Moll, 2009). This is largely due to the assumption of high system costs of plug-in hybrids and battery-powered vehicles which are not competitive even in the presence of carbon prices.

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 and 45% for the 410 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. The very high carbon prices in the 410 ppm scenario induce a breakthrough of advanced biomass, giving rise to a substantial increase of biomass use and primary energy supply in the non-electricity sector after 2050. 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 and 410 ppm policy scenarios project a reduction by 40% and 45%, respectively, relative to BAU. This contraction of non-electric energy supply gives rise to a substantial decrease in macro-economic productivity.

Figure 11 displays the non-electric energy demand in the stationary sectors. For WITCH, this component is included in the non-electric sector (cf. Jakob et al., 2009b). 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. For the 410 ppm scenario, energy demand is projected to stabilize after 2010 and to decrease rapidly after 2040. Subsequently, the demand of the industry for non-electric energy is projected to be almost negligible.

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 a high potential of very efficient buildings, which rely mainly on electricity for their residual energy demand.

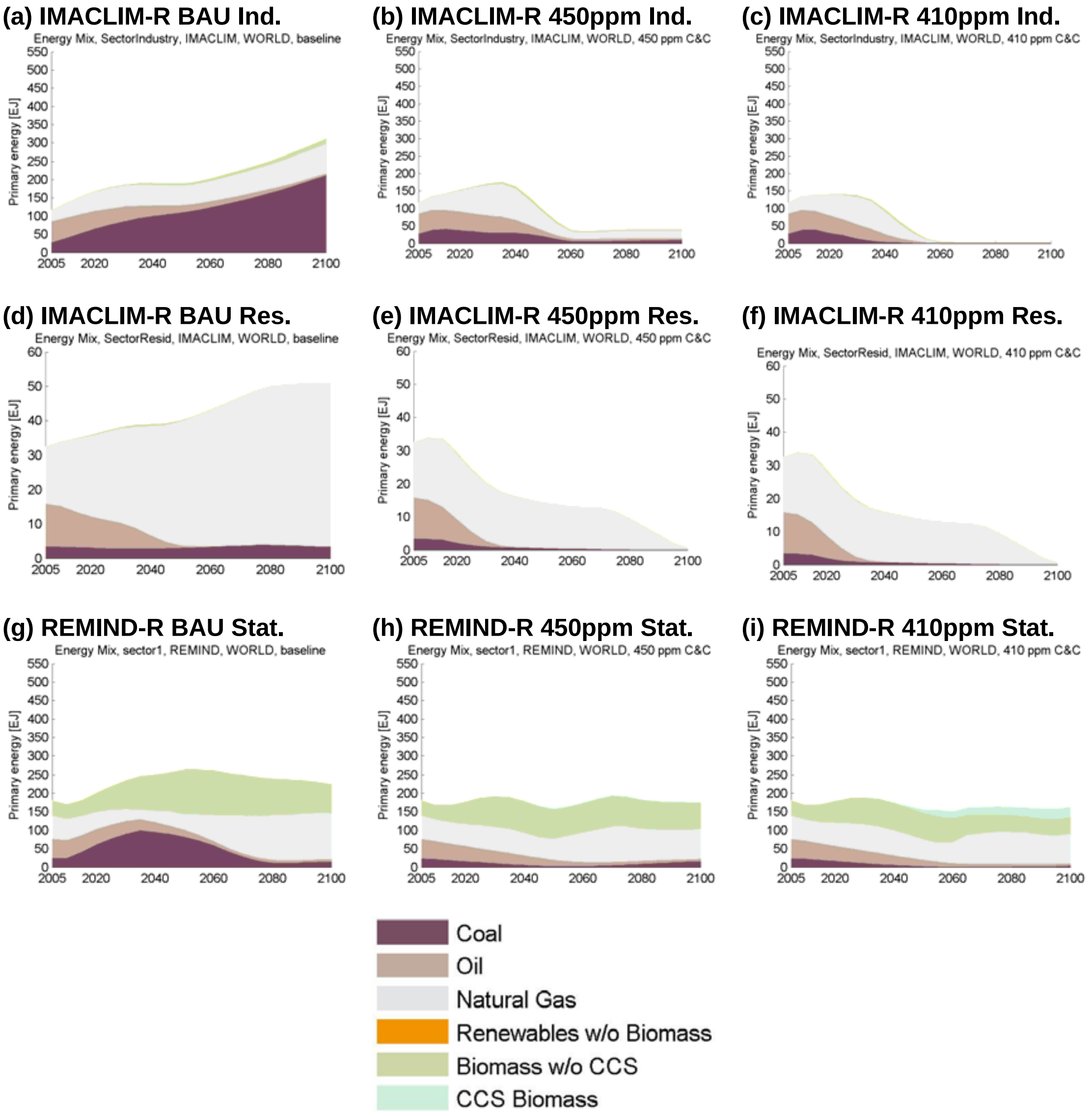
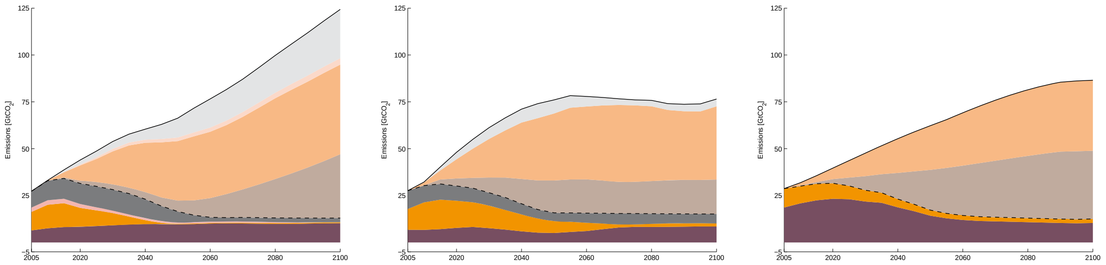


Figure 11: Residential and industrial sectors for IMACLIM-R and non-electric stationary sector for REMIND-R. In WITCH, the stationary sector is included in the non-electricity sector. As CCS does not play a role for the sector, fossil fuels are further decomposed into coal, oil and natural gas.

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 gas. Due to initial cost advantages, coal is projected to replace oil and gas in stationary, non-electric applications[2]. 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. Particularly in the 410 ppm 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 450 ppm **(b) REMIND 450 ppm** **(c) WITCH 450 ppm**



(d) IMACLIM 410 ppm **(e) REMIND 410 ppm** **(f) WITCH 410 ppm**

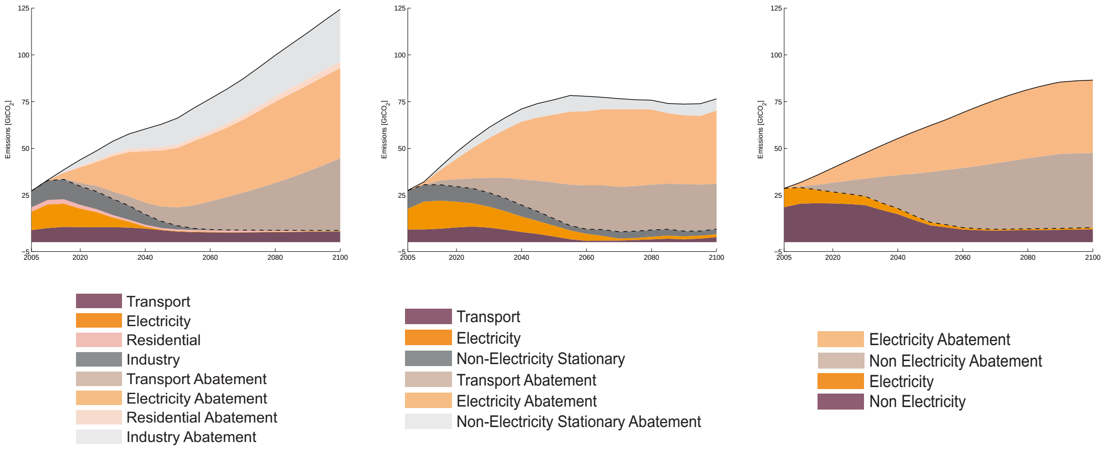


Figure 12: Global CO_2 emissions decomposed by different sectors for the three models IMACLIM, REMIND and WITCH for the 450 ppm. The upper solid line indicates baseline emissions. The dashed line indicates the emission trajectory in the climate policy scenarios. The emissions abatement – the area between the baseline and policy emissions – can be attributed to the different sectors (light colors). Note that the sectoral breakdown differs between models.

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[2] It must be noted that in REMIND-R the primary energy supply for non-electric stationary energy is highly sensitive to relative prices between price coal and gas. For this study, large coal reserves were assumed, giving rise to cost advantages of coal over gas in the first half of the 21st century.

The contribution of various sectors to the overall mitigation effort is depicted in Figure 12. 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 CO2 emissions, it even enables additional headroom for emissions from the stationary sectors.

1.5. Sensitivity analysis and robustness of results

The three different models were harmonized with respect to their macroeconomic development in terms of growth dynamics, population and fossil fuel prices. However, each model still preserves its own parameterizations, especially regarding specific features on technologies and fossil fuels resources. This section aims at exploring the sensitivity of the results to two key parameter sets: (a) parameters for experience learning in the energy sector, and (b) relative prices of various fossil fuels. The technology portfolio is another key determinant for the costs of climate stabilization. The sensitivity of policy costs to availability and penetration rates of technology options is analyzed in depth in Section 3.

1.5.1. Technological learning in the energy sector

In order to assess the sensitivity of the model results to assumptions on technological learning, two sensitivity studies were conducted: In a first set of model runs, optimistic learning parameters were chosen, with learning rates higher than in the default scenario and the asymptotic floor-costs lower (*“Fast Learning”)*. In the second set, pessimistic assumptions were made, with low learning rates and high floor-costs (*“Slow Learning”)*.

All models project that an improvement in learning parameters would result in a substantial decrease of mitigation cots. In REMIND-R more pessimistic assumptions on learning parameters results only in marginally higher mitigation costs. The WITCH model on the other hand is most sensitive to learning parameters. This can mainly be explained by the fact that technological change, and in particular the process affecting the cost of the backstop technology, is not exogenous but depends on investments in R&D first and learning by doing once the technology starts penetrating the market. Therefore, learning rates, and in particular those determining the effectiveness of R&D programs in lowering the cost of the backstop technologies, strongly affect the time period when the backstop technology becomes available and the pace of its penetration. This mechanism is eventually reflected in the policy costs.

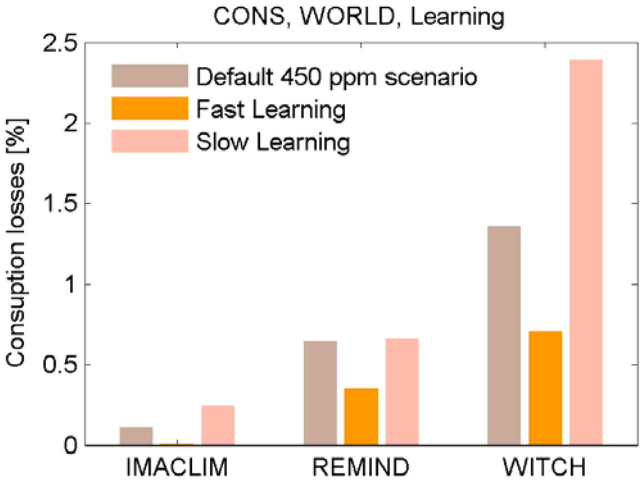


Figure 13: Sensitivity of mitigation costs to learning parameters. LEARNINGHI, FLOORCOSTSLOW is optimistic with respect to both learning rates and floor costs, while LEARNINGLOW, FLOORCOSTSHI is pessimistic about technological learning with low learning rates and high floor costs.

1.5.2. Scarcity of coal

Significant uncertainty exists about the availability of fossil resources. In the default setting, optimistic assumptions about the availability of coal were made, i.e. coal reserves were assumed to be large. In order to test the sensitivity of the results to this assumption, a scenario calculation with coal reserves reduced by 33% was made. In general, results are robust to different assumptions on coal scarcity, which translate into a higher price for coal, even though the magnitude varies from model to model. As discussed in Jakob et al. (2009a), the availability of coal results in changes in the primary energy mix but only has a small effect on the overall primary energy mix consumption in the baseline. For the policy scenario, both for IMACLIM-R and for WITCH the energy mix are unaffected, since coal use is largely constraint by the climate policy target. In REMIND-R, scarce coal leads to a substitution of fossil CCS by renewable energy. Due to the extensive use of CCS, REMIND-R is more sensitive to the assumptions of coal prices than WITCH and IMACLIM-R.

