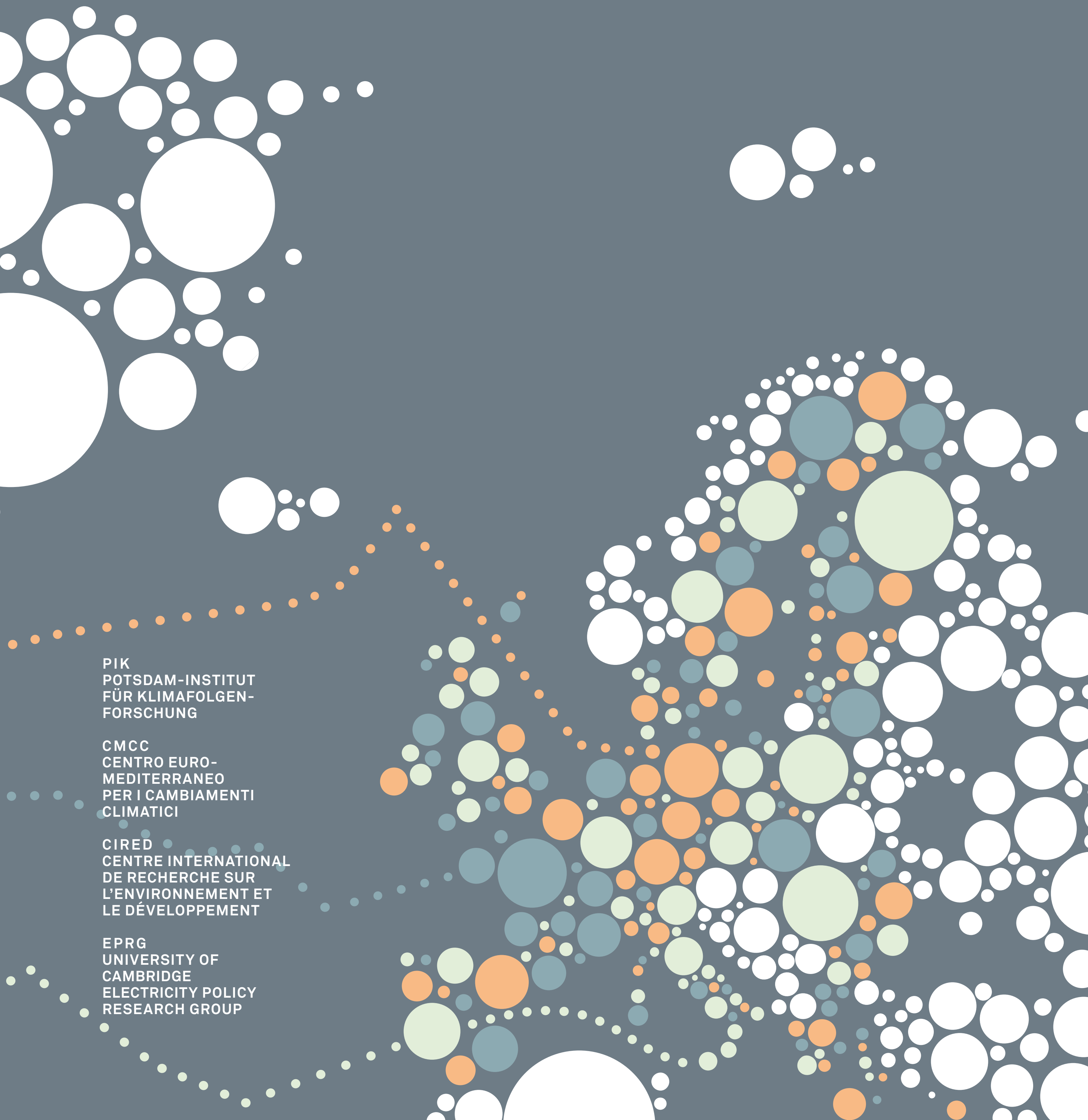
REPORT ON ENERGY AND CLIMATE POLICY IN EUROPE

RECIPE

THE ECONOMICS OF DECARBONIZATION



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For more information on RECIPE please visit http://www.pik-potsdam.de/recipe.

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EXECUTIVE SUMMARY

The global economy's appetite for energy is big and rising. At the same time, the Earth's ability to digest the waste products of energy consumption is decreasing. Newest scientific evidence suggests that global warming proceeds more rapidly than previously anticipated: CO_2 emissions growth is higher than thought, the oceans' capacity to act as natural carbon sinks has declined, and a future decrease of the cooling effect caused by aerosols is likely. Dangerous climate change becomes ever more likely, its mitigation ever more pressing.

RECIPE (Report on Energy and Climate Policy in Europe) outlines roadmaps towards a low-carbon world economy. Three structurally different energy-economy models were used to explore possible future development paths under a range of different assumptions about the nature of the low-carbon transition. RECIPE projects that without measures to decarbonize energy systems, unabated carbon emissions will raise atmospheric concentrations to between 730 parts per million (ppm) and 840 ppm CO_2, inducing a global mean temperature increase of 3–7°C above pre-industrial levels. The warming would come with severe impacts on natural and social systems. In addition, several tipping points, i. e. critical thresholds at which small perturbations can induce a qualitative shift in the mode of operation of the climate system, would likely be crossed, inflicting unprecedented damages on human settlements and ecosystems.

MITIGATION TARGETS AND COSTS

RECIPE shows that stabilizing atmospheric CO_2 concentrations at 450 ppm is technically feasible and economically affordable. For this target, discounted welfare losses range between 0.1 % and 1.4 % of the global GDP relative to baseline levels. Costs are expressed in 'gross' terms, i. e. they do not reflect the benefits of avoided climate change. More ambitious climate policy aiming at CO_2 stabilization at 410 ppm improves the chance of limiting global warming to no more than 2°C above pre-industrial levels. Here, the costs lie in the range of 0.7 to 4 %. Carbon prices as well as mitigation costs depend critically on assumptions about (1) innovation and the availability of low-carbon alternatives to conventional fossil fuels, (2) flexibility of substitution within the energy-economic system, (3) the ability of policy-makers to stabilize investors' confidence in the carbon market and (4) the immediate action of major emitters.

Current atmospheric CO_2 concentrations accrue to about 385 ppm. The stabilization trajectories of the RECIPE policy scenarios (450 ppm and 410 ppm) for the first half of the 21st century correspond to a medium likelihood of reaching the 2°C target. Ensuring a high likelihood will need even deeper emission reductions than those considered here. Very low stabilization requires advanced mitigation options for generating 'negative emissions' such as biomass in combination with carbon capture and storage (CCS).

The generation of rents resulting from selling emission permits in a global cap-and-trade system raises large-scale distributional issues. Previous assessments of mitigation costs (including IPCC, 2007 c; Stern, 2006) remained largely silent about the question of how the global mitigation effort translates into regional mitigation costs. RECIPE shows that if global cooperation is based on international emissions trading, then rents created in transfers depend decisively on the price of CO_2. Technological innovation and the stabilization of expectations can contribute to lower carbon prices and thus reduce rent transfers and potential conflicts over the allocation of emission rights.

TECHNOLOGIES

The relative importance of different technologies can be quantified by considering scenarios in which the deployment of certain technologies is restricted to baseline level. RECIPE's technology-constrained scenarios suggest that CCS and renewables have the highest potential to act as low-cost mitigation options. The option value of nuclear energy is smaller. Although it can contribute substantially to emissions abatement, it entails specific risks and barriers that are not fully accounted for in the models. Energy efficiency improvements and demand side management hold significant low-cost and short-term emissions abatement potential. In the long-term, the higher the restrictions on technology availability, the larger is the role of energy efficiency. For the decision which mitigation technologies are deemed most appropriate to reduce CO_2 emissions, their positive as well as negative side effects should be taken into account and discussed with affected stakeholders.

INVESTMENTS

To keep mitigation costs low, investments into conventional coal-fired power generation capacity need to be halted immediately. Otherwise, the aggravated lock-in into long-lived carbon-intensive infrastructure will significantly raise mitigation cost. For the policy scenario, RECIPE projects investments in low-carbon technologies to amount to about 0.2 % to 1 % of world GDP over the course of the 21st century. This corresponds to US$ 1200 billion of additional (i. e. above baseline) investments in mitigation technologies by the middle of the century. The largest part would be targeted at renewable energy sources and CCS. Investments in conventional fossil fuel based sources of energy generation would fall by US$ 300 to 500 bn. Private sector involvement will be crucial to raise investments in clean energy technologies above their historical peak of US$ 150 bn in 2007. Credible long-term climate policies reduce uncertainty for private investors, and provide incentives for early movers to establish technological leadership in this sizeable market. The projected developments have important repercussions for investments in extractive industries, the agricultural sector, and commodity markets in general.

SECTORAL RESULTS

The decarbonization of power generation is achievable with relative ease due to the availability of a broad portfolio of economically viable mitigation technologies. The generation mix could be almost fully decarbonized by mid-century. However, non-electricity sectors, in particular the transport sector are more difficult to decarbonize at least if the electrification of this sector is not an option. In the European industry sector, emissions reductions are less dependent on new installations but rather on improving technologies of existing installations as only few new installations are scheduled for construction in the mid-term. In agriculture, a range of mitigation options is available at low, zero or even negative costs, but considerable non-price-related barriers need to be overcome.

POLICIES

Putting a price on CO_2 emissions is at the heart of any efficient climate policy framework. At the international level, one option towards a carbon pricing regime is the implementation of a global emissions trading system stepwise. National economy-wide caps and emissions trade on the government level can be complemented with bottom-up linking of emerging OECD cap-and-trade schemes operating at company level.

Developing countries can join this carbon market step-by-step, with suitable trading mechanisms for different countries and sector trading mechanisms substituting the current CDM in an intermediate period.

In addition to carbon pricing, policy makers should remove existing regulatory barriers and implement low-carbon technology policies to support research and development (R&D) and the diffusion of new technologies. R&D, demonstration projects, and policies to broaden the portfolio of mitigation options can help to provide insurance against uncertainty in future technology development. Countries can reduce costs and risks by jointly engaging in R&D and coordinating national R&D efforts. To permit developing countries to leapfrog to low-carbon growth paths and facilitate international technology cooperation, a global climate agreement should establish appropriate financial mechanisms and clarify the role of intellectual property rights for low-carbon technologies.

At the European level, we suggest that over the long-term all sectors should be included in the emissions trading system where this is feasible. Clearly, there are critical issues that need to be observed in the transition process, including questions of political economy. Concerning complementary policies, for the power sector the EU Renewables Directive provides a crucial framework to deliver a portfolio of renewable technologies. The Directive requires Member States to provide financial support for renewables deployment through feed-in tariffs or other mechanisms, to provide the necessary regulatory framework including enusred grid access, and to adopt grid infrastructure and market design to the new requirements. For transportation, R&D and pilot projects should be given highest priority in order to assess the viability of alternative options. Policies promoting the use of biofuels should take into account the well-to-wheel energy efficiency and greenhouse gas emissions of the production of these fuels. For industry, asymmetric carbon prices bear a limited risk of carbon leakage for some sectors which could be tackled through border adjustments, free allowances for industries at risk or investment support for efficiency improvements. In the long-term, comparable carbon prices across sectors internationally is the first best tool for addressing leakage concerns. An expansion of the emissions trading system to the agricultural sector is currently not appropriate to incentivize mitigation in a cost-efficient manner. A climate change mitigation strategy in the European agriculture sector should rather be part of a wider policy approach towards sustainable agriculture and rural development.

THE CASE FOR IMMEDIATE ACTION

The window of opportunity for climate policy is narrow and closing. If the world continues according to business-as-usual until 2030, stabilizing atmospheric CO_2 concentrations at 450 ppm will no longer be possible. Reaching 450 ppm CO_2 stabilization by 2100 remains feasible if ambitious mitigation policies at global scale are postponed until 2020, but this delay will boost global mitigation cost by at least 46%. It also entails overshooting of CO_2 concentrations, thus lowering the probability of staying below 2°C. Climate policy aiming at CO_2 stabilization at 410 ppm leaves even less leeway for a delay of cooperative mitigation action.

Even if other regions delay carbon pricing until 2020, Europe will enjoy a first mover advantage when unilaterally implementing climate policy. Europe is better off in this case compared to a scenario in which all world regions, including Europe, delay action until 2020. The benefits of anticipating future emission reductions and redirecting investments early on exceed the costs of higher cumulative emission reduction commitments.

1 THE CLIMATE CRISIS IN THE MAKING

KEY MESSAGES

- Climate change is under way, and it is mainly caused by man-made emissions of greenhouse gases. If climate change continues unmitigated, global warming can reach 3–7°C relative to pre-industrial levels by the end of the 21st century.

- Recent research has highlighted that global warming might proceed more rapidly than previously anticipated because (1) CO_2 emissions have increased at a higher rate than projected, (2) the oceans' capacity to act as natural carbon sinks has declined, and (3) a future decrease of the cooling effect caused by aerosols is likely.

- Both human and natural systems will be severely impacted by climate change. Based on a survey of recent literature, the impacts for each 'reason for concern' (IPCC, 2001) are more severe at any given temperature increase than previously assumed.

- A substantial number of so-called 'tipping points' that were identified in recent literature are covered by the range of warming that could result if carbon emissions stayed on their business-as-usual path.

- Without measures to decarbonize the world's energy systems, unabated carbon emissions will result in atmospheric concentrations between 730 ppm and 840 ppm CO_2. This would yield an equilibrium global mean temperature increase of 3–7°C above pre-industrial values.

As the IPCC's Fourth Assessment Report (AR4) in 2007 (IPCC, 2007a) points out, climate change is a global problem of unprecedented scale triggered by anthropogenic influences. More recent findings suggest that some fundamental driving forces of global warming might have been seriously underestimated. Raupach et al. (2007) document that, due to reversals of earlier declines in energy intensity of GDP (E/GDP) and carbon intensity of energy production (CO_2/E) in conjunction with continued growth of global GDP and world population, the growth rate of CO_2 emissions has increased considerably from 1.1 % per year in 1990-1999 to more than 3% in 2000–2004. The lion's share of this increase (73 %) can be attributed to developing and least-developed countries, in particular China. CO_2 emission trends exceed even the most fossil-fuel intensive of the IPCC SRES scenarios (A1FI). Canadell et al. (2007) present evidence that a further cause of increasing atmospheric concentrations of CO_2 – besides increasing emissions – is a decline in the efficiency of CO_2 sinks. This decrease in the planet's capacity to sequester carbon accounts for 18% (±15 %) of the observed growth rate of atmospheric CO_2 concentrations for the period 2000–2006. Ramanathan and Feng (2008) caution that global warming commitment (i. e. the 'unavoidable' increase of global mean temperature) and potential future warming is commonly underestimated largely because the cooling effect of aerosols – small particulates that scatter sunlight back to space – were ignored. As humans cut down aerosol emissions as part of CO_2 abatement, fuel switch and efforts to combat local air pollution, global warming will thus further increase, even if concentrations are stabilized at the current level.

IPCC AR4, based on 6 IPCC SRES scenarios, projects temperature changes ranging from 1.1°C to 6.4°C for 1990–2100. The likely range for the most emissions-intensive scenario (SRES A1FI) is 2.4°C to 6.4°C. As mentioned above, recent findings suggest that even higher ranges will be likely if no strong steps to restrict carbon emissions are taken. Warming on this unprecedented scale is very likely to have massive adverse impacts on ecosystems and human development, caused by higher frequency of droughts, sea-level rise, higher incidence of extreme weather events (such as tropical storms), ocean acidification, and an altered prevalence of disease vectors. To assess the impacts, the IPCC's Third Assessment Report (TAR, IPCC, 2001) highlighted five reasons for concerns, including (1) the risk to unique and threatened systems, (2) the risk of extreme weather events, (3) the distribution of impacts, (4) aggregate damages, and (5) risks of large scale discontinuities. There is now additional evidence that suggests that dangers and risks arising from climate change have been underestimated in the past. Figure 1-1, taken from Smith et al. (2009), compares the original 'burning embers diagram' that appeared in the TAR with an updated version based on the IPCC's Fourth Assessment Report (IPCC, 2007b). The updated diagram (right hand side) implies that smaller increases in global mean temperature as previously assumed suffice to result in serious impacts for anyone of the five reasons for concern.

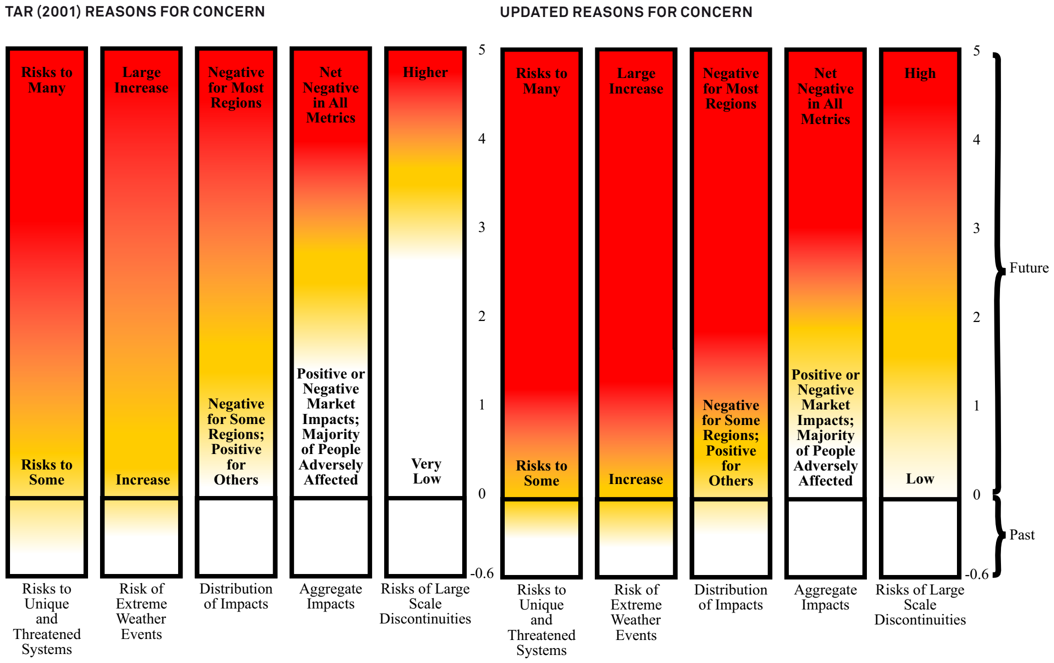
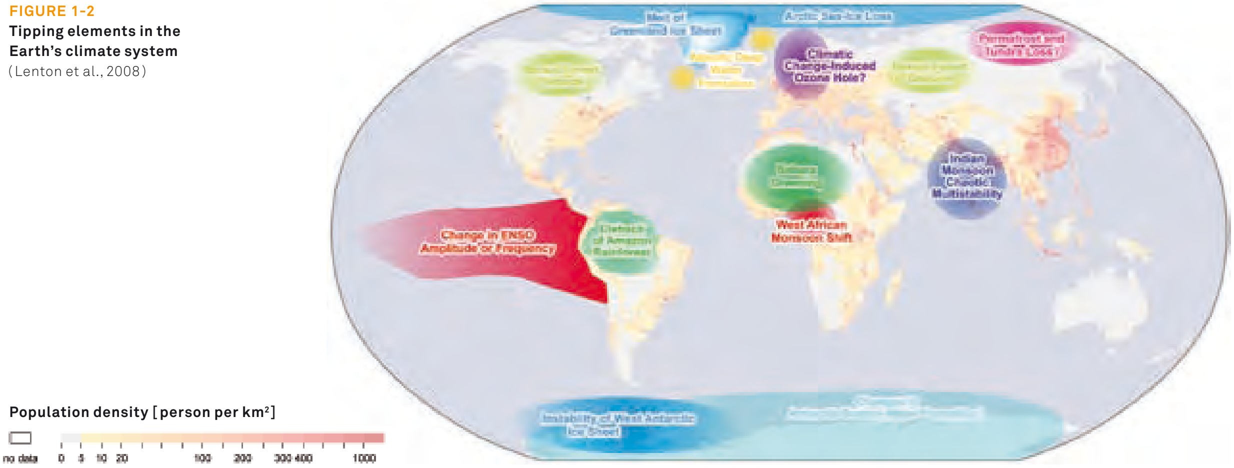


FIGURE 1-1
Risks from climate change by reason for concern, as appraised by the IPCC Third Assessment report compared with recently updated data. Climate change impacts are depicted against increases in global mean temperature (°C) after 1990
(Smith et al., 2009)

A further serious risk related to temperature rise are so-called 'tipping points' in the Earth's climate system (Lenton et al., 2008). This term refers to critical thresholds at which small perturbations can induce a qualitative shift in the climate system's mode of operation. The nine policy-relevant tipping elements identified by Lenton et al. are shown in Figure 1-2. They include (1) melting of the Arctic sea-ice, (2) melting of the Greenland ice sheet, (3) melting of the West-Antarctic ice sheet, (4) the slowing down of the Atlantic thermohaline circulation, (5) shifts in El-Niño-Southern Oscillation (ENSO), (6) ceasing of the Indian summer monsoon, (7) ceasing of the Sahara / Sahel and West African monsoon, (8) disappearance of the Amazon rainforest, and (9) disappearance of boreal forests. Crossing any one of these thresholds might result in serious and irreversible damages for ecosystems and human well-being. Experts' evaluations suggest that the Arctic sea-ice might already have crossed the threshold and that the critical temperature range for the Greenland ice sheet ranges between 1 and 2°C above present temperatures, i. e. roughly 2°C above pre-industrial levels. All other tipping points for which temperature ranges can be applied are estimated to be in the interval between 3 and 6°C and are therefore covered by the range of warming that could result if carbon emissions stayed on their business-as-usual path.

FIGURE 1-2
Tipping elements in the Earth's climate system
(Lenton et al., 2008)



The RECIPE reference scenario assumes a world without climate mitigation measures, thereby presenting a rather pessimistic outlook. The three models employed use harmonized assumptions with regards to the development of global population and partially harmonized assumptions regarding economic activity. World population is assumed to keep growing, with a peak at 9.5 billion in the year 2070 and thereafter slightly declining to roughly 9 billion in 2100. Global GDP is projected to grow at an average annual rate ranging from 2.1 % (WITCH) to 2.4 % (REMIND-R). As improvements in energy efficiency are in the reference scenario outpaced by growing economic activity, energy demand is projected to increase throughout the whole of the 21st century. Due to an energy mix that remains largely dominated by fossil fuel use, IMACLIM-R and WITCH project steady increases of annual energy related CO_2 emissions from 27.5 $GtCO_2$ in 2005 to 124 $GtCO_2$ and 86 $GtCO_2$ in 2100, respectively (Figure 1-3). In REMIND-R annual emissions are projected to peak in 2055 and decline modestly thereafter to reach 72 $GtCO_2$ in 2100 (more than 160 % above their year 2005-level). The range of RECIPE reference scenario emissions lies roughly between the most emission-intensive IPCC scenarios A2 and A1FI.

Currently, atmospheric CO_2 concentrations are at about 385 ppm. Unabated emissions raise atmospheric concentrations in the year 2100 to between 730 ppm CO_2 (WITCH), 750 ppm CO_2 (REMIND-R), and 840 ppm CO_2 (IMACLIM-R) (Figure 1 - 4). Projected concentration levels for the year 2100 correspond to global mean temperature increases in equilibrium values (i. e. the rise in temperatures in the very long run when the Earth's climate system has reached its new equilibrium within a few centuries following changes in radiative forcing due to higher GHG concentrations) between 3 and 7°C.

FIGURE 1-3
Global energy-related CO_2 emissions in the reference scenario for IMACLIM-R, REMIND-R, and WITCH

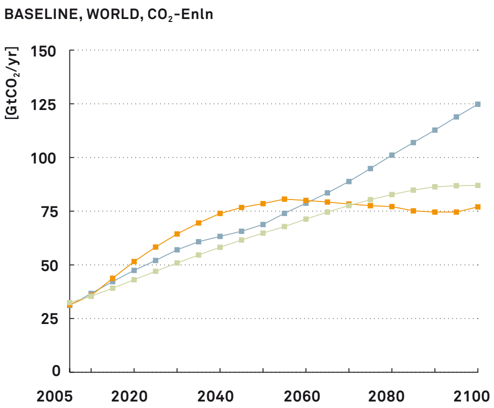
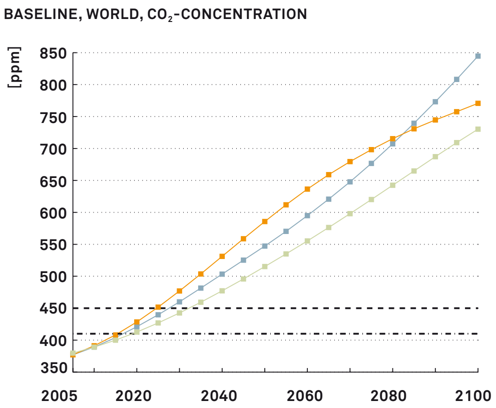


FIGURE 1-4
Atmospheric concentrations of CO_2 in the reference scenario for IMACLIM-R, REMIND-R, and WITCH



2 THE CHALLENGE OF CLIMATE STABILIZATION

KEY MESSAGES

- Stabilizing atmospheric CO_2 concentrations at 450 ppm is possible at globally aggregated costs of 0.1–1.4 % relative to the baseline[2]. Stabilization at 410 ppm costs between 0.8 to 4 % (see Section 2.3).

- Stabilization requires a radical shift from conventional fossil to low-carbon energy sources, including renewables, carbon capture and storage (CCS), and, to a lesser extent, nuclear (see Section 2.4).

- The relative importance of energy efficiency improvements, particularly in the short to medium term, increases with more ambitious stabilization levels and under more pessimistic assumptions about the availability of low-carbon technologies (see Section 2.4).

- Current atmospheric CO_2 concentrations are at about 385 ppm. Stabilization trajectories (450 ppm and 410 ppm) for the first half of the 21st century correspond to a medium likelihood of reaching the 2° C target. Ensuring a high likelihood will require long-term emission reductions towards the end of the 21st century that are even stronger than those considered. Very low stabilization requires advanced mitigation options for generating 'negative emissions', such as biomass in combination with CCS (see Section 2.3).

- The level of future carbon prices primarily depends on (1) innovation and the availability of low-carbon alternatives to conventional fossil fuels, (2) flexibility of substitution within the energy-economic system, (3) the ability of policymakers to stabilize the expectations of investors, and (4) the participation of major emitters in a global agreement to control climate change (see Section 2.3).

- The regional distribution of mitigation costs depends on (1) domestic abatement costs, (2) effects related to shifts in energy prices and energy trade volumes, and (3) the international carbon market and the allocation of emission rights.Technological innovation and stabilization of the expectations of investors will contribute to lower carbon prices, thus reducing the potential conflict between nations over the allocation of emission rights (see Section 2.5).

- The window of opportunity to achieve climate stabilization is narrow. Delaying the implementation of ambitious climate policy at global level until 2030 renders RECIPE mitigation targets infeasible in all models. If global action starts in 2020, 450 ppm climate stabilization is feasible but world consumption losses over the 21st century increase from 1.4 % to 2 % in WITCH, from 0.6 % to 1 % in REMIND-R and from 0.1 % to 0.8 % in IMACLIM-R (see Section 2.6).

- Even if other world regions delay ambitious climate policy until 2020, Europe will enjoy a first mover advantage. Benefits result from the avoided build-up of carbon intensive infrastructure. Early action also entails a global benefit by fostering low-carbon technology development. The United States, too, benefit from acting early within a coalition of Annex-I countries (see Section 2.3).

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[2] Box 2-1 describes how consumption losses are calculated

2.1 THE NEED FOR LOW STABILIZATION

The ultimate goal of global climate policy is to stabilize "greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UN, 1992). Unabated emission growth must be considered dangerous. While no level of global warming can be considered inherently safe, stabilization of climate change at 2° C above pre-industrial levels is expected to prevent the most severe impacts (see Chapter 1).

The IPCC (2007b) estimates climate damages associated with unabated global warming to between 1-5 % of GDP, while Stern (2006) 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. That might explain why more than 100 countries have adopted the objective of limiting global warming to 2°C (Meinshausen et al., 2009). This section discusses current state of knowledge with respect to emission limits consistent with the 2°C target and their achievability from the perspective of energy-economic research.

2.1.1 *FROM CLIMATE TARGETS TO EMISSION CONSTRAINTS*

Due to the complexity of the climate system, it is not possible to determine the temperature increase resulting from a given budget of GHG emissions with absolute confidence. The three most important sources of uncertainty are (1) the response of the global carbon cycle which determines how CO_2 emissions translate into increases in atmospheric CO_2 concentrations, (2) emissions of other radiation-trapping substances such as non-CO_2 greenhouse gases and particulates, and (3) climate system properties which determine the climate response to changes in atmospheric greenhouse gas concentration.

One option to deal with these uncertainties is to perform statistical analyses providing insights on emission budgets and properties of emission trajectories that are consistent with probability ranges for achieving a given temperature stabilization target. Meinshausen et al. (2009) combined the statistical properties of carbon-cycle models, atmosphere-ocean models, and energy-economy models to account for the entire cause-effect chain from emissions to climate response in calculating the probability of overshooting the 2°C limit. They conclude that the cumulative total CO_2 emissions budget from 2000–2049 is the most robust indicator for the likelihood of achieving a temperature stabilization target. According to their analysis, a CO_2 emission budget of 1440 $GtCO_2$ would result in a 50 % likelihood of limiting warming to below 2° C. The budget shrinks to 1000 Gt CO_2 if a 75 % chance is to be achieved.

2.1.2 *ENERGY-ECONOMIC MODELING*

Comparing the emission reductions required to avoid dangerous climate change with the energy-economic literature on mitigation scenarios demonstrates the scale of the challenge. Substantial discrepancies exist between what is necessary to ensure a high likelihood of limiting global warming to 2° C and the level of ambition reflected in energy-economic modeling. So far, most model assessments of mitigation costs considered stabilization levels of atmospheric greenhouse gas concentrations above 500 ppm CO_2eq. Stern (2006) focuses on mitigation scenarios aiming at 500 to 550 ppm CO_2eq. Such stabilization levels are, however, likely to be insufficient for keeping warming below 2°C (Meinshausen et al., 2006).

A limited number of studies consider reduction targets that are consistent with the 2°C target. Out of 177 mitigation scenarios considered in the IPCC AR4, only six were grouped in the lowest category stabilization (corresponding to 445–490 ppm CO_2eq), consistent with a medium likelihood of achieving the 2°C target. Such low stabilization can only be attained if models assume a high degree of flexibility and a broad portfolio of technology options, including bioenergy, other renewables and carbon capture and storage. This also explains the scarceness of very low stabilization scenarios: many models assume (1) limited flexibilities and opportunities for substitution in the way emission reductions are achieved, (2) limited availability of low-carbon technologies, (3) high baseline emissions, or (4) high emissions of non-CO_2 greenhouse gases, or a combination of these factors and thus find it infeasible to achieve low stabilization (e. g. , Tol, 2009).

Recent research efforts explored the achievability of very low stabilization, i. e. GHG concentration targets of 450 ppm CO_2eq or lower (van Vuuren et al., 2007; Rao et al., 2008; Knopf et al., 2009) which aim at a high probability of keeping global warming below 2°C. These scenarios have in common that they assume a full and immediate participation in a global mitigation effort and include a broad portfolio of mitigation options.

All model studies of very low stabilization emphasize the necessity of generating negative emissions. One technological option for doing so is capturing the emissions from bioenergy with carbon capture and storage. Given the competition for land, this raises concerns about food security and biodiversity conservation. Moreover, the large-scale production of biomass is not necessarily carbon-neutral as is often assumed in modeling studies (Farigone et al., 2008; Searchinger et al., 2008). Side-risks have to be taken into account and carefully analyzed (cf. Section 4.3), a research challenge for the next few years which will be one of the dominant debates in preparation for the Fifth Assessment Report of the IPCC. With respect to CCS, one needs to consider that the technology is uncertain and not proven on a large scale. Uncertainties exist about the sufficient provision of financial incentives and whether the risks of storage can be managed (Metz et al., 2005). In addition to technological challenges, a delay in participation of main emitters is a realistic scenario for the international climate policy process. The RECIPE project has calculated the window of opportunity which remains to pursue action at a global scale. The results show that stabilization of atmospheric CO_2 concentrations at 450 ppm can be achieved even if the availability of technologies is limited or if there is some delay in international participation. It is important to note, however, that this will result in a higher risk of overshooting the 2° C target and incur higher costs.

BOX 2-1
CLIMATE-ENERGY-ECONOMY MODELING

Climate-energy-economy models are a fundamental tool to evaluate mitigation strategies and assess their economic costs. These models include a representation of socio-economic processes, such as economic growth and the dynamics of consumption and investment. Energy is usually regarded as a production factor, alongside capital and labor. Energy, in turn, is generated through conversion processes from primary energy sources, such as fossil fuels, uranium, wind, solar radiation, hydropower, or biomass. To link energy use to climate impacts, carbon emissions from the combustion of fossil fuels are computed and their effects on atmospheric concentrations and temperatures are assessed using a coupled climate module. To account for the fact that climate change is a global and long-term challenge, climate-energy-economy models are required to represent the entire world economy and carry out simulations over the period of a century. This integrated view permits establishing plausible and self-consistent scenarios how the world will develop if business-as-usual is continued or climate policies are adopted. Climate policy scenarios provide information about optimal emission trajectories, carbon prices, economic costs of GHG mitigation and their distribution across regions, and about possible energy futures with regards to energy sources and energy technologies. To keep the analysis tractable, models have to abstract from reality and represent economic sectors and technologies in a simplified way. Hence, climate-energy-economy models are best suited for the analysis of long-term stabilization strategies rather than providing very detailed descriptions of short-term impacts of climate policies. It should be emphasized that – owing to the complexity and uncertainties related to the issue under study – the model results should be interpreted as scenarios rather than accurate forecasts of future developments. Different models may generate very different sets of scenarios, depending on the view of the world they represent regarding e. g. assumptions on future technological developments in the energy sector, inertia in the deployment of new technologies, and how economic agents form expectations.

2.1.3 *MITIGATION TARGETS*

RECIPE considers a default stabilization target of 450 ppm CO_2 . Depending on assumptions about emissions of other greenhouse gases such as CH_4, N_2O and fluorinated gases, this corresponds to overall GHG concentrations of 500–550 ppm CO_2 eq (Fisher et al., 2007). The target results in a less than 50 % chance of keeping warming below 2°C. Current greenhouse gas concentrations are at 385 ppm CO_2, or 440 ppm CO_2 eq. The principal objective of the project is to explore (1) the economics of mitigation across a broad variety of model settings, accounting for the uncertainties in representing the real-world dynamics, and (2) the cost escalations induced by incomplete participation in a global mitigation effort or incomplete technology portfolios. A reasonable analysis of such second-best-scenarios is not possible for very stringent mitigation targets, as their achievability crucially depends on the assumption of a comprehensive and immediate onset of a global mitigation effort and the full availability of a broad set of technology options. Moreover, the rather carbon-intensive baseline of RECIPE models implies a significant emission reduction effort, thus making very low stabilization levels more difficult to achieve.

In addition to the default climate policy target of 450 ppm CO_2 , a policy scenario aiming at 410 ppm CO_2 stabilization was considered to assess costs, feasibility and energy system implications of more ambitious climate policies. For this scenario, a first-best-setting was chosen, with the assumption of full availability of technology options and an immediate global mitigation effort.

The reduction trajectories produced by RECIPE for the 450 ppm and 410 ppm CO_2 targets are compared to the mitigation scenarios considered by the IPCC AR4 in Figure 2-1 (a). The 450 ppm RECIPE trajectories lie in the lower middle range of the mitigation scenarios considered. For the time period until 2050, the RECIPE 410 ppm trajectories are comparable to the most ambitious category I scenarios produced by IMAGE and MESSAGE models. Only the emission trajectories from the GET model are considerably more ambitious. However, they assume that climate policies started already in the year

2000 and emissions stabilize or decline thereafter. Substantial differences exist between the RECIPE trajectories and the category I trajectories with respect to the emissions after 2050. While the RECIPE 410 ppm emissions remain at a level of almost 10 $GtCO_2$ /year, the IPCC category I scenarios make use of advanced carbon sequestration options to produce close-to-zero or negative emission levels.

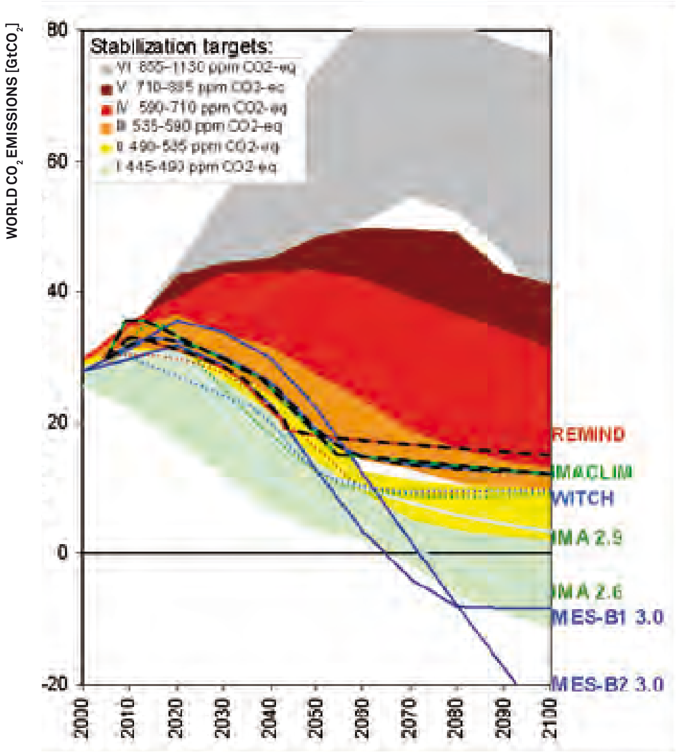
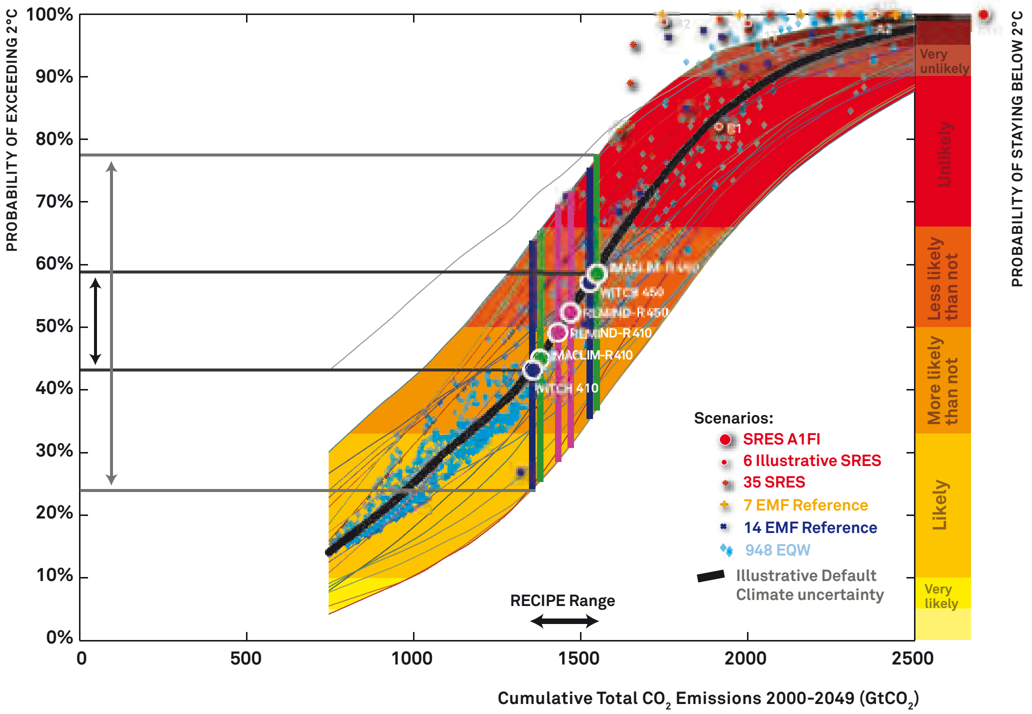


FIGURE 2-1
a) RECIPE emission trajectories for the 450 ppm (black-and-colored dashed lines) and 410 ppm (dotted lines) CO_2 concentration targets compared to the six low-stabilization scenarios considered in the IPCC AR4 (Fisher et al., 2007). The figure is adopted from Rao et al. (2008, p. 8)



b) Probability of exceeding 2°C warming versus CO_2 emitted in the first half of the 21st century as calculated by Meinshausen et al. (2009). According to this metric, RECIPE emission budgets until 2050 yield a medium likelihood of limiting warming to less the 2°C

According to the metric of cumulative emission budgets as proposed by Meinshausen et al. (2009), the mitigation effort envisaged by the RECIPE scenarios for the first half of the 21st century keeps the world on track for a medium probability of meeting the 2°C target. While for the 450 ppm scenario the emission budget results in an average probability of 55 % for exceeding 2°C warming, the probability of exceeding declines to 46 % on average for the 410 ppm scenario (Table 2-1).

TABLE 2-1
Cumulated CO_2 emissions from 2000 to 2049 for the RECIPE models in different scenarios as well as related mean probabilities based on Meinshausen et al. (2009)[3]. RECIPE scenarios from 2005–2049 have been complemented with data obtained from IEA for the years 2000–2004

	CUMULATED EMISSIONS (Gt CO_2)			PROBABILITY OF EXCEEDING 2°C		
	BAU	450 ppm	410 ppm	BAU	450 ppm	410 ppm
IMACLIM-R	2404	1533	1366	97 %	58 %	45 %
REMIND-R	2650	1455	1436	100 %	51 %	50 %
WITCH	2235	1518	1360	94 %	57 %	43 %

The probabilities of exceeding 2°C calculated by Meinshausen et al. (2009) are illustrated graphically in Figure 2-1b. The vast majority of model-based mitigation scenarios feature below 50 % likelihoods of keeping the temperature target, while high probability ranges for staying below 2°C mostly relies on emission profiles that were constructed without underlying economic assessments. While the 2000–2049 emissions in all three 450 ppm RECIPE scenarios result in a "less likely than not" probability to stay below 2°C, it is "more likely than not" to reach the target for the 410 ppm scenarios.

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[3] As Meinshausen et al. (2009) calculate emission budgets from 2000–2049, RECIPE results starting from 2005 had to be complemented by historical data.

2.2 RECIPE: BEYOND STERN AND IPCC AR4

There is considerable uncertainty about the costs of climate change mitigation. The estimates from models considered for the IPCC AR4 for stabilization at 550 ppm CO_2eq range from small GDP gains to 4 % GDP losses in 2050 (Fisher et al., 2007) . For a comparable category (500–550 ppm CO_2eq), the Stern Review found a range of -2 to 5 % GDP losses (Stern, 2006).

The uncertainty in model-based assessments of the costs of climate stabilization arises largely from (1) differences about the baseline development of socio-economic drivers, most importantly population and GDP growth; (2) assumptions about emissions from land-use change and non-CO_2 greenhouse gases; (3) assumptions about the availability and prices of fossil fuels; (4) cost and availability of low-carbon mitigation technologies; (5) assumptions about the nature of the decision process and formation of expectations; and (6) assumptions about flexibilities in the macro-economic system with respect to substitutability between different input factors, trade, and the timing of the emission reduction effort.

Combustion of fossil fuels is by far the dominant source of greenhouse gases (IPCC, 2007c). In order to shed light on the specific sources of uncertainty in assessing the costs of the energy system transformation, RECIPE focused on the energy-related emissions by considering a stabilization target for CO_2 concentrations and assuming the same emission trajectory for CO_2 emissions from land use, land use change and forestry (LULUCF) for all models[4]. Moreover, assumptions on population growth, GDP development and the scarcity of fossil fuels were harmonized across models, thus minimizing the uncertainty arising from socio-economic factors[5]. Hence, the remaining differences in model results can be attributed to model-specific differences in the representation of the energy sector as well as conceptual differences in the description of the macro-economic structure, the formation of expectations and the nature of the decision process.

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

Substantial differences exist in the approaches and underlying assumption for energy-economic modeling. The three models used in RECIPE capture well the spectrum of pertinent model designs (Jakob et al., 2009a). IMACLIM-R is a recursive-dynamic computable general equilibrium model with a special focus on inertia in the development and deployment of new technologies. Semi perfect-foresight is assumed in the power sector, i. e. investment decisions are based on a 30-years time horizon, while all other agents are assumed to be myopic, i. e. they have imperfect foresight and base their investment decisions on the assumption that current prices and market conditions are the best indicator for the future development. Among the three models considered, it features the highest sectoral detail. REMIND-R and WITCH, by contrast, are optimal growth models that simulate optimal development pathways for maximizing intertemporal welfare. They operate under the assumption of perfect foresight and full internalization of external effects. While REMIND-R is characterized by a flexible

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[4] In the mitigation scenarios, all models assumed CO_2 emissions from LULUCF to follow a trajectory based on the IIASA A2 scenario (Nakicenovic et al., 2000).

[5] The RECIPE baseline scenario is documented in Jakob et al. (2009b).

description of the macro-economy and the assumption of a large number of mitigation options in the energy system, WITCH has a stronger emphasis on rigidities and inertias in both the macro economy and the energy system. It also represents the innovation process in more detail by explicitly accounting for R&D. This constellation induces free-riding incentives in both the baseline and policy scenarios, as the benefits from technology spillovers are not internalized.

BOX 2-2
MODELS EMPLOYED IN RECIPE

IMACLIM-R, developed by CIRED (see Crassous et al., 2006), is a recursive computable general equilibrium model capturing explicitly the underlying mechanisms driving the dynamics of technical parameters, structural change in demand for goods and services and micro- as well as macro-economic behavioral parameters. The model considers open economies with international trade of all goods and CO_2 permits. A major feature of **IMACLIM-R** is the partial use of production factors (underused capacities, unemployment) due to sub-optimal investment decisions resulting from the interplay between inertia, imperfect foresight and 'routine' behaviours. This allows distinguishing between potential and real economic growth, and, more specifically, to capture the transitory costs resulting from unexpected shocks affecting the economy. In **IMACLIM-R**, climate policies can be a means of remedying market failures and implement no-regret options which are profitable in the long term but which are not taken under normal conditions due to myopic behavior. This property can also result in some kind of 'bi-stability' in the sense that initially large efforts are required to move the system from its current path (i.e. fossil based) to an alternative one (i.e. low-carbon) but little extra effort is required once it is located on this new trajectory.

The global multi-region model **REMIND-R** as introduced by Leimbach et al. (2009) from PIK represents an inter-temporal energy-economy-environment model which maximizes global welfare based on nested regional macro-economic production functions. **REMIND-R** incorporates a detailed description of energy carriers and conversion technologies (including a wide range of carbon free energy sources), and allows for unrestricted inter-temporal trade relations and capital movements between regions. Mitigation costs estimates are based on technological opportunities and constraints in the development of new energy technologies. By embedding technological change in the energy sector into a representation of the macroeconomic environment, **REMIND-R** combines the major strengths of bottom-up and top-down models. Economic dynamics are calculated through inter-temporal optimization, assuming perfect foresight by economic actors. This implies that technological options requiring large up-front investments that have long pay-back times (e.g. via technological learning) are taken into account in determining the optimal solution.

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

The RECIPE project aims at fostering the scientific understanding of the economics of climate change mitigation by taking novel approaches to tackle the following research questions:

- **HOW DOES THE OVERALL MITIGATION EFFORT BREAK DOWN IN TERMS OF TRANSFORMATION AND EMISSION REDUCTION STRATEGIES IN VARIOUS END-USE SECTORS? WHAT ARE RELEVANT TECHNOLOGIES?** In climate change mitigation literature, there is a substantial gap between bottom-up analysis of sector-specific mitigation strategies and top-down modeling approaches assessing global mitigation costs from an aggregated perspective (IPCC, 2007c); the RECIPE project aims at filling this gap. Due to their hybrid structure, the models used in RECIPE calculate technology-resolved scenarios of the low-carbon transition in sectors such as power generation or transport embedded in a consistent global and long-term macro economic development. The model analysis is complemented by a set of detailed sectoral studies to develop a more refined understanding of the nature of the transformation process, barriers and policies in each sector (Chapter 5).

- **HOW DOES THE GLOBAL MITIGATION EFFORT TRANSLATE TO REGIONAL MITIGATION COSTS?** While the IPCC provides an estimate of 0–4 % GDP losses for climate change mitigation, regional costs may deviate substantially from the global average. Clearly, the regional distribution of mitigation costs will play an important role for international climate negotiations and strongly affects the acceptability of a global agreement. By using models with different representations of the macro economy and energy system and by running them with different stylized scenarios with regard to the global distribution of emission rights, RECIPE is able to assess the range of cost effects on different world regions. (Section 2.5)

- **WHAT IS THE EFFECT OF A DELAY IN PURSUING GLOBAL COOPERATIVE ACTION ON CLIMATE CHANGE OR INCOMPLETE PARTICIPATION IN A GLOBAL AGREEMENT? HOW WILL MITIGATION COSTS CHANGE IF RESTRICTIONS ARE IMPOSED ON KEY LOW-CARBON TECHNOLOGY OPTIONS?** Analysis of second best worlds: Typically, mitigation costs are calculated based on the assumption of (1) the immediate and global effort to setup policy frameworks suitable for incentivizing the low-carbon transformation and (2) the full availability of a portfolio of technological options. These research questions are addressed by considering ‘second-best’ scenarios in which the setup of a global carbon market was assumed to be delayed (Section 2.6) or the deployment of certain technologies was restricted to the baseline level (Section 4.1).

- **HOW CAN DIFFERENCES IN THE MODEL RESULTS BE ATTRIBUTED TO MODEL-SPECIFIC DIFFERENCES IN THE REPRESENTATION OF MACRO-ECONOMIC AND ENERGY SYSTEM PARAMETERS? WHAT ARE IMPLICATIONS FOR CLIMATE POLICY?** The harmonization in the baseline, the in-depth comparison of model output and targeted sensitivity studies allows RECIPE to determine what factors drive the results in terms of the model-inherent mechanics and assumptions.

2.3 MACRO-ECONOMIC EFFECTS OF CLIMATE POLICY

Despite the daunting climate crises, so far little progress has been made in reducing emissions. Emission growth has even accelerated in recent years, largely driven by rapid and carbon-intensive growth in emerging economies (Raupach et al., 2007). In line with these findings, the RECIPE models assume abundant availability of cheap coal, resulting in high CO_2 emissions in the baseline. As depicted in Figure 2-2, the IMACLIM-R baseline predicts the highest CO_2 emissions (124 $GtCO_2$ in 2100) with a continuous increase beyond 2050 due to the availability of cheap coal as a substitute for oil which prevents the penetration of non-fossil energies and does not induce a large decoupling between energy demand and economic growth. In contrast to this ‘black baseline’, the REMIND-R baseline can be characterized as a ‘green baseline’ with emissions of 77 $GtCO_2$ in 2100. After a high growth up to 2040, emissions decline after 2050. This can be explained by a stabilizing energy demand in REMIND-R, being 25 % lower than in IMACLIM-R in the year 2100, and a higher penetration of carbon-free energy technologies (biomass and renewable energy). The aggregated WITCH baseline is comparable to the REMIND-R one; it reaches 86 $GtCO_2$ emissions in 2100 with a decreasing emission growth rate in the second half of the century. It can be classified as a less energy-intensive baseline: the energy intensity in 2050 is 17 % lower than in IMACLIM-R and 19% lower than in REMIND-R, whereas the carbon intensity of its energy mix is 30 % higher than in REMIND-R and 7 % higher than in IMACLIM-R.

The gap between business-as-usual CO_2 emissions and emission trajectories required to achieve the stabilization targets as illustrated in Figure 2-2 demonstrates the scale of the climate stabilization challenge.

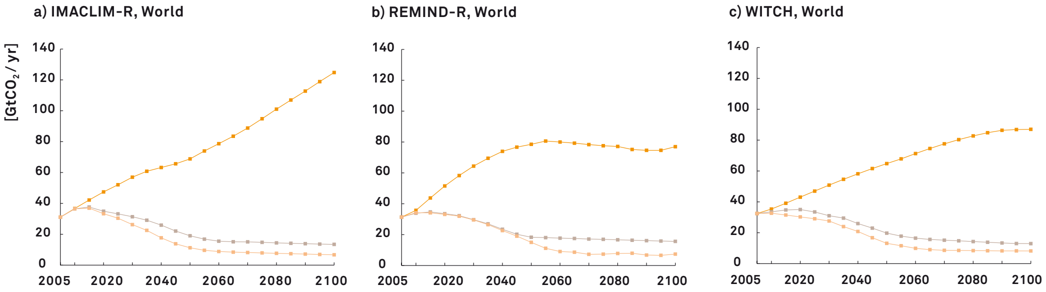


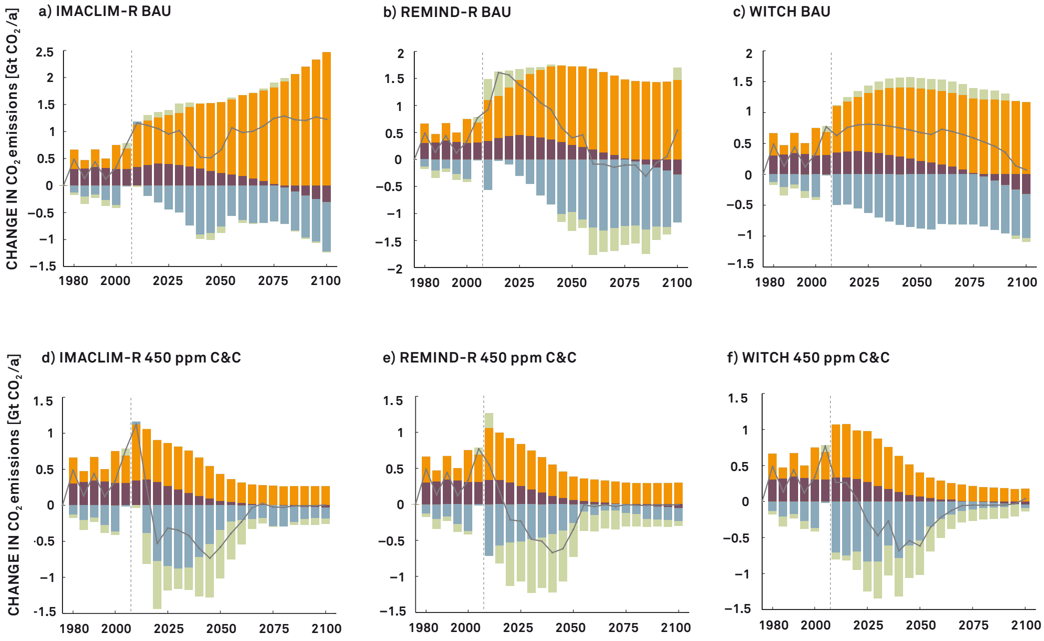
FIGURE 2-2
Global pathways for CO_2 emissions from fossil fuel combustion for the baseline scenario as well as policy scenarios aiming at stabilization of atmospheric CO_2 concentrations at 450 ppm and 410 ppm only calculated by IMACLIM-R, REMIND-R and WITCH

■ baseline
■ 450 ppm C&C
■ 410 ppm C&C

Energy-related emissions are driven by population, per capita GDP, energy intensity of economic output, and the amount of CO_2 emitted per unit of primary energy consumption. These developments are shown in Figure 2-3. Since policymakers have no or only little influence on population growth and the reduction of economic output is usually not considered an option, the focus of climate change mitigation is on achieving emissions cuts by reducing the energy and carbon intensity of the economic system. Emissions can be reduced by switching from carbon-intensive energy carriers such as coal to low-carbon or carbon-free energy carriers such as renewables. Alternatively or in addition to carbon intensity reductions, production processes can be optimized or changed as to generate more output for a given amount of energy input. Figure 2.3 also illustrates that in the low-carbon scenarios improved energy efficiency and lower carbon intensity of fuels reduces the impact on GDP growth on CO_2 emissions.

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

FIGURE 2-3
Decomposition of historic CO_2 emission trends and model projections for IMACLIM-R, REMIND-R and WITCH for the baseline and the 450 ppm scenario based on Kaya (1990). The figures show the annual contribution of changes in the driving factors population growth, per capita GDP, energy intensity of economic output, and carbon intensity of primary energy use on global CO_2 emissions. The vertical dashed lines indicate the transition from historic data (IEA) to modeled data (RECIPE models). Horizontal lines indicate the absolute annual change in CO_2 emissions. Note the different scales between BAU and policy scenarios



Due to their structural differences and different representations of the energy system, the models project different economic effects of climate policy. The aggregated mitigation costs in terms of consumption losses relative to the baseline discounted over the period to 2100 accrue to 0.1 % (IMACLIM-R), 0.6 % (REMIND-R), and 1.4 % (WITCH). The size and temporal evolution of mitigation costs and the carbon price are shown in Figure 2-4. The differences in model approaches are reflected in the structural differences of carbon price trajectories. In IMACLIM-R, due to the assumptions on imperfect foresight, very high carbon prices are required initially to create a sufficiently strong signal to trigger a transition to a low-carbon energy system (Figure 2-4c). These high prices result in very high transitional mitigation costs and welfare losses in the first 30 years of the modeled period. Once this transition is accomplished, IMACLIM-R projects negative mitigation costs due to additional technical change that is induced by climate policies allowing economies to be more efficient than in the sub-optimal baseline. For Europe, mitigation costs also peak in 2030, but remain positive afterwards. Aggregated European consumption losses are thus considerably higher than on the global level and are projected to be highest among the three models. The flat profile of the carbon price in IMACLIM-R after 2030 can be attributed to (1) the learning processes in carbon saving energy technologies that increase the reduction potentials available at a given carbon price and by (2) climate-friendly infrastructure policies that avoid a costly lock-in to carbon-intensive transportation systems, thus removing a critical obstacle to stabilization in the long run.

BOX 2-3
HOW TO CALCULATE MITIGATION COSTS

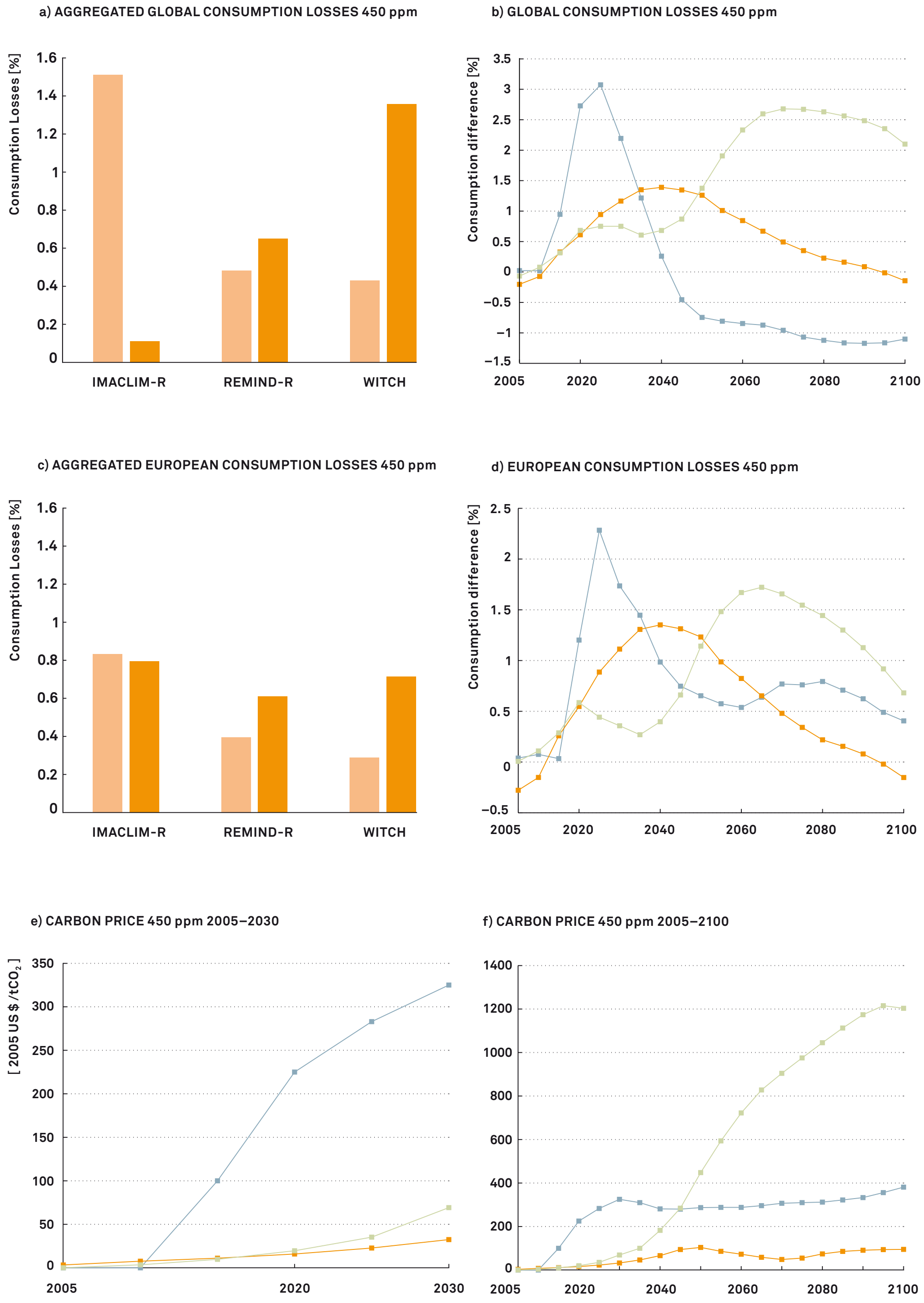
The economic costs of climate policy are computed by comparing the macro-economic consumption paths that are obtained in the respective policy scenario with the one in the business-as-usual scenario. The difference between these two trajectories determines mitigation costs in each point in time. *Damages caused by climate change are not part of this analysis* as there is still substantial scientific uncertainty regarding the precise nature of impacts, no consensus exists how to express them in monetary terms, and damages occurring in the far future are very sensitive to the discount rate used. Therefore, the model results should not be interpreted as a cost-benefit-analysis but as best estimates of the costs of stabilizing atmospheric concentration of CO_2 at a certain level. The mitigation costs are expressed in terms of consumption losses. Consumption is the portion of GDP that is not invested, thus providing utility. To make costs that appear in different points in time comparable – i.e. costs in the far future are valued less than costs at present or in the near future – all costs are converted to net present values. RECIPE used a constant discount rate of 3%. Total mitigation costs are then calculated by summing up these net present values, expressed as a fraction of the net present value of the consumption path that would prevail over the century if no climate measures were implemented.

REMIND-R and WITCH, by contrast, are perfect foresight intertemporal optimization models and therefore envisage smoother development of the carbon price and almost steady increases until the middle of the 21st century. WITCH projects significantly higher welfare losses compared to REMIND-R, and long-term mitigation losses also exceed those estimated by IMACLIM-R on the global scale. Due to the relatively more conservative assumptions concerning technology substitution within the energy sector, a larger share of the emissions reduction has to be delivered by curbing the economy's energy demand, resulting in a reduction of economic output. Moreover, the existence of free-riding incentives in WITCH also tends to increase mitigation costs. In Europe, welfare losses are lower than on the global scale and comparable to those that are projected by REMIND-R.