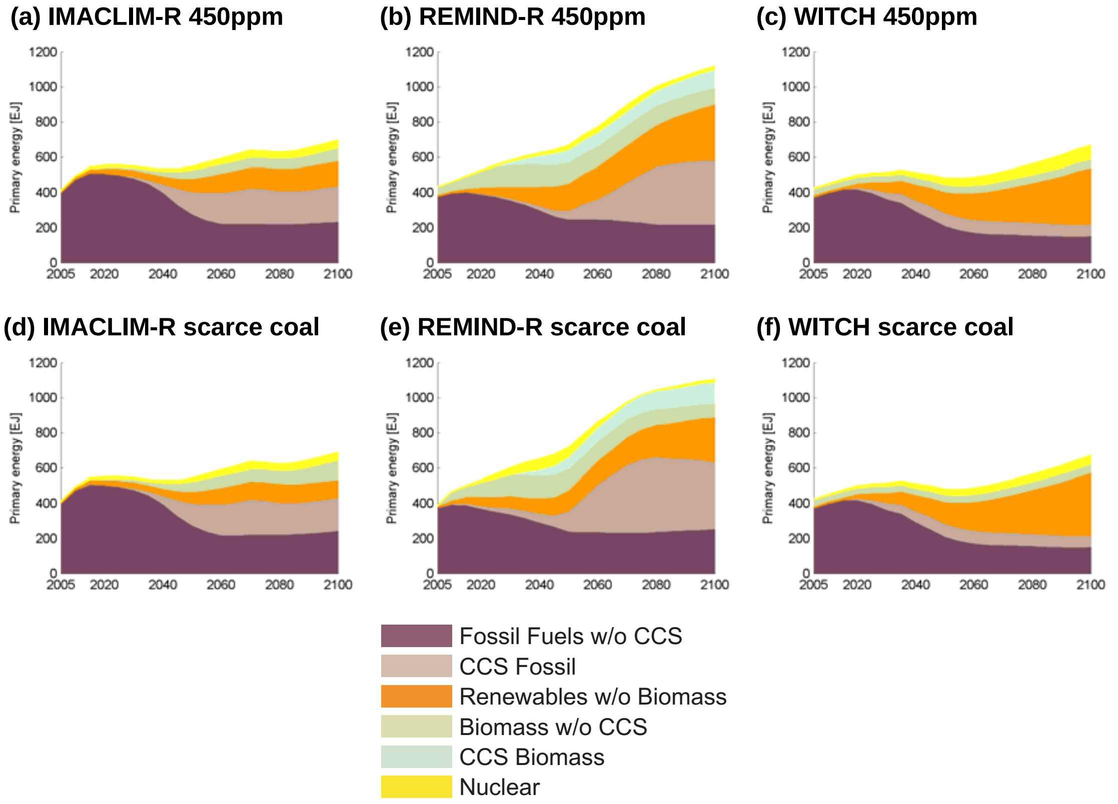


Figure 14: Sensitivity of energy mix to scarcer coal

With regard to costs, scarcer coal leads to lower mitigation costs in REMIND-R and WITCH. This is due the fact that the mitigation gap between baseline emissions and policy target is smaller in the scarce coal scenario. In IMACLIM-R, costs are projected to increase slightly if coal is scarce. This can be explained by the importance of CCS technologies in the mitigation strategy, while assumptions on the potential of renewables and nuclear are more pessimistic.

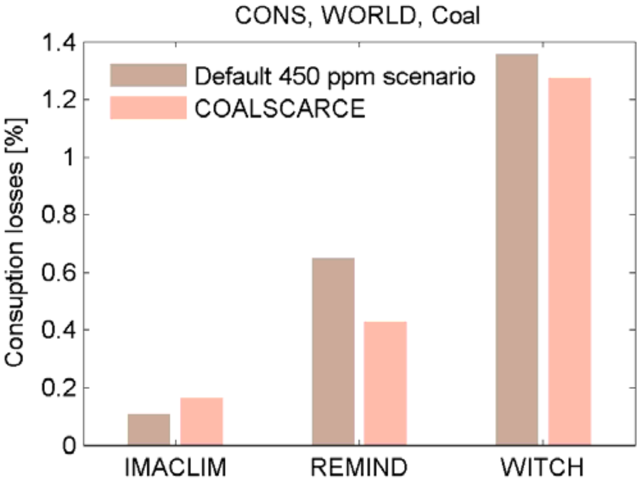


Figure 15: Mitigation costs in the default policy scenario and a scenario with scarce coal.

1.6. A stabilized world: Discussion and conclusions

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 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, as well as fewer and more costly low carbon-free 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 0.9% for the 410 ppm 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, despite very high carbon prices, the deployment of low-carbon technologies must 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 contraction 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. 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.

2. Regional dimension and allocation rules

- **This chapter compares the regional distribution of mitigation costs for four different stylized allocation rules. Differences across models are analyzed in terms of the carbon-trade balance and domestic effects.**
- **Climate policy has the potential to result in a massive shift of welfare as global losses due to abatement and resource revaluation on the one hand and potential gains from emissions rights on the other hand are in the order of several tens of trillion USD over the course of the 21st century. Welfare effects depend strongly on model assumptions on macro-economic structures and technology availability.**
- **WITCH and IMACLIM-R project a large sensitivity of regional mitigation costs to the allocation rule. In REMIND-R, the role of allocations is less important. These differences can be explained in terms of the carbon price, which is significantly higher in WITCH and IMACLIM-R than in REMIND-R.**
- **The EU and USA would benefit most from a GDP shares allocation scheme, while contraction and convergence (C&C) and common but differentiated convergence (CDC), which are based on long-term equalization of per-capita emissions, would imply moderately higher welfare losses.**
- **India and most other non-Annex I countries tend to benefit from the contraction and convergence (C&C) and common but differentiated convergence (CDC) allocation rules. By contrast, an allocation based on GDP shares as well as a globally uniform carbon tax with national revenue recycling would result in high welfare losses for these countries.**
- **According to REMIND-R and WITCH, for all four allocation rules considered, China would face above world average consumption losses. IMACLIM-R projects above world average losses for all allocation rules but the CDC scheme.**

Section 1 discussed the types of investments, the energy mix transformation and the improvements in energy and carbon intensity consistent with the stabilization of CO_2 concentrations at 450 ppm. This section analyses the regional distribution of those mitigation costs and it quantifies their sensitivity to different rules for allocating emissions rights among world regions. Reaching ambitious climate stabilization targets requires large-scale restructuring in the energy sector. Global consumption losses for the default 450 ppm policy scenario were found to range from 0.11% in the IMACLIM-R model to 1.4% in the WITCH model. Regional mitigation costs, however, can depart significantly from the global average, depending not only on the allocation rules, but also the regional energy system properties.

The first section of this chapter presents results for four different allocation rules. In the second section, an analytical approach for assessing regional mitigation costs in terms of (a) regional abatement cost structure and changes in the value of the regions' primary energy endowment, and (b) the allocation of emission allowances.

2.1. Four different allocation rules

For the model-based analysis of regional mitigation costs we considered the following four stylized allocation rules:

1) Contraction and Convergence (C&C): The *C&C* scheme (Meyer, 2004) envisages a smooth transition of emission shares from status-quo (emissions in 2005) to equal per capita emissions in 2050. It combines elements of grandfathering – allocation based on historic emissions – and equal per capita emissions. It can thus be considered a compromise between a pure egalitarian regime and a grandfathering approach. This is the scheme that was used in the default policy scenario discussed in Section 1;

2) Common but differentiated convergence (CDC): Similar to C&C, the CDC scheme (Hoehne et al., 2006) also envisages a long-term transition from status-quo to equal per capita emissions. In order to account for historic responsibility, stringent reductions are implemented for industrialized countries, resulting in per-capita allocations below world average after two decades. Countries that do not belong to Annex I of the UNFCCC are allocated according to their business-as-usual trajectory until their emission allocation is more than 20% above global average per-capita emissions. After crossing this ‘graduation threshold’, per-capita allocations converge within 40 years to the level of the industrialized countries;

3) GDP shares: Emission allowances are allocated in proportion to ‘GDP shares’ for each time step, i.e. equal emission right of emission per unit of GDP;

4) Global tax regime: A uniform global tax with national recycling of revenues is imposed. Due to the equalization of marginal abatement costs in all regions, this scheme is in absence of uncertainty equivalent to an emissions trading scheme in which the allocation corresponds to the optimal regional abatement level, such that net trade-balances are zero for all regions.

For all four allocation scenarios a policy target of stabilizing atmospheric greenhouse gas emissions at 450 ppm was considered.

Figure 16 shows the global (WORLD) and regional long-term costs of climate stabilization (2005-2100) in terms of consumption losses relative to the baseline scenario. Generally speaking, the models agree that industrialized countries would fare best with the *GDP shares* and *tax regime* rules while most developing countries would benefit from the *C&C* and *CDC* allocation rules. Due to their strong economy with relatively low emissions per unit GDP, mitigation costs of the EU and the USA are projected to be below world average mitigation costs for the *GDP shares* allocation. India and RNAI, by contrast, are characterized by low per-capita emissions and thus would benefit from long-term equal per capita emission rights as envisaged by the *C&C* and *CDC* scenarios. The situation for China, however, is distinctly different: For virtually all constellations (with the exception of *CDC* in IMACLIM-R), the models project above world average consumption losses. Currently, China’s per capita emissions are roughly equal to the world average. Due to its highly emission-intensive growth trajectory, China is projected to become a net buyer of emission permits over large stretches of the 21st century. The *tax regime* according to which all revenues from carbon pricing remain in the national budget is the least costly option for China according to REMIND-R and WITCH. IMACLIM-R projects moderate net gains for China for the *CDC* rule, due to significant revenues implied by the high permit prices projected in this model for the time after the onset of climate policy, which coincides with the time span in which China acts as a net seller of permits.

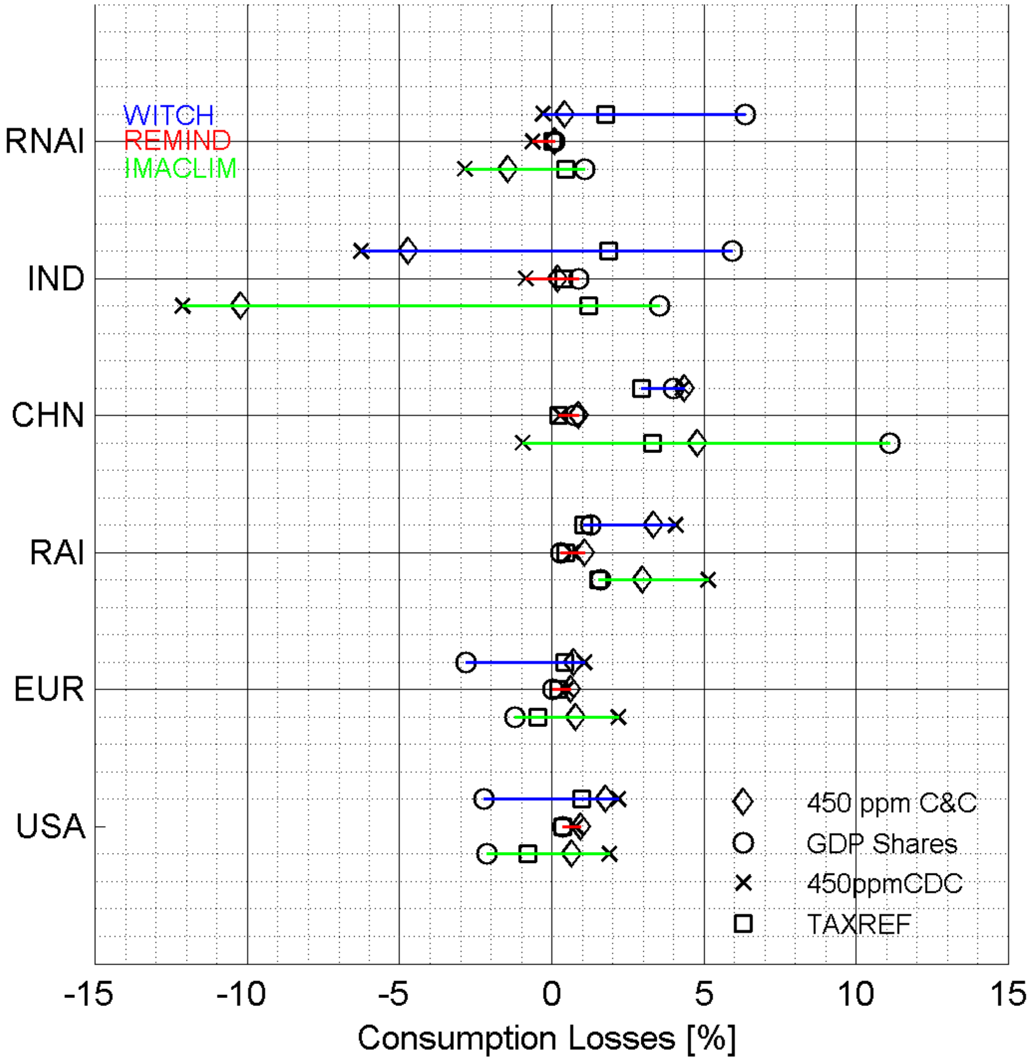


Figure 16: Distributional effects of various allocation schemes to achieve 450 ppm CO_2 in terms of consumption losses for the models IMACLIM-R, REMIND-R and WITCH. Percentage changes are given relative to baseline using a 3% discount rate.

Despite some common conclusions, the regional distribution of mitigation costs and the spread between different allocation schemes vary substantially across models. This is largely due to different representations of the energy system, macro-economic inertias and trade, and, to a minor extent, the economic and energy growth assumed in the baseline. As elaborated further in the more generic analysis in Section 2.2, the carbon price paths, which exhibit distinct differences across the three models, play an important role in explaining the regional distribution of mitigation costs and the role of allocation rules.

IMACLIM-R projects a high sensitivity of mitigation costs on the allocation rule, particularly for China and India. While losses for China are projected to exceed 10% over the course of the 21^{st} century in the *GDP shares* case, India is projected to experience welfare gains of 10% for *C&C* as well as *CDC*. The long term mitigation costs borne by industrialized countries are more moderate at about 2% for *CDC* and under 1% for the *C&C* scenario in Europe and USA. For other Annex I countries, the *CDC* and *C&C* rule would result in 5% and 3% consumption losses, respectively.