In REMIND-R, the carbon price is projected to remain on a moderate level. Learning processes reduce the cost of low-carbon technologies, most notably renewables. The availability of cheap alternative energy sources reduces CO_2 abatement costs and allows focusing the mitigation effort on decarbonization, while the reduction of energy demand plays a less important role. After the RECIPE concentration target of 450 ppm is reached, CO_2 emissions remain stable at roughly 15 Gt CO_2 / yr. Therefore, REMIND-R projects both the carbon price and mitigation costs to peak in the middle of the century and decrease afterwards when the effect of technological learning becomes stronger. For the default climate policy scenario with emission allocations based on contraction and convergence, the European welfare losses in REMIND-R and WITCH follow a pattern that is similar to the global aggregate. In REMIND-R, losses are almost equal to the global average, while WITCH projects them to be lower. According to IMACLIM-R, transitionary costs in Europe are similar to those incurred globally, but Europe is expected to have above-average costs in the long-term due to smaller potential for efficiency gains relative to the baseline development.

Different carbon price trajectories across the three models reflect the general uncertainty about CO_2 prices. Model assumptions on macro-economic flexibilities, the nature of the decision process (perfect foresight vs. imperfect foresight), and the availability and cost of low-carbon technologies have a strong impact on the simulated carbon price level.

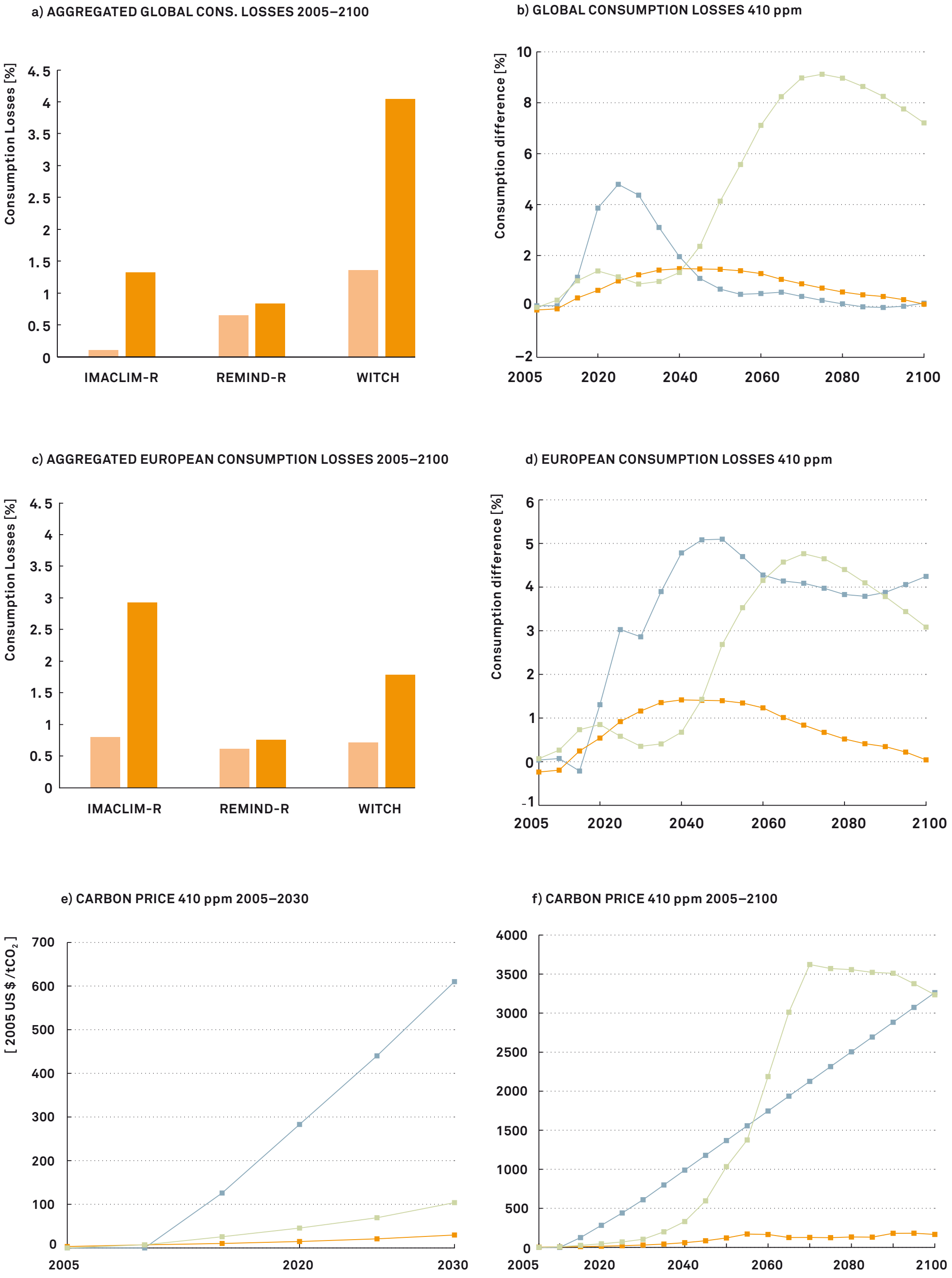
FIGURE 2-4
Global (a,b) and European (c,d) welfare losses as consumption differences relative to baseline as well as the global carbon price (e,f) for the 450 ppm scenario. Aggregated consumption losses (a,c) are discounted by 3%



Similarly, real-world carbon prices will depend strongly on (1) a stringent yet flexible global framework for achieving deep emission reductions, (2) the ability of policymakers to establish credible expectations of short, medium and long term reduction targets, (3) the portfolio of technological abatement options and their rate of innovation, and (4) the participation of major emitters in a global agreement to control climate change. Thus, carbon prices will remain moderate only if policymakers succeed in credibly establishing the expectation of future emission cuts, in fostering low-carbon innovation, and in achieving broad regional and sectoral coverage of climate policy.

As outlined in Section 2.1, the 450 ppm CO_2 only stabilization target will more likely than not result in exceeding the 2°C limit. Therefore, a mitigation scenario aiming at achieving a stabilization of atmospheric CO_2 at 410 ppm was considered in the form of a sensitivity study within RECIPE which results in a higher probability of reaching the 2°C target. From the perspective of energy economics, this target is very demanding as it would require substantially stronger reduction efforts than 450 ppm stabilization.

FIGURE 2-5
Global (a,b) and European (c,d) welfare losses as consumption differences relative to baseline as well as the global carbon price (e,f) for the 410 ppm scenario. Aggregated consumption losses (a,c) are discounted by 3%



According to all models, low stabilization at 410 ppm CO_2 is feasible (Figure 2-5). WITCH and IMACLIM-R, the models that are less optimistic with respect to macro-economic flexibility and the availability of technological alternatives, project economic impacts of climate policy to increase significantly with the level of ambition globally as well as on the European level. Aggregated global consumption losses are projected to more than triple compared to the 450 ppm scenario in WITCH on the global scale and more than double in Europe (Figure 2-5b, d). In IMACLIM-R, aggregated consumption losses are projected to increase by almost one percentage point globally and by two percentage points for Europe. Both models also project carbon prices to increase disproportionately with increasing emission reduction effort. REMIND-R is more optimistic with respect to 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.This is true globally as well as for Europe.

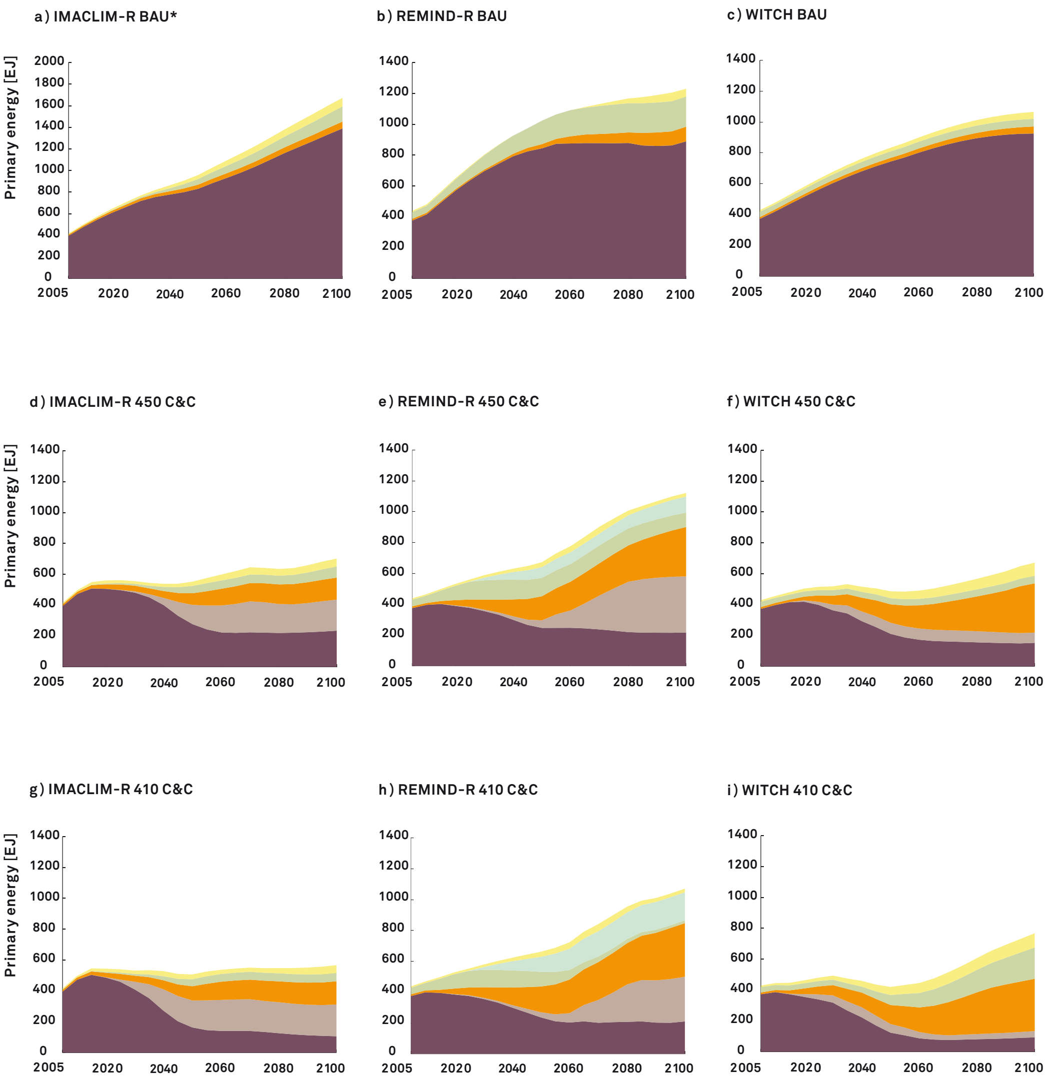
2.4 TOWARDS A LOW-CARBON ENERGY SYSTEM

A full-scale transformation of the global energy system is a key pre-requisite for climate stabilization. While the models were harmonized with respect to the macroeconomic dimension, particularly GDP growth rates, fossil fuel prices and population, they reflect three different representations of the energy sector. As elaborated in Section 2.3, this becomes already evident in the division of labor between energy efficiency improvements and reduction of carbon intensity in meeting the mitigation challenge. IMACLIM-R and WITCH impute a comparable contribution to energy efficiency and reductions of carbon intensity, while in REMIND-R the emphasis lies mainly on decarbonization.

Figure 2-6 shows the different primary energy supply mixes envisaged by the three models for the baseline scenario as well as the 450 ppm and 410 ppm mitigation scenarios. In this representation, the different significance of energy efficiency across the three models becomes evident. In IMACLIM-R, having the highest primary energy consumption in the baseline, the reduction of energy demand induced by climate policy is largest and constitutes the most important mitigation option. IMACLIM-R explicitly represents demand-side energy efficiency technologies such as plug-in hybrid vehicles and very low energy buildings. Moreover, in the IMACLIM-R mitigation scenarios, carbon pricing is assumed to be complemented with suitable infrastructure policies, thus providing scope for additional energy efficiency improvements. Key low-carbon energy carriers are renewables and CCS, while the deployment of nuclear is even projected to decrease.

In REMIND-R, primary energy consumption is projected to grow slower than in the baseline case until 2040. Low-carbon technologies like CCS, biomass and renewables are deployed at large scale once they are mature. Among the three participating models, REMIND-R is the only one to consider the option of combining bioenergy with CCS (BECCS). Given the limited CCS storage potential, BECCS tends to crowd out fossil CCS for increasingly stringent climate targets. In the 450 ppm mitigation scenario, primary energy consumption is projected to reach a level not significantly lower than in the baseline case by the end of the 21st century. By contrast, WITCH is less optimistic about the availability of cheap low-carbon alternatives and the substitutability of different energy carriers. While renewables, nuclear and – to a lesser extent than in the other models – CCS contribute to the decarbonization of the electricity supply, backstop technologies in the non-electric sector are costly. Their availability is therefore limited. A substantial reduction of non-electric energy demand is required to achieve the climate policy target (cf. also Chapter 4.3).

FIGURE 2-6
Global 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.
*Please note different scales



For Europe, the introduction of climate policy results in a substantial transformation of the energy system. After peaking in 2015, a pronounced contraction of primary energy input is observed in the IMACLIM-R model. However, the relative reduction between baseline and policy scenarios is much lower in Europe than on the global scale, indicating that IMACLIM-R projects a lower potential for energy efficiency improvements in Europe compared to other regions. In contrast to the global level, according to REMIND-R, Europe significantly slows down the increase in primary energy demand during the first half of the century compared to the baseline scenario. 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 going back 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 largely increased use of biomass in the non-electricity sector.

The relative shares of major low-carbon energy carriers in Europe is different across models. In REMIND-R and IMACLIM-R, CCS accounts for a substantial share of emission reductions. In WITCH, by contrast, it plays only a very limited role with a lower share in Europe compared to the global scale. Neither IMACLIM-R nor REMIND-R project an increase of biomass use in the policy scenarios. In IMACLIM-R, biomass use even declines compared to the baseline. In REMIND-R, biomass in combination with CCS is phased in after 2040, and, faster than on the global average, replaces biomass without CCS. While WITCH projects biomass to be negligible 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. The WITCH energy mix in the policy scenarios is dominated by the generic backstop technologies which emulate the development of carbon-free renewables. Renewables are also the second important mitigation option in IMACLIM-R. In addition to biomass, other renewables, particularly wind and solar contribute significantly to the European energy mix. Renewables have, however, a smaller share in Europe than on global average.

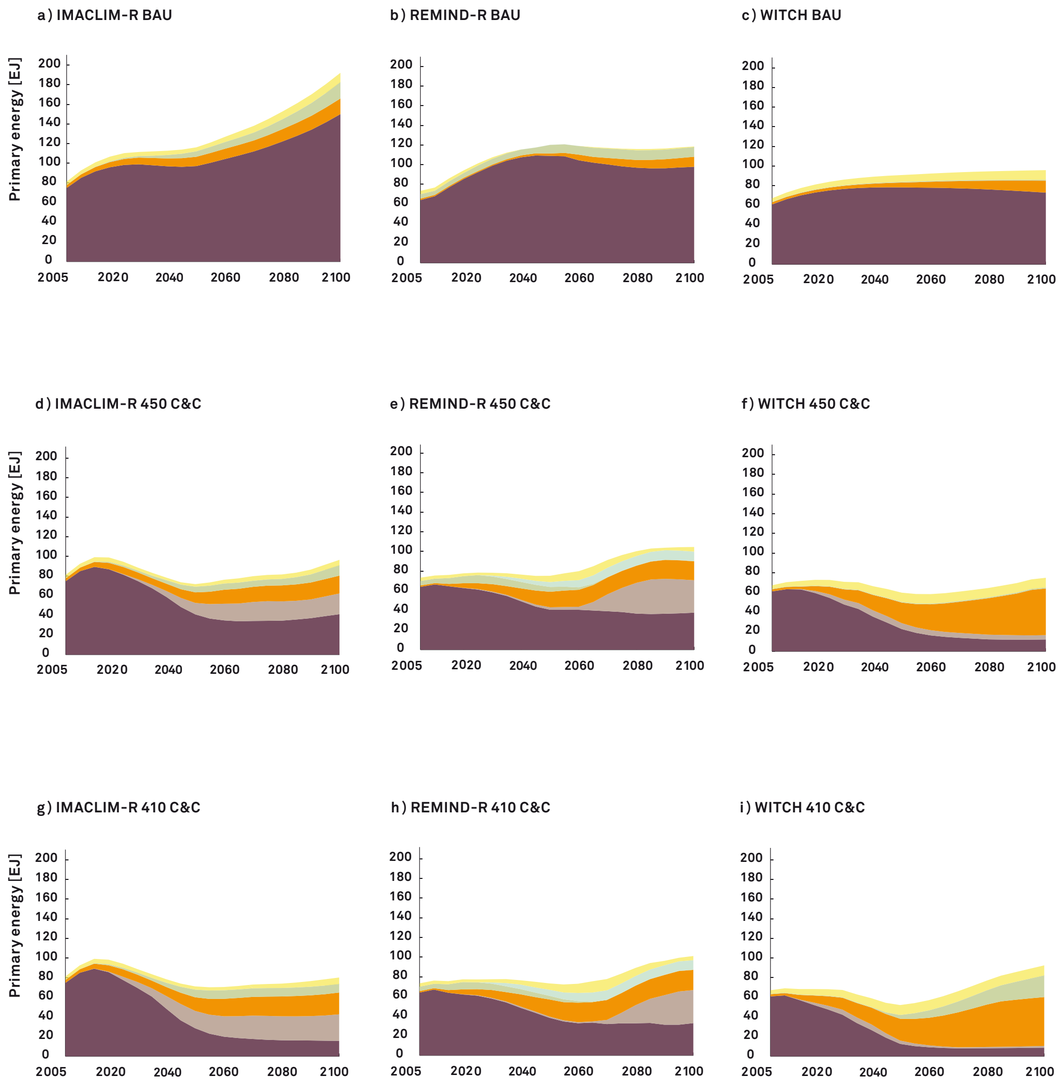


FIGURE 2-7
Primary energy supply in IMACLIM-R, REMIND-R and WITCH for the baseline case, the 450 ppm C&C and the 410 ppm C&C scenarios for Europe

- ■ FOSSIL FUELS W/O CCS
- ■ CCS FOSSIL
- ■ RENEWABLES W/O BIOMASS
- ■ BIOMASS W/O CCS
- ■ CCS BIOMASS
- ■ NUCLEAR

Both the representation of end-use sectors and sector-specific mitigation technologies vary across models (cf. Chapter 5). This is particularly true for the non-electric energy demand. While all models show that decarbonization of the power sector proceeds rapidly, emissions abatement in the other sectors is considerably more demanding. Our model-comparison exercise demonstrates that assumptions on the availability of mitigation options for non-electric energy demand are a crucial determinant for the over all mitigation strategy and costs. IMACLM-R features a high sectoral resolution. It envisages substantial abatement potential through the reduction of final energy demand and a switch towards electricity as a final energy carrier in all end-use sectors. For instance, plug-in hybrid vehicles which are characterized by high efficiency and partly substitute fossil fuels for electricity play an important role in the transport sector. In REMIND-R, biomass use in combination with CCS is the key abatement option in the transport sector. As this technology results in net negative CO_2 emissions, it provides headroom for a larger amount of fossil fuel use and residual emissions from other sectors. In WITCH, due to the absence of cheap low-carbon alternatives in the non-electric sector, the costly introduction of advanced biomass and other non-electric backstop technologies along with a large scale contraction of non-electric energy demand is required to meet stabilization targets – a pathway that results in high overall mitigation costs.

2.5

REGIONAL DISTRIBUTION OF MITIGATION COSTS

This section analyzes the regional distribution of mitigation costs and quantifies their sensitivity to different rules for allocating emissions rights among world regions. 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 on regional decarbonization costs and allocation rules.

For the model-based analysis of regional mitigation costs, RECIPE considered the following four stylized allocations:

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 and the 410 ppm scenario discussed above;

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

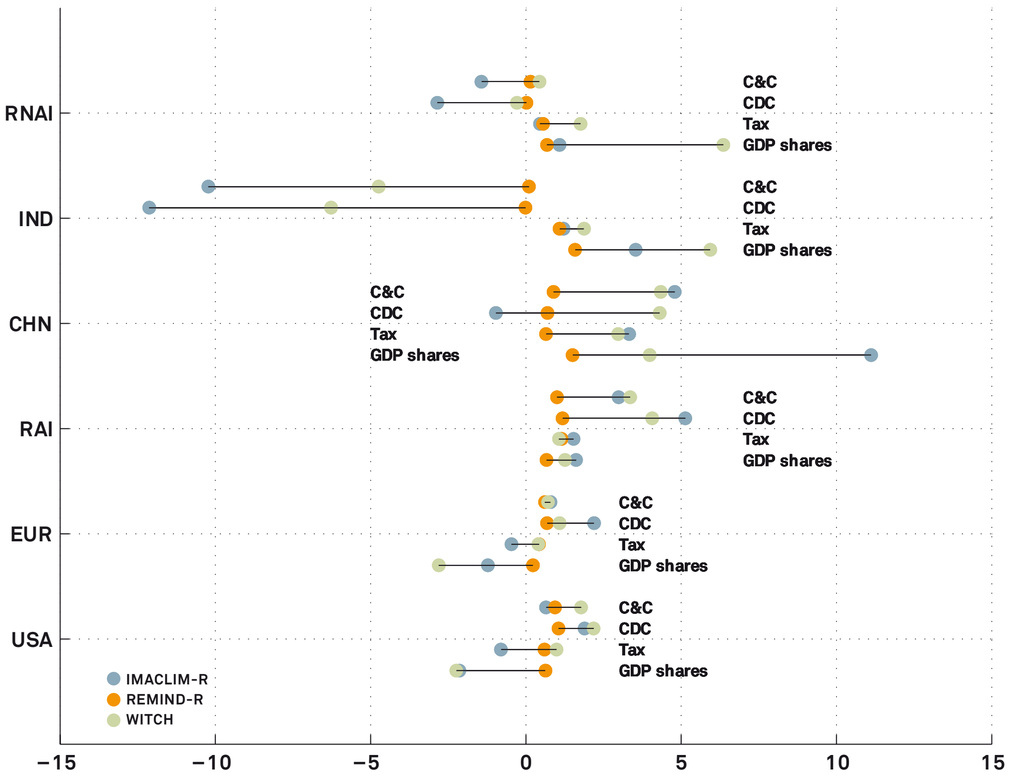
4) GDP SHARES: Emission allowances are allocated in proportion to 'GDP shares', i.e. equal emission right of emission per unit of GDP.

For all four allocation scenarios, a policy target of stabilizing atmospheric CO_2 concentrations at 450 ppm was considered.

In their stand-alone versions, each model features a particular aggregation scheme which defines how country-level data are represented on the basis of 10–12 world regions. To make results from the scenario runs comparable across models, we grouped the model-specific regions into macro-regions which are fairly similar across models [4]: Europe (EUR), USA, Annex-I countries (R-AI), China (CHN), India (IND), other non-Annex-I countries (R-NAI). Aggregated costs for these groups of countries are depicted in Figure 2-8. It shows the effects of different allocation schemes on regional costs of climate stabilization in terms of consumption losses relative to the baseline scenario.

FIGURE 2-8
Distributional effects of various allocation schemes to achieve 450 ppm CO_2 only in terms of consumption losses for the models IMACLIM-R (blue), REMIND-R (orange) and WITCH (green). Percentage changes are given relative to baseline using a 3% discount rate. The figure shows the ranges of consumption losses over the different models and regions which can be interpreted as uncertainty ranges

CONSUMPTION LOSSES, 2005–2100



The analysis of the distribution of mitigation costs exhibits substantial differences across regions. The models agree that industrialized countries would benefit from *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 lower emissions per unit GDP, mitigation costs of the EU and the USA are projected to be below world average mitigation costs

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[6] Due to the different underlying structures, slight differences in the layout of macro regions remain (Jakob et al., 2009a). Most notably, IMACLIM-R includes non-EU eastern European countries and Turkey in the Europe macro region, while it constitutes the EU-27 and EFTA for WITCH, and the EU-27 only for REMIND-R. Moreover, 'IND' includes other South-East Asian countries in WITCH, while REMIND-R and IMACLIM-R consider only India

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 in the baseline, significant efforts will be necessary to switch to a low-carbon growth trajectory. China is projected to become a net buyer of emission permits over the 21^{st} 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.

Our 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 the case of the *GDP shares* regime, this is due to the high energy and carbon intensity of economic output in emerging economies. Under a *tax* regime, this group of countries would be imposed the entire costs of reaping their domestic abatement potential. 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 international climate negotiations, are more beneficial for most developing countries.

Despite some common conclusions, large uncertainty remains about the distributional outcome of climate policy. IMACLIM-R features a high sensitivity of mitigation costs to the allocation rule, particularly for India in China. WITCH provides a midway scenario in which regional domestic costs and transfers from emissions trading account for a significant share of economic activity, mostly after 2030 and especially in the second half of the century. In REMIND-R, mitigation costs are more evenly distributed across regions with smaller differences across allocation schemes. Regional costs are smaller than the ones reported by the other two models with no region experiencing losses above 2%. In general, mitigation cost expressed in percentage consumption losses exhibit a higher uncertainty across models and higher sensitivity to the allocation rule in lower-income countries than in the developed world. This effect is due to the fact that abatement costs and transfers from the carbon market account for a larger share of these countries' GDP. It is particularly evident for China and India.

Policy-makers should be aware of this uncertainty with respect to the regional distribution of mitigation costs. In a more in-depth analysis, Luderer et al. (2009) show, based on RECIPE data, that the differences between models can be attributed to (1) differences in domestic costs of greenhouse gas abatement (due to different representations of the energy system), (2) effects related to shifts in trade volumes and prices of primary energy carriers (which, again, is represented differently in the three models), and (3) different financial transfers implied by the trade in emission rights. It is important to note that the last component depends not only on the global rule for the allocation of emission allowances but also strongly on the carbon price level. The higher the carbon prices, the larger is the potential redistribution of wealth and the more important is the allocation rule.

The policy-implication of this finding lies in the fact that the potential conflict over the distribution of mitigation rights will be more severe in a world with imperfect foresight and pronounced inertias (as represented in IMACLIM-R) or with fewer opportunities for substitution within the energy system and higher costs of abatement (WITCH) which result in high carbon prices. By contrast, if a large number of low-carbon alternatives are available and the macro-economy is characterized by a high degree of flexibility (as assumed in REMIND-R), carbon prices will be low thus resulting in lower welfare effects induced by choice of allocation rule. Policies fostering innovation and joint international collaborative action on mitigation are key priorities for reducing the distributional conflicts over the allocation of emission rights.

2.6 TIMING AND PROGRESSIVE ACTION

The default policy scenarios presented above are based on the assumption of immediate and global collaborative action on climate change. However, a strong international climate policy regime including e.g. an international cap-and-trade regime (see Chapter 3) will not emerge overnight. Current negotiations on the post-2012 climate regime indicate that substantial climate policy efforts may be absent in some world regions for several years to come. Against this background, RECIPE assesses the feasibility and cost of delaying the implementation of ambitious climate policy in some regions in intermediate periods.

Figure 2-9 shows global and Figure 2-10 regional mitigation costs calculated by IMACLIM-R, REMIND-R and WITCH for five scenarios differing in their timing of introducing regional climate policy. The benchmark *450 ppm C&C* scenario assumes implementation of a global carbon market by 2010 with regional allowance allocation following the Contraction and Convergence rule with 2005 as the base-year. At the other extreme, *Delay 2020* assumes complete absence of climate policy until the year 2020 when a full-scale global carbon market is incepted. Three intermediate scenarios explore the impacts of stepwise carbon market implementation:

(i) The European Union acts as a first mover being the only world region to implement climate policy. All other regions are assumed to follow their business-as usual trajectory until joining global action in 2020 [7] *(EU 2010, others 2020).*

(ii) Active climate policy in all Annex-I countries by 2010, with the rest of the world following business-as-usual until joining global action by 2020 *(Annex-I 2010, others 2020).*

(iii) All Annex-I countries plus China and India pursue active climate policy from 2010, the rest of the world joins in 2020 *(All but RNAI 2010).*

Before analyzing the results of the modeling exercise, some information on further modeling assumptions is useful. First, the model runs assume that prior to adopting cap-and-trade regions behave myopic, i.e. they do not expect the arrival of carbon constraints, and follow their economic business-as-usual development pathway. Second, in the three intermediate cases, the year 2010 to 2020 emission allocations of the first movers equal their endowment in the benchmark *450 ppm C&C* scenario. International allowance trade is enabled between all regions implementing cap-and-trade. Third, in all delay scenarios allowances are allocated according to the

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[7] In the models, the accession to the climate coalition is represented by the introduction of a cap-and-trade system linked to the global carbon market.

Contraction and Convergence allocation rule beginning in 2020 with 2005 as a base year and 2050 as the convergence year. Thus, regions' relative shares in global emissions remain unchanged compared to the default C&C scenario. However, to make up for excess emissions during the delay, regional caps are contracted proportionally starting in 2020. Thus, in the delay scenarios, the cumulative emissions across regions are shifted in favor of late movers who emit more than their endowment prior to 2020 with the world jointly making up for these excess emissions post-2020.

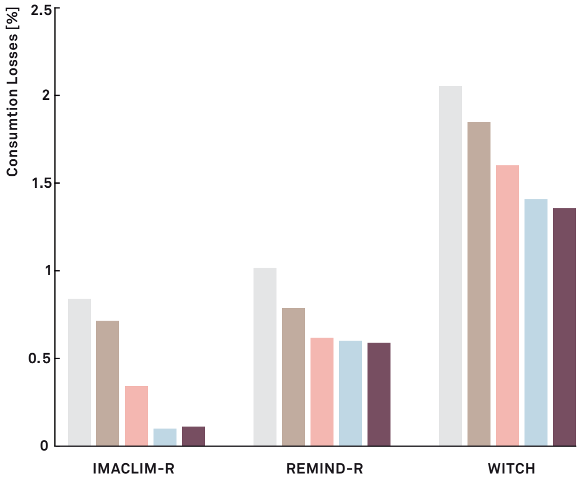


FIGURE 2-9
Global mitigation costs (displayed as consumption losses) for various scenarios with delayed participation in a global carbon market, and a benchmark case with global participation from 2010. Percentage changes are relative to baseline using a 3 % discount rate

- ■ DELAY 2020
- ■ EU 2010, OTHERS 2020
- ■ ANNEX I 2010, OTHERS 2020
- ■ ALLBUT RNAI 2010
- ■ 450ppm C&C

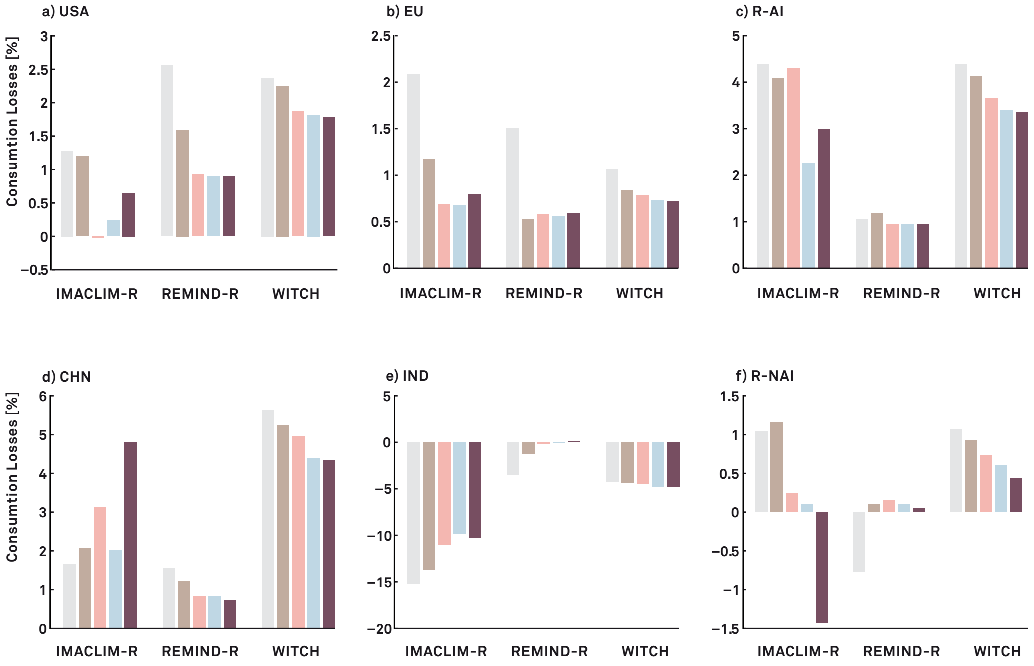


FIGURE 2-10
Consumption losses for all world regions for various scenarios of fragmentation. Percentage changes relative to baseline using 3 % discount rate. Please note different scales

- ■ DELAY 2020
- ■ EU 2010, OTHERS 2020
- ■ ANNEX I 2010, OTHERS 2020
- ■ ALLBUT RNAI 2010
- ■ 450ppm C&C

THE BENEFIT OF EARLY ACTION

As a first result, delaying ambitious global climate policy implementation until 2030 renders 450 ppm CO_2 stabilization infeasible in all models. 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 of the energy sector capital stock. Due to the substantial fossil energy conversion capacities accumulated by 2030, the world would be committed to a large quantity of further CO_2 emissions after the onset of climate policy.

Delaying mitigation action until 2020 allows stabilization at 450 ppm CO_2 by 2100. However, global consumption losses over the course of the 21st century increase from 1.4 % to 2 % in WITCH, from 0.6 % to 1 % in REMIND-R and from 0.1% to 0.8% in IMACLIM-R (Figure 2-9). In these simulation runs it was assumed that all technology options are viable. Clearly, with a restricted set of technology options it will become increasingly difficult to achieve the 450 ppm if countries delay climate change action.

With a rising number of regions taking early action by 2010, global costs of stabilization decrease. The participation of big Annex I countries, China and India is particularly relevant for the magnitude of mitigation costs. All models project that early participation of Annex-I countries is particularly important, with global consumption losses in the Annex-I only scenarios between 22 % (WITCH), 38 % (REMIND-R) and 59 % (IMACLIM-R) lower than in the Delay 2020 scenario. According to IMACLIM-R and WITCH, an early participation of China and India will also result in significant cost decreases.

EUROPE'S FIRST MOVER ADVANTAGE

In all models, early EU adoption of cap-and-trade results in lowered EU mitigation costs compared to the global Delay 2020 case (Figure 2-10). This indicates that there is an incentive for the EU to take action even if the other regions do not participate immediately. Similarly, mitigation costs for the USA will decrease if they join a climate policy regime alongside other Annex-I countries by 2010 compared to the case where only the European Union adopts carbon trading. Further, if Annex-I countries are committed to climate policy, China will increase its welfare by participating early in the reduction effort. The effect of an early participation of China and India in a global carbon market is, by contrast, projected to be almost neutral for India.

Considering the effects of unilateral early action for the European Union, two forces play a role. On the one hand, the EU has a more stringent emissions target post-2020 which results in a lower cumulative EU carbon budget. On the other hand, early adjustment of the energy system avoids locking the economy into carbon-intensive investments, making emission reductions beyond 2020 easier and allowing the EU to sell allowances 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 and the ecursive model IMACLIM-R, where the EU's energy system benefits from being pushed into a more efficient mode of operation early on. Early action by the EU stimulates investments in energy R&D and faster learning in wind and solar technology, bringing down the cost of backstop, wind, and solar technologies and increasing energy efficiency. For this reason, partial early adoption of climate policy (e.g. by the EU) would be beneficial also to other regions by the time a global climate policy is incepted. Beyond these techno-economic dynamics, initial actions in some developed countries create experience with climate policies and therefore increase political acceptability and facilitates their implementation in other countries.

3

ESTABLISHING A PRICE ON CARBON

KEY MESSAGES

- A credible price on carbon emissions addressing the negative climate externality across countries and sectors is a key pillar for climate policy. In OECD countries, cap-and-trade systems are emerging as policy-makers' instrument of choice for pricing carbon, largely because they allow to control the emissions directly (see Section 3.1).

- The EU Commission has proposed to construct a global carbon market bottom-up by linking regional trading schemes. Starting with a transatlantic EU – US carbon market for companies, it suggests establishing an OECD-wide integrated cap-and-trade system by 2015, with inclusion of major developing countries like China and India by 2020 (see Section 3.2).

- In an intermediate period, large developing countries could adopt sectoral no-lose caps or other crediting and non-market related approaches substituting the current CDM to support developing countries in their transition to low-carbon growth paths (see Section 3.2).

- Many proposals of developing countries and the climate action plan of the EU Commission emphasize National Appropriate Mitigation Actions (NAMAs). They might comprise a set of policies and actions that facilitate the transition of specific sectors to low-carbon growth paths. Currently discussed international mechanisms could provide tailored capacity building, technical assistance, technology cooperation and financial support (see Section 3.3).

- The EU Commission vision is ambitious in view of the challenges related to linking of trading systems, most notably international transfers of rents and need for harmonization of sensible trading system features such as price controls. Yet it represents a very promising way forward and is feasible assuming an internationally shared vision over policy priorities and sufficient political willingness to share mitigation costs among relevant actors (see Section 3.3).

- Asymmetric carbon prices across world regions are likely to persist at least for an intermediate period until an integrated global carbon pricing regime emerges. This raises leakage concerns, typically resulting in the full free allowance allocation to most industry sectors. Free allocation creates distortions to the carbon price signal, limiting incentives for low-carbon innovation, investment and substitution. Border adjustments could allow for a shift from free allocation to full auctioning, but raise serious concerns about discrimination or trade sanctions. International cooperation would be essential to limit the use of border measures and to create trust and avoid discrimination (see Section 3.4).

RECIPE indicates that climate stabilization is possible at tolerable economic cost. But at the core of these projections lies one fundamental assumption which is not implemented in reality yet: the existence of a global carbon market. Establishing an explicit price on greenhouse gas emissions to internalize the externality of global warming is the *conditio sine qua non* of environmentally effective and economically efficient climate policy.

This Chapter first discusses the rationale for carbon pricing (3.1), followed by a discussion of options, pathways and challenges for creating an international emissions trading regime (3.2). Complementing policies will be required to engage with developing countries and support these in shifting to low-carbon growth paths (3.3). Finally, stepwise implementation of an ambitious climate policy regime will entail at least initially a period of asymmetric carbon prices across regions. In this context, Section 3.4 discusses concerns over carbon leakage and options for mitigating them.

3.1 CARBON PRICING

Greenhouse gas emissions cause damages that are, absent regulatory intervention, not reflected in market prices giving rise to the large-scale market failure that is at the heart of the economics of climate change. It is a well-understood economic prescription to put a price on such negative externalities to enable producers and consumers throughout the economy to internalize the associated social costs in their private decision-making. Another important function of a carbon price is to set an incentive for developing and introducing low-carbon products and processes to replace existing technologies.

Command-and-control regulations such as technology standards can have an important role to play where explicit carbon pricing policies are difficult to implement, e.g. due to non-price related market failures and barriers or technical challenges in monitoring emissions or where explicit carbon pricing regimes have not (yet) been put in place.

Two instruments can be used for explicit carbon pricing. The Pigovian approach suggests the implementation of a tax reflecting the social costs of emissions (Pigou, 1946). The Coase tradition proposes to introduce well-defined property rights for carbon emissions with an allowance price signaling the scarcity of these rights on markets where they are traded (Coase, 1960). A tax fixes the price of carbon, while leaving actual emission reductions subject to uncertainty, as the precise reaction of techno-economic systems to carbon taxes is unknown. By contrast, a trading system determines the quantity of emissions with the carbon prices being inherently uncertain *ex ante*. In a world of uncertainty, only one of the two parameters can be fixed with the other necessarily remaining subject to uncertainty. Increasingly, hybrid schemes are being discussed, for example linking a target with a reserve price in auctions so as to ensure that the politically desired emissions trajectory is achieved, while, in the case of the identification of cheaper mitigation options, these will be realized and other cheap emission reduction options will not be forgone.

There is a long-standing debate in climate change economics whether taxes or emissions trading are superior instruments under uncertainty, with respect to inducing low-carbon technology development and deployment, and regarding their political economy features. Empirically, both the Kyoto Protocol and the EU ETS implemented a quantity approach, and discussions on implementing emissions trading markets are prominent in major OECD countries, for example in the United States (e.g. Tuerk et al., 2009). Therefore, a substantial part of this section focuses on the policy option of developing an international emissions trading system.

To enable investors to manage their portfolios, it will be of key importance that policymakers implement a long-term signal regarding the level of ambition in climate policy. For example, if the global community adopted the 2°C objective, according to recent findings by Meinshausen et al. (2009), global annual greenhouse gas emissions would need to be halved by 2050 compared to current levels to ensure that this target be met with at least 50 % probability. Such a signal over the global carbon budget enables investors to calculate the relative shares of low carbon and carbon intensive technologies and assess the value of their mid to long-term investments and adjust their actions accordingly. Given that input costs, for example for oil, gas or raw materials, are almost impossible to predict over long time frames, investors will not expect a very precise prediction of the future carbon price. For these investors, it is more important to have confidence that policymakers implement ambitious climate policy in a credible manner, i.e. reduction targets are not relaxed with view to short-term political priorities (Neuhoff et al., 2009 a).

For investments at project level, however, uncertainty from volatile carbon prices in cap-and-trade systems can be a more significant problem. It may reduce over time, but in the initial years may hinder the financing of low-carbon technologies. Several policy instruments are discussed to enhance investor confidence, including reserve prices in auctions.

There are a number of arguments suggesting that short-term caps should be set at more ambitious levels than indicated by optimal growth models such as REMIND-R and WITCH. First, several studies suggest the availability of negative-cost mitigation options which are not taken into account in models calibrated under the assumption of perfect markets (e.g. Jaffe 2001, McKinsey 2009). Targeted policy measures might enable agents to economize on these low-hanging fruits, allowing for the adoption of more ambitious and cost effective reduction targets. Second, if investors do not believe governments' long-term announcements and only react to present implemented policies, it may be dynamically more efficient to implement ambitious and costly targets in the short-term as a 'credible commitment'. This scenario is described by the IMACLIM-R model. And third, in case the portfolio of mitigation options turns out to perform less well than anticipated by the models (e.g. because some technologies are not available, see Section 4.1), there may be some value in hedging against this outcome and reduce more emissions earlier on than suggested by the default runs of the models (for more details, see Neuhoff et al., 2009 a).

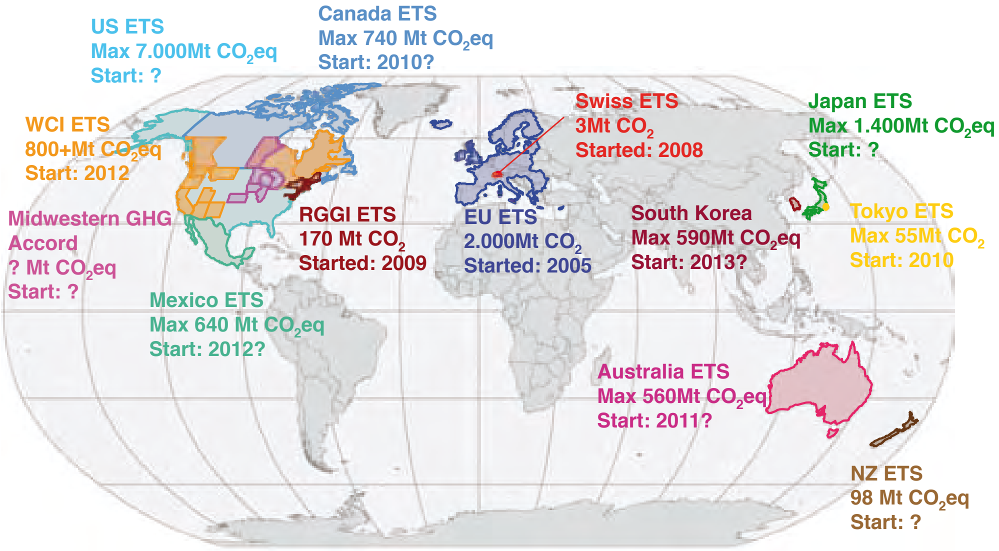
3.2 TOWARDS AN INTERNATIONAL CARBON MARKET?

The previous section discussed the rationale and economics of emissions trading regimes. In this section, we focus on the institutional dimension of creating an international carbon market over time (for a more detailed treatment, see Neuhoff et al., 2009 a).

As of today, a multitude of emissions trading systems are co-existing and emerging, such as the Kyoto Protocol's flexibility mechanisms, the EU ETS, and other domestic cap-and-trade initiatives in OECD countries. In the USA, for example, intense deliberations of the Waxman-Markey Bill proposing a US ETS are currently underway (e.g. Sterk et al., 2009). Figure 3-1 provides an overview of regional initiatives to establish cap-and-trade systems. In addition, new carbon market mechanisms such as sectoral approaches for developing countries that would include major emitters like China and India are discussed.

In recent years, a vivid debate on the future international carbon market architecture has evolved, with linking of regional emissions trading system as one approach particularly supported by the EU Commission (EU Commission, 2009 a; Tuerk et al., 2009). This sub-section focuses on this debate. First, some basic terminology is introduced. Then, three stylized post-2012 carbon market scenarios are identified, followed by a discussion of the pros and cons of integrating carbon markets and alternative approaches. Finally, questions of timing are addressed from an institutional point of view.

FIGURE 3-1
Overview of emerging regional carbon markets



BASIC CONCEPTS

Cap-and-trade systems set a binding, absolute cap on total emissions, but allow for allowances to be traded among covered entities which are either *nations* or *companies*. The Kyoto Protocol trading system for Annex-B countries is an example for cap-and-trade at the government level, while the EU ETS operates at the company level. In contrast, credit schemes define a certain baseline such as (a fraction of) absolute business-as-usual emissions or an intensity benchmark, and allow emission reductions relative to this baseline to be sold as credits. The CDM and JI mechanisms established under the Kyoto protocol are examples of such credit schemes.

A link between two or more emissions trading systems can be *indirect* or *direct*. Indirect links occur if two trading systems are not directly linked, but both link to a third system, e.g. a credit scheme like the CDM.This can lead to price convergence across the indirectly linked systems. The basic mechanism is illustrated by the following example: consider two cap-and-trade systems with pre-link autarky allowance prices of 20 and 30 Euros. If these link to some credit system with unlimited supply of credits at 10 Euros, and place no restriction on this link, their prices will converge at 10 Euro (Flachsland et al., 2009a). For example, the EU ETS and the Kyoto AAU[8] trading system are indirectly connected via the CDM.

Direct links, by contrast, allow direct trade between different schemes and can be distinguished on whether they allow trading in only one or more directions. In a full *bilateral* link, allowances can be freely traded between two systems and each system's allowances are equally valid for compliance in these regions. If more than two schemes participate, this becomes a *multilateral* link. Under a *unilateral* link, entities in system A can purchase and use allowances from system B for compliance, but not vice versa (Mehling and Haites, 2009). If A's allowance price is higher than B's, entities in A will purchase allowances from B until the systems' prices converge at some intermediate level. If A's price is lower than in B, there is no incentive for inter-system trading (Jaffe and Stavins, 2008). For example, the EU ETS features a unilateral link to the CDM mechanism.

[8] The Kyoto Protocol established an accounting system where countries are required to hold allowances – called Assigned Amount Units (AAU) – corresponding to their emission budgets agreed under the Protocol.

POST-2012 CARBON MARKET SCENARIOS

Building on these basic distinctions we identify three plausible international emissions trading architectures for the period post-2012.[9] First, a *Kyoto-type* approach continues with the principle of targets and trading at the national level. Governments that do not meet their target can buy AAUs from countries that reduce emissions beyond their target (developing countries can participate by selling some type of credits, generated for example with a reformed CDM or novel sectoral mechanisms). Domestic policy instruments need to be implemented in addition to translate the international carbon price to economic agents (Hahn and Stavins, 1999).

By contrast, company-level cap-and-trade systems like the EU ETS or a future federal US trading scheme can establish direct bilateral links (EU Commission, 2009 a; ICAP, 2007). These systems can be linked in absence of a Kyoto-type agreement, or within the framework it would set. In the latter case, governments devolve trading activity to the level of companies, and trade only on behalf of sectors not covered by domestic ETS. Figure 3 - 2a illustrates this case which is in fact adopted by the European Union in the First Commitment Period of Kyoto Protocol 2008–2012 where international allowance trades across companies within the EU ETS are mirrored by transfers of Kyoto allowances in country's registries (Ellerman, 2008). Equivalently of directly linking regional cap-and-trade scheme, sectoral cap-and-trade systems targeting sectors e. g. particularly affected by leakage concerns (such as cement, steel, aluminum; see the following Chapter 3.4) in the context of an international sectoral agreement can be linked, thus creating a better integrated international carbon market.

Indirect links of regional cap-and-trade systems might emerge as the de facto architecture of international emissions trading after 2012, at least for an intermediate period and in particular if a Kyoto-type agreement does not materialize (Jaffe and Stavins, 2008). All of the existing and emerging cap-and-trade systems foresee links to the CDM, albeit often with qualitative and quantitative restrictions. Thus, if the CDM or new crediting mechanisms continues to play a strong role in an international architecture post 2012, it can be expected that even in absence of bilateral links between regional carbon markets indirect links will inevitably emerge.

All of these scenarios foresee the participation of developing countries in international emissions trading. Three major options can be distinguished for their carbon market integration. First, CDM-type crediting schemes can be continued and expanded. Given the shortcomings of the current CDM, in particular regarding environmental additionality and transaction costs (Neuhoff et al., 2009 a), this appears to be a problematic option. Second, developing countries may agree on sectoral no-lose targets or other sectoral crediting mechanisms. Emission reductions below some baseline would be credited and could be sold in an international market, but no penalty applies in case the baseline is exceeded. Baselines may be intensity targets such as emissions per unit of production (electricity, cement etc.), but given uncertain projections over business-as-usual developments and the distributional implications of setting baselines their precise implementation is challenging. Third, developing countries can adopt absolute targets, both economy-wide and on a sectoral level. Modeling results in Section 2.4 suggest that – depending on allocation rules – this can promise beneficial net outcomes for developing countries. However, concerns that caps would be too tight and awareness that other support, e. g. on technology and capacity building is necessary, lead developing

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[9] See Flachsland et al. (2009a) for a more detailed treatment of these issues.

countries to reject approaches containing emission targets for any international framework prior to 2020. Section 3.3 points to the opportunities that emerge for the engagement of developing countries using auction revenues from national emissions trading schemes, or from carbon pricing policies on international aviation and shipping.

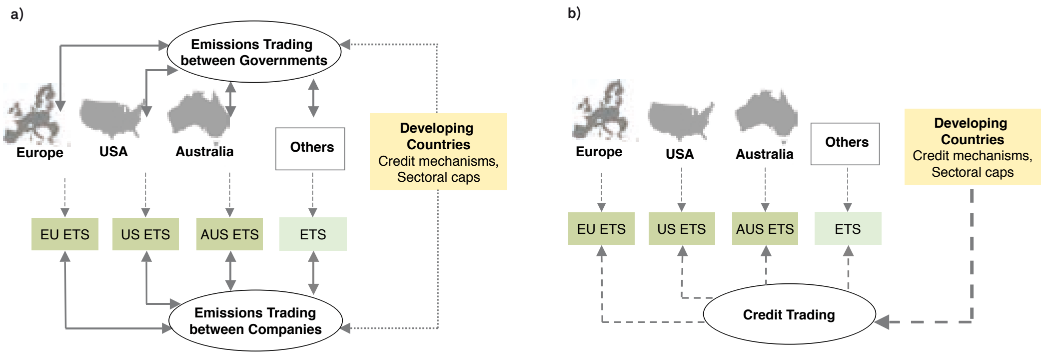

FIGURE 3-2

Scenarios for international emissions trading. Figure (a) displays how Kyoto-type trading on the government level can be combined with direct linking of domestic trading systems

Figure (b) illustrates indirect links that emerge if regional cap-and-trade markets enable imports from the international credit market

PROS AND CONS OF INTEGRATING CARBON MARKETS

The major generic economic benefit from linking any type of emissions trading systems derives from the efficiency gains of enabling trade across systems with different marginal abatement costs (allowance prices). Also, smaller carbon markets should benefit from improved liquidity when linking to other systems. Larger markets created by linking smaller systems feature more players and thus reduce concerns over market power. In addition, concerns about leakage resulting from different carbon price levels are eliminated between countries that have linked their schemes and thus harmonize carbon prices. This does not address concerns about leakage towards third parties that are not part of the linked scheme.

In political terms, linking trading systems can be seen as one way of signaling commitment to multilateral climate change policy which is essential for achieving significant cuts in global emissions associated e.g. with 450 ppm CO_2 stabilization. The most important impact of implementing a well-functioning transatlantic link between a US cap-and-trade system and the EU ETS, for example, would probably lie in demonstrating the feasibility of this approach vis-à-vis other major developing country players such as China and India which could eventually join such a regime. Transfer mechanisms as embodied in international emissions trading, or other mechanisms that support low-carbon growth with public funds, technology cooperation, technical assistances and capacity building, will be necessary to support developing countries in shifting to low-carbon growth trajectories.

However, the decision to set up joined trading systems also entails a number of caveats. Maybe most importantly, linking partners need to accept each others cap trajectories or baselines (in credit schemes) as these determine the distributional outcome when enabling trade across regions. If one player adopts a non-ambitious cap or baseline it can benefit disproportionally from selling allowances internationally. This issue is complicated by the uncertainty over distributional outcomes from international emissions trading illustrated by the modeling comparison exercise (Section 2.4). Also, as noted by Babiker et al. (2004) and Paltsev et al. (2007), in second-best settings there may be situations where linking is not always beneficial for *all* linking partners, for example if carbon price changes from linking intensify pre-existing distortions such as high energy taxes. In addition, if some linking partners envisage certain minimum carbon price levels for fostering research and development or would like to avoid very high allowance prices to contain costs, it would have to be ensured that these price objectives are not violated when linking. For example, setting an expansive cap in one region results in large financial transfers to the country and will drive down allowance prices within the entire linked carbon market. Thus, linking carbon markets will undermine incentives to commit to ambitious emission reduction targets by subsequent rounds of international negotiations. Finally, if governments want to achieve some level of abatement domestically and intend to ensure that abatement investments are undertaken within their economy to reap perceived co-benefits such as reduced fossil fuel imports and the creation of green jobs, this can be a barrier to linking.

In general, prior to linking two schemes basic consensus on their design[10], MRV requirements and compliance mechanisms are required. International integration of carbon markets will reduce domestic regulators' unilateral control, pointing to the need of some joined institutional framework for carbon market governance (Flachsland et al., 2009b; Tuerk et al., 2009). In 2007, several governments inaugurated the International Climate Action Partnership (ICAP), a forum aiming at exploring opportunities and barriers to linking emerging regional cap-and-trade systems and to work towards the establishment of a global carbon market (ICAP, 2007; Bergfelder, 2008).[11] Such a forum may provide a starting point for coordinating the international effort to build an integrated carbon market.

In addition to these generic issues, there are some specific pros and cons of the three carbon market architectures considered in the previous section. To begin with, a major advantage of the *Kyoto-type* approach is that it facilitates international negotiations of regional levels of ambition in terms of emission caps. Thus, a Kyoto-type trading scheme may facilitate the adoption of more ambitious global emission reductions. However, in case of stalemate in negotiations over regional allocations, this approach cannot be implemented. Another concern is that government-level emissions trading is prone to economic inefficiency due to market power (e.g. Böhringer and Löschel, 2003)[12], and the question of whether governments are generally able to act as cost minimizes on carbon markets, given e.g. their geopolitical interests (Hahn and Stavins 1999; see also reporting by Point Carbon (2009) on irregularities in government-level AAU trading).

Regarding *full bilateral links between regional cap-and-trade systems* in presence of a Kyoto-type system, these promise to mitigate the economic efficiency problems of the latter as they entail devolution of permit trading from government to company-level. This is because firms can be expected to act as cost minimizers and will be less able to exert market power than governments. Concerning pros and cons of bilateral links in absence of a Kyoto-type agreement, all generic arguments outlined above apply.[13]

Concerning *indirect linkages*, their major advantage is that they do not require complex international coordination efforts. As an intermediate architecture, indirect linkages may achieve cost savings by harmonizing regional carbon prices. As a downside, the indirect linking approach does not facilitate negotiations of a comprehensive agreement addressing equity issues, and fails to provide a perspective of development towards a future integrated and stable international carbon market. If price harmonization and

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[10] For example, if one trading system features a price cap (Jacoby and Ellerman, 2004), this will impact the entire linked market.

[11] ICAP members are the EU Commission and several EU Member states, several US states from both the Regional Greenhouse Gas Initiative (RGGI) and the Western Climate Initiative (WCI), and Australia, New Zealand, Norway as well as the observers Japan, the Tokyo Metropolitan Government, and Ukraine.

[12] Only 3 countries (USA, Russia, Japan) accounted for 57% percent of Annex-I GHG emissions in 2005 (CAIT, 2008).

[13] For a more detailed treatment of the issues involved in bilateral linkages in absence of a Kyoto-type agreement, see Flachsland et al. (2009b).

mutual influence of emissions trading systems is considered detrimental e. g. because it leads to inacceptable changes in the domestic allowance prices, this represents a drawback to indirect linking.

TIMING

Assuming that a global carbon market will be a main instrument for achieving e. g. the 2°C objective, instantaneous implementation of a global trading system for companies with a clear indication of the global reduction schedule at least until 2050 and a globally accepted distribution rule for allowances at least in the short- to mid-term is generally desirable. Also, clear rules for a procedure for updating the global reduction schedule in the light of new information on costs and benefits of mitigation would be desirable. In practice, however, a global carbon market for companies can only be implemented step-by-step.

The EU Commission has communicated very clearly that linking of regional emissions trading systems is at the core of its international climate policy strategy (EU Commission, 2009 a; see Russ et al., 2009 for an EU Joint Research centre assessment of this proposal). It has proposed to set up an OECD-wide cap-and-trade system by 2015, pioneered by a transatlantic EU-US carbon market. Major developing countries shall join this international carbon market by 2020.

Given that the EU ETS is the only cap-and-trade system currently in operation and the prospect and timing e. g. for a US cap-and-trade is still not certain, and that linking partners will likely want to observe single systems' performance for a few years prior to linking (e. g. ECCP, 2007), the vision of an OECD-wide company-level carbon market by 2015 is ambitious. Clearly, a US-EU carbon market would constitute the major share of an OECD-wide system and would send a strong political signal to stakeholders regarding the further development of international climate policy based on the construction of a global carbon market.

Concerning market integration of large emitters like China and India, it currently appears unlikely that they will sign up to binding caps prior to 2020. However, they may commit to do so by 2020 at the latest, for example, and implement large-scale crediting schemes in the intermediate period to incentivize emission reductions and the flow of carbon finance, and redirect long-lived investments towards a low-carbon infrastructure. Additional policy tools and explicit international payments can help in financing the incremental cost of decarbonizing economic growth in developing countries.

Regarding the prospect for a Kyoto-type system featuring country-level caps and trade of allowances among governments, this could be implemented immediately at the 2009 Copenhagen negotiations and may start in 2013 to directly follow the Kyoto Protocol's First Commitment period. Distributional issues, i. e. the determination of regional caps, are the major obstacle to agreement.

Linking regional cap-and-trade systems in the context of an overarching Kyoto-type framework – an approach pioneered by the European Union – appears as one plausible approach to international emissions trading after 2012, as it combines the possibility to negotiate ambitious regional emission budgets with setting up an efficient international carbon market. Clearly, substantial distributional and institutional questions need to be resolved to make this a viable policy option.

3.3 NON-CARBON MARKET ENGAGEMENT WITH DEVELOPING COUNTRIES

While emissions trading could become one part of the instrument mix for decarbonizing economic growth in developing countries, it may not become implemented in many countries and sectors for some time to come, and it will clearly not be sufficient as the single instrument to drive decarbonization at the required scale due to a conundrum of market failures and a variety of market and non-market barriers.

The sector results presented in Chapter 5 illustrate the comprehensive sets of actions and policies that need to be pursued by a government, so as to create a framework for a low-carbon development of individual sectors and ultimately the entire economy. This emerging bottom-up experience in developed countries is increasingly reflected in international negotiations. Countries like South Africa have already in 2006 developed a long-term mitigation strategy that outlines the intended economic, energy and emissions trajectory for the country (Winkler, 2007). Such approaches were later replicated by other countries including Mexico and South Korea, and the Climate Action Plan of the European Commission from February 2009 (EU Commission, 2009 b).

Figure 3-3 illustrates how such an overall strategy helps to identify trigger points for actions that allow for a transition in individual sectors or technologies. Thus, the negotiation text issued by the UNFCCC in May 2009 has picked up terminology from several submissions by developing countries on “National Appropriate Mitigation Actions” (UNFCCC, 2009). In a recent project (Climate Strategies, 2009) teams from India, China, Ghana, Brazil, and South Africa explored for specific sectors the characteristics of such NAMAs. In all instances non-climate benefits are the drivers for domestic stakeholders to initiate the policy or action in question. Given the complexities of policy processes and political sensitivities, such domestic ownership is seen to be essential for the success of a NAMA. In all instances, several barriers for a transition to the use of low-carbon technology or infrastructure were identified, pointing to the importance of a comprehensive set of actions to be pursued in parallel to facilitate a successful transition.

While domestic initiative is essential for the success of any NAMA, the discussion of stakeholders in the countries also illustrated how international support could enhance the scale, scope or speed of the implementation of such NAMAs. After all, co-benefits like energy savings and reduced human health impacts from shifts to energy efficiency and low-carbon energy sources, could have already been harvested decades ago. The failure of past policies to realize these opportunities points to the need for additional

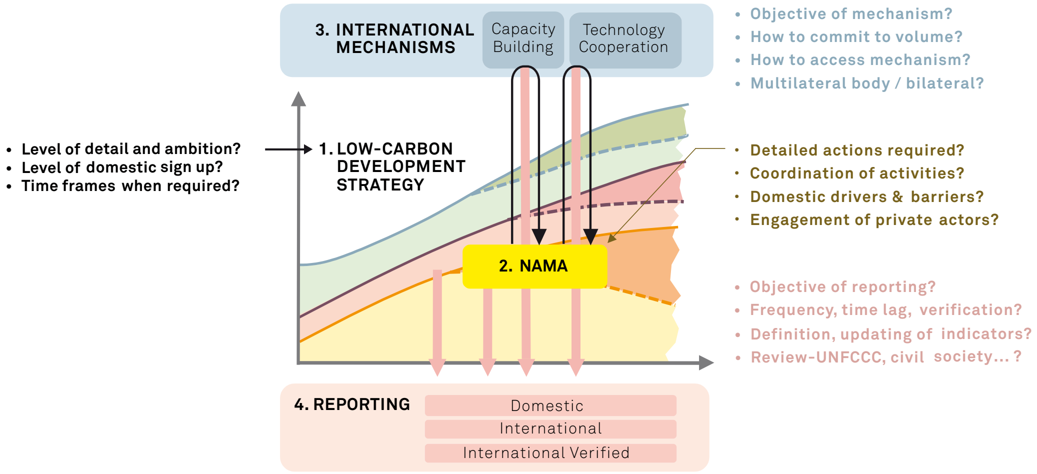

FIGURE 3-3
Stylized concept for actions that allow for a transition in individual sectors or technologies
Climate Strategies (2009)

international support to overcome inertia and regulatory, technical and financial barriers for the implementation of NAMAs. This is also reflected in the UNFCCC principle of common but differentiated responsibility which entails support from developed countries for developing countries with their implementation of policies with climate benefits.

Submissions by developed and developing countries to the UNFCCC process have outlined many mechanisms for international support that could be used to enhance the scale, scope or speed of the implementation of NAMAs. Dependent on the specific needs of a country and sector, they could require: capacity building measures, technical assistance, technology cooperation and financial assistance (see Neuhoff, 2009, for summary). These proposals both entail concepts of multi-lateral bodies providing some of the support, and options for bilateral cooperation under the umbrella of the UNFCCC. The negotiations of the coming months will have the task of focusing on a sub-set of the large amount of proposals so as to clearly define and make operational a small number of mechanisms. Some of the criteria for the selection and definition of these mechanisms are that they are:

- in their combination able to provide for the set of needs of developing countries for their implementation of NAMAs,
- sufficiently flexible to address the specific needs of a country and sector,
- accessible by developing countries in a timely manner to facilitate the implementation of individual NAMAs. Design and implementation of initial NAMAs can then provide experience and encouragement for the development of additional NAMAs to cover additional sectors and technologies.