In REMIND-R, mitigation costs are more evenly distributed across regions, with appreciably smaller differences across allocation schemes. Regional costs are significantly smaller than the ones reported by the other two models, with no region experiencing losses above 2%. If costs are aggregated over the entire simulation period, all macro-regions are projected to have net costs induced by climate policy, albeit at a rather moderate level. The EU's losses are close to the global average for *C&C* and *CDC*, while *GDP shares* and *tax regime* would imply below average mitigation costs. US costs are projected to be slightly higher than those of the EU, with similar dependence on the allocation rule. Even for *CDC* and the tax regime, the consumption losses of China exceed the global average. India and other non-Annex I countries are projected to have medium term gains from climate policy for the *C&C* and *CDC* regimes, while, on the long term, they are projected to have net losses. *GDP shares* and *tax regime* would result in above world-average mitigation costs in all three macro-regions of the developing world.

WITCH provides a midway scenario in which regional costs and transfers account for a significant share of economic activities, but mostly after 2030 and especially in the second part of the century. According to the WITCH model, the *GDP shares* regime would result in significant consumption losses for developing countries, in the order of 4 and 5.5%, respectively for India and China over 2005-2100, while the EU and USA would have net gains. India is projected to be a significant beneficiary of the *C&C* and *CDC* regimes with increases of aggregated consumption of 5% and 6%, respectively. Losses in the EU are below world average for all four scenarios, while in contrast for China they are projected to be about double of world average at up to 4.5% for the *C&C* and *CDC* scenarios. The WITCH results, in agreement with IMACLIM-R, allude at a very important role for burden sharing rules.

2.2. The role of allocation rules vs. domestic abatement costs and trade effects: A conceptual analysis

It is possible to separate the effect of the allocation of emission rights from effects related to domestic abatement costs and revaluation of natural resources. In intertemporal optimization models such as WITCH and REMIND-R, for a given global stabilization target, the amount of emission reductions performed in a region is almost entirely independent of the amount of emission allowances allocated. This is a result of equalization of marginal abatement costs in the presence of a functioning international carbon market. An increase in emission allowances thus merely results in an increase of the region's revenue from selling emission rights to other regions. By the same token, the carbon prize path is also independent of the allocation rule. In intertemporal optimization models, this will result in an increase in consumption that corresponds to the value of the additional allowances received.

Thus, discounted consumption losses, *DCL*, of a region induced by climate policy can be decomposed into discounted domestic costs *(DDC)* and the discounted trade balance *(DCTB)*:

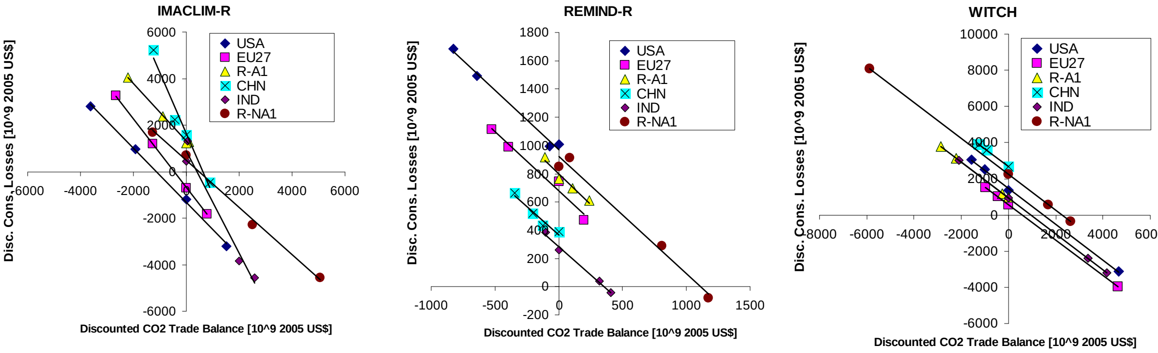
$$DCL = DDC - c \cdot DCTB \qquad (1).$$

The discounted carbon trade balance (DCTB) used in this equation is defined as

$$DCTB = \int_{t0}^{T} \exp(-\rho t) \cdot \left(A(t) - E(t)\right) \cdot p(t) \;\; dt \qquad (2)$$

It is a function of the allocation in emission allowances *A(t)*, the CO_2 emissions *E(t)* and the CO_2 price *p(t)*. A notable feature about equation (1) is that the domestic costs are simply a function of the global mitigation target but not of the allocation rule, while the DCTB only depends on the allocation rule and the carbon price path.

The discounted domestic costs, *DDC*, as introduced in Eq. (1) account for all costs other than those related to carbon trade. These comprise of costs of adjusting the domestic energy system as well as effects related to revaluation of primary energy resources. For the intertemporal optimization models REMIND-R and WITCH, the seprability of allocation effects from other effects is demonstrated by the tight correlation between *DCTB* and *DCL* (Figure 17).



(a) IMACLIM-R: c=1.0-2.65

(b) REMIND-R: c=0.8-0.9

(c) WITCH: c=1.0

Figure 17: Consumption losses vs. discounted allocation values for WITCH, REMIND-R and IMACLIM-R. Note the differences in scale for the three models.

The constant *c* in Eq. (1) refers to macroeconomic feedbacks relating to the revenues from carbon trade. For WITCH, the constant *c* equals unity, thus each additional dollar of the allocation value results in one dollar of consumption gains. In REMIND-R, c equals between 0.8 and 0.9 – the consumption gain from more beneficial allocation is 80-90% of the additional allocation value. This can be explained by terms-of-trade effects: as regional trade patterns change, slight variations in the relative prices between imported and exported goods occur. Thus, parts of the revenue from carbon trading are offset by higher expenses for imports and lower yields for exports.

Despite equal carbon prices across the globe emission reductions do not result from intertemporal equalization of marginal abatement costs in IMACLIM-R, which is a simulation model. Indeed, non-perfect foresight raises risks of ‘lock-in’ into carbon intensive energy systems, especially for the most inertial sectors (transport, infrastructure) that are likely to report an increased burden on other sectors for a given CO_2 emission reductions target. As a result, the amount of emission reductions performed in a region results from the sectoral mitigation policies adopted, which are in turn influenced by the emission allowances allocation. Indeed, sectors are influenced in a different manner by changes in a region's revenue associated to selling (or buying) of permits. As a consequence the amount of emission reductions performed in a region is *a priori* dependent on the amount of emission allowances, in contrast to the case of optimizing models.

In IMACLIM-R, consumption gains are also correlated with the allocation value. The constant *c*, however, varies strongly across regions, with highest values in China (*c*=2.8) and India (c=2.3), and values between 1.0 and 1.5 for the other regions. This is a clear indication of sub-optimality: A given amount of monetary transfer in the form of emission rights yields higher consumption gains in some regions than in others. In particular, China and India are most impacted by changes in the allocation regime (higher c-value). This captures the higher carbon intensity of those economies, rendering them more dependent on permits. The share of trade allowances in total consumption is the highest in those two regions. As a consequence, the amount of domestic emission reductions is much more sensitive to changes of the allocation regime in China and India than in other regions, resulting in significant variations of discounted losses.

	10^{12} USD_{2005}	USA	EU	Rest of Annex-I	China	India	Rest of Non-AnnexI	World
IMACLIM-R	DDC	-6,6	-3,4	6,5	8,1	4,4	2,4	11,4
	DCTB	-9,7	-6,4	-4,4	-2,1	10,0	12,5	0,0
	DCL	4,8	5,9	11,8	11,2	-19,2	-11,5	3,0
REMIND-R	DDC	4,9	3,4	4,0	1,8	1,4	4,6	20,1
	DCTB	-3,2	-2,0	0,5	-1,0	1,6	4,0	0,0
	DCL	7,5	4,9	3,5	2,6	0,2	1,5	20,1
WITCH	DDC	7,0	2,9	4,8	13,4	4,7	11,2	44,0
	DCTB	-4,9	-2,2	-11,0	-6,4	16,9	8,5	0,0
	DCL	12,5	5,0	15,7	19,7	-12,0	2,8	43,6

Table 3: Decomposition of regional consumption losses for the contraction and convergence allocation rule into the allocation-independent component (discounted domestic costs DDC) and discounted carbon trade balance (DCTB), which depends on the allocation rule. By definition, net import of emission rights results in a negative carbon trade balance.

The mitigation portfolio affects the regional distribution of welfare losses via both the domestic abatement cost and the discounted trade balance (through the price of carbon). The more options are available, and the cheaper they are, the lower the domestic abatement costs. Moreover, the revaluation of various types of fossil resources as well as uranium, which in turn affects the macroeconomic feedbacks, depends on the energy mix. Finally, the mitigation portfolio affects the carbon price, which is an important determinant of the monetary CO_2 trade balance.

2.3. Regional cost distribution – discussion and conclusions

The analysis of the regional distribution of mitigation costs exhibits substantial differences across regions. Allocation rules envisaging a convergence of per-capita emissions such as *C&C* and *CDC* tend to decrease the consumption losses in India and the Rest of non-Annex I countries or result in net gains, while the *GDP shares* approach and, to a lesser extent, the *tax regim*e tend to favor industrialized countries. Generally speaking, developing countries are more sensitive to allocation rules than industrialized countries. China, an emerging economy with rapidly increasing emissions, are projected to be imposed above world average mitigation costs for all four allocation rules. These findings demonstrate the importance of considering aspects of global equity, development goals and fairness in distributing the costs of climate policy. *GDP shares* and *tax regime* would impose prohibitively high burdens on developing countries, while industrialized countries would benefit. In view of the current emission patterns and the historic responsibility of the industrialized countries, this situation is clearly at odds with the polluter pays principle. *C&C* and *CDC*, two allocation schemes that are more closely related to burden sharing rules currently discussed in the framework of international climate negotiations, are more beneficial for most developing countries.

It is important to recognize that the distributional outcome of a global mitigation effort depends not only on allocation and trade of emission allowances, but also on the cost of domestic abatement and the effects on trade of energy carriers. In Section 2.2, a method for separating welfare effects related to carbon trade from the other costs was presented. The high carbon prices in WITCH and IMACLIM-R result in a high value of emission allocations. Thus, in these models regional gains and losses depend strongly on the allocation rule applied. REMIND-R, being the most technology optimistic among the three models, projects carbon prices that are almost five times smaller than in WITCH. Hence, allocation rules play a much smaller role in determining the regional distribution of costs, and overall losses are much smaller. According to REMIND-R, aggregated welfare losses are below 2% for all regions irrespective of the allocation rule.

Overall, these results suggest that the inertia in the energy related infrastructure and the associated transition costs are important determinants of policy costs and of the resulting differences in the burden across regions. Only in the case of optimistic availability of low carbon technologies the potential for conflict over the allocation of emission rights will be reduced. Fast and successful development of low-carbon alternatives and innovation will be central in defusing this conflict.

3. Living in a second best world: The role of technology portfolios and the effect of limited participation in international climate agreements

- **This section focuses on analyzing mitigation costs if (a) only a limited set of technological options for mitigation is available, or (b) delays occur in the setup of a global climate agreement.**
- **A broad portfolio of technology options will be needed to keep costs of climate stabilization in check; there is no silver bullet. By means of an option value analysis, it is possible to rank mitigation options according to relative importance.**
- **Renewables and CCS are particularly important. In absence of either of these options, all three models project mitigation costs to increase substantially. Nuclear energy expansion above the level projected for the baseline has a relatively low additional value in the long term, but, according to WITCH, is valuable in the transition.**
- **The technology portfolio has a significant effect on the regional distribution of mitigation costs. China is projected to be the most adversely affected by technology restrictions.**
- **All models emphasize the role of innovation and technological learning in low-carbon or carbon-free technologies. Substantial additional investments are required to induce a low-carbon transformation.**
- **The three models agree in projecting that delaying mitigation action until 2030 renders it impossible to stabilize atmospheric CO_2 concentrations at 450 ppm.**
- **The larger the number of regions taking early action, the lower the costs of the stabilization policy. Particularly relevant for the size of mitigation costs is the participation of big polluters such as Annex I countries, China and India.**
- **If no mitigation action is undertaken before 2020, the consumption losses induced by stabilization policy increase from 1.4% to 2.1% for the WITCH model, from 0.1% to 0.8% for IMACLIM-R and from 0.6% to 0.9% for the REMIND-R model.**
- **The extent to which regions can anticipate a future climate policy (by strategically changing the energy technology portfolio and innovation investments) has a positive effect on both regional and global mitigation costs;**
- **Both the EU and USA benefit from early action: The benefits of anticipating future reduction targets and earlier adjusting the energy systems outweigh the cost of higher cumulative emission reductions adopted.**

The default policy scenario presented in Section 1 is based on the assumption that (a) the full portfolio of mitigation options is available, and (b) all regions participate immediately in a global agreement. In this chapter, these assumptions will be loosened: Section 3.1 discusses how energy systems structures and mitigation costs are affected if the climate stabilization target is to be achieved without expanding certain low-carbon technologies beyond their use in the baseline or entirely excluding the use of certain technologies (CCS), respectively. Section 3.2 examines the effect of an institutional delay in pursuing global co-operative action on climate change.

3.1. The role of technology portfolios

3.1.1. Global technology option value

In all three models, the stabilization target is optimally achieved using a portfolio of all technologies available in each model. The scenarios presented in the previous sections assumed no exogenous constraints on the use of any technology, so technology mixes were determined by endogenous optimization. It is important to note that no external effects other than CO_2 emissions were considered. This section analyses the effect of exogenous constraints on technology use and derives the relative importance of various low-carbon options. In this context we define the increase in mitigation costs relative to the scenario with the full technology portfolio as the technology's *option value.* This metric is a useful indicator of the potential of individual low-carbon technologies to contribute to cost-efficient climate change mitigation. In a second step, the regional costs are also considered.

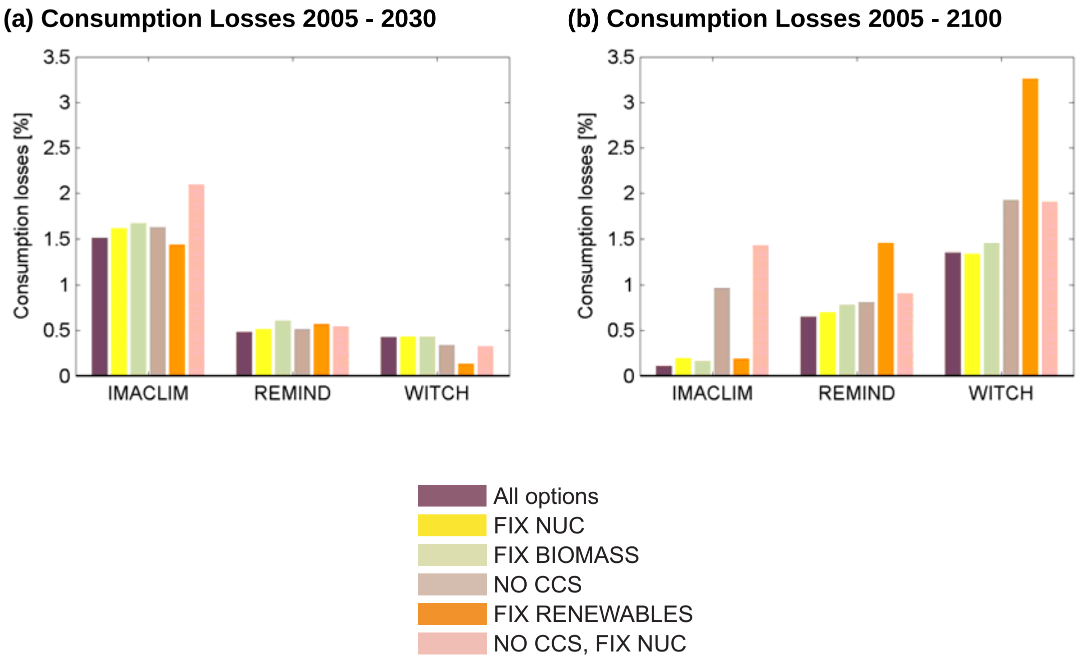


Figure 18: Option values of certain technologies in terms of consumption losses for scenarios in which the option indicated is foregone or limited to BAU levels. Option values were calculated as relative difference of a scenario in which the use of certain technologies is limited with respect to the baseline scenario. Note that for WITCH the generic backstop technology was assumed to be unavailable in the "no renewables" scenario.

For the analysis, the following scenarios with constraints on technology use are considered:

1) *noCCS:* Carbon capture and storage for CO_2 from conversion of fossil fuels and biomass is assumed to be unavailable.

2) *fixBiomass:* No expansion of biomass primary energy beyond the baseline level.

3) *fixRenewables:* No expansion of renewables other than biomass beyond the level in the baseline. For WITCH, this includes the generic backstop technology.

4) *fixNuclear:* No expansion of nuclear energy beyond the level in the baseline

5) *noCCS, fixNuc:* No availability of CCS in combination with fixing nuclear on the baseline level.

Figure 18 compares the costs of limiting atmospheric CO_2 concentrations to 450 ppm both for the “all options” scenario as well as the five technology-constrained scenarios listed above.

All three models project long-term costs of reaching the stabilization target to increase substantially without carbon capture and storage. In the default policy scenarios, CCS is projected to contribute significantly to the reduction of cumulative CO_2 emissions. In addition to applications in electricity generation, REMIND-R and IMACLIM-R consider the option of using CCS outside the power sector, notably in coal liquefaction. REMIND-R also includes the option of combining biomass with CCS, an option that results in negative net emissions (Jakob et al., 2009b). Consequently, REMIND-R and IMACLIM-R both project high option values for CCS. According to IMACLIM-R, CCS is the most valuable mitigation option, as foregoing it would result in an almost ten-fold increase of welfare losses from 0.1% to 1.0%. REMIND-R projects an increase by 25%. Even though the overall deployment of CCS in WITCH is significantly smaller than in the other two models, consumption losses are projected to increase by over 40% when this mitigation option is excluded. Since large-scale deployment of CCS is projected to play a role only after 2030, medium term losses from foregoing the CCS option are small or, in the case of WITCH, even slightly negative.

The attractiveness of biomass lies in its versatility: It can be used both in the electricity sector and as raw material for secondary energy carriers in transport and other sectors. REMIND-R also includes conversion technologies that can be combined with CCS, thus yielding negative emissions. At the same time, significant concerns exist about adverse side-effects of expanding biomass use, particularly with respect to food security and biodiversity. Despite its flexibility, limiting biomass to its use in the baseline scenario is projected to result only in moderate cost increases in all models. To a certain extent, this reflects the fact that biomass already plays an important role in the baseline scenarios in REMIND-R, IMACLIM and - to a lesser extent - WITCH.

In the policy scenario, all models project renewables to account for a substantial share of the primary energy mix. At the same time, renewable energy carriers are generally perceived as the least problematic low-carbon option in terms of negative side effects and social acceptability. Nonetheless, issues concerning grid integration and handling fluctuations in energy supply persist. Both, REMIND-R and WITCH assign a high option value to the availability of renewable energies. WITCH projects long-term welfare losses to more than double in the absence of the expansion of renewables and breakthrough low carbon technologies, while REMIND-R projects costs to increase by half for renewables only. IMACLIM-R projects that limiting renewables to the baseline level would result in a cost increase of 0.1 percentage points. In the medium term, the availability of renewables has a much smaller effect on mitigation costs. Due to the significant up-front investments required for technological learning, aggregated consumption until 2030 is projected to increase in the *fixRenewables* scenario relative to the default scenario.

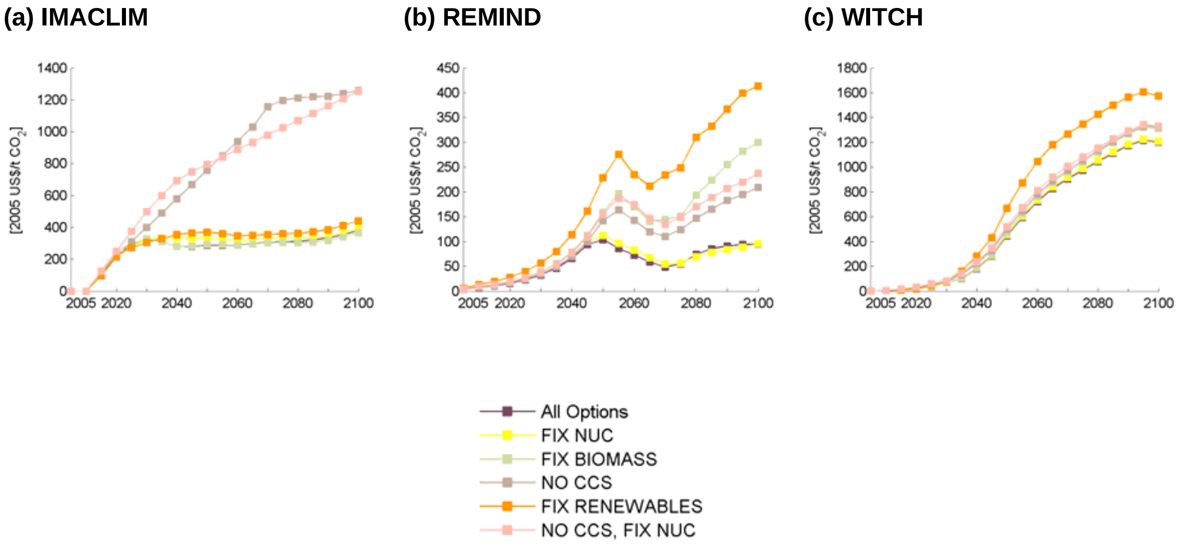
The expansion of nuclear energy is arguably the most controversial mitigation option. Concerns persist with respect to the long-term safety of geological storage of waste, the risk of nuclear accidents, and control of nuclear proliferation for military use. With respect to the option value of nuclear energy, all three models project that expanding nuclear energy beyond its use in the baseline would result in a marginal increase of mitigation costs in the long term. However, it should be kept in mind that nuclear energy plays a significant role in the baseline for all models (cf. Section 1.4). Hence, although an expansion beyond baseline proves to have a relatively low value compared to that of other mitigation options, nuclear is projected to keep a share of up to 7% of primary energy consumption in the *fixNuc* policy scenario.

The most stringent technology scenario assesses a situation in which neither CCS nor the expansion of nuclear are available as mitigation options. Both REMIND-R and IMACLIM-R project that cost increases for this setting are higher than the sum of cost increases for the *noCCS* and the *fixNuc* scenarios, suggesting that the global option value of nuclear energy is somewhat higher in the case of constraints on CCS. For WITCH, by contrast, foregoing both CCS and nuclear expansion results in mitigation costs that are only marginally higher than in the case where only CCS is unavailable.

An important result of this analysis is that, despite differences in the representation of the energy system, all three models rank the option value of different technology options in a similar way. In particular, CCS and renewable energy are the key technologies to meet increasing energy demand in a carbon-constrained world, especially in the second half of the century. The CCS and renewable options rely strongly on innovation and experience learning. Therefore the high option values found for these technologies points at the paramount importance of innovation and learning by doing.

3.1.2. Regional effects of constraints on technology

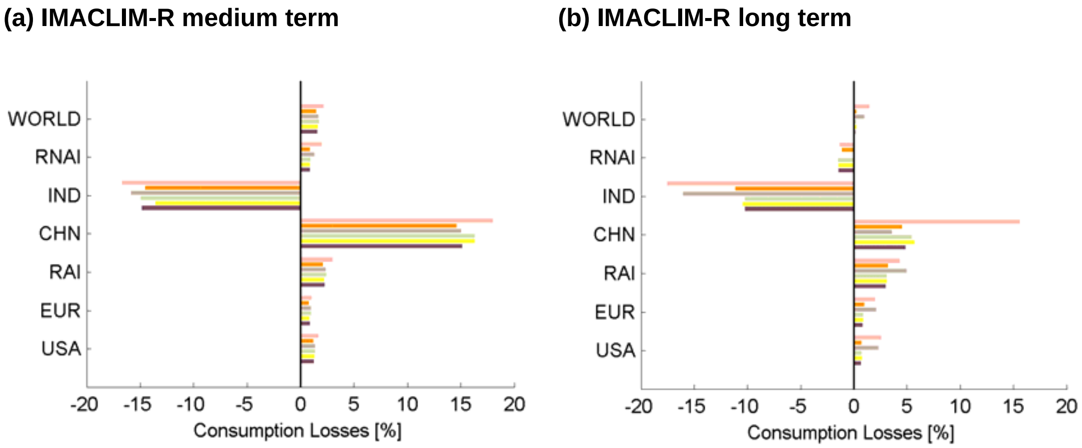
Figure 20 disaggregates the global losses into the option values of different regions. In general, it is indicative to interpret the regional effects in terms of the decomposition of regional costs as introduced in Section 2: On the one hand, restrictions on the technology portfolio tend to increase the domestic mitigation costs. On the other hand, as carbon prices surge, emissions trade balances change, yielding higher expenses for net importers of permits and higher revenues for exporters.


(a) IMACLIM

(b) REMIND

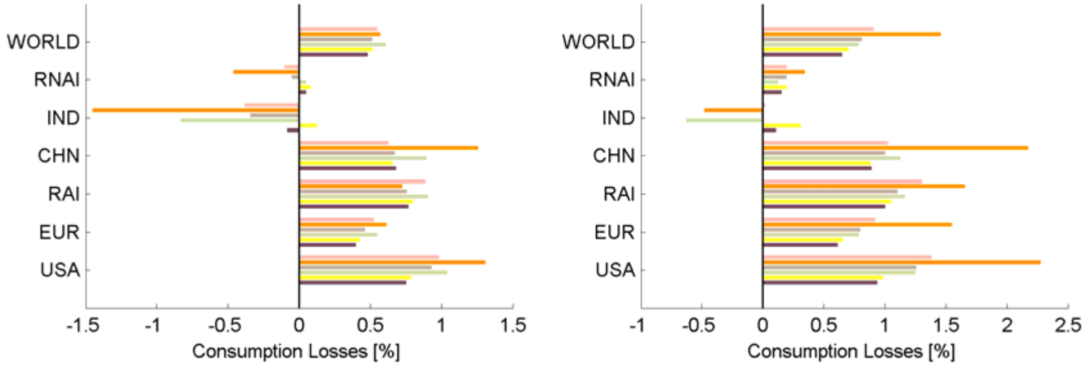
(c) WITCH

Figure 19: Carbon price trajectories for various technology constraint scenarios.