While capacity building and technical assistance are generally seen to be tailored to the needs of a sector and country, an ongoing discussion is evolving around the question of how to best determine the volume and structure of international financial support that is to be provided for the implementation of NAMAs. It is evident that the long-term mitigation objectives outlined in Chapter 2 cannot be achieved by marginal emission reductions, but require a substantial transition to low-carbon technologies, processes, and industrial structures. This often involves high up-front costs for technologies or infrastructure. In presence of imperfect capital market access of developing countries and ex ante uncertainty over project performance, it might not be desirable to make financial support for NAMAs conditional on the volume of emission reductions they deliver. Thus, while it is therefore important to quantify the potential impact of NAMAs, so as to ensure the selection of NAMAs that can have a positive effect, international financial support, whether in the form of grants, loans or credit guarantees for the implementation of NAMAs might be granted not necessarily in proportion to immediate impact on CO_2 emissions, but also reflecting transformational character of action as well as incremental costs. The final dimension of the NAMAs framework that is receiving increasing attention is on improving the use of information. Experiences from industry, national policy implementation, and international cooperation e.g. with Poverty Reduction Strategy Papers, points to the importance of a comprehensive set of indicators (also referred to as metrics or key performance indicators) to facilitate the effective implementation of a policy, to identify best practice from international learning and to create transparency that in turn achieves greater clarity and allows for private sector investment and innovation. While in principle, these objectives would not require internationally harmonized or reported indicators, in practice it is difficult to learn from best practice without the availability of detailed quantitative evidence. To the extent that NAMAs also receive some international support, both the domestic and the international contributions would have to be reported to an UNFCCC body. Otherwise developed countries might abuse the cooperation for non-climate related objectives, e.g. by financing 'energy efficient' fighter airplanes under their commitment to provide international support. Also, developing countries might not be forthcoming in reporting failure of individual components of a NAMA, so as to not jeopardize ongoing financial support, even if they are thus also undermining opportunity for improvements and international learning from initial experiences.

Hence, a clear UNFCCC framework for reporting, not only as currently obligatory, of CO_2 emissions, but of a more comprehensive set of policy indicators, both by developed and developing countries, will be an essential part of cooperative climate policy. This contributes to increased confidence in the effectiveness of international cooperation, and therefore enhances the willingness of developed countries to provide the resources, e.g. using auction revenue from national emissions trading schemes, or international aviation and shipping trading schemes.

3.4 ASYMMETRIC CARBON PRICES AND LEAKAGE

Unless comparable carbon prices are implemented instantaneously in all relevant world regions e.g. following a Copenhagen climate agreement, there will be a period of asymmetric regional carbon prices. Carbon prices may converge as more countries implement emissions trading schemes with auctioned allowances, but in the interim period there are concerns that higher carbon prices in one region coupled with auctioning of CO_2 allowances would shift production or investment to regions with low-carbon prices, thereby limiting the environmental effectiveness of climate policy.

Academic literature and policy research have pointed out that only a few sectors face significant costs from carbon pricing at current levels in the order of 20-40€ /t CO_2. Studies on UK and Germany industry show that these sectors only contribute to 1.1 % and 2.1 % of respective country GDP (Hourcade et al., 2008). These studies, and the subsequent draft Directive issued by the European Commission in January 2008 (EU Commission, 2008b) argue that cost increases are not a sufficient reason to assume leakage concerns, but additional factors like transport costs, product differentiation, investment costs and trade volumes need to be considered to make a sub-sector specific assessment of the leakage costs.

In Europe, industry representations to member states and European parliament lobbied for abandoning this latter part of leakage testing, and the EU ETS Directive now encompasses very generous criteria for the definition of sectors at risk of leakage (EU Commission, 2009b). For each of the sectors considered to be at risk of leakage, the European Commission has to propose in June 2010 what mechanism to use to address specific leakage concerns. The options, outlined in the Directive, are (1) free allowance allocation of the full share of the sector in the overall cap, (2) a global sectoral agreement for the sector (3) inclusion of importers into the European Emission Trading System. All of these 'medicines' for leakage can have serious side-effects – and would therefore have to be carefully assessed.

The negative side-effects of free allowance allocation under the EU ETS exemplifies the distortions and perverse incentives that this approach can create. It constitutes a subsidy for incumbent producers and technologies and thus undermines opportunities and incentives for innovation and investment in low-carbon technologies, processes and substitutes as terminating emission activities would lead to a loss of the subsidy. The widely shared expectation is that the majority of industry emitters will receive most of their allowances for free up to the year 2020. This will significantly reduce their incentives for and contributions to emission reductions. This European precedent has undermined efforts of US policy makers to implement a more efficient scheme with larger shares of auctioning to industry. This is a serious set-back for international climate policy, because the industry sector is the one sector that is most dependent on the carbon price signal, as highly differentiated and specialized production processes are least accessible for other regulatory instruments. With Europe and the USA exempting industry from serious mitigation efforts, it will be difficult to encourage other countries to be more ambitious.

Some academics and industry lobbies still argue that free allowance allocation does not undermine incentives for decarbonization based on the following arguments:

- If free allocation is not conditioned on ongoing activity or production, then it does not distort production and investment decisions. However, such unconditional free allowance allocation does also not address leakage concerns as facilities may shift production while operators continue to receive free allocation, and is therefore not considered in any of the proposals.

- If, as is likely in the European context, free allocation will be granted once an installation exceeds a certain activity level, this creates incentives to maintain production at this level, and to retain old production facilities even where they are inefficient. Allocation to new installations constitutes a subsidy to carbon intensive products, thus undermining opportunities for substitution to low-carbon products and processes.

- If, as envisaged in the Waxman-Markey bill, free allocation is proportional to the production volume of an installation, it will create administrative barriers for innovation and improvements in production processes, and constitutes a subsidy for every unit of production of a carbon intensive process. Thus, it eliminates opportunities for low-carbon alternatives and processes.

Where allowances are not auctioned, the EU ETS and most likely also the Waxman Markey bill will at most incentivize some efficiency improvements in the production process, but will prevent the further ranging transitions to lower-carbon production processes and products. This suggests that international support is necessary to facilitate a shift towards auctioning of allowances in industrial sectors.

One option for such international support is a global sectoral agreement implementing a similar effective carbon price for installations of an industry sector in all countries. This requires carbon taxes or emissions trading schemes with full auctioning and similar stringency of a cap or trade for all participating countries. It is an approach worthwhile pursuing that would eliminate concerns over carbon leakage, but might well require a long time for its achievement (see also Section 3.2).

The currently envisaged sectoral crediting schemes do not address carbon leakage concerns. By contrast, as producers that are more efficient than the benchmark – often new installations in developing countries – can sell allowances, these approaches may even act as a subsidy to shifting efficient production facilities to these countries.

This leaves border measures as the final option to facilitate a shift from free allowance allocation to auctioning (Ismer and Neuhoff, 2007). The instrument has very bad political associations, and should therefore not be applied unilaterally, but only as part of a formal or informal international cooperation that clearly limits the use to:

- a small set of carbon intensive commodities such as steel and clinker,
- a requirement of full auctioning of allowances, so as to ensure a shift away from subsidies for carbon intensive products and production processes implied by free allocation,
- a maximum adjustment factor determined by the carbon intensity of the best available technology, thus avoiding discrimination against foreign producers.

The limitations contribute to WTO compatibility of a resulting border adjustment scheme, and are at the same time reinforced by WTO rules that prevent discrimination against foreign producers. This prevention of discrimination against foreign producers also ensures that it cannot be used as trade sanctions to enforce compliance with international climate objectives. As climate policy requires domestic initiative and support, it is unlikely that such sanctions would be effective in achieving climate objectives. The limitations furthermore imply that all importers are treated as if they are produced with the best available technology. Thus the scheme does not create incentives to improve production efficiency in third countries. It is unlikely that this would be effective any way. With many new production facilities for steel, chemicals and aluminum in developing countries, more complex schemes that would attempt to create incentives for foreign producers to reduce their carbon intensity are likely to only shift production from the new facilities to the international market rather than to create real incentives for efficiency improvements. Further quantitative analysis of the trade-offs is required.

Leakage is a major concern for climate policy in industrial sectors – mainly because it prevents a shift towards auctioning of CO_2 allowances and thus undermines an effective carbon price signal. International support for the implementation of border measures for individual carbon intensive commodities could facilitate a shift towards full auctioning and therefore facilitate a low-carbon transition for industry. In the longer term, comparable carbon pricing across regions and sectors is the best approach to resolve the issue of carbon leakage.

4 THE ROLE OF TECHNOLOGIES

KEY MESSAGES

- Carbon capture and storage (CCS) and renewables have the highest potential to act as low-cost mitigation options. Nuclear energy can contribute substantially to emissions abatement; however, it entails specific risks and barriers that are not fully accounted for in the models. The cost increase for restricting its use to the business-as-usual level is significantly smaller than for renewables and CCS (see Section 4.1).

- Energy efficiency improvements and demand side management hold significant low-cost and short-term emissions abatement potential. In the long-term, the higher the restrictions on technology availability, the larger the role of energy efficiency (see Section 4.1).

- Due to distortions in technology development not related to environmental externalities, decision-makers need to implement appropriate low-carbon technology policies on the national as well as the international level to create an environment which is supportive of R&D and the deployment of novel mitigation options. This process also requires targeted infrastructure policies suited to address network effects and coordination failures (see Section 4.2).

- Given major uncertainties in future technology development, it is necessary to (1) encourage diversification in order to have a broad portfolio of options which act as an insurance, and (2) invest in R&D demonstration and deployment to increase our knowledge with regards to technological opportunities (see Section 4.2).

- Mitigation technologies carry additional risks and co-benefits: For CCS, there is the possibility of leakage of stored carbon. Production of biomass can result in additional emissions of N_2O, destroy carbon sinks, and have adverse impacts on biodiversity and food prices. Hydropower can have detrimental effects in terms of destroying human habitats and ecosystems, and other renewables suffer from their intermittent availability. For nuclear energy, there are risks of accidents, problems related to the disposal and final storage of radioactive waste and proliferation concerns (see Section 4.3).

- Possible advantages of alternative (non-fossil) sources of energy include reducing ambient air pollution, increasing energy security, involving local communities and providing employment opportunities (see Section 4.3).

- Transformation of the global energy system requires sizable flows of new, additional investments and fundamental changes in investment patterns. Climate policy could trigger additional investments in mitigation technologies exceeding US$ 1200 bn per year by the middle of the century, while reducing investments in conventional fossil fuel based sources of energy generation by US$ 300 to 500 bn. Model results suggest that optimally investments in fossil based energies not equipped with CCS should be reduced sharply in the near future, while investments in CCS and renewables should be scaled up significantly (see Section 4.4).

- Private sector involvement will be crucial to raise finance for clean energy technologies. Credible long-term climate policies allow private investors to provide incentives for early movers to establish technological leadership in this sizeable market (see Section 4.4).

Chapter 2 outlined how climate stabilization can be achieved at least cost, provided that the right technologies are available. However, future technological developments are highly uncertain, and low-carbon technologies have to overcome a number of barriers, which are not accounted for in the models, before their widespread adoption.

This chapter examines the relative values of single technologies in the portfolio of mitigation options (4.1), and discusses technology policies to support development and deployment of low-carbon technologies (4.2). Section 4.3 assesses risks and co-benefits related to each of these technologies which should be taken into account when designing mitigation strategies. Section 4.4 presents estimates how investment flows will have to be redirected to transform the global energy system.

4.1

LIMITED AVAILABILITY OF TECHNOLOGIES

One message that emerged clearly from RECIPE is that developing and commercializing new abatement technologies as well as incrementally lowering the costs of already existing mitigation options is fundamental for preventing dangerous anthropogenic climate change in a cost-efficient manner. This means that with the right technologies at hand, it will be possible to stabilize the climate without adversely affecting other human development objectives such as sharply decreasing global poverty or investing in education and healthcare.

In the framework of the model comparison, the relative importance of individual technologies was assessed by calculating the cost of restricted technology portfolios, i. e. the increase in mitigation costs that results if a particular technology is either excluded (CCS) or its use restricted to its baseline level (all other technologies). These costs for the mid- as well as long-term (2005–2030, and 2005–2100, respectively) are shown in Figure 4-1. Although the models do not deliver unequivocal conclusions with regards to the ranking of technologies, the following robust results emerge:

In all models, Carbon Capture and Storage (CCS) is an important mitigation option which contributes 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 for transportation. REMIND-R also includes the option of combining biomass with CCS, an option that results in negative net emissions. Consequently, REMIND-R and IMACLIM-R both project high option values for CCS; an increase of global consumption losses from 0.6 % to 0.8 % for REMIND-R and from 0.1 % to 0.9 % for IMACLIM-R (for which CCS is the most valuable mitigation option). Even though the overall deployment of CCS in WITCH is significantly lower than in the other two models, consumption losses are projected to increase by more than 40 % when this mitigation option is excluded. Since large-scale deployment of CCS is projected to play a role only after 2030 in all models, medium-term losses from foregoing the CCS option are small or, in the case of REMIND-R and WITCH, even slightly negative.

All models project renewables (such as hydro, wind, solar, biomass and geothermal energy) to account for a substantial share of the primary energy mix in the climate policy scenario. 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 until 2030, the availability of renewables has a much smaller effect on consumption. In fact, due to the significant up-front investments required for technological learning, aggregated welfare until 2030 is projected to increase relative to the default scenario if the use of renewables is fixed to its baseline level.

Among the renewables, biomass constitutes a versatile mitigation option that can be employed 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. 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-R and – to a lesser extent – in WITCH.

The adoption of climate policy measures results in the expansion of nuclear energy as an option to mitigate GHG emissions in all three models. However, nuclear is found to have a quite low option value, and all three models project that expanding nuclear energy beyond its use in the baseline would result only in a marginal reduction 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 2.4). 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 policy scenario which restricts nuclear energy to its baseline level.

The most stringent technology scenario assesses a situation in which neither CCS nor 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.

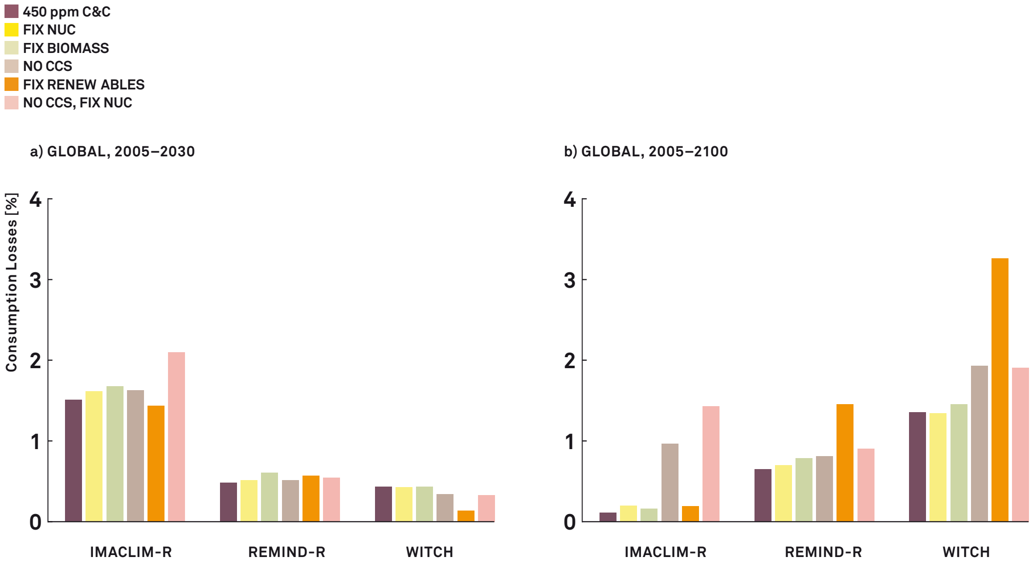

FIGURE 4-1
Option values of technologies in terms of consumption losses for scenarios in which the option indicated is foregone (CCS) or limited to BAU levels (all other technologies) for the periods 2005–2030 (a) and 2005–2100 (b). Option values are calculated as differences of consumption losses of 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 "fix renewables" scenario

Besides developing new low-carbon energy sources, supplementary energy efficiency improvements and demand side management – which are not explicitly modeled – could provide additional flexibility in case that certain technologies fail to unfold their expected potential. The relative importance of energy efficiency and demand side management depends (1) on the flexibility of the energy system to replace fossil sources of energy with low-carbon technologies, and (2) the flexibility on the macroeconomic level to adopt less energy-using modes of production. This explains the different effects that climate policy measures induce on energy consumption across models (Figure 2-6): IMACLIM-R and WITCH project considerable reductions in energy demand (compared to the BAU scenario) to avoid carbon emissions, while in REMIND-R energy use decreases only slightly as decarbonization can predominantly be achieved by switching to low-carbon sources of energy.

By considering more general indicators in the models that give information about the role of energy efficiency improvements compared to decarbonization, some important insights can be derived from the development of energy intensity (i.e. energy needed for a unit of GDP) and carbon intensity (i.e. carbon emissions per unit of energy) in different scenarios. Differences in the developments of carbon and energy intensity are greatest between the baseline and policy scenarios, while differences between technology scenarios are relatively small. However, when excluding technologies that contribute significantly to decarbonization (CCS, renewables), it can be found that energy intensity plays a more important role, meaning that a lack of suitable decarbonizing technologies can partly be replaced by energy efficiency improvements.

Economy-wide increases in energy efficiency can be achieved either by demand-side measures (e.g. smart metering, energy efficiency standards, or changes in consumers' behavior) or on the supply side (e.g. through replacement of outdated power plants with more efficient, up-to-date technologies or switching to fuels with conversion efficiencies). Some estimates suggest that in the short to medium term, improvements in energy efficiency carry considerable abatement potential at low, or even negative, costs (McKinsey, 2009). The fact that many of these 'no-regret options' are not yet exploited suggests the existence of important market failures (like informational costs, lack of access to credit, landlord-tenant problems, etc.). Hence, it seems unlikely that carbon pricing alone will prove sufficient to incentivize those efficiency improvements. Additional policy instrument are required instead; the appropriate instruments will have to be designed on a case-by-case basis after identifying the concrete type of market failure involved.

In summary, the model results suggest that on the supply side CCS and renewables are the most important mitigation options. Given the huge uncertainties with regards to future technological progress over the course of the century – which are not included in the deterministic model settings – it appears as a dangerous strategy to focus on a narrow subset of prominent technologies and try to pick winners a priori. A much more promising approach is to 'let a thousand flowers bloom' by establishing and supporting a broad portfolio of technological options that provide insurance against risks in technology developments and allows to select a portfolio of lower cost technologies at the appropriate points later in time. This requires an environment conducive to R&D and deployment of technology in the first place. Furthermore, as the private sector cannot be expected to provide the insurance granted by diversified portfolios, public policies that encourage diversification and increase our knowledge of technological options are needed.

4.2 LOW-CARBON TECHNOLOGY POLICY

From an economic perspective, a central policy instrument to guide decisions of consumers, firms and investors towards a low-carbon economy is putting a price on carbon emissions. A carbon price influences expectations about the future market environment, spurs investments in mitigation of GHG emissions and creates incentives to engage in R&D through increased demand for novel abatement technologies. However, it is well known that technology markets are distorted by multiple additional market failures besides the environmental externality. These include innovators' inability to capture the full rewards of their innovation and process improvement activities, technology suppliers that are not rewarded for lowering other firms' production costs by their contribution to learning-by-doing, network externalities, as well as underinvestment in the face of uncertainty, credit constraints, and myopic behavior. For this reason, a strong case can be made for 'low-carbon technology policy', i.e. complementing economic instruments to deal with the aforementioned market failures and facilitate the transition towards a low-carbon economy. Technology policies can be targeted at different stages of the innovation chain.

Innovation policies provide incentives to engage in research and development. OECD member countries account for over US $800bn annually (OECD, 2007). Of this, IEA members spend around US$11bn on public sector energy technology R&D, whilst the private sector accounts for another estimated US$40–60bn annually (IEA, 2008a). Historically, research and development expenditure shares in the energy sector have been lower than that in product-driven industries (Grubb et al, 2008), and recent estimates suggest that overall power sector R&D spending has declined in both the public and private sectors since its peak around 1980[14]. Decision makers have a number of R&D policies appropriate to reverse this trend at hand (see also Chapter 5):

- Publicly funded research and development programs, for instance, are provided as direct funding for R&D in renewables by the Department of Energy in the US or the Research Councils in the UK.

- Direct capital grants and subsidies have turned out effective for the Japanese PV as well as Danish wind turbine producers.

- Technology demonstration can establish whether emerging technologies are capable of working on a commercial scale. In the US, government-supported demonstration plants which led to private sector participation in the development of next-generation concepts, are seen as key factor in the development of clean coal technologies (Bañales-López and Norberg-Bohm, 2002).

Many infant technologies are initially not cost competitive. They require an enabling environment that helps to bridge the gap between demonstration and commercialization:

- Growing initial markets can be achieved through tenders, feed-in schemes or other subsidies for low-carbon generation sources. Larger markets allow for lower unit costs through economies of scale, as initially small operations shift mass production and facilitates subsequent technology use through training and development of other facilities.

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[14] It should be noted that public R&D expenditures are only a partial proxy for overall energy R&D activity. For several emerging low-carbon technologies such as solar PV and biomass, many of the important technological steps have occurred outside the energy sector and beyond conventional energy research funding, e.g. in the biotech and electronics industries.

- Non-financial support during commercialization, in the form of stringent quality standards and regulations, can mitigate the risk associated with the adoption of new technologies.
- Improving the regulatory environment can be an appropriate way to remove non-market barriers that hamper the implementation of new energy technologies and create an environment conducive to diffusion of novel mitigation options.

Infrastructure policies are an essential aspect of public policy in order to deal with network externalities and coordination failures. To increase the share of low-carbon mitigation options in the power sector, manage the intermittent availability of renewables, and foster electrification across the entire economy, upgrades and extensions of existing electricity grids will be necessary, possibly towards super-grids[15] and / or smart grids[16]. Electricity from nuclear cannot be dispatched according to demand, thus making it challenging to combine large shares of nuclear power with in an energy system dominated by fluctuating renewables. If electrification is to play a major role in abating emissions in the transport sector, the infrastructure to recharge or replace batteries will have to be in place. Another way to reduce emissions from transportation is increased use of public transportation and promoting sustainable urban development. Finally, if CCS is to be deployed on a large scale, pipelines to transport CO_2 from power plants to geological deposits will be needed. The role of the state in these issues depends on each country's economic conditions as well as legal and institutional frameworks and ranges from setting of standards to technology support and the direct provision of the infrastructure in question.

Besides instruments that unfold their potential on the domestic level, technology policy also has an important international dimension. As the process of innovation bears some characteristics of a public good, engaging jointly in research, development, demonstration and deployment and coordinating national deployment and diffusion efforts via dedicated technology action plans helps in sharing the costs as well as the risks associated with the development of new technologies among countries. Furthermore, providing sustainable energy for developing and emerging economies is of key importance if high rates of economic growth are to be maintained while meeting the global climate challenge. It is essential to create an environment which is conducive for technology cooperation and allows for leapfrogging (i. e. making the move from relatively outdated to modern technologies without going through intermediate stages). One component could be provisions with regards to intellectual property rights and financial mechanisms that could either be part of a comprehensive post-2012 agreement on climate change or be channeled through external funds (e. g. the Global Environmental Facility, or the World Bank's Clean Technology Fund or Strategic Climate Fund). International cooperation to support the creation of conducive environments for innovation, diffusion and use of new technologies is essential (low-carbon innovation networks, capacity building efforts, technical and financial assistance), and policymakers should aim at including low-carbon development as a goal into broader development policies.

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[15] Super-grids are electricity networks which extend over a large geographical range. This feature facilitates the inclusion of renewable sources of energy into the energy system, as overall fluctuations in supply are balanced out across regions and become smaller the more intermittent sources are included. Furthermore, large grids could potentially allow imports of electricity from regions with abundant supply of carbon-free sources (e. g. from Northern Africa and the Middle East to Europe; see DESERTEC Foundation, 2009, and Bauer et al., 2009).

[16] Smart grids are electricity networks in which producers and consumers of energy are connected via information networks. This allows an optimal balancing of the load profile, as consumers respond to price signals by shifting their energy consumption to times where prices are lower due to lower demand or higher supply of energy.

4.3 MANAGING RISKS AND CO-BENEFITS

All mitigation technologies included in the climate-energy-economy models employed in this report bear some additional risks as well as co-benefits. In the following, these will be discussed in a qualitative way – there is no simple metric for weighting these risks against benefits, or even estimating their impact in monetary terms. While science can identify risks and co-benefits in an objective manner, it is the task of policy makers and stakeholders to make use of this information and evaluate which options are most or least desirable, based on their respective value systems.

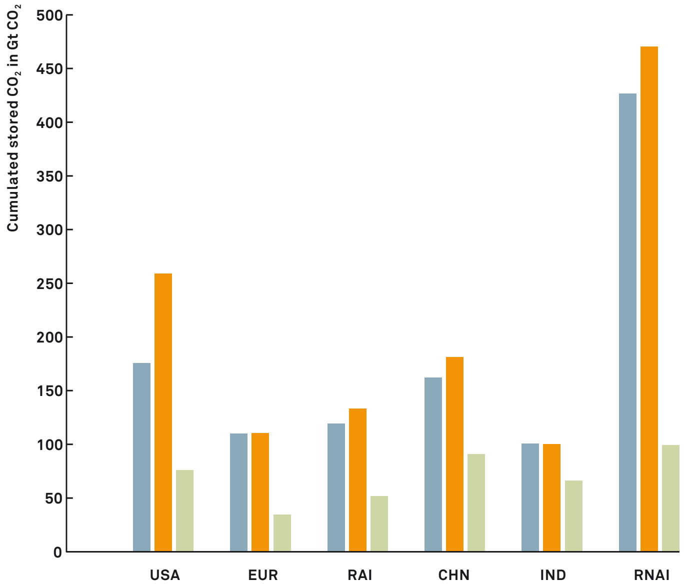
Renewables other than biomass bear relatively few additional risks. Currently, hydropower (which can have detrimental effects in terms of destroying human habitats and ecosystems), accounts for the lion's share of renewable electricity production, but further expansion is constrained by the limited overall potential. Other renewable energy carriers such as wind and solar are expected to contribute substantially to a future low-carbon energy supply. These renewable energy sources are 'intermittent' by their very nature, i. e. prone to natural fluctuations due to variations in incoming solar radiation and wind speeds. The principle options for mitigating the intermittency problem of renewables are (1) dispatchable backup capacities, e. g. gas turbines, (2) storage systems, (3) large scale grid-integration to even out fluctuations across regions, e. g. by establishing a trans-continental super-grid, and (4) demand side management, e. g. via smart grids (cf. Section 4.2). Designing and putting into place appropriate (large-scale) grid-infrastructures which ensure sufficient diversification to deal with the volatility in supply, in combination with back-up and storage capacities will be a challenge from engineering as well as an institutional perspective.

The use of biomass is often depicted as a source of renewable energy that is essentially carbon neutral, as the carbon that is released in the process of combustion matches the amount of carbon absorbed from the atmosphere during plant growth. However, as large-scale energy crop production will increase the competition for land, water, and other inputs, they may create conflicts with other sustainability aspects, like food security, land-use emissions and deforestation, water use and biodiversity loss. First, for estimating the net contribution of bio-energy to a sustainable energy mix one needs to include CO_2 emissions from fertilizer production and application, biomass conversion and trade. Furthermore, if important carbon sinks, such as wetlands or forests, are cleared to make way for the cultivation of energy crops, biomass can have a highly unfavorable carbon balance in the short and medium term. For instance, Searchiner et al. (2008) estimate that, as farmers worldwide respond to higher prices and convert forest and grassland to new cropland to replace the grain (or cropland) diverted to biofuels, corn-based ethanol nearly doubles greenhouse emissions over 30 years. Therefore, there appears to be widespread consensus in the community that biomass entails the greatest climate benefits if degraded and marginal lands and if residues are used (WBGU, 2009). A further issue is the release of N_2O, a highly potent GHG, associated with the use of nitrogen-based fertilizer. If this additional effect is taken into account, commonly used biofuels, such as biodiesel from rapeseed and bioethanol from corn, can contribute as much (or even more) to global warming as fossil fuels (Crutzen et al., 2007). Second, large-scale bioenergy production can have negative consequences for biodiversity. Degradation of natural areas will reduce valuable habitats and ecosystem services from complex ecological systems (Groom et al., 2008). Third, large-scale bio-energy production may affect water scarcity and quality which are highly dependent on particular crop needs. In many regions, additional irrigation for bio-energy will further intensify existing pressures on water resources. Worldwide, agriculture accounts for roughly 70 percent of global freshwater use, but in the future a growing share will be needed for industrial and household uses. Finally, bioenergy expansion will have mixed impacts on poor population in urban and rural areas, as it puts an upward pressure on food prices, raises land values, and potentially increases rural employment (Goldemberg, 2007). Pro-poor policies need to enhance the potential benefits and reduce the adverse impacts, particularly with regard to increasing and potentially more volatile food prices.

Currently, Carbon Capture and Storage (CCS) is in its demonstration stage. The ultimate cost of CCS facilities and the share of the emissions that will be captured are the main technical uncertainties about the technology that might affect its commercial viability. Another major uncertainty concerns the extent of available geological sites where carbon can be stored safely. However, probably the main risk associated with CCS is leakage, i.e. the possibility that a fraction of the carbon dioxide stored in geological reservoirs gradually escapes and is thus released to the atmosphere.

FIGURE 4-2
Stored CO_2 in different world regions as calculated by IMACLIM-R (blue), REMIND-R (orange) and WITCH (green), cumulated from 2005 to 2100

🟦 IMACLIM-R
🟧 REMIND-R
🟩 WITCH



The models project CCS to contribute significantly to future global mitigation efforts in all world regions (Figure 4-2). For Europe, IMACLIM-R and REMIND-R estimate an amount of 120 Gt CO_2 stored in geological formations until the year 2100, while the amount in WITCH is only 35 Gt CO_2. From today's perspective, it is however uncertain whether CCS will ever become a viable mitigation technology. At the current state of play, there is considerable uncertainty about potential leakage rates as well as the extent of safe storage sites which are available. A key challenge for policy regulators will be to devise incentive systems that compensate early movers for bearing high initial costs and assuming risks related to technological uncertainties, while at the same time providing the right incentives for operators to ensure that the captured CO_2 is stored in the best way possible at appropriate geological sites.