(a) IMACLIM-R medium term

(b) IMACLIM-R long term

(c) REMIND-R medium term **(d) REMIND-R long term**



(e) WITCH medium term **(f) WITCH long term**

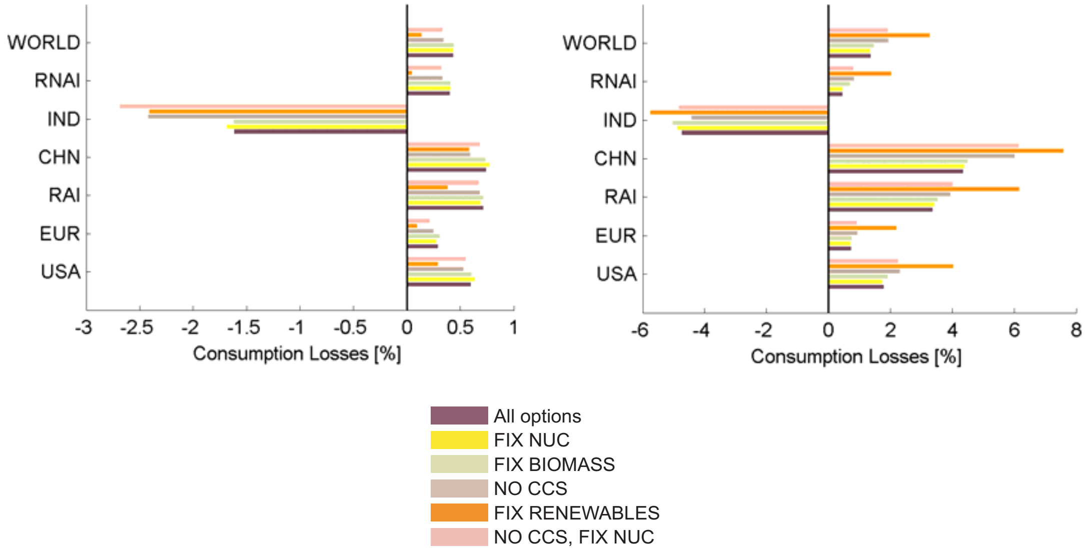


Figure 20: Regional consumption losses in the absence of certain mitigation options. Percentage changes relative to baseline, using 3% discounting. Note different scales.

For most regions, the ranking of technologies that emerges at the global level is preserved also at the regional level, with substantial cost increases for the *noCCS* and *fixRenwables* scenarios. This holds especially for the *noCCS* scenario, for which all regions (with the exception of India in IMACLIM-R and RNAI in REMIND-R) report higher costs. In line with the findings on the global scale, foregoing the expansion of renewables has a strong effect on regional mitigation costs in REMIND-R and WITCH. They report significant increases of losses for all regions with the exception of India, which, as a net exporter of permits, benefits from higher carbon trade revenues. Similarly, the two models project restrictions on biomass to result in negative welfare effects in all industrialized regions and China. IMACLIM-R projects low sensitivity to biomass availability in all regions. Also, fixing nuclear energy to baseline use has a small effect on the regional distribution of mitigation costs.

China exhibits higher mitigation costs because its high economic growth induces an increase in energy demand, which is met by fossil energies, at least in the beginning. This fact requests higher efforts in restructuring the energy system later on. In addition, allocation of permits contracts fast and China becomes a buyer of emission permits soon. India benefits from selling permits, in particular in the *fixRenewables* or *fixBiomass* scenarios, when the permit prices increase substantially. In this model setting the effect cannot necessarily be seen in the composite region RNAI, as it includes winners (e.g. Africa) and losers (e.g the Middle East).

When CCS is excluded from the mitigation portfolio and at the same time nuclear energy is fixed to its baseline level, in all three models China is the region facing highest consumption losses (together with the US in the case of the REMIND-R model). All models agree that India benefits in the absence of renewables and biomass. Since coal plays an important role in the energy mix of India, REMIND-R and WITCH project that the mitigation costs increase if CCS is not available as a mitigation option.

3.1.3. Technology Dimension – discussion and conclusions

Regarding the ranking of different technology options, the three models share a common vision. There are several robust results emerging from the comparison. A central conclusion is that there is no ‘silver bullet technology’ to solve the climate stabilization challenge. Rather, a variety of different carbon free technologies will be needed to keep costs of mitigation low and to hedge against uncertainties in future technological development. Additional losses induced by excluding certain groups of available technologies may be large, depending on their cost structure and application potential. According to the model-based analysis, renewables and CCS have the highest option values, since they are the most important options for the decarbonization of the energy system. Nuclear is not a dominant mitigation option, even though it retains a considerable role especially in the first half of the century.

The welfare effects of constraints on technology use vary across regions, technologies and models. The differences can be explained in terms of changes in domestic abatement costs, which depend on specific regional potentials, the availability of low-cost alternatives, and carbon trade effects. The latter scale with overall global mitigation costs and depend on regions being net exporters or importers of emission permits. Under certain circumstances, regions that are net sellers of emission rights even benefit from constraints on the technology portfolio. In general, the higher the option value of a technology on the global scale, the larger the effect on regional mitigation costs.

Each mitigation technology comes with its own set of opportunities, drawbacks and uncertainties. A central challenge for policy makers in shaping economically viable and socially acceptable energy policy is to weigh between different kinds of risks, e.g. those implied by expansion of biomass, nuclear energy, and CCS.

3.2. Timing and progressive action

This section analyses how the costs of stabilization change when immediate and complete participation of all world regions to an agreement is not achieved. These scenarios are less economically efficient and imply higher mitigation costs. They are, however, worth studying because they allow for assessing the consequences the international community has to face when struggling to reach an agreement on immediate global mitigation efforts and the setup of a global carbon market.

3.2.1. The cost of delay

Figure 21 and Figure 22 show consumption losses on the global and regional level for various scenarios of fragmentation. It is important to note that all scenarios presented in this section were calculated under the assumption that during the delay the agents follow their business-as-usual trajectory in a myopic way, i.e. without anticipating future climate policy restrictions.

A first central result is that none of the models finds a feasible solution if climate policy is delayed until 2030[3]. This holds even in the case of REMIND-R, which embodies the most optimistic assumptions on flexibility and availability of low cost carbon free technologies. This finding can be explained by the long lived nature of energy technology investments and the inertia characterizing the energy sector, together with the inertia characterizing the climate system. Due to the substantial stock of fossil energy conversion capacity accumulated by 2030 in this scenario, the world would be committed to a large quantity of further CO_2 emissions for the time after the onset of climate policy, which in turn would render the 450 ppm climate policy target unachievable.

According to the models, by contrast, a delay in action until 2020 in all world regions is feasible, although global consumption losses over the course of the 21st century increase from 1.4% to 2.1% in WITCH, from 0.7% to 1.0% in REMIND-R and from 0.1% to 0.8% in IMACLIM-R.

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[3] Models follow a business-as-usual path until 2030 before considering the 450 ppm CO2 stabilization target.

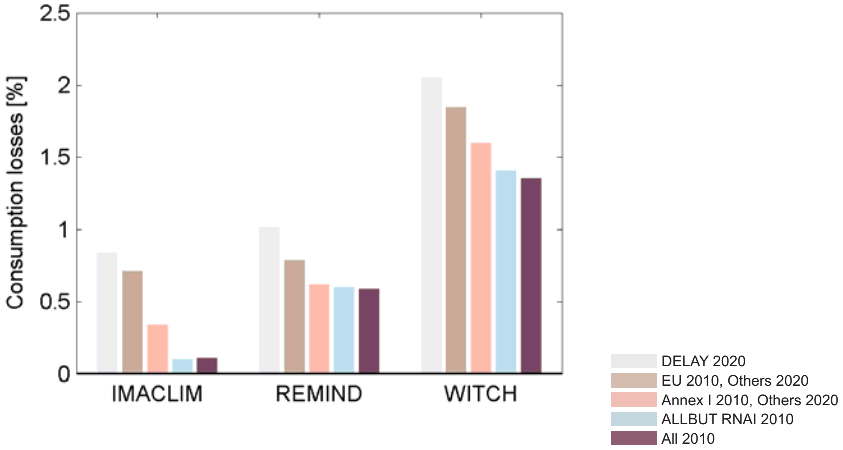

Figure 21: Global mitigation costs (displayed as consumption losses) for various scenarios concerning delayed participation in a global carbon market. Percentage changes are relative to baseline, using a 3% discount rate.

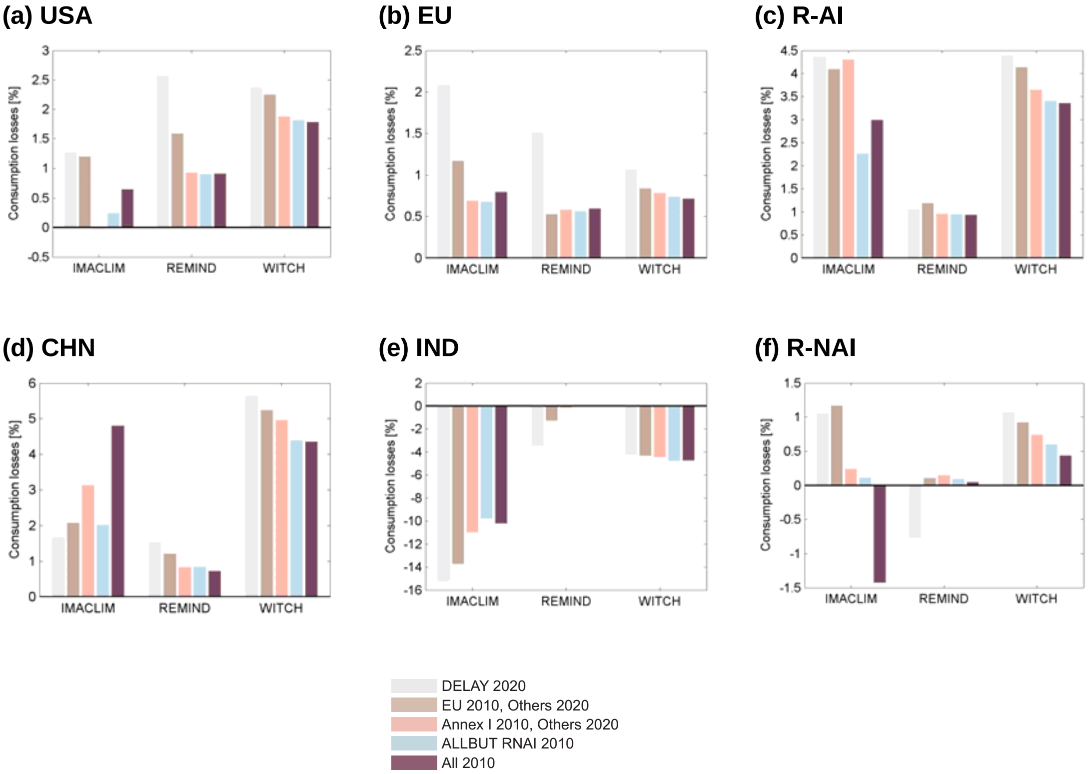

Figure 22: Consumption losses for all world regions for various scenarios of fragmentation. Percentage changes relative to baseline, using 3% discount rate. Please note different scales.

In order to assess the effect of a fragmented carbon market in which some regions participate while others do not, the following scenarios were analyzed and compared:

i) Delay of action by all countries with emissions according to BAU until 2020 *(‘delay 2020’)*

ii) Immediate action by the EU, BAU emissions by others until 2020 *(‘EU only’)*

iii) Immediate action by all Annex-I countries, BAU emissions by others until 2020 *(‘Annex-I only’)*

iv) Immediate action by all Annex-I countries, China and India, BAU emissions by rest of non-Annex-I countries until 2020 *(‘all but RNAI 2010’)*

v) Immediate action by all countries *(‘all 2010’)* – this setting is equivalent to the default policy scenario.

In scenarios (ii)-(iv) it was assumed that early participating regions take reduction obligations for the time from 2010 to 2020, equal to those that would have resulted from a contraction and convergence rule if all regions participated immediately. For all scenarios, it was assumed that the other regions join the global carbon market in 2020. A contraction and convergence rule for the time after 2020 with 2005 as a base year and 2050 as the convergence year was applied. While the region’s emission shares after 2020 are equal to those in the default C&C scenario, the absolute emission levels have to be lower in all regions, including those that assumed emission constraints early, to make up for the delay.

The results concerning global mitigation costs are shown in Figure 21. Regional mitigation costs are depicted in Figure 22. As expected, it can generally be concluded that the more countries participate, the lower are global mitigation costs. All models project that early participation of Annex-I countries is particularly important, with welfare losses in the *Annex-I only* scenarios between 22% (WITCH), 39% (REMIND) and 59% (IMACLIM-R) lower than in the *delay 2020* scenario. According to IMACLIM-R and WITCH, early participation of China and India will also result in significant cost decreases. All models agree that the early integration of non-Annex-I countries is of lesser importance in terms of the global mitigation costs.

3.2.2. The case for early action

An important aspect is the incentive structure for a region to take early action on climate change. What happens if the EU takes immediate action, while the rest of the world follows in 2020? Is there a first mover advantage?

In all models, the EU has lower aggregated mitigation costs in the *‘EU-only’* than in the *‘delay 2020’* scenario – thus, the result suggests that there is an incentive for the EU to take action even if the other regions do not participate immediately. Similarly, the mitigation costs in the USA decrease in *‘Annex-I only’* compared to the *‘EU only’* scenario, thus suggesting that the USA would benefit if it joined the EU in its mitigation efforts along with the other Annex-I countries. We can spin this even further: If Annex-I countries are committed to climate policy, China will increase its welfare by participating early in a global carbon market. The effect of a participation of China and India in a global carbon market is, by contrast, is almost neutral for India.

Considering the effects of early action, there are two forces at play: on the one hand, the EU has a more stringent target from the beginning, which results in a larger cumulative reduction effort compared to the delay-2020 scenario. On the other hand, early adjustment of the energy system avoids a lock-in into carbon-intensive investments, making emission reductions beyond 2020 easier and allowing the EU to sell allowances at a high price to other regions once the international carbon market is in place. This effect holds both for the forward looking models WITCH and REMIND-R, in which the EU strongly benefits from the anticipation of future climate policy constraints, as well as the semy-myopic model IMACLIM-R, in which the EU's energy system benefits from being pushed into a more efficient mode of operation early due to the policy constraint. Early action by the EU stimulates investments in energy R&D and faster learning in wind and solar technology, bringing down the prices of backstop technologies, the costs of wind and solar technology and increasing energy efficiency. For this reason, early adoption of climate policy by a part of the world's regions (as for example the EU) would be beneficial also to other regions once the global climate policy is implemented.

Box 2: The role of anticipation – myopic vs. non-myopic delays

An additional analysis performed for the WITCH model suggests that if countries do not take on binding targets immediately but are sufficiently forward looking to anticipate the emission constraints to be imposed from 2020, the costs are substantially reduced compared to the myopic case, in which countries continue on their business-as-usual path until 2020. Figure 23 compares world consumption losses over the century for three cases: (i) the default *450 ppm C&C* scenario with immediate participation by all regions; (ii) delayed action from all regions with myopic behavior until 2020; and (iii) delayed action without myopic behavior. In a world with myopic behavior until 2020, when the target is imposed, regions do not foresee that they will have to take action and therefore follow a BAU path. In the non-myopic scenario, instead, regions optimize the choice of investments for the entire century, anticipating the 2020 climate target and adjusting investments accordingly. On the global scale, this results in a decrease of additional costs of delay relative to the scenario envisaging immediate action by half. Industrialized countries benefit most from anticipating the reduction target. Due to lower carbon prices, which reduce the revenue from emissions trading, India and other developing countries have consumption losses relative to the myopic case.

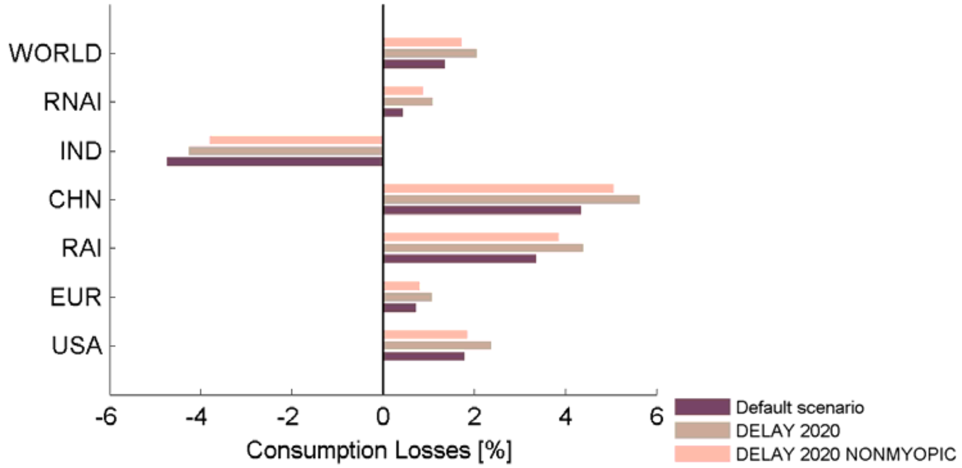

Figure 23: Consumption losses for the WITCH scenario concerning delayed participation with and without a credible threat on future global climate policy. Percentage changes relative to baseline, discounted at 3%.

3.2.3. Timing and Progressive Action – Discussion and Conclusions

Despite the recent progress in the negotiations for a global comprehensive climate agreement for the time after the first commitment period of the Kyoto-Protocol, an immediate setup of a fully functioning international carbon market is still a far cry. Therefore, it is important to consider 'real-world' scenarios with less idealized settings.

The three models deliver similar results in terms of costs of delaying or fragmenting the action toward a global agreement. At the same time, the different nature of decision processes in the three models makes it possible to identify the relevance of features such as anticipation and forward looking behavior.

Several central conclusions can be drawn. First of all, according to all three models delaying mitigation action until 2030 renders it impossible to achieve stabilization of CO_2-concentrations at 450 ppm. If action is delayed until 2020, by contrast, the stabilization target can still be achieved. In this case, global welfare losses costs increase by 56% for REMIND-R, 51% for WITCH and almost 8-fold for IMACLIM-R compared to a scenario with immediate action. In a fragmented world with some regions adopting reduction targets immediately and other regions delaying action until 2020, global overall costs decrease with the number of regions taking early action. The size of mitigation costs depends strongly on the participation of major emitters such as the EU, USA, other industrialized countries, as well as China and India. In these settings, it is of particular importance whether regions start to adjust early to a future climate target (by strategically changing the energy technology portfolio and innovation investments). Anticipation of future reduction obligations has a positive effect on both regional and global mitigation costs. Finally, we find that both the EU and USA have a strong incentive for early action. The benefits of anticipating future reduction targets and adjusting energy systems early outweigh the cost of higher cumulative emission reductions commitments.

4. The European perspective

- **This chapter analyses the effect of climate policy as projected by the models with a special focus on Europe.**
- **All models project a rapid decarbonization of the electricity sector, mostly by CCS and expansion of renewables. By contrast, the transport sector is more difficult to decarbonize due to the lack of cheap low-carbon alternatives.**
- **Excluding the expansion of renewables as part of the global mitigation portfolio would result in an up to three-fold increase of European welfare losses.**
- **Europe has a comparatively high share of nuclear energy consumption both in the BAU and in the policy scenarios. Fixing its use to BAU level leads to low additional welfare losses or – in the case of WITCH - even to welfare gains. For REMIND-R and WITCH, all allocation schemes considered are projected to result in below world average mitigation costs for Europe. IMACLIM-R projects above average costs for the CDC allocation scheme.**

The following section will focus on model results for Europe. The Europe macro-region is not entirely congruent across models; this should be kept in mind when analyzing results. While in REMIND-R 'Europe' is composed of all EU27 countries, IMACLIM-R and WITCH also include EFTA[4] countries. IMACLIM-R additionally includes Turkey.

4.1.1. The low-carbon transition in Europe

Figure 24 depicts the primary energy mix in Europe for the baseline scenario as well as the policy scenarios, aiming to stabilize CO_2 concentrations at 450 and 410 ppm, respectively. Sectoral results on energy consumption are shown in Figure 27. In the baseline scenario, the growth of primary energy demand in Europe is rather moderate compared to other world regions. IMACLIM-R projects a 2.5-fold increase of primary energy demand from 2005 to 2100, while REMIND-R and WITCH project a rise by 80 and 35%, respectively. According to both models, a stabilization of overall energy consumption will occur even in the absence of climate policy after the year 2030. All three models agree that fossil fuels will be the most important energy carrier for Europe until 2100. For the baseline scenario, the European energy mix is characterized by a lower share of biomass use and a higher contribution of nuclear energy compared to the global average. In all three models a significant penetration of renewables occurs already in the baseline scenario.

Introducing a climate policy target results in a substantial transformation of the European energy system. After peaking in 2015, a pronounced contraction of primary energy input is observed in the IMACLIM-R model. This can be primarily explained by the ample use of coal to liquid in the baseline scenario (cf. Section 1.2), which is replaced by less energy-intensive alternatives in the policy scenarios. The reduction of overall energy consumption is most pronounced in the transportation sector, as liquid fuels are primarily used there (Figure 26 d,g). However, the relative reduction between baseline and policy scenarios is much lower

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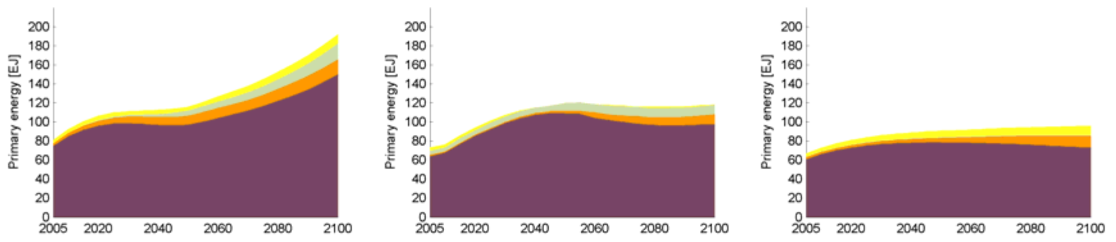
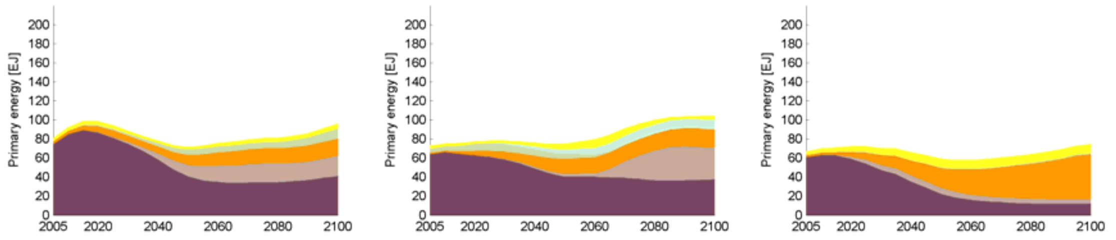
[4] EFTA countries are Iceland, Lichtenstein, Norway and Switzerland.

in Europe than globally, indicating a lower potential for energy efficiency improvements in Europe compared to other regions. According to REMIND-R, Europe significantly slows down the increase in primary energy demand during the first half of the century relative to the baseline scenario, and also compared to the global trend. In 2100, however, the absolute level is comparable to the baseline value. Similarly, in WITCH European energy demand reaches a minimum in the middle of the century before rebounding to values comparable to the baseline by the end of the century. After 2060, primary energy consumption in the 410 ppm scenario increases considerably, especially driven by the considerably increased use of biomass in the non-electricity sector (cf. Figure 26 f,i).


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


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

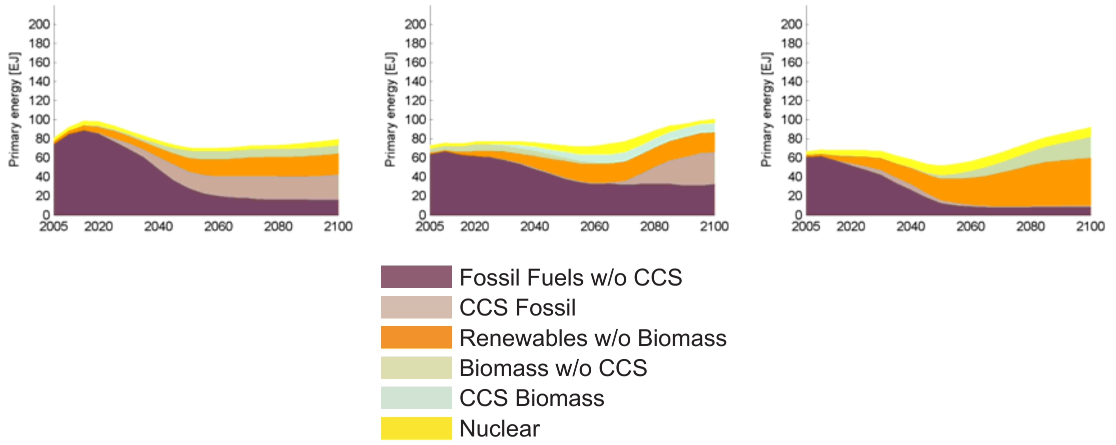

(g) IMACLIM-R 410 C&C **(h) REMIND-R 410 C&C** **(i) WITCH 410 C&C**

Figure 24: Primary Energy Supply in IMACLIM-R, REMIND-R and WITCH for the baseline case, the 450ppm C&C and the 410ppm C&C scenarios for Europe.

The relative share of major low-carbon energy carriers is different across models. Renewables are the most important mitigation option in all three models. There expansion starts immediately after the start of climate policy, and deployment reaches 20-35 EJ/yr by 2050. The WITCH energy mix in the policy scenarios is dominated by the generic backstop technologies, which emulate the development of carbon-free renewables (Jakob et al., 2009b).

Biomass holds a relatively small share of the primary energy production in Europpe compared to the global average. Neither IMACLIM-R nor REMIND-R project an increase of biomass utilization in the policy scenarios compared to the baseline scenario. In REMIND-R, biomass in combination with CCS is phased in after 2035, and dominates biomass utilization in the second half of the century. Biomass CCS is expanded significantly in the 410 ppm scenario compared to the 450 ppm scenario. While WITCH projects biomass to be irrelevant in the European energy mix in the baseline and 450 ppm scenarios, advanced biomass is introduced in the non-electricity sector after 2040 for the more ambitious 410 ppm scenario. This can be explained by high carbon prices that are reached in this more stringent scenario.

In IMACLIM-R, CCS in combination with fossil fuels is one of the most important mitigation options in Europe. In REMIND-R, CCS deployment in Europe reaches significant levels only in the second half of the century. Fossil CCS deployment is reduced in the 410 ppm scenarion compared to the 410 ppm scenario, largely due to the competition with biomass CCS for the limited storage potential.

In general, the additional stringency implied by the 410 ppm stabilization target is met differently by each model. In IMACLIM-R, CCS and renewable energy are expanded, while total primary energy consumption is contracted further, especially in the end of the century. In REMIND-R, most of the additional emission reductions are performed in the second half of the century. The necessary abatement is performed through expansion of biomass CCS and a reduction of energy consumption. Faced with a very high carbon price, advanced biomass technologies become competitive in WITCH and thus have a more important role in the 410 ppm C&C scenario. Once advanced biomass is available, overall primary energy consumption increases compared to the 450 ppm policy scenario.