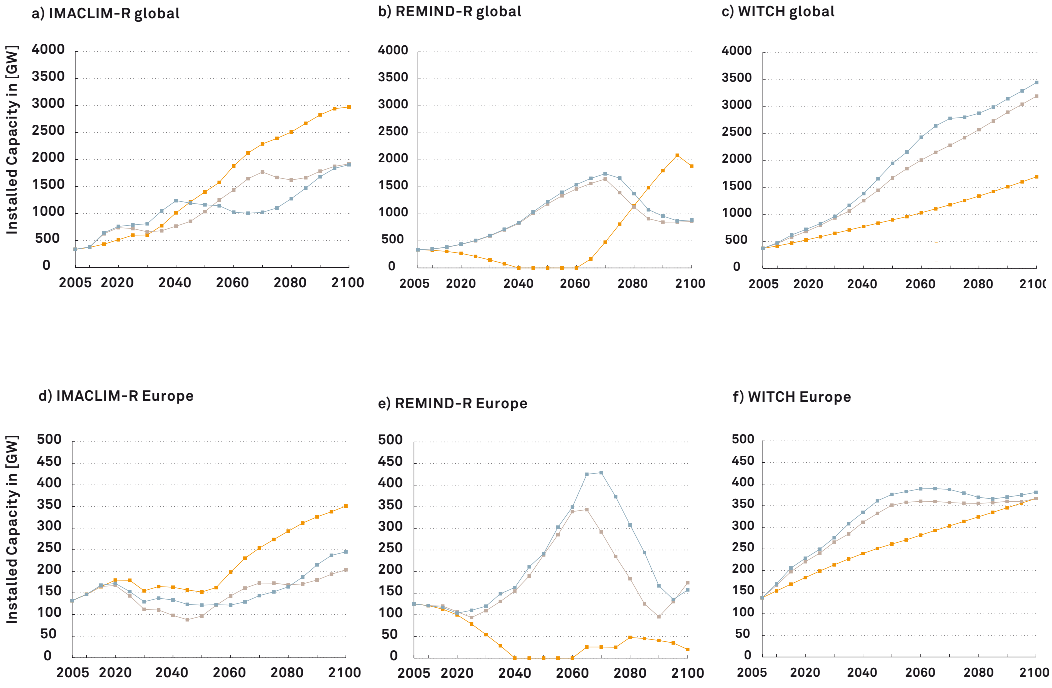
Nuclear energy has low specific CO_2 emissions, even if the energy requirement for extraction and processing of uranium from currently used sites is taken into account. In scenarios with large scale penetration of nuclear power at a global scale, uranium resources at more marginal locations will have to be accessed which is likely to be more energy intensive and therefore also more carbon intensive. The models project a substantial expansion of nuclear power beyond current levels in all scenarios except the REMIND-R baseline[17]. It is important to note, however, that they do not account for

barriers such as limited public acceptance and the specific risks associated with this technology, which are likely to create additional constraints and costs. In the 450 ppm policy scenario, WITCH foresees 1850 GW nuclear capacity by 2050 – an almost five-fold increase relative to currently installed capacity. For the same policy constraint, the total installed nuclear capacity in 2050 in IMACLIM-R and REMIND-R is 1030 and 1340 GW, respectively (Figure 4-3). Expansion of nuclear energy, however, is arguably the most controversial mitigation option due to the following problems related with its use. The potential damage caused by nuclear accidents is very large, even if advances in technology and operation procedures have reduced risks of accidents during operation to low probabilities. A more prominent role of nuclear energy in global energy supply – i.e. a larger number of nuclear power plants – would necessitate higher safety standards to prevent an increase of the global risk from nuclear accidents (MIT, 2003). Such scenarios would also imply the deployment of nuclear power stations in politically less stable regions with potential conflicts with regards to enforcement of security standards and maintenance. The possibility of terrorist attacks on nuclear power plants with potentially devastating consequences needs to be addressed. Further, no site that could be deemed absolutely safe for geological storage of radioactive waste products over the required time horizon of several millennia has to date been identified.
A pronounced increase in nuclear capacities might require fast breeding technology using a closed Plutonium fuel cycle to reprocess fissible material. In this case the transport of radioactive waste from the power plant would entail additional risks of accidents. Finally, as the large majority of reactor types currently in use generate fissible material (Plutonium or ^{235}U) which can be used to construct nuclear weapons, nuclear proliferation is an additional concern responsible for the rather low social acceptance of nuclear power.

FIGURE 4-3
Installed nuclear capacity (global and Europe) for the baseline and default policy scenarios

BASELINE
450 ppm
410 ppm

BASELINE
450 ppm C&C
410 ppm C&C



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[17] In the REMIND-R baseline, nuclear energy is competitive with the largely abundant and cheap coal only after 2060

Energy sources suited to reduce or completely phase out the use of fossil fuels can offer co-benefits beyond reduced emissions of GHGs. They include reducing ambient air pollution (predominantly caused by coal combustion in electricity generation, industry, and household uses, as well as use of petroleum products in transportation) and the resulting impacts on human health, agriculture, forestry and the wider environment. Second, as oil and gas reserves are concentrated in a small number of countries, domestically available energy sources increase energy security for importing countries and can contribute towards easing existing geo-political tensions. The base-line scenarios have illustrated that limited reserves of oil and gas, in conjunction with steadily increasing energy demand, results in high future energy prices if no alternative ways to meet energy demand are developed and thus undermine future economic growth. Third, renewable energy sources can involve local communities and provide employment opportunities. Rural inhabitants in developing countries are most likely to benefit from this aspect.

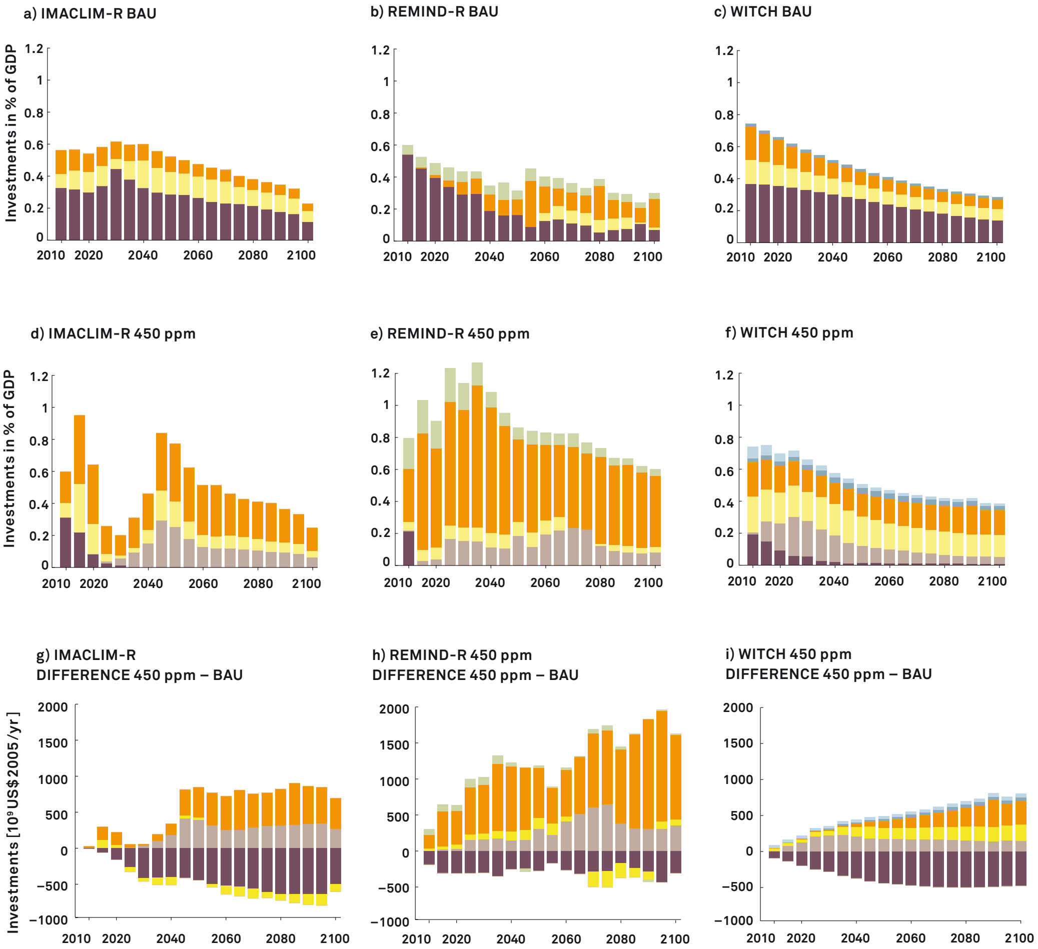
4.4 INVESTMENTS IN LOW-CARBON TECHNOLOGIES

All models project substantial investments into the global energy system over the century. These are in the order of 0.3 % to 0.7 % of world GDP for the baseline scenario, in which investment in fossil fuel based technologies continue to play an important role, as shown in Figure 4-4. In absolute terms, energy system investments show an upward trend; however, this trend is more than outweighed by GDP growth, so that energy system investments as a fraction of GDP show a slowly decline.

In order to achieve the stabilization target, a rapid transformation of the global energy system is needed. According to the model results, this challenge will require sizable flows of new, additional investments. In the projections for the default stabilization scenario, total energy system investments relative to BAU (Figure 4-4) increase by about 0.1 % of world GDP for WITCH and 0.4 % for REMIND-R, while IMACLIM-R projects a cyclical behavior with two peaks in investment activities occurring by the beginning and middle of the century, caused by transitory losses in terms of economic activity and investment decisions under imperfect foresight taken by energy producers. In the policy scenario, REMIND-R projects a higher increase of total energy system investments compared to BAU than WITCH and IMACLIM-R. This result is consistent with the finding that, in the presence of a stabilization policy, WITCH and IMACLIM-R foresee a pronounced contraction of energy supply (cf. Section 2.4) implying less need for extra-investments. This result does not emerge from the REMIND-R model which instead is characterized by a strong switch in investments from traditional sources to carbon free options, especially renewables.

The model projections imply fundamental changes in investment patterns compared to the business-as-usual scenario. 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 up-scaling of investments in renewables and substantial investments in energy conversion technologies equipped with CCS. This means that an ambitious climate policy could trigger additional investments (compared to BAU) in mitigation technologies exceeding US$ 1200 billion by the middle of the century, while reducing investments in conventional fossil fuel based sources of energy generation by US$ 300 to 500 bn. For the WITCH model, which 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 US$ 40bn per year for the next decades, whereas R&D investments for energy efficiency roughly double in the presence of a stabilization policy.

FIGURE 4-4
Investments in the global energy system as percent of GDP in the business-as-usual scenario (a)–(c) and the 450 ppm stabilization scenario (d)–(f). Panel (g)–(i) show changes in total investment flows targeted at the energy sector which are induced by climate policy (calculated as differences between investments in the business-as-usual and the stabilization scenario)



The numbers on overall investments in the reference scenarios are in line with the IEA's most recent projections. The latest World Energy Outlook (IEA, 2008a) projects cumulated investments in the power sector of US$ 13.6 trillion over the period 2010–2030. RECIPE projects US$ 9.6 tn (IMACLIM-R), US$ 10.7 tn (REMIND-R), and US$ 12 tn (WITCH), respectively. In the IEA's climate policy scenario which aims at stabilization at 550 ppm CO_2eq., additional investments amounting to US$ 1.2 tn are required. In addition, the World Energy Outlook projects investments in energy efficiency on the demand side – which are not included in the investment figures calculated in RECIPE – of about US$ 3 tn. With regard to the incremental investments triggered by climate policy, the models' estimates differ significantly from the IEA's. Over the period 2010–2030, IMACLIM-R projects a modest decline in total investments in the energy sector due to the cyclical behavior of investments. For WITCH, the composition of investment changes, but the total volume remains nearly constant, while REMIND-R projects a cumulative increase of US$ 8.7tn[18]. These results underline that additional investments in carbon free instead of fossil sources of energy are clearly mandated. However, considerable uncertainty surrounds the exact volume and timing of these investments.

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[18] These results should be viewed taking into account that RECIPE aims at a more ambitious mitigation goal as the one used in the World Energy Outlook and features a longer time horizon under which larger up-front investments into mitigation technologies become more profitable

Private sector involvement will be crucial to realize these investments. As the above calculations have shown, there are sizable investment opportunities in the energy sector. RECIPE clearly suggest that climate policy will increase total demand for energy sector investment and shift investment demand to alternative energy sources which are cleaner but also more capital intensive than conventional energy generation. This process can be expected to start when policy uncertainty is resolved, i. e. when countries agree on the level of emission reductions. As capital stocks in the energy sector have long lifetimes (often about 50 years), governments should establish credible long-term climate policies so that private investors can include this information in their evaluation of strategy and investment decisions. However, investors will still be confronted with some amount of uncertainty regarding which technologies will prove successful.

Before the onset of the financial and economic crisis, global annual investments in clean energy technologies were growing at annual rates exceeding 50 %, peaking at about US$ 150bn in 2007. The largest part of these investments were targeted at wind power, but investments in solar power accelerated rapidly with an average annual growth rate of more than 250 % in the period 2004–2007 (Boyle et al., 2008). It is very likely that ambitious climate policy will raise investment flows beyond these levels. In the near future, the highest fraction of energy sector investment is expected to take place in developing countries. If advanced developed countries (such as China and India) accept binding obligations to reduce their emissions, carbon prices in combination with additional domestic technology policies are appropriate instruments to guide investment towards low-carbon technologies. For less advanced countries without reduction obligations, investments in low-carbon technologies can still pay off if incremental costs are covered through finance and technology cooperation mechanisms of the UNFCCC or increased development assistance[19].

Climate policy not only induces changes in investment patterns, but also alters fuel demand. In the policy scenarios, additional investment costs for new capacities are partially balanced by lower fuel costs, especially if energy sources such as wind, hydro, or solar power which do not require fuel inputs, are employed. Demand for and prices of fossil fuels will be lower in the policy scenarios compared to the business-as-usual case, while for biomass higher demand and higher prices prevail. These projected developments bear important implications for investors in extractive industries and the agricultural sector, and commodity markets in general, due to their intrinsic linkages.

The calculations do not show an unequivocal link between carbon prices and investment flows. For instance, WITCH features carbon prices that exceed US$ 1000 by the end of the century (see Section 2.3). However, even with such a high carbon price, investments in mitigation technologies remain below those projected by REMIND-R which features a carbon price that is by far lower. This observation can be explained by the differing visions of technological futures (which link mitigation options, carbon prices, and energy system investments) represented by those two models. In REMIND-R, a broader scope of cheap mitigation technologies is available which attracts sizable investments and helps to keep carbon prices low. In WITCH, on the other hand, the model representation of increased energy efficiency and substitution possibilities plays more important roles to achieve the mitigation goal at moderate consumption losses. Therefore, investment flows as well as carbon prices are determined by the interplay between climate policy, the availability of technological options in the energy sector, and opportunities to enhance efficiency and reduce energy consumption.

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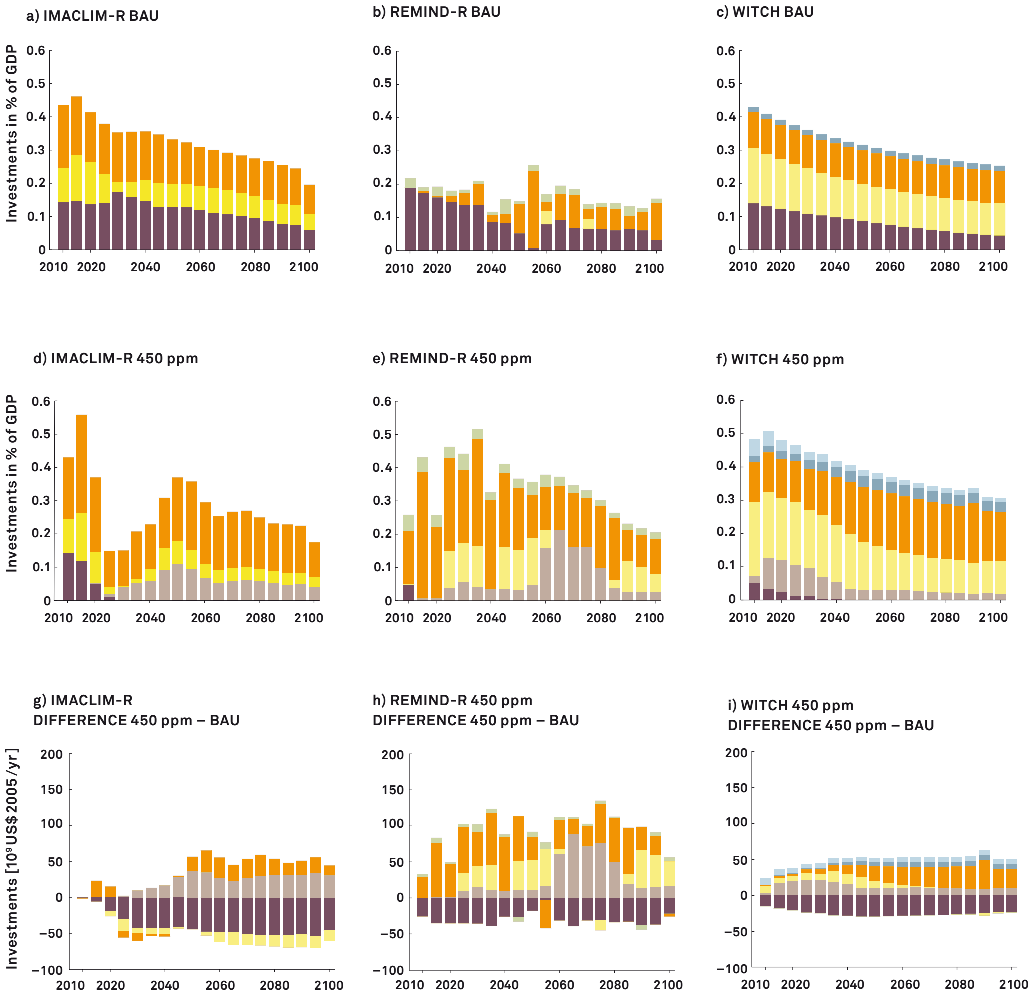
[19] One study (JRC, 2008) comparing several solar PV projects in developing countries found that these yielded internal rates of return of 8-15% and payback times of 8-10 years (assuming an interest rate of 6 % as a benchmark)

FIGURE 4-5
Investments in the European energy system as percent of GDP in the business-as-usual scenario (a)–(c) and the 450 ppm stabilization scenario (d)–(f). Panel (g)–(i) show changes in total investment flows targeted at the energy sector which are induced by climate policy (calculated as differences between investments in the business-as-usual and the stabilization scenario)



Focusing on Europe reveals a picture similar to developments on the global scale (see Figure 4-5). Because of Europe's mature economy and advanced stage of development, demand for investment into energy generation infrastructure is relatively lower than for newly industrializing countries with high rates of economic growth. Investments in the European energy system range from 0.2 % to 0.4 % of GDP, clearly below the world average. To reach the 450 ppm CO_2 stabilization target, investment flows will need to be scaled up by the order of 0.1 % of GDP and redirected from conventional fossil fuels to renewables, fossils equipped with CCS and nuclear energy, as well as increased spending on R&D.

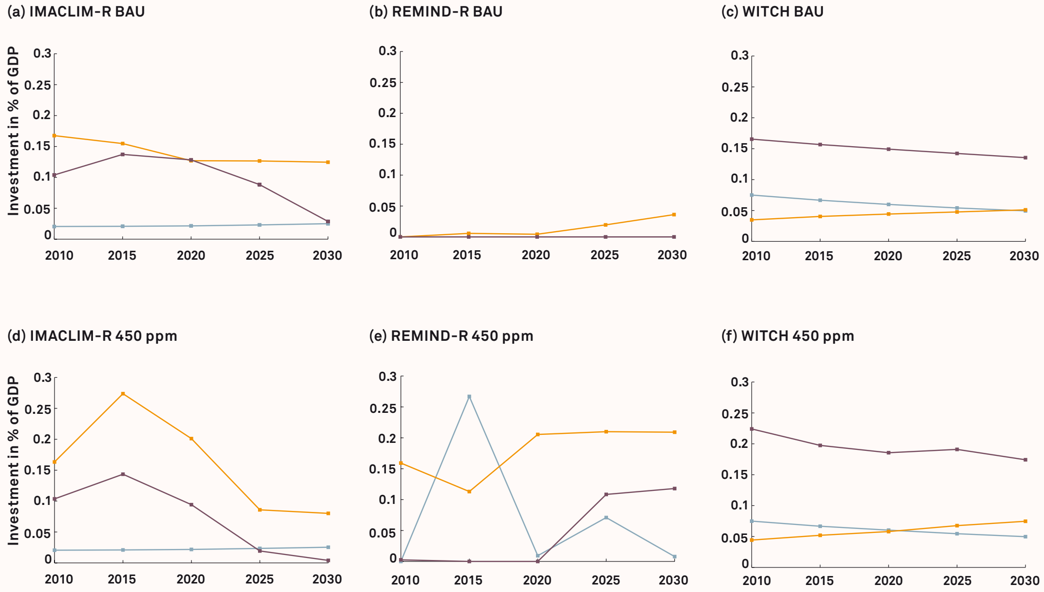
Technology options available today are not sufficient to meet the growing demand for carbon-free energy as it is simulated in the stabilization scenarios. All models emphasize the role of innovation and technological learning in carbon free or low-carbon technologies, be it in the form of a more efficient capturing rate for CCS technologies, or of a substantial improvement in already available renewable energies, such as wind and solar. Additional innovation is likely to occur as a result of a ramp-up in energy R&D investments, at least comparable to levels that were reached in the 1980s as a reaction to the oil price shocks. This is emphasized by the results of the WITCH model where not only experience learning but also energy R&D (which can either increase energy efficiency or lower the costs of backstop technologies) is modeled as an endogenous process.

BOX 4-1
INVESTMENTS IN THE EUROPEAN POWER SECTOR IN 2010–2030

For Europe, rapid decarbonization of the power sector is essential to achieve ambitious climate targets. This box analyses the investment flows in the RECIPE models for wind, hydro and nuclear in Europe for the period 2010–2030 for both the baseline and the 450 ppm C&C scenario (Figure 4-6). In general, wind experiences substantial growth in investment in all models, whereas the trends in hydro are much flatter and results for nuclear widely differ across the models. With some exceptions, investment flows in these low-carbon technologies are larger in the policy scenario than in the baseline scenario, since climate policy encourages the uptake of all these technologies.

RENEWABLES WITHOUT BIOMASS IMACLIM-R projects investments in renewable energies to approximately follow inverted-U shapes. Two major aspects explain this development. On the one hand, generation capacity is likely to increase substantially in the period 2010–2030, and investment costs are expected to fall due to learning effects. Countering this effect, decreasing returns play an additional role, i. e., once the best locations have been occupied, the next ones will induce higher costs, discouraging further investments. REMIND-R shows an almost constant increase of investments in renewable energy, reaching nearly 0.3 % of GDP in 2030.

HYDRO No large increases in investments are projected in hydro in the three models, although they differ regarding the trends in those flows. A sustained but modest increase is projected by IMACLIM-R and a constant flow in WITCH. Investment flows in the 450 ppm C&C scenario do not differ to the baseline in these two models (IMACLIM-R and WITCH), suggesting that an ambitious climate policy is unlikely to have any significant influence on hydro capacity investments. In REMIND-R, no hydropower capacity expansion is undertaken in the baseline until 2030. In the policy scenario, some investment projects, mostly related to the replacement of old vintages, are undertaken. In contrast to renewable energy (and nuclear), there are no major new potentials for this already mature technology. Therefore, investors may expect low risks but probably also low returns for investment in hydropower.



(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 4-6
Investments in the European power sector 2010-2030 as percent of GDP in the business-as-usual (a)–(c) and the 450 ppm stabilization scenarios (d)–(f)

NUCLEAR Investment flows related to nuclear power generation widely differ across the models, because of large uncertainties regarding economic (e. g. evolution of investment costs) and political (e. g. social acceptability) aspects. Therefore, the development of investment flows crucially depends on assumptions on capacity additions in the three models. As a result, the models only provide partial evidence that a more ambitious climate policy would have a greater influence on nuclear. In IMACLIM-R, nuclear capacity declines in the baseline scenario and even more in the 450 ppm C&C scenario, whereas WITCH projects substantial increases for the baseline scenarios and even larger ones for the stabilization scenario. In REMIND-R, capacities decline in the baseline, with no investments into capacity expansion, but a considerable amount of nuclear power is used as a mitigation option in the 450 ppm C&C scenario.

The differing time profiles of investments in mitigation technologies across models point to one of the biggest challenges for their successful deployment. It is clear that they will be required at large scale, but small changes in the assumptions and economic circumstances can shift the deployment by a few years. Such uncertainty acts as a disincentive for any investment in projects and manufacturing capacity (e. g. of wind turbines). The EU Renewables Directive aims to address this challenge by outlining a clear deployment trajectory for renewables and reduce this regulatory uncertainty. Thus it can contribute to increased investment and innovation, and reduce deployment costs.

5 THE ROAD AHEAD FOR ECONOMIC SECTORS IN EUROPE[20]

KEY MESSAGES

- Model results show that all analyzed sectors will have to contribute to the mitigation efforts.
- The power sector plays a strategic role in decarbonization, as other sectors will increasingly cover their energy demand with electricity.
- While in the power generation sector a wide array of mature and immature technology options exist for mitigating CO_2, other sectors – especially the transport sector – are characterized by large uncertainties about technology options.

POLICY IMPLICATIONS

- To incentivize abatement in all sectors carbon pricing plays a crucial role. It has to be part of a well designed policy mix.

Mitigation potentials and strategies vary strongly across source sectors. In the climate change mitigation literature, there is a considerable gap between bottom-up analyses of sector-specific mitigation potentials and top-down modeling approaches. This Chapter aims at filling this gap by providing a sectoral analysis of the model result, complemented by bottom-up sectoral assessments.

This chapter starts off with an assessment of the mitigation effort from a cross-sectoral perspective. It then discusses the status quo, scenarios of future development, and policy instruments for the power sector (5.1), transport (5.2), industry (5.3), and agriculture (5.4). For detailed bottom-up sectoral analyses see Bodirsky et al. (2009).

The sectoral representation of the three models is rather different. IMACLIM-R, a recursive CGE model features the highest sectoral resolution, differentiating 12 sectors.[21] For the model comparison exercise, these sectors are aggregated to four source sectors: electricity, industry, residential and transport. In REMIND-R, the macro-economic demand for final energy is split into stationary (subdivided into electric energy and non-electric energy) and transport applications. WITCH distinguishes between the electricity and the non-electricity sector. The contribution of different end-use sectors of the energy system to the global reduction effort is depicted in Figure 5-1. Full colors represent the emissions caused by a specific sector in the mitigation scenario, while lighter colors show the amount of emission abatement performed in comparison to the baseline scenario.

According to all three models, 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 (cf. also Chapter 2.3). In the policy scenarios, one major mitigation option in the transport sector is the deployment of plug-in hybrid vehicles, resulting in considerable efficiency gains and a shift from non-electric to electric energy demand. In REMIND-R, by contrast, the option to generate transport fuels from biomass in combination with CCS is used extensively. As this technology results in negative CO_2 emissions, it even enables additional headroom for emissions from the stationary sectors.

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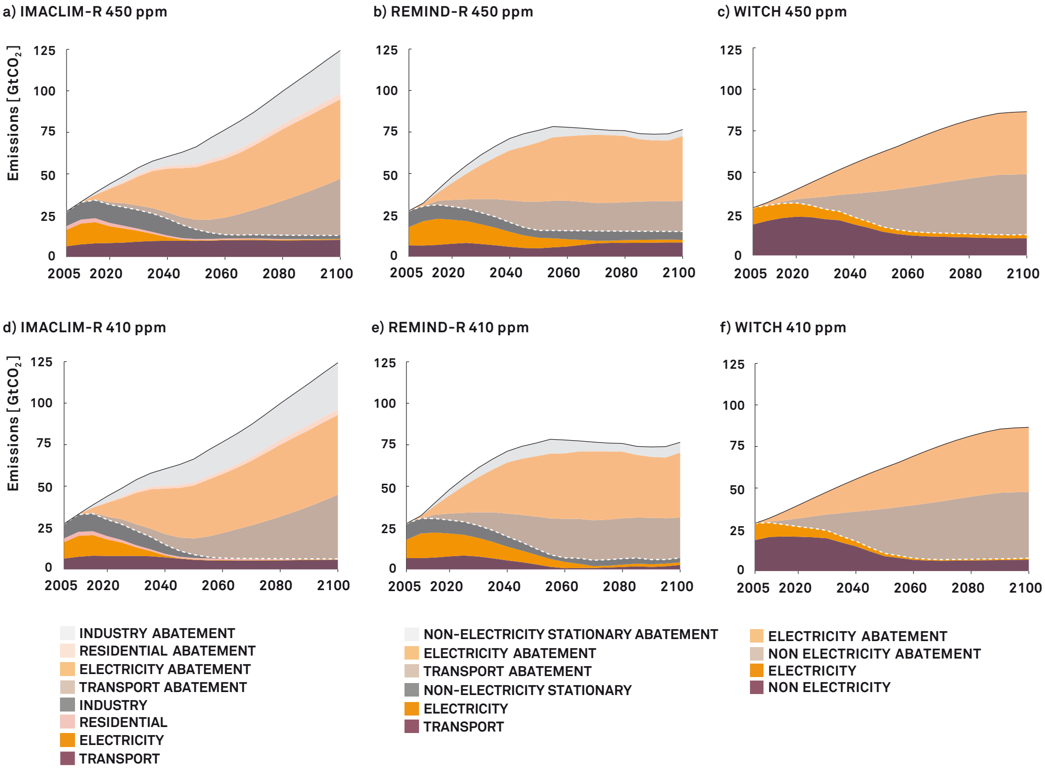
[20] Sector-specific key messages and policy implications are given at the beginning of Sections 5.1–5.4.

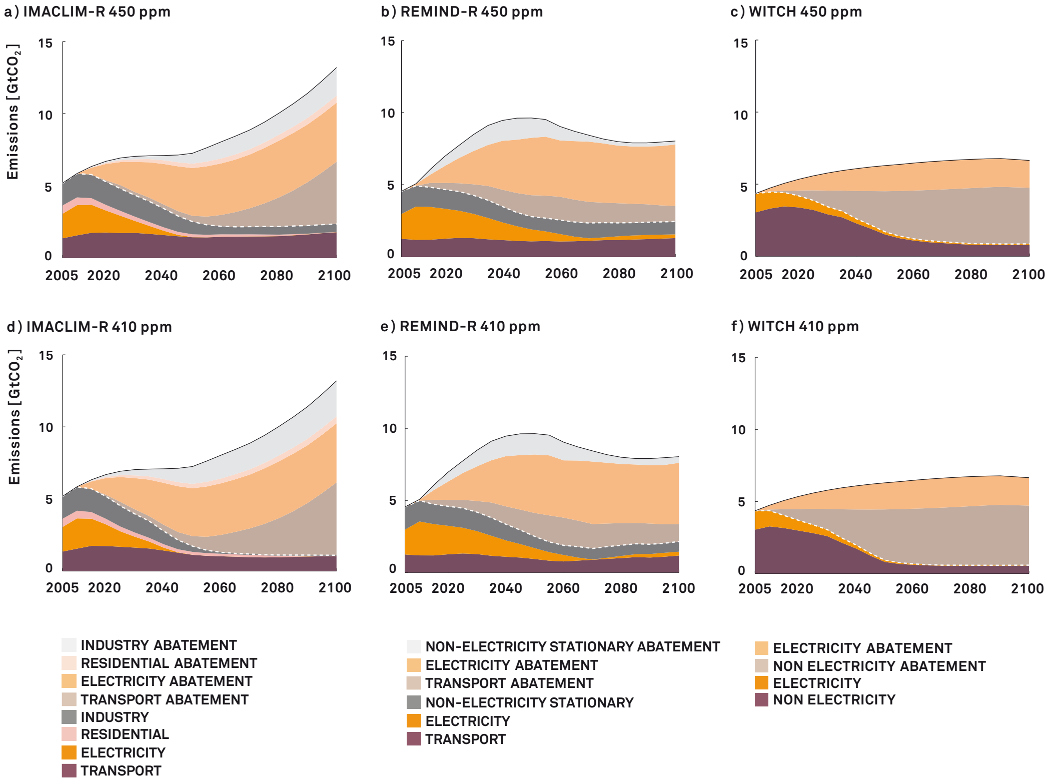
[21] For a more detailed description of the RECIPE models, see Jakob et al. (2009a)

FIGURE 5-1
Global CO_2 emissions decomposed by different sectors for the three models IMACLIM-R, REMIND-R and WITCH for the 450 ppm and the 410 ppm scenario. The upper solid line indicates baseline emissions. The dashed line indicates the emission trajectory in the climate policy scenarios. The emissions abatement – the area between the baseline and policy emissions – can be attributed to the different sectors (light colors). Note that the sectoral breakdown differs between models



The focus of this Chapter is on European sectors and necessary policies. Figure 5-2 displays sectoral emissions and abatement for the European sectors. The general pattern of the decarbonization effort is rather similar to that on the global scale. While all models project deep emission reductions in the electricity sector, the remaining emissions are dominated by the non-electric sectors, particularly transport.