4.2. Sectoral results

Emission reduction strategies vary among sectors. Models are very consistent in emphasizing the need of a swift and large-scale decarbonization of Europe’s power sector in order to achieve deep emission reductions. For both, the 450 ppm and the 410 ppm policy scenario, power sector emissions are reduced to a small residuum until the mid of the century in all three models. Decarbonization in the transportation sector is significantly more challenging, due to the absence of cheap carbon-free alternative primary energy carriers. This fact can be illustrated by fossil energy consumption without CCS not falling below 5 EJ to 20 EJ in any of the models. In general, the sectoral patterns of decarbonization in Europe are very similar to those on the global level as discussed in Section 1.4.

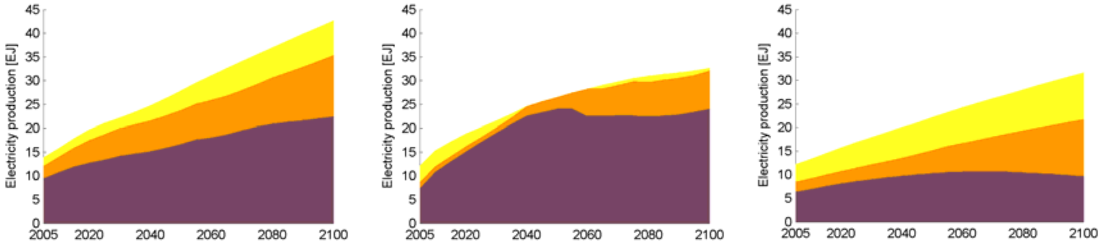
Figure 25 shows the electricity mix as projected by the three models. Nuclear has a higher share in electricity production in Europe than on global average. For the policy scenarios, REMIND-R projects a moderate increase of nuclear energy production, while WITCH projects nuclear production in absolute terms to be comparable to baseline levels.

As shown in Figure 26, decarbonization in the transportation sector is significantly more challenging due to the absence of cheap carbon-free alternative primary energy carriers. All models project that a substantial stock of conventional fossil energy consumption remains. The large uncertainty about future developments in the transport sector is also reflected in the different visions of mitigation options as implemented in the three models. In IMACLIM-R, efficiency improvements, biofuels and electrification (via plug-in hybrids), as well as coal-to-liquid are the main mitigation options. Despite the use of plug-in hybrids, electricity accounts only for a small fraction of primary energy demand in the transport sector. In REMIND-R, the principal mitigation options are the generation of liquid fuels from biomass and H_2 from biomass and coal in combination with CCS. The negative emissions implied by the biomass plus CCS option allow the residual fossil emissions to be higher than in the other two models. WITCH includes advanced biomass and a generic backstop technology as carbon-free technology options for the non-electricity sector, both of which are not used in the baseline scenario. Due to high costs of these technologies and limited substitutability, achieving the stabilization targets also requires a substantial decrease in non-electric energy demand.

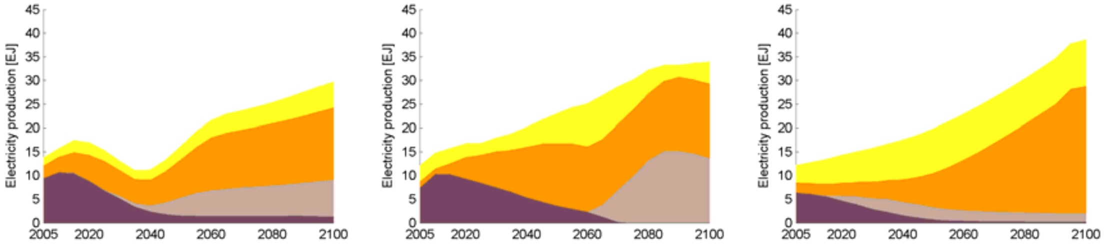
Results for non-electric stationary energy consumption are shown in Figure 27. It should be noted that its representation of the differs markedly across the three models. WITCH aggregates non-electric stationary and transport energy. In REMIND-R, non-electric stationary energy demand is represented as a separate end-use sector. IMACLIM-R differentiates further between energy demand in the residential and industrial sectors.

According to the results from REMIND-R and IMACLIM-R, the non-electric stationary sector holds significant potential for energy efficiency improvements. Also a shift to electricity as secondary energy carrier and fuel-switch form coal to gas play an important role. Alternative non-fossil primary energy carriers, by contrast, do not play an important role.

(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**



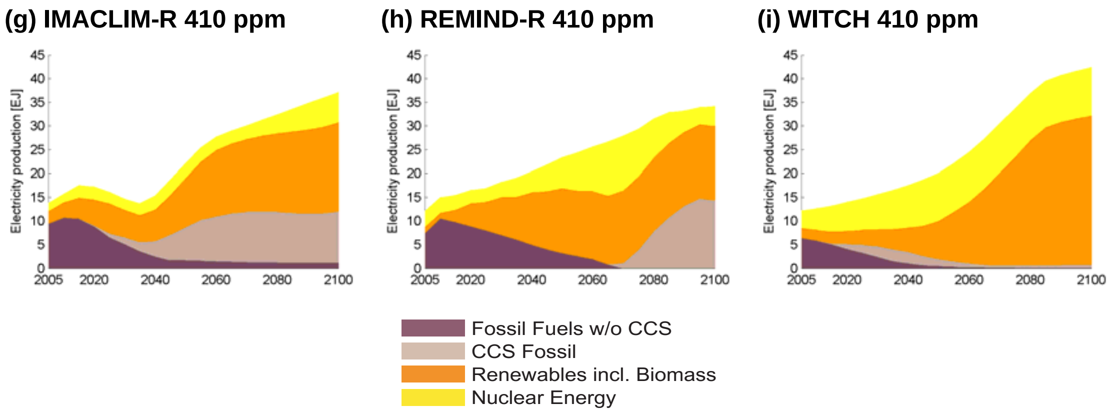


Figure 25: Electricity mix for the European power sector (IMACLIM-R and WITCH) as well as power and heat for REMIND-R

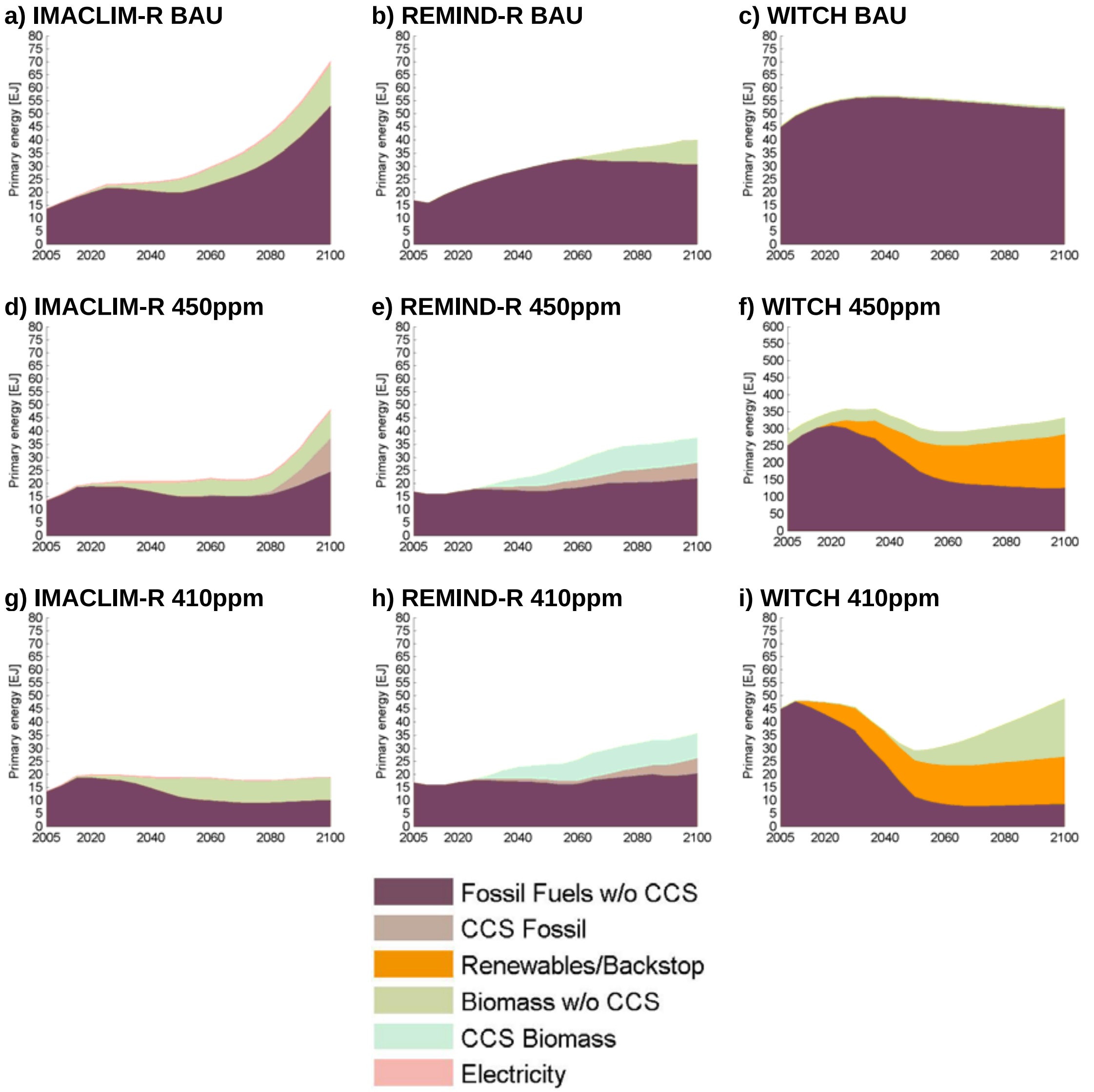
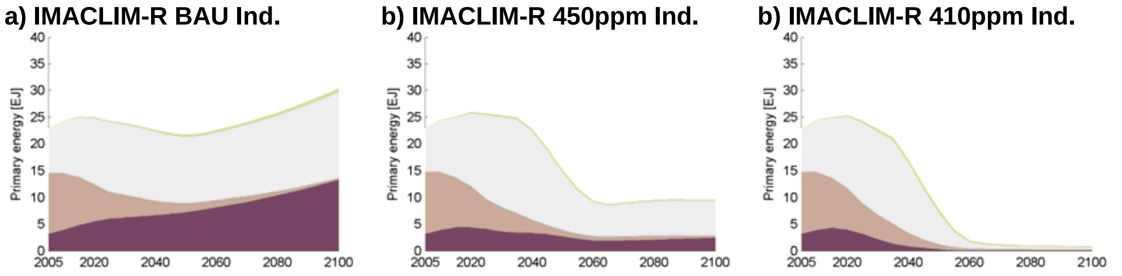
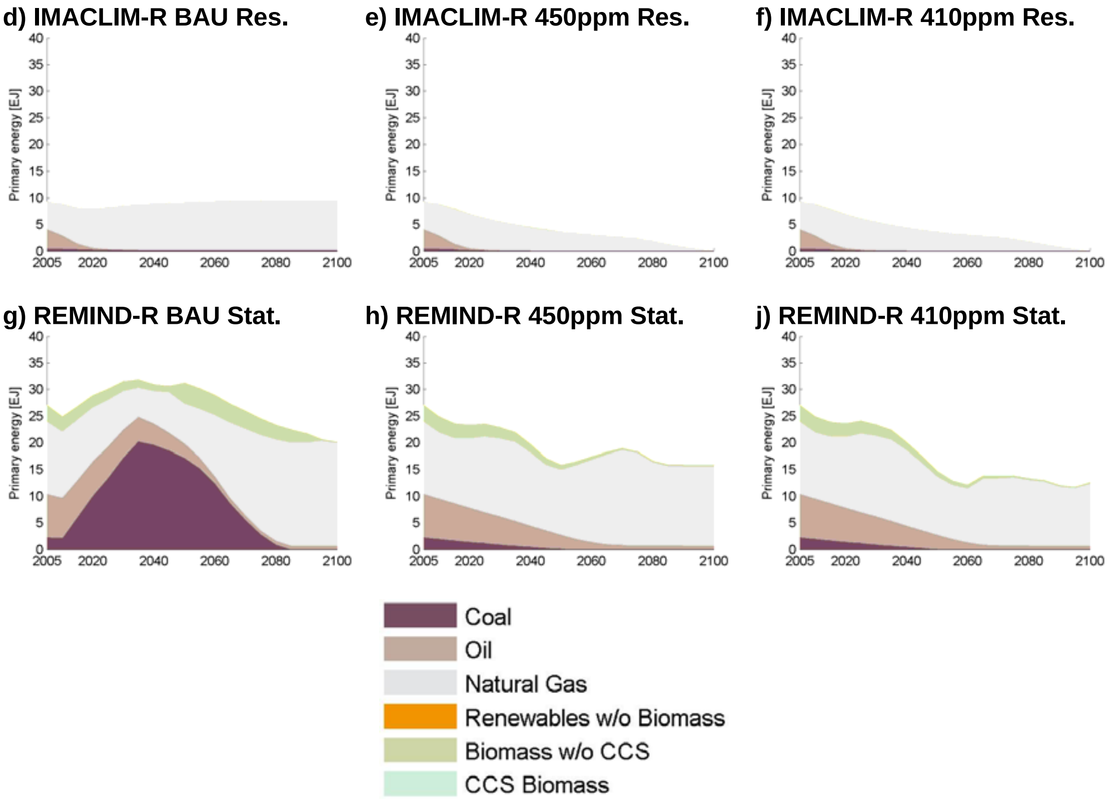


Figure 26: Projected energy mix for the European transport sector (non-electricity sector for WITCH) in the IMACLIM-R, REMIND-R and WITCH models for the baseline, 450ppm C&C and 410ppm C&C scenarios.





d) IMACLIM-R BAU Res. e) IMACLIM-R 450ppm Res. f) IMACLIM-R 410ppm Res.

g) REMIND-R BAU Stat. h) REMIND-R 450ppm Stat. j) REMIND-R 410ppm Stat.