FIGURE 5-2
European CO_2 emissions decomposed by different sectors for the three models IMACLIM-R, REMIND-R and WITCH for the 450 ppm and the 410 ppm scenario. The upper solid line indicates baseline emissions. The dashed line indicates the emission trajectory in the climate policy scenarios. The emissions abatement – the area between the baseline and policy emissions – can be attributed to the different sectors (light colors). Note that the sectoral breakdown differs between models



5.1 POWER GENERATION

KEY MESSAGES

- Power generation is the key sector for the mitigation of greenhouse gases. The sector has a large potential to make a significant contribution to overall GHG emissions mitigation in the EU.
- A wide array of (mature and immature) mitigation technologies with significant abatement potential is and will be available at moderate costs in this sector. Many of these will be required in parallel to achieve ambitious mitigation targets.
- Most low-carbon technologies have a significant potential for cost reductions, if the appropriate policies are in place to encourage their development and diffusion.

POLICY IMPLICATIONS

- Cap-and-trade is the central instrument for fostering the low carbon transition in the European power sector.
- Many low-carbon technologies, particularly renewables, are characterized by considerable learning potential. The European Renewables Directive ensures that Member States provide regulatory frameworks, complementing infrastructure and where necessary financial support for a 20% renewable energy share by 2020.

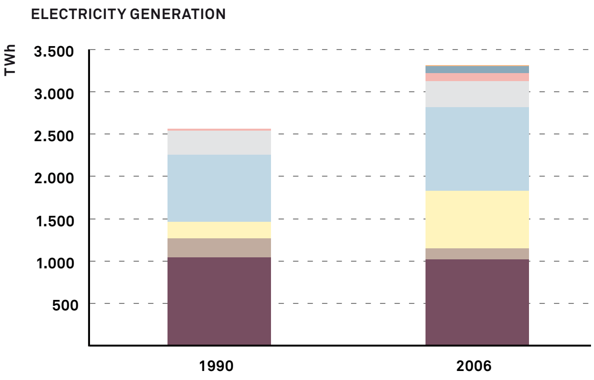
5. 1. 1 STATUS QUO

Power generation data in the EU from 1990 to 2006 shows distinct developments for the use of fossil primary energy carriers in European power generation (Figure 5-2). While the amount of electricity produced by coal has remained constant in absolute terms, oil has been substantially reduced and gas has experienced a three-fold increase. Looking at aggregated numbers, fossil fuels show an increase from 1990 to 2006 of 372 TWh.

Low-carbon generation technologies expanded at different rates. Those with the highest increase are also the ones starting from the lowest base (wind, solar and biomass). The greatest absolute and relative increase has been in wind electricity (from 1 TWh in 1990 to 82 TWh in 2006). In turn, the growth rates of nuclear and hydro have been more modest, but their current shares in total electricity generation are significant. All renewables together (incl. waste) gained importance for electricity generation in the past. In absolute terms the increase was 186 TWh and the renewables (incl. waste) share increased from 12 % to 15 %.

Despite the rise of low-carbon technologies, the EU generation mix today is dominated by fossil fuels (55 %). Compared to 1990, the share of fossil-fuel generation has remained constant, but less carbon intensive fossil-fuels (gas) have a greater share today compared to more carbon intensive fuels like coal.

FIGURE 5-3
Electricity generation in the European Union (IEA, 2008a)


ELECTRICITY GENERATION

5. 1. 2 SCENARIOS OF FUTURE DEVELOPMENT

The European electricity mix as projected by the three models for the baseline as well as the 450 ppm and 410 ppm stabilization scenarios are depicted in Figure 5-4. In the baseline, the European electricity generation mix is dominated by fossil fuels during the century apart from WITCH where fossil fuels, renewables and nuclear power have similar shares by the end of the century.

A variety of low-carbon or even carbon-free technologies is available for electricity production: renewables, nuclear and CCS. Consequently, all models project that in climate policy scenarios the decarbonization in the electricity sector proceeds faster than in other sectors. All models project a steep decline of conventional fossil power generation capacity, while electricity production from 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. According to all models, cost-efficient mitigation requires investments in conventional coal-fired power generation capacity to be phased out until 2020 (cf. Section 4.4). Against this background and in view of the inertia and imperfect foresight in investment behavior, regulators should evaluate complementary, non-market based policies such as carbon efficiency standards to limit the use of coal without CCS.

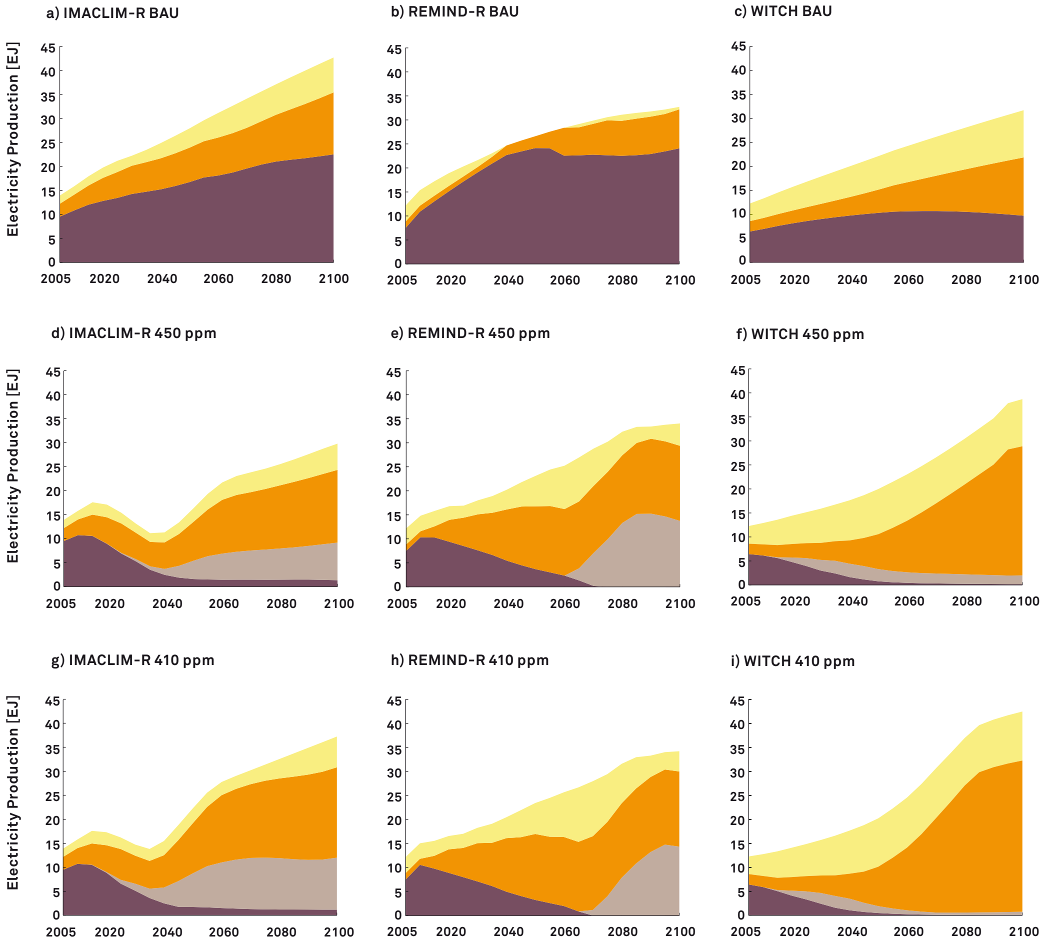
Renewables play a very important role in all three models, and their shares increase substantially with increasing stringency of climate policy. While the European renewables shares in WITCH and IMACLIM-R are more or less in line with the global projections of these models, REMIND-R projects a significantly smaller renewables share in Europe compared to the global level.

Currently, nuclear has a higher share in electricity production in Europe than on the global average. IMACLIM-R and WITCH project a significant expansion of nuclear energy use over the course of the 21st century even in the baseline. Under the assumption of large abundance of coal which was adopted as part of the RECIPE harmonization, REMIND-R projects a gradual phase-out of nuclear power in the baseline. For the policy scenarios, both REMIND-R and WITCH project a significant increase of nuclear energy production. It is important to note that none of the models consider non-economic barriers to nuclear expansion, such as lack of public acceptance, nor nuclear-specific concerns, such as the long-term safety of nuclear storage, the risk of accidents, or proliferation for military use.

In IMACLIM-R the period from 2015 to 2035 is characterized by a substantial contraction of electricity demand. This is mainly driven by large investments in energy efficiency, reducing the demand for power in the economy.

FIGURE 5-4
Electricity mix for the European power sector (IMACLIM-R and WITCH) as well as power and heat for REMIND-R

🟨 NUCLEAR ENERGY
🟧 RENEWABLES INCL. BIOMASS
▨ CCS FOSSIL
🟪 FOSSIL FUELS W/O CCS

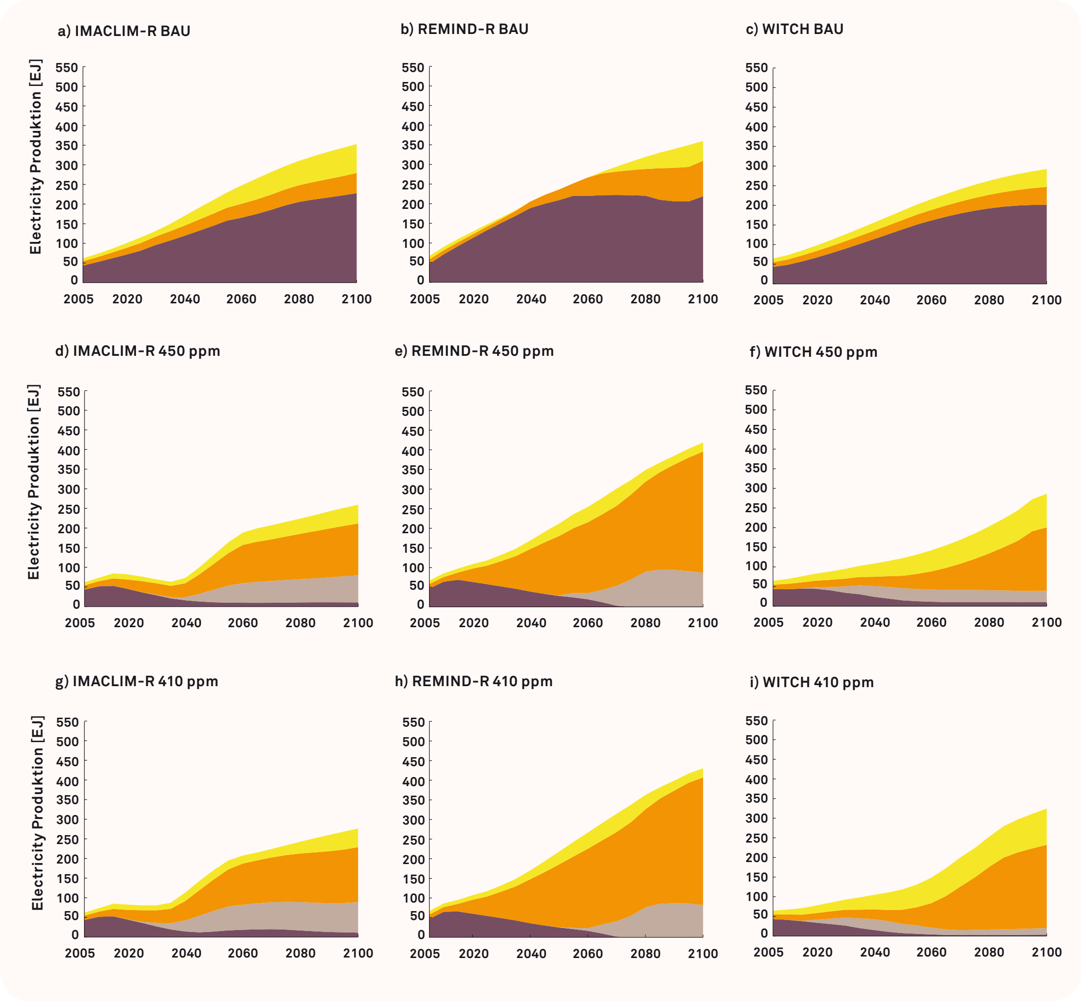


BOX 5-1
FUTURE GLOBAL PERSPECTIVE FOR THE POWER SECTOR

In 2005, global power production accounted for roughly 40 % of overall global primary energy consumption. According to IMACLIM-R and REMIND-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. In the REMIND-R baseline, renewables and nuclear hold a small share in the global electricity mix until 2050, but are expanded significantly afterwards. By 2100, renewables account for 17 % and nuclear for 10 % of the electricity production. IMACLIM-R and WITCH project lower shares of renewables, while nuclear energy plays a more important role in the first half of the century.

In the climate policy scenarios, the decarbonization of the power sector is mainly accomplished by large-scale deployment of renewables, with further contributions from CCS and the expansion of nuclear energy. In the 450 ppm scenario, renewables account for 51 % of the electricity generation in IMACLIM-R, 57 % in WITCH, and as much as 75 % in REMIND-R. CCS deployment is most significant in IMACLIM-R, while it remains on a much lower level in WITCH. In REMIND-R, due to constraints in the geological potential and significant storage needs for CCS use in the production of hydrogen and liquid fuels, CCS in the electricity sector is phased in only after 2050.

FIGURE 5-5
Global electricity 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 share of renewables includes biomass and biomass with CCS



BOX 5-2
HEAT CONSUMPTION

It is expected that in the heat subsector large efficiency gains can be realized in the near future. Besides better insulation of buildings new heating systems are much more efficient than older appliances. Based on the Energy Performance of Buildings Directive (2002 / 91 / EC) Member States have to adopt regulations concerning standards for the energy performance of new and refurbished buildings and the issuing of energy certificates for buildings. To realize the potentials – especially in the residential sector – it is also necessary to tackle long refurbishment cycles

There are significant remaining potentials for renewable sources of heat compared to the total achievable potential in the 2005–2020 period in Europe. Table 5-1 shows the countries with the largest potentials in absolute terms.

The extent to which these potentials for heat from renewable sources are exploited will mainly depend on the removal of the barriers to their deployment and the implementation and fine-tuning of support schemes including combined heat and power under an ETS. These barriers include cost, complex planning and permission procedures and the distance between resources and centers of heat demand for geothermal and inadequate planning guidelines and

TABLE 5-1
Potentials for heat from renewable sources in OECD-Europe in TWh
(based on IEA, 2008c)

ADDITIONAL (TO 2005) REALIZABLE MID-TERM POTENTIALS FOR HEAT FROM RENEWABLES (TWh)

	Geothermal heat	Solar thermal heat
FRANCE	47,9	68,5
GERMANY	86,7	74,1
ITALY	55,0	70,1
POLAND	20,2	20,6
SPAIN	14,9	38,5
UNITED KINGDOM	53,7	55,8
SHARE OF THE ABOVE IN OECD-EUROPE	*69,9 %*	*73,5 %*
OECD-EUROPE TOTAL	*398*	*446*

lack of consistent economic incentives for solar thermal heat.[22]. Whereas there are some instruments – like investment incentives, tax measures, low interest loans and bonus models – in place, promotion of heat from renewable sources is still in an early stage. In some regions – where demographic change and downsizing industrial production capacity take place – heat demand can decrease. In the long run, heat demand will also decrease with increasingly stringent efficiency standards for buildings. This can be problematic where heat supply is realized grid-based (especially district heating) because heating grids need a minimum demand to be operable. There are two main options to deal with this issue: (i) downgrading heating grid systems which is costly and (ii) identifying new heat sinks like cooling technologies.

5.1.3 POLICY INSTRUMENTS

Albeit currently more expensive than their conventional, fossil-fired competitors, most low-carbon technologies in the power sector feature significant potential for cost reductions, if the appropriate policies are in place to encourage their development and diffusion. In addition, low-carbon technologies sometimes suffer from other market failures or regulatory barriers which eventually have a cost implication and can be very relevant for their uptake. For example, grid access and planning permits for some renewable electricity technologies, particularly hydro, can result in significant lead times. These delays entail significant cost for investors.

The European power generation sector is covered by the EU ETS, where it constitutes the major share of emissions. It is expected that the EU ETS will have a major impact on the future structure of the power sector. This will be the case especially after 2013 when auctioning – with exceptions in Eastern Europe – will transmit a full fledged price signal. Electric utilities now face and will continue to face the cost of CO_2 emissions as another input cost. Thus, the carbon price provides an on-going incentive to adopt all types of mitigation technologies, especially the most mature.

Complementary policies should tackle additional economic and non-economic barriers and address market failures at different maturity levels of mitigation technologies. Support in addition to that provided by the carbon price is justified in the case of immature technologies (in the form of R&D and demonstration), whereas such additional support loses legitimacy as technologies reach maturity.

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[22] For a detailed analysis, see the K4RES-H project. www.erec.org/projects/finalised-projects/k4-res-h.html

SUPPORT FOR RENEWABLES

While it is certain that a portfolio of different renewable energy technologies is needed to achieve low stabilization there is a vivid discussion about the support schemes for the use of renewables and their efficiency and effectiveness. Empirical analysis by Ragwitz et al. (2007) showed that technology-specific support schemes, such as feed-in tariffs, have successfully triggered a substantial capacity expansion. For such schemes to be effective and cost-efficient some conditions have to be met. For example, it is necessary for the feed-in tariff rate to decrease over time and technologically differentiated tariff rates must be applied. Tradable quotas for renewable shares in the generation mix may be suitable tools once technologies become more mature, as they incentivize a competition across the different renewable technologies for decreasing their costs.

R&D support is important in addition to support schemes aiming at market introduction, as it will improve the quality of the technology and encourages cost reductions. This holds especially for technologies like concentrating solar power and off-shore wind. The continuation of support schemes throughout the innovation chain – from basic research to large-scale deployment – is a key element to reduce risks for investors with a simultaneous positive effect on the effectiveness and cost-efficiency criteria. In the case of support for renewable energy, this has proven to be the case of feed-in tariffs schemes (del Río, 2008).

With growing shares of renewables in electricity generation, it becomes more and more crucial to ensure their integration in the electricity grid. The EU-funded project GreenNet suggests several policy measures to enable large-scale grid integration of renewable electricity into the European electricity systems: these include the implementation of full-scale unbundling, i.e. the separation of the grid operation from power supply companies, and flexible power market design to facilitate effective use of transmission capacity and optimization of dispatch across all generation assets connected to the grid (Auer et al., 2006).

SUPPORT FOR CCS

While the individual components of the carbon capture and storage process chain are technologically available, large-scale implementation of CCS remains unproven. The absence of large-scale reference projects discourages investments from the private sector. Governmental funding for the large-scale demonstration of this new technology would (1) reduce the risks of the first stage of commercialisation, (2) help to improve the technical quality of the technologies and (3) result in cost reduction, allowing it to mature and compete with other technologies in the carbon market. In particular, given its potentially significant role in mitigation as shown above, full-scale deployment of CCS requires significant efforts in demonstrating and testing the feasibility and costs of this approach, and requires implementation of a suitable infrastructure exhibiting some public good properties (IEA 2008b). Development of the necessary legal and regulatory frameworks, CO_2 reduction incentive pricing, financial support for RD&D, and public outreach are complementary policies to enable CCS. A key challenge for regulators will be devising incentive systems that compensate early movers for bearing high initial costs and assuming risks related to technological uncertainties, while at the same time providing the right incentives for operators to ensure that the captured CO_2 is stored in the best way possible at appropriate geological sites. A possible approach for internalizing the risk associated with CO_2 leakage once the technology is more established and investors can carry the full risk is the implementation of a CCS bond scheme (Edenhofer et al., 2005; Held et al., 2006).
For a detailed discussion of support for renewables and CCS, see Neuhoff et al. (2009a).

5.2 TRANSPORT

KEY MESSAGES

- Without policy intervention, CO_2 emissions from transport will continue to increase strongly. GDP growth, removal of trade barriers, cost reduction and a shift to faster transport modes are the main drivers for growth.
- The future development of low-carbon technologies in the transport sector like electrification, hydrogen and advanced biofuels is highly uncertain.

POLICY IMPLICATIONS

- The short-term priority for the transport sector lies in research, development and demonstration in order to assess the viability of alternative options, to reduce uncertainties and to bring costs down.
- The economic availability of CO_2 neutral fuels, specifically biofuels and hydrogen from renewable sources, will be limited for a long time. Policies promoting the use of biofuels should take the well-to-wheel energy efficiency and greenhouse gas emissions of the production of these fuels into account.
- For the transport sector to contribute to ambitious long term targets in an economically efficient manner, inclusion of transport into emissions trading is unlikely to be sufficient. A combination of complementary policy tools addressing specific market failures and consumer behavior is required, e.g. transport-reducing spatial planning, the provision of public transport systems and efficiency standards.

5.2.1 *STATUS QUO*

The transport sector in Europe has been growing in the last decade. Although improvements in fuel efficiency were achieved and non-fossil fuels were introduced, ever increasing transport demand is outweighing the associated emission reduction. Since 1990, both freight and passenger transport volumes and the respective energy consumption increased (Figure 5-6). Since 1970, the transport volumes even doubled.

FINAL ENERGY CONSUMPTION TRANSPORT IN EUROPE

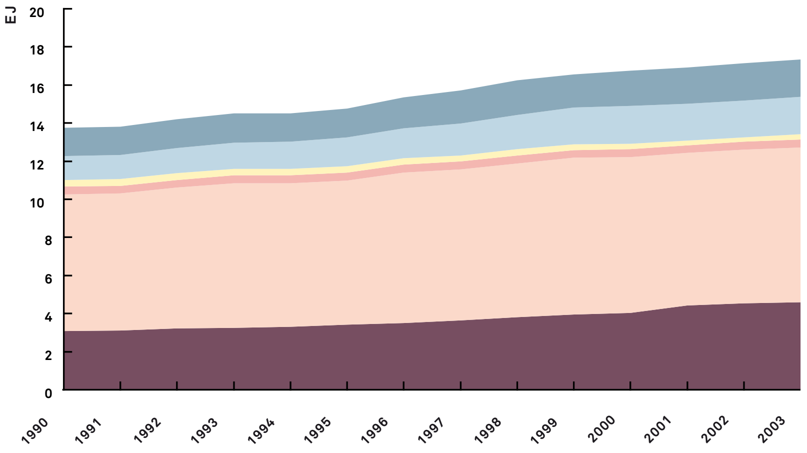


FIGURE 5-6
Final energy consumption in the European transport sector
(CE et al., 2006; based on Eurostat data and EEA, 2005)

■ SEA
■ AIR
■ INLAND NAVIGATION
■ RAIL
■ ROAD (PASSENGER)
■ ROAD (FREIGHT)

The main subsectors responsible for this trend are passenger cars and lorries as well as passenger aviation and maritime shipping. New Member States of the EU exhibited the highest growth rate in energy consumption of the transport sector (about 30 % during the period 1990–2003 which is about 10 % more than average).

5.2.2 *SCENARIOS OF FUTURE DEVELOPMENT*

Currently, transportation energy is almost exclusively provided from fossil fuels. As oil will become increasingly scarce, the IMACLIM-R and REMIND-R models project that alternative fuels will play an important role already in the baseline (Section 2.4). IMACLIM-R projects that in the baseline the transport sector will heavily rely on coal-liquefaction (not displayed in Figure 5-6), and biomass is also projected to assume an increasing share of primary energy supply from 2020 (IMACLIM-R) or 2030 (REMIND-R) under business-as-usual. WITCH does not explicitly model the transport sector.

Emissions abatement in the transportation sector is considerably more challenging than in the power sector due to the absence of cheap carbon-free alternative primary energy carriers in the short-term and the presence of long-lived transport infrastructure like road and railway networks.

The principal mitigation options in transportation are:

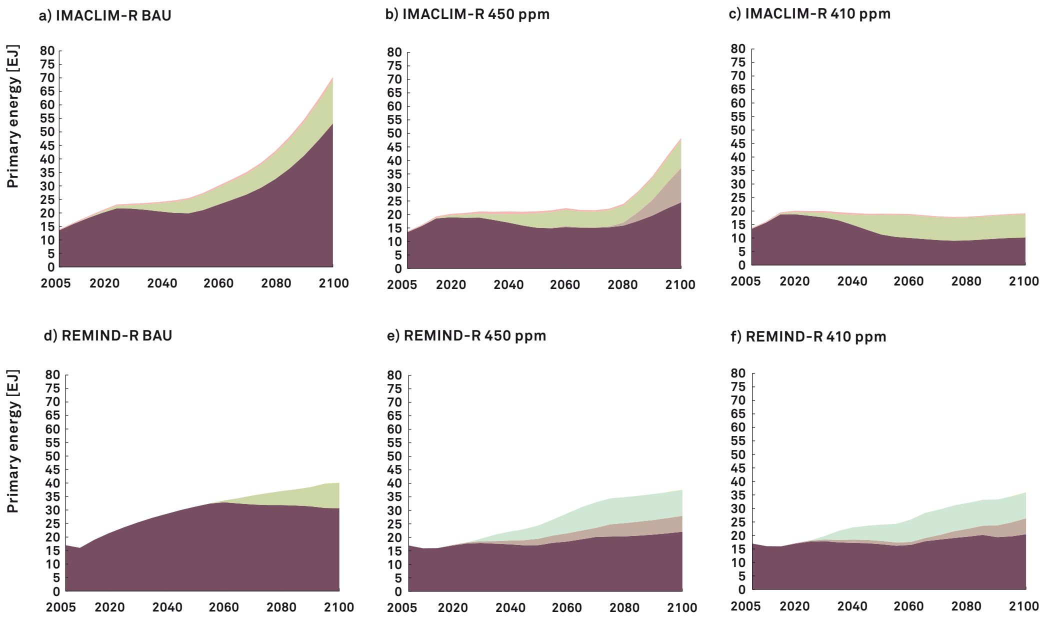
(1) reducing transport volumes;
(2) reducing energy consumption through modal shift, e. g. from road to rail;
(3) improving fuel efficiency;
(4) using biofuels;
(5) electricity as secondary energy carrier;
(6) hydrogen as a secondary energy carrier.

The first two options largely rely on changes in consumer behavior, while the latter four are mainly technology-oriented. Changes in consumer behavior are notoriously difficult to achieve, and they require substantial policy intervention to materialize. Their potential is in the short term assumed to be limited. The large expansion of economic activities over the model horizon also entails a significant evolution of consumption patterns. The long-term challenge is to use the opportunity of this unavoidable change, to guide the development towards low-carbon growth – both using technical options and opportunities associated with individual choices for products and services that are lower carbon.

In terms of technological mitigation options in the transport sector, the models represent different visions (Section 2.3). In IMACLIM-R – a model with distinctively detailed treatment of the transport sector – reductions of energy demand for transport plays a dominant role. They results from (1) energy efficiency improvements in the vehicles fleet, (2) the penetration of plug-in hybrid technology, and (3) infrastructure policy introduced as complementary measures of carbon pricing to decrease the transport intensity of the economy. The introduction of plug-in hybrid vehicles also enables partial shifts from fossil and biofuels to other renewables primary energy sources via the electricity supply. As outlined in Section 5.1, a number of low-carbon technology options exist for electricity generation.

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.

FIGURE 5-7
Projected energy mix for the European transport sector in the IMACLIM-R and REMIND-R models for the baseline, 450 ppm and 410 ppm scenarios. WITCH does not report the transport sector separately



The difference in the models' visions on the future development of transport points to the large uncertainty about decarbonization strategies in this sector. The robustness of individual model results with respect to techno-economic parameters, the portfolio of energy conversion technologies, carbon-prices and biomass availability remains to be explored further.

Since the main technological mitigation options for transport are still in a rather immature stage, research, development and demonstration inducing technological innovation in the transport sector is therefore of particular significance to make deep long-term reduction targets attainable at acceptable costs.

BOX 5-3
FUTURE GLOBAL PERSPECTIVE FOR THE TRANSPORT SECTOR

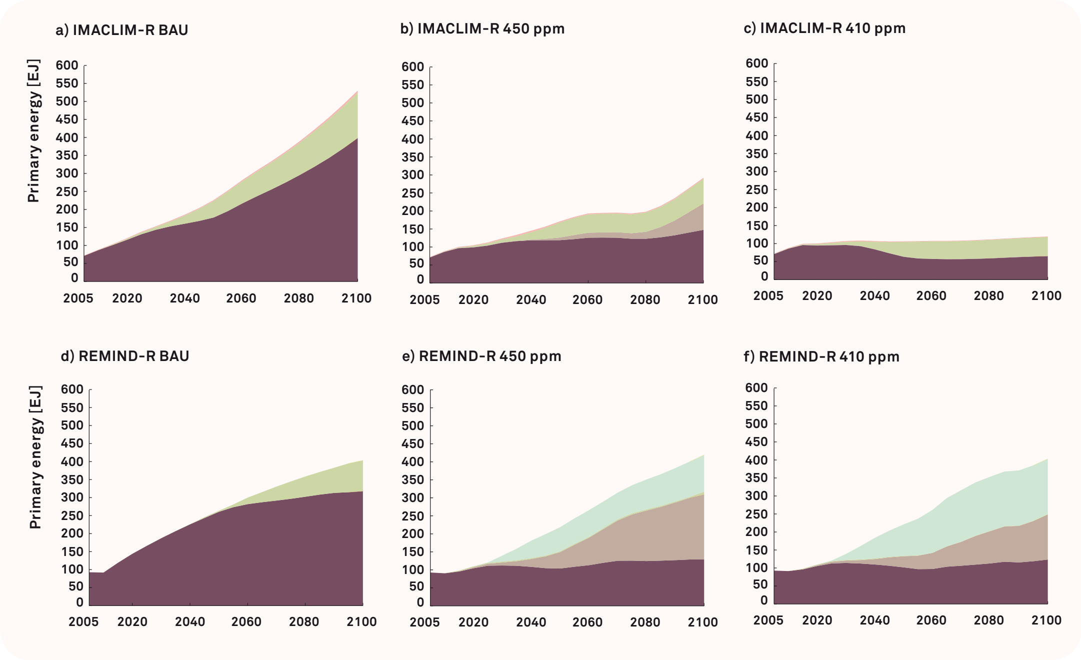
According to REMIND-R and IMACLIM-R, the primary energy use in the transport sector will globally grow by a factor of 4.5 to 6, respectively, over the course of the 21st century if no climate policy is in place. Currently, transportation energy is almost exclusively provided by fossil fuels. As oil will become increasingly scarce, both models project that alternative fuels will play an important role already in the baseline. IMACLIM-R projects that the transport sector heavily relies on coal-liquefaction. Biomass is also projected to assume an increasing share of primary energy supply from 2020 (IMACLIM-R) or 2030 (REMIND-R).

In IMACLIM-R, efficiency improvements play a dominant role. They largely derive from the introduction of highly efficient plug-in hybrid vehicles. This results also in a partial shift from liquid fuels to electricity as a secondary energy carrier. As outlined in Section 5.1, a number of low-carbon technology options exist for electricity generation.

REMIND-R envisages large-scale production of liquid fuels and hydrogen from biomass and coal[23] combination with CCS in the mitigation scenarios. By 2100, these conversion pathways account for roughly two thirds of the total primary energy demand. The negative emissions generated from biofuels allow for a larger amount of remaining fossil fuel use.

[23] It is important to note that coal liquefaction in combination with CCS has no emission reduction potential compared to conventional fuels. In REMIND-R, this technology is mainly used as a result of the scarce oil reserves

FIGURE 5-8
Primary energy mix for the transport sector (IMACLIM-R and REMIND-R), in the baseline as well as the 450 ppm and 410 ppm stabilization scenarios. In its current version, WITCH does not report the transport sector separately



5.2.3 POLICY INSTRUMENTS

In general, cost-effective climate mitigation policy requires an equalization of marginal abatement costs across sectors and regions, achievable by a comprehensive and credible cap-and-trade scheme. This provides a principle case for eventually including transport into emissions trading systems in the future. Including the transport sector in the EU ETS also signals that fossil fuel prices will rise in the future, setting an incentive to develop low-carbon technologies.