Figure 27: Projected energy mixes for stationary non-electricity energy demand in Europe for IMACLIM-R and REMIND-R. WITCH does not report the non-electric stationary sector separately. Note that IMACLIM-R further distinguishes between the industrial (Ind.) and residential (Res.) sector. Cf. also Section 1.4 for a discussion of the sector representations in the models.

4.3. Technology option values

As discussed in Section 3.1, the relative importance of different mitigation options can be quantified by determining their option values. These are defined as the increase in mitigation costs if a particular mitigation option is foregone relative to the mitigation costs in a scenario allowing for all available mitigation options. The results on the global scale indicate that certain mitigation options are more important than others. While the models consistently show that climate policy induced expansion of nuclear energy has a low option value, renewable energy and CCS are identified as most important mitigation options.

Figure 28 reviews the scenarios on technological fragmentation with a special focus on Europe. The scenarios considered include (a) *noCCS* (b) *fixBiomass*, (c) *fixRenewables*, (d) *fixNuclear*, and (e) *noCCS_fixNuc*. For the *noCCS* scenario it is assumed that the CCS option is not available. Scenarios (b)-(d) assume that primary energy use of biomass, renewables and nuclear, respectively, is fixed to the level used in the baseline for all macro-regions. *noCCS, fixNuc* assumes unavailability of CCS in combination with fixing nuclear to baseline levels. All technology scenarios were calculated under a 450 ppm CO_2 concentration target. It is important to note that for all these scenarios, technology constraints were assumed to be applied globally. This is important for this analysis as Europe is affected indirectly, most importantly via resource prices, by the mitigation portfolio chosen in other regions.

Nuclear energy takes a higher share in the electricity mix of Europe than in other world regions. When renouncing any further expansion the models agree that nuclear energy is the technology with the relatively lowest option value in Europe. Thus, if expansion of nuclear energy os excluded from the global portfolio, mitigation costs for Europe would not rise significantly. WITCH and IMACLIM-R even project small gains in the medium term for this scenario, largely because a restriction on the global use of nuclear energy would result in lower uranium prices. For REMIND-R and WITCH, foregoing an expansion of renewable energy would imply a tripling of aggregated mitigation costs over the course of the 21st century. In REMIND-R, this outcome is partly induced by trade related effects: if the availability of renewables is limited, resource intensive alternatives (CCS and nuclear) become more important. Thus, prices for these resources increase, which has particularly strong effects for Europe as a resource importer. CCS has the highest option value in IMACLIM-R (a 2.5-fold increase of mitigation costs) and also plays an important role in the other two models. For REMIND-R mitigation costs would be elevated by 25%, while the cost increase for WITCH amounts to 30%. If both CCS and nuclear expansion are not used as mitigation options, costs in all three models resemble the costs projected for the *noCCS* case. Even if CCS is not available, foregoing expansion of nuclear results in very small changes of overall mitigation costs. Not expanding biomass beyond baseline use has small effects in IMACLIM-R and WITCH. Even for REMIND-R, which relies stronger than the other models on biomass as a mitigation option, limiting its availability results only in moderate cost increases in Europe.

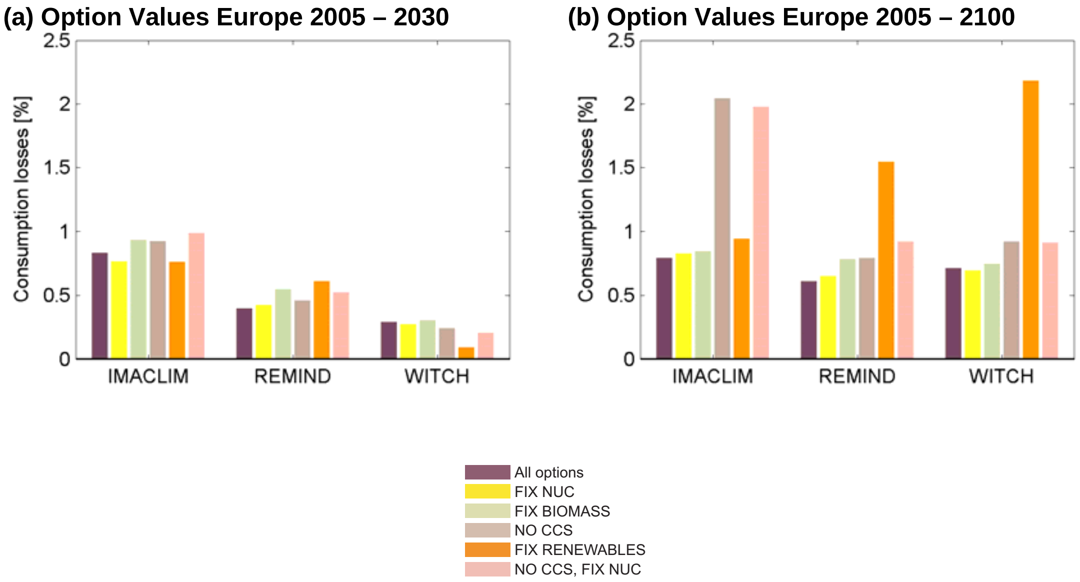


Figure 28: Discounted (3%) option values for various technology options for the models IMACLIM-R, REMIND-R and WITCH for (a) 2005-2030 and (b) 2005 – 2100.

4.4. Mitigation costs and allocation rules

Various schemes for allocating emission rights under a global climate policy target are discussed in Section 2. Estimating the regional impact of different allocation rules is a question of particular interest in the international debate on climate agreements. This section provides an in-depth analysis of implications for Europe. Figure 29 shows projected mitigation costs, consumption losses, trade balances and permit allocations for different allocation schemes for the IMACLIM-R, REMIND-R and WITCH model until the year 2100. Analogously to Section 2.1, we present results for four different allocation rules in the context of a 450 ppm CO_2 concentration target: (a) contraction and convergence (C&C), (b) common but differentiated convergence (CDC), (c) an allocation scheme based on GDP shares, and (d) a tax regime with national revenue recycling. Furthermore, the implications for the European economy of the more stringent 410 ppm scenario in conjunction with a contraction and convergence allocation rule are explored.

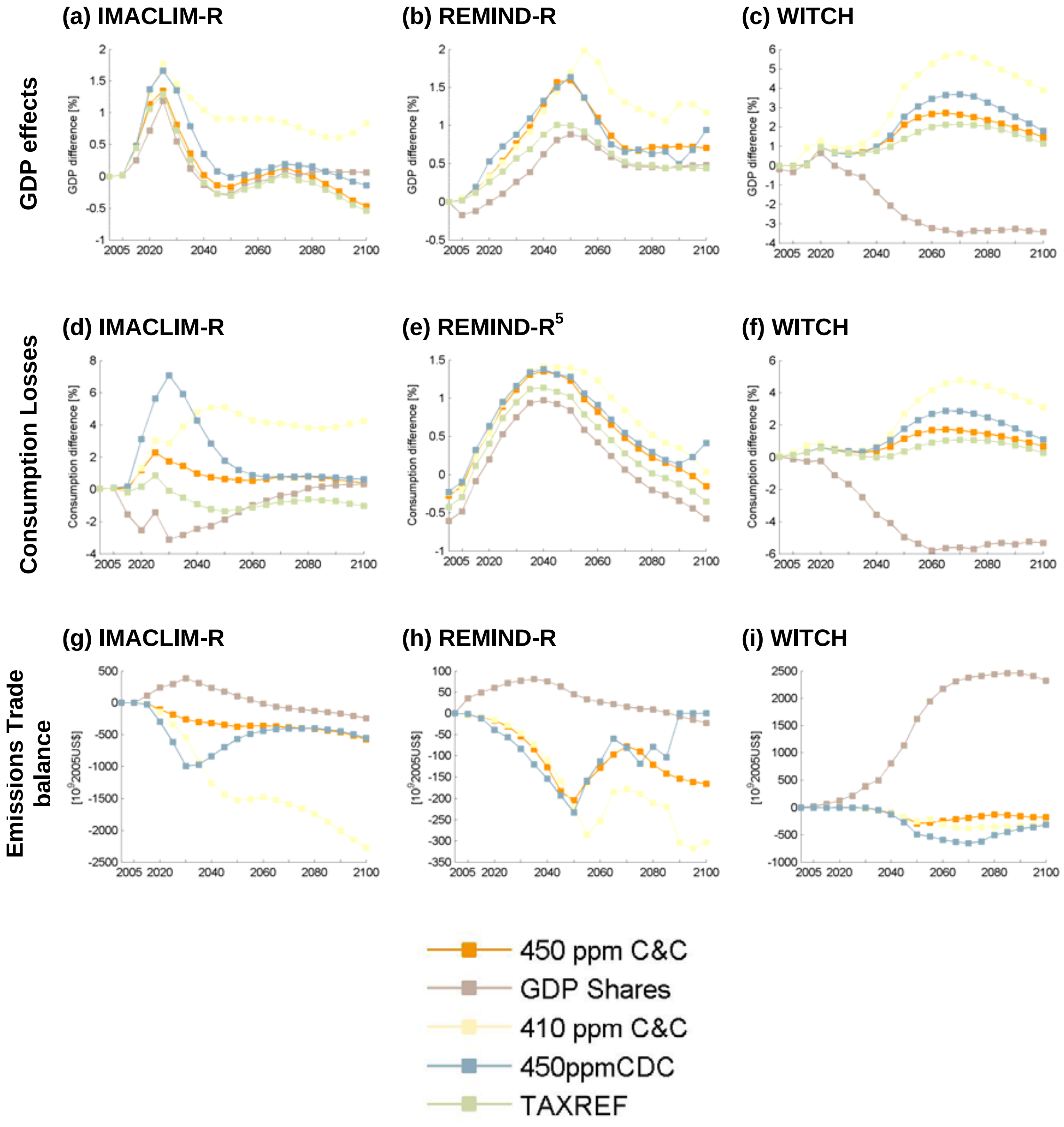


Figure 29: Mitigation costs in terms of GDP (a,b,c) and consumption losses (d,e,f) in percent relative to baseline and emission trade balances (g,h,i) for Europe for the models IMACLIM-R, REMIND-R and WITCH for different allocation rules (Contraction and Convergence, GDP shares , Contraction and Differentiated Convergence and a tax regime) as well as for different stabilization targets (450 ppm and 410 ppm).

As carbon emissions per unit of GDP are low in Europe compared to other world regions, Europe would be best off if an allocation scheme based on GDP shares is implemented

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[5] In REMIND-R, the international capital market implied by intertemporal trade allows regions to optimally distribute the welfare gain resulting from a more beneficial allocation rule smoothly over time. Thus, Europe has consumption gains already at the beginning of the simulation period for the GDP shares and tax regimes.

internationally, with WITCH and IMACLIM-R even projecting consumption gains from this allocation scheme. For the GDP shares scenario, all models forecast that Europe would be a net seller of emission certificates. The tax regime, by definition, is equivalent to an emissions trading scheme in which the allocation matches the actual emission, thus rendering trade of permits unnecessary. However, mitigation costs for Europe would be lower than in all allocation schemes other than GDP shares. For C&C and CDC, all models project Europe to be a net buyer of emission permits.

For the 450 ppm C&C scenario IMACLIM-R simulates a steep initial increase of mitigation costs with a pronounced peak in 2025. In line with the projections for the global losses, the transformation of the energy system is initially costly but leads to negative mitigation costs in the long run. Consumption losses decrease to values close to zero once the transformation of the energy system is completed after 2030. Nonetheless, Europe remains a net importer of emission certificates over the entire simulation period. The temporal pattern of macro-economic effects induced by climate policy is similar for REMIND-R and WITCH. For REMIND-R, however, mitigation costs as well as carbon prices are on a lower level compared to the other two models. Costs increase relatively smoothly until the mid of the century before the experience curves of low-carbon learning technologies are passed through and the availability of cheap alternative energy sources makes CO_2 abatement less expensive (see also pp. 7). Free international trade results in further cost reductions. In WITCH, which predicts the highest mitigation costs of all models, consumption losses remain moderate until 2040 before rising significantly in the second half of the century.

For the CDC approach, which tends to result in a more favorable outcome for developing countries, mitigation costs remain comparable to those calculated for the C&C scheme for REMIND-R and WITCH. In IMACLIM-R, consumption losses more than triple compared to C&C until 2050, before converging to the C&C level thereafter. Analogously, the trade balance is highly negative at the beginning of the century. While CDC is projected to increase costs in Europe relative to C&C mainly during the first half of the century, WITCH also projects a moderate increase in costs for the second half of the century. The difference can mainly be explained by the differences in the global CO_2 emissions trajectory as well as higher carbon prices in the WITCH model.

In addition to determining various allocation schemes, we also analyze a 410 ppm scenario with a contraction and convergence allocation scheme (cf. Box 1). In terms of the mitigation costs for Europe, the models agree that increasing the stringency of the target mostly affects the mitigation costs in the long run, while the short term effects are rather small. In IMACLIM-R, the costs start to deviate from the 450 ppm scenario already after 2050, while in REMIND-R and WITCH significant cost increases occur only after 2050.

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