The feasibility of including aviation into emissions trading will be explored in the EU ETS from 2011. In this sector a limited number of relatively large companies are active, so that an effective trading system can easily be set up (e.g. CE, 2005 b). In July 2008 the European Parliament agreed on inclusion of aviation in the EU ETS from 2012 onwards. Including sea shipping into emissions trading requires a global agreement as incomplete regional coverage will simply shift bunkering across international ports. Options are currently explored by UNFCCC and the International Maritime Organization (IMO).

A trading system for road transport can be incorporated in the ETS by means of upstream coverage at the refinery level, as envisaged in the Waxman-Markey bill – thus avoiding high transaction costs that would arise under downstream coverage at the level of car users. Mixed upstream (transport) and downstream (e.g. power sector) coverage within a single ETS represents no problem (UBA, 2005), as long as double counting or non-coverage of fuels traded across sectors is excluded (Hargrave, 2000).

Caveats to the inclusion of transport into the EU ETS relate to concerns over public support due to rising fuel prices, and interaction with fuel taxes. For example, Babiker et al. (2005) and Paltsev et al. (2007) argue that in presence of the high already existing fuel taxes in some EU countries inclusion of transport into emissions trading can be welfare-decreasing. Others argue that strong additional policies will be necessary if the transport sector is to provide a contribution to reaching future global CO_2 reduction goals. This will likely include modal shift, i.e. increased use of public transport systems which often require public infrastructure investment. For reaching ambitious long term goals for CO_2 reduction, a strong combination of efficiency improvement, CO_2 neutral fuels and volume measures is likely to be necessary.

BIOFUELS POLICY

Biofuel policy has to ensure that (1) the biofuel use has a positive effect on GHG mitigation and (2) sustainability issues are addressed. The Directive on the promotion of the use of biofuels or other renewable fuels (2003/30/EC) sets indicative targets for a minimum proportion of biofuels placed on national markets with reference values for 2005 and 2010 of 2% and 5.75%, respectively. The target for 2005 has not been achieved (the share in 2005 was approximately 1%) and it is doubtful if the target for 2010 will be reached (EU Commission, 2007 a). Nonetheless, the national policies pursued to comply with the directive have created a very significant increase of biofuel production and consumption in the EU.

Recent studies showed that particularly the so-called first generation of biofuels have many negative side effects and hardly reduce GHG emissions. They even may significantly increase GHG emissions and cause other negative environmental and socio-economic effects when induced land use change impacts are taken into account. Therefore, the target for biofuels has been challenged and heavily criticized by stakeholders and NGOs. To address these concerns the Commission intends to introduce sustainability standards for bioenergy crops and biofuels. It has also broadened the target, so as to allow electric cars to contribute to the targets.

VEHICLE REGULATION

Setting efficiency standards is a widely applied policy in addition to fuel taxes to achieve emission reductions and decrease the dependency on foreign oil. In 2008, the European Union decided on binding fuel efficiency targets for passenger cars. A target of 130 g/vkm for 2015 is combined with an indicative long-term target of 95 g/km for 2020. Also several US states and the federal US government have introduced fuel efficiency standards for passenger cars. Standards, although considerably lower than in the EU, also exist in Japan and China.

This type of vehicle regulation has the advantage that it guarantees improvement of the fuel efficiency of the fleet, and is therefore regarded as a key element in GHG policy for transport. Long-term targets can help car manufacturers to invest in time in technological innovation (King, 2008).

RESEARCH, DEVELOPMENT AND DEMONSTRATION

The optimal mix of technological mitigation options for the transport sector remains largely unclear. Models remain inconclusive about the relative importance of advanced biofuels, electrification of the vehicle fleet, hydrogen, and efficiency improvements. The technologies are still immature and need substantial further development before being rolled out at large scale. As emissions abatement in the transport sector is more expensive than in other sectors, the mitigation costs in transport are a key determinant for the carbon price level. The model results also demonstrate that the availability of mitigation options in the transport sector is decisive for the overall mitigation costs. Thus, there is a strong case for enhanced R&D funding for the relevant technologies as means to induce innovation and to make long-term reduction targets attainable at acceptable costs. Basic research and effective demonstration programs on advanced biofuels, batteries, electric propulsion systems, and hydrogen motors is important to improve these technologies and to explore possible innovative technology pathways. In view of the uncertainties with respect to limitations of each technology, a wider portfolio of technologies should be brought to the early stages of commercialization before letting the markets determine the most successful technology.

5.3 INDUSTRY

KEY MESSAGES

- Absent policy intervention, the industry sector's primary energy mix will be dominated by fossil fuels, in particular coal. In presence of climate policy more electricity is used and the energy mix is decarbonized in accordance with the power sector generation mix.
- The industry sector holds significant potential for energy efficiency improvements.
- Asymmetric carbon prices bear limited risk of carbon leakage for a few sectors, i.e. cement, iron and steel, aluminium, refineries and fertilizers.

POLICY IMPLICATIONS

- A key barrier to mitigation is the slow rate of capital turnover. In Europe, emission reductions in the near to medium term will not be implemented by investing in new installations but rather by improving technologies of existing installations as only a few new installations are scheduled for construction in the mid-term. After 2020, a new capital turnover cycle is expected in Europe. This dynamic has to be taken into account when implementing a carbon constraint for the industrial sector.
- Due to the long-lived nature of the production capital, reliability is of key importance. Industry thus needs a stable, transparent policy regime to encourage investments in more expensive but more carbon-efficient technology.
- Asymmetric carbon prices raise leakage concerns, typically resulting in the full free allowance allocation to most industry sectors. This creates investment uncertainty and distortions to the carbon price signal, limiting incentives for low-carbon innovation, investment and substitution. Border adjustment could allow for a shift from free allocation to full auctioning, but raises serious concerns about discrimination or trade sanctions. International cooperation would be essential to limit the use of border measures to create trust and avoid discrimination

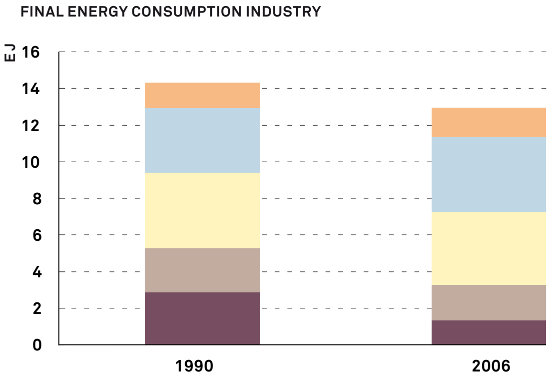
5.3.1 STATUS QUO

CO_2 emissions from industry arise from three sources: (i) the use of fossil fuels for energy, either directly by industry for heat and power generation or indirectly in the generation of purchased electricity and steam; (ii) non-energy uses of fossil fuels in chemical processing and metal smelting; and (iii) non-fossil fuel sources, for example cement and lime manufacture. Industrial processes also emit other greenhouse gases like N_2O, HFCs, PFCs, SF_6 and CH_4. Total greenhouse gas emissions from the industry sector were 12 $GtCO_2eq$ in the year 2000 (including indirect emissions). Non-energy related CO_2 emissions are estimated to be 1.7 $GtCO_2$. Non-CO_2 gases contribute another 0.4 $GtCO_2eq$. IPCC (2007c)

Globally, the iron and steel sector is the largest industrial emitter of energy and process CO_2. In 2005, it accounted for 20% of world industrial energy use and 30 % of energy and process CO_2 emissions (WRI, 2005).

EU-27 steel output has increased slightly between 1997 and 2007, from 194 Mt to 210 Mt. Despite this growth in output, energy consumption decreased between 1990 and 2006 (Figure 5-9). Especially the final energy use from coal – and to a lesser extend oil – has decreased. The use of electricity increased both in absolute numbers and shares.

FIGURE 5-9
Final energy consumption in the European industry sector (IEA, 2008a)



In 2006, European non-energy related industrial greenhouse gas emissions represented 8 % of total emissions in the EU-15 (305 Mt CO_2eq.) (EEA, 2008b). These emissions of greenhouse gases in the European industrial sector comprise mainly CO_2 from cement and iron and steel production, N_2O from nitric acid production, and HFCs from refrigeration and air conditioning equipment.

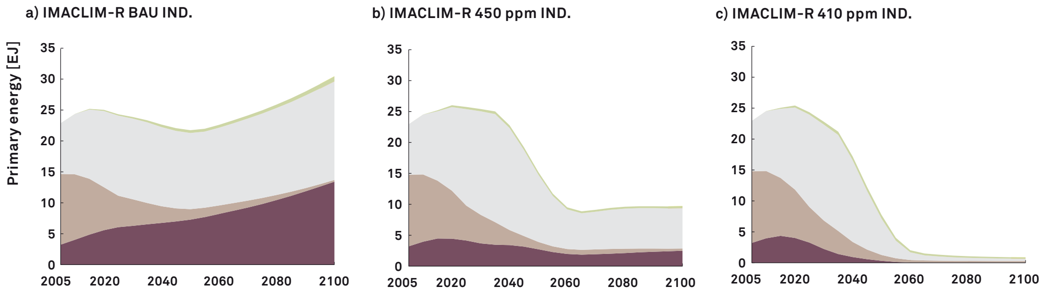
Mitigation potentials with state-of-the-art technologies are already realized in European installations, e. g. by energy savings measures like dry processes and the reduction of flue-gas temperature in cement production and reducing heat losses by insulation in steel production (EU Commission, 2008c).

5.3.2 *SCENARIOS OF FUTURE DEVELOPMENT*

The projected primary energy demand for the industry sector in Europe is depicted in Figure 5-10. As only IMACLIM-R explicitly represents the industry sector, no results from REMIND-R and WITCH are available.

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. According to the results from IMACLIM-R, the industry sector holds significant possibilities for energy efficiency improvements and shift to electricity, while alternative non-fossil primary energy carriers do not play an important role. 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 is a result of a switch in the energy mix from non-electric energy carriers to electricity in the new capital vintages after the introduction of a carbon price. Because of the increasing utilization of electricity, the development of direct and indirect emissions from industry sector is closely interlinked with the power sector. 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 direct primary energy use in industry is projected to be very small.

According to the results from IMACLIM-R, the industry sector holds significant possibilities for energy efficiency improvements and shift to electricity, while alternative non-fossil primary energy carriers do not play an important role.


a) IMACLIM-R BAU IND.

b) IMACLIM-R 450 ppm IND.

c) IMACLIM-R 410 ppm IND.

FIGURE 5-10
Projected direct primary energy use for energy demand in the industry sector in Europe for IMACLIM-R. Note that the demand for electricity and the implied primary energy input is not accounted for. REMIND-R and WITCH do not report the industry sector separately

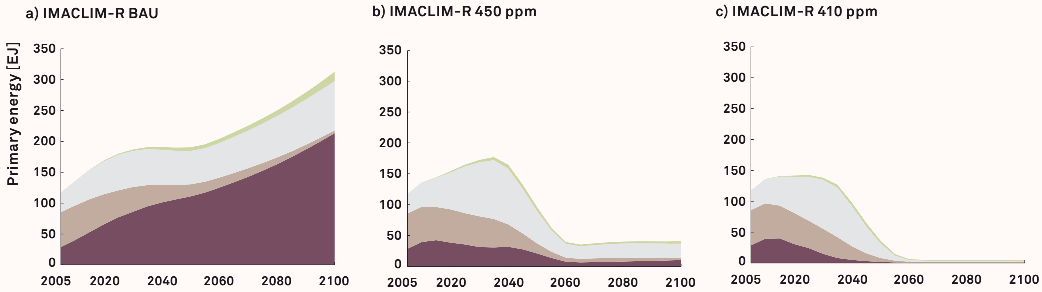
🟨 BIOMASS
⬜ NATURAL GAS
🟫 OIL
🟪 COAL

BOX 5-4
FUTURE GLOBAL PERSPECTIVE FOR THE INDUSTRY SECTOR

On a global scale, the industry sector currently accounts for roughly 30 % of the primary energy demand and a similar share of energy-related CO_2 emissions. According to IMACLIM-R results, absent climate policy, both primary energy demand and emissions are projected to more than double by 2100. The industry sector holds significant possibilities for energy efficiency improvements and shift to electricity, while alternative non-fossil primary energy carriers do not play an important role in the models. The major emission reduction strategy is thus the replacement of old capital vintages with more efficient equipment, largely run with electricity as a secondary energy carrier. On the long-term, the reduction of direct and indirect emissions from industry thus hinges critically on effective decarbonization strategies in the power sector. According to some studies, also hydrogen will play a major role as secondary energy carrier in the industry sector (IPCC, 2007c).

On global scale, steel, cement and pulp and paper industries have the largest mitigation potentials within the industry sector. Large potentials exist particularly in emerging economies. Besides several sector-wide mitigation options there are also process-specific mitigation options, e. g. the use of blended cement (with less clinker) in cement production.

To realize these potentials outdated technologies have to be replaced, e. g with the help of technology transfer and the implementation of standards. Especially in the cement production process energy efficiency improvements are promising, first of all in countries that use outdated technologies (IPCC, 2007c).


a) IMACLIM-R BAU

b) IMACLIM-R 450 ppm

c) IMACLIM-R 410 ppm

FIGURE 5-11
Direct primary energy use of global industrial sector for IMACLIM-R. Note that the demand for electricity and the implied primary energy input is not accounted for. As CCS does not play a role for the sector, fossil fuels are further decomposed into coal, oil and natural gas. REMIND-R and WITCH do not report the industry sector separately

🟨 BIOMASS
⬜ NATURAL GAS
🟫 OIL
🟪 COAL

CCS can be applied to industrial processes with CO_2 emissions both from energetic and non-energetic use of fossil fuels. However, CCS for non-power applications has not been studied as detailed as in the power sector. Thus, little knowledge exists about the required capacities and infrastructure. Because industrial processes are very different in terms of process characteristics, scale, CO_2 concentration and gas stream characteristics cost estimations show a very broad range. Low capture costs are expected for processes that produce a very pure stream of CO_2. In that case costs might even be lower than in the power sector (McKinsey, 2008). For iron and steel and also cement, the products focused on in this report, CCS is one option when looking at blast furnaces for reducing iron ore to iron and direct reduction iron (DRI). Also steel recycling by melting of scrap steel in electric-arc furnaces has mitigation potentials which are directly linked to the source of electricity (IPCC, 2007c). Moreover, the use of hydrogen to reduce iron ore is a longer-term mitigation option for steelmaking.

5.3.3 POLICY INSTRUMENTS

Much of the mitigation potential is not realized today, because it is not demanded by either the market or government regulation. Investors will implement abatement technologies if they expect efficiency gains that provide an economic payout or a possible achievement of sustainability goals of the company. These investments are risky for investors if the product gets more expensive and looses competitiveness because of carbon prices and/or more costly production processes. A stable, transparent policy regime has to address several barriers: (i) slow capital stock turnover in the sector, (ii) resource constraints and (iii) technology adoption for sectors and countries.

Emissions from the European industry subsectors paper, cement and steel are covered by the EU ETS. In the case of Germany, the EU ETS is complemented by self-commitments of the German steel and cement subsectors to reduce CO_2 emissions by 22 % until 2012 and 28 % by 2008 / 2012, respectively, compared to 1990.

But since in other countries the sector is not integrated in an emissions trading system, there are fears that companies move their production capacities from countries with a cap-and-trade system to countries without such a system. Due to the asymmetric CO_2 prices, concerns about the loss of industrial competitiveness and leakage of CO_2 emissions feature prominent in policy discussions (see also Section 3.4; Neuhoff et al., 2009a).

There are three *short-term* options to level carbon costs with respect to operation and investment:

Border adjustments can be pursued to level carbon costs for a small number of energy-intensive commodities that are prone to carbon leakage. However, also ideas are circulating for a border application to final products and linked to countries' overall effort in addressing climate change. The challenge is to ensure that the implementation is pursued in a way that is compatible with WTO rules and that the application of border adjustment does not undermine the sense of cooperation in climate policy. It might be valuable to explore approaches to pursue international cooperation to limit the use of border adjustment, thus both creating a basis for further trust in cooperation, and facilitating the focused and non-discriminatory use of the instrument to avoid free allowance allocation.

Free allowances for industries at risk can compensate for the cost increase a producer incurs due to carbon pricing, but do not automatically address leakage concerns. After all, an installation might sell freely allocated allowances and use the revenues to finance the relocation of production facilities. Therefore, the free allocation of allowances has to be linked to existence, availability or production of the respective installation in order to be effective in addressing leakage. Such linkages do however, as was demonstrated in analyses of national allocation plans during the first two trading periods of EU ETS, create perverse incentives, and might thus severely limit the ability of EU ETS to create incentives for emission reductions and innovation in the industry sector.

Investment support for efficiency improvements in sectors that might be at risk of leakage. The direct compensation option to address leakage could be added to existing tools in order to ensure that investment and re-investment in low(er)-carbon technology takes place in the ETS territory. If return on investment hinges on carbon costs and the higher returns are expected outside the ETS, then this can be compensated with a subsidy for carbon-friendly technology. This is likely to be an effective mechanism for sectors with high capital-costs, particularly if they are at a point in their investment cycle where near re-investment in the light of carbon pricing will not be profitable in the ETS territory. Thus, direct compensation on a case by case basis could address investment leakage very effectively, if it is made conditional on information disclosure by industry as well as on its continued operation. Moreover, the indirect carbon costs from electricity cost pass through could be addressed by this tool mainly for sectors with a high share of indirect cost (such as aluminium). Electricity production as such is not subject to high trade intensity, thus, the substitution of power from regions without carbon pricing is not required for the power consumers, but may be a relevant issue for sectors with high share of electricity use.

RESEARCH AND DEVELOPMENT

The European Commission supports an Europe-wide consortium (ULCOS, Ultra-low CO_2 Steelmaking) which aims at research and development of new technologies for the steel production process. There is a need for new technologies if further emission reductions should be realized because when looking at the most modern steel plants in Europe there are no more potentials due to physical constraints.

STANDARDS

Based on the Integrated Pollution Prevention and Control – IPPC Directive (Directive 2008/1/EC, the former Directive 96/61/EC) the EU Commission launched an EU-wide consultation process. This process aims at developing Best Reference Documents (BREFs) for various subsectors including iron and steel, ferrous metals, cement and lime, pulp and paper and others. These documents are the main reference documents used by competent authorities in Member States when issuing operating permits for the installations that represent a significant pollution potential in Europe. Because the BREFs include the best available techniques they will have an important impact on less-carbon intensive appliances and processes, ensuring that basic environmental standards thus complementing incentives for emissions reductions under the ETS.

5.4 AGRICULTURE

KEY MESSAGES

- A range of mitigation options for the agricultural sector is available at low, zero or even negative costs. These include soil management, precision fertilizing, and manure management. However, considerable non-price-related barriers such as difficulty of monitoring, uncertainty, and non-permanence have to be overcome.

POLICY IMPLICATIONS

- Due to potentially high transaction costs, an expansion of the emission trading system to the agricultural sector is not appropriate to incentivize the available mitigation potentials in a cost efficient manner.
- A climate change mitigation strategy in European agriculture should be part of a wider policy approach towards sustainable agriculture and rural development, consistent with related goals in environment policy and development policy.

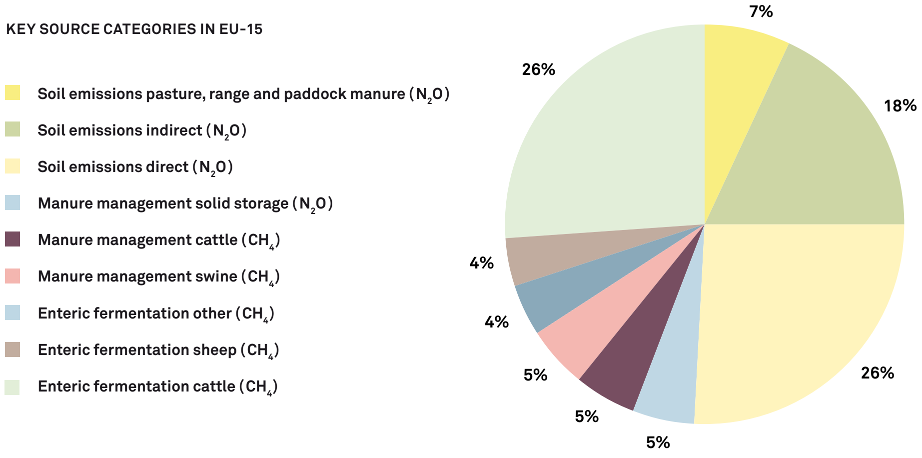
5.4.1 *STATUS QUO*

In the EU-15, N_2O and CH_4 emissions from the agricultural sector contribute about 5 % and 4 % of total GHG emissions respectively (EEA, 2008 a). The main sources of agricultural GHG emissions in the EU-15 are 34 % enteric fermentation from ruminants, 15 % manure management, 51% emissions from agricultural soils. Emissions from biomass burning and rice production are negligible in the EU.

CH_4 (METHANE): CH_4 emissions in the EU are nearly exclusively associated with livestock production. Roughly 73 % of agricultural CH_4 emissions derive from enteric fermentation and 27% from manure management (EEA, 2008 a). Enteric fermentation from cattle form the largest part of CH_4 emissions, accounting for 2.4% of total and for 25 % of agricultural GHG emissions of EU-15 in 2006. Enteric fermentation from sheep is of minor importance. CH_4 emissions from manure management account for roughly 1 % of total GHG emissions. Emissions from rice cultivation are negligible.

N_2O (NITROUS OXIDE): The major share of agricultural N_2O emissions derive from agricultural soils which account for nearly 5 % of total GHG emissions. The main source is direct soils emissions (2.5 % of total GHG emission). In the EU-15, Germany and France are responsible for nearly half of emissions from this source. Emissions from pasture, range and paddock manure account for 0.6% of total GHG emissions. Indirect (= off-site) N_2O soil emissions account for 1.6 % of total GHG emissions in the EU-15. A minor share of agricultural N_2O emissions is generated by manure management in “solid storage”. In this category the share of new member states is remarkably high.

FIGURE 5-12
Share of key source categories in the agricultural sector for non-CO_2 emissions in 2005
adapted from EEA, 2008a


KEY SOURCE CATEGORIES IN EU-15

5.4.2 *SCENARIOS OF FUTURE DEVELOPMENT*

Abatement in agriculture plays a key role in mitigating greenhouse gases. 10–40 % of global mitigation across sectors in the next century may come from agricultural abatement and biomass (Rose et al. 2007). Given the variety of agricultural structures, farming systems and site conditions, there can be no "one-fits-all" priority list at the EU-level. The effectiveness of most measures depends on regional and local conditions. Moreover, it must be taken into account that a measure can have a certain mitigation potential in one region while it induces higher emissions elsewhere (leakage). So the possible impacts for measures in the EU have to be considered at the global level, e. g. with regard to shifts in land use.

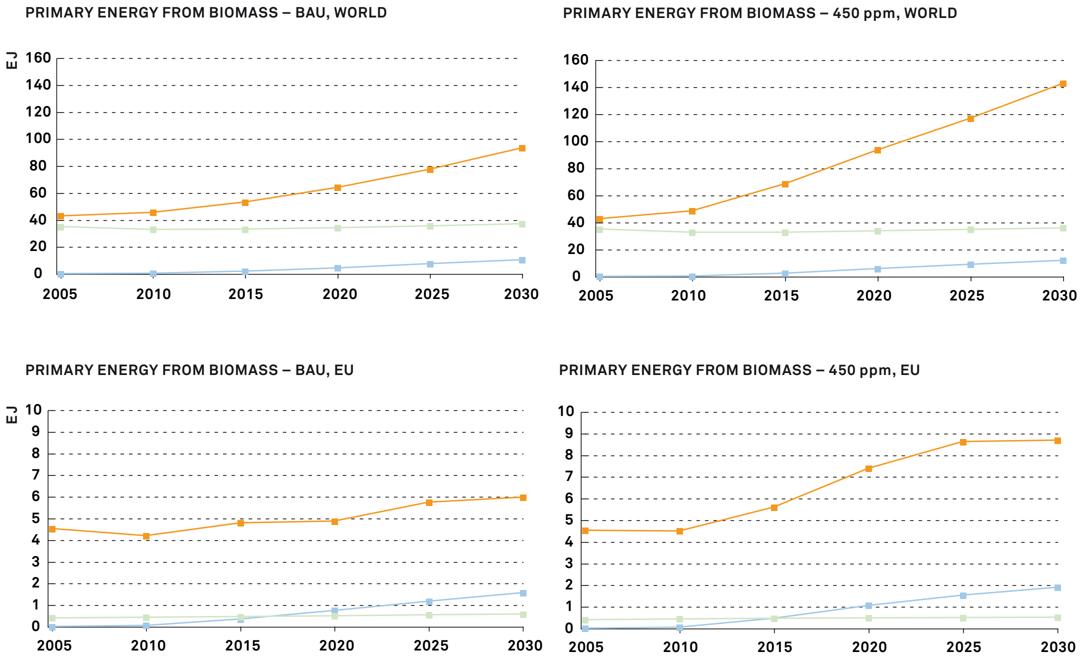
The extent to which emission mitigation in agriculture will be undertaken crucially depends on the incentive structure for farmers. The cheapest mitigation options comprise mainly instruments which are already in line with best practices in agricultural production, such as no-tillage or conservation tillage, precision fertilization, manure management or changes in livestock diet. However, currently most of these management options are not compulsory. At higher emission prices, shifts in production and land use may occur, and bio-energy becomes more profitable (Smith et al. 2007 b).

By far the highest mitigation potential has been estimated for various types of bio-energy production, mainly from cellulose-based feedstocks. Improved energy efficiency also seems to offer great mitigation potential in the EU. However, this is not ascribed to the agricultural sector. CO_2 sequestration is also a promising mitigation measure. It can be distinguished between preservation of existing carbon stocks (permanent grasslands, forests, soils with high organic matter content like peat lands, bogs and wetlands) and carbon sequestration in mineral soils. Measures for CO_2 sequestration are afforestation and agroforestry. Certain bio-energy crops like short-rotation trees and perennial grasses do also offer potential for CO_2 sequestration, in addition to the substitution of fossil fuels. CO_2 sequestration in mineral soils via cropland management measures (reduced tillage, diversified crop rotation systems and monitoring of carbon balances) offer less potential per area, but are not to be neglected, as they are applicable on all cropland and thus amount to a high overall potential. They offer co-benefits in terms of agronomy, biodiversity and soil protection, but they suffer from specific problems and barriers of implementation, i.e. non-permanence, uncertainty, additionality and high monitoring costs. CO_2 sequestration in mineral soils is partly overlapping with measures to reduce N_2O emissions from soils which also can be implemented widespread and offer many co-benefits for water protection and biodiversity. The effectiveness of these measures is rather uncertain, as they depend much on site and weather conditions and skills of the farmer. With regard to the abatement potential for N_2O from legume crops, there is little consensus in literature. They can lead to both reduced and increased N_2O emissions. The mitigation potential is rather low compared to CO_2 sequestration. The abatement potential in the livestock sector (mainly manure management and feeding practices) is estimated to be much higher, compared to N_2O abatement via crop management, but significantly lower than the potential for CO_2 sequestration. Some measures are rather costly and afford investment, some are available at low cost.

Emissions from the agricultural sector are not modeled explicitly by any of the three models. The models currently neglect non-CO_2 emissions which are the main contribution to climate change from the agricultural sector as well as carbon emissions from land use and land use change. The models do, however, model the demand for biomass in the energy system.

Until the year 2030, the three models project similar levels of total energy consumption at about 750-800 EJ in the BAU, and 500-600 EJ in the policy scenario. Major differences occur only after 2050. The level of primary energy production from biomass is shown in Figure 5-13.

FIGURE 5-13
Primary energy production from biomass in the three models (baseline and 450 ppm policy scenario)



REMIND-R shows the highest share of bioenergy in primary energy supply in the BAU and the policy scenario in 2030. The lowest levels of bioenergy are projected by IMACLIM-R. IMACLIM-R and WITCH show no significant difference in biomass production between the BAU and the policy scenario. In REMIND-R, biomass production in 2030 increases to 145 EJ per year in the policy scenario, compared to 93 EJ in the BAU scenario.

These numbers can be compared with recent estimates of global sustainable biomass energy potential from the German Advisory Council on Global Change (WBGU, 2009) and Smith et al. (2007 a). WBGU (2009) estimates the global technical potential for bio-energy from waste and residues in 2050 to be 80 EJ per year (or rather 50 EJ per year taking into account sustainability criteria, especially soil protection). The global potential for cellulose-based energy plants is estimated to be 30–120 EJ per year, if forests, peat lands and wetlands are excluded from use. This gives in total a range of 80–170 EJ per year in 2050. Smith et al. (2007 a) estimate a global mitigation potential from bioenergy production equivalent to 50–200 EJ per year in 2030.

IMACLIM-R projects global bioenergy production at 10–12 EJ per year in 2030, and EU production at around 2 EJ. This level is rather low and is not expected to put any serious pressure on agricultural production or land-use change. WITCH projects global bioenergy production at around 36 EJ per year in 2030, and EU production around 0.5 EJ per year. These estimates are very low for the EU, and at the lower end of global figures in the references cited above (WBGU, 2009, Smith et al., 2007a). These numbers would affect agricultural production, but would probably not add serious pressure to agricultural resource use. REMIND-R projections for the BAU scenario are still in the lower range of the reference numbers for world totals, but already fairly high for the EU, compared to current levels and different estimates in literature. REMIND-R projections for the policy scenario for 2030 are at the higher end of WBGU estimates (given that these are for 2050 only) and of the range given by Smith et al. (2007 a). Again, REMIND-R projections for EU are relatively high, but still within the range of other sources.

In the BAU scenario, the REMIND-R projections for 2030, bioenergy contributes around 12 % to total energy use worldwide and around 5 % in Europe. In the REMIND-R policy scenario, biomass contributes around 24 % to total energy consumption worldwide, and around 10 % in Europe. Given the estimates in literature and modest assumptions about future technological change in agricultural production, these numbers are not expected to put serious pressure on agricultural production systems in Europe and worldwide.

In this scenario, IMACLIM-R shows a sharp rise of carbon prices up to 350 US$ / t CO_2 until 2030. Although there is so far considerable uncertainty about abatement costs for carbon sequestration in soils, prices of several hundred dollars could be a sufficient incentive to engage a lot more in this. Although this is not covered by the models, it can be assumed that an increase in carbon prices would probably result in a rise of food prices, especially for meat and dairy products, if the agricultural sector was included in emission reduction schemes. This would most likely be associated with structural changes in the livestock sector in the EU. Carbon prices in the REMIND-R stabilization scenario remain low during the whole period. Hence, it is unlikely that there would be strong incentives to integrate carbon sequestration in soils in an emission trading scheme. Carbon prices in the WITCH stabilization scenario start to increase strongly from 2030 on. In 2050 they would be around 500 US$ / t CO_2. This should be an incentive for carbon sequestration in soils, and also for forest and peat land preservation as well as further GHG mitigation, but only if the international community and national policy indicators find a way to adequately integrate this into climate mitigation policies. Of course, the inclusion of land-use related emissions into a global climate policy regime also depends on many other factors and objectives, not just the level of carbon prices.

In addition, high demand for bio-energy is influencing agricultural markets and, hence, agricultural production. This holds true for the EU as well (OECD, 2008 a). Recent projections (OECD and FAO, 2008; von Witzke et al., 2008) show that bio-ethanol as well as bio-diesel production will still increase in upcoming years. Compared to 2008, OECD and FAO (2008) – assuming no major importance of cellulose-based technologies – expect that the production of bio-ethanol will triple by 2017, whereas the production of bio-diesel will double. Such an increase would require devoting a major share of oilseed production in the EU as well as a substantial share of grain production to bio-energy production (von Witzke et al., 2008, Bamiere et al., 2007). This may not be a sustainable strategy (Bringezu et al., 2007), especially not if food-security aspects are taken into account. Hence, rather strong uncertainties are associated with the future development of crop production for bio-energy purposes in the EU. The future development heavily depends on the availability of cellulose-based (second generation) technologies and on policy changes. Current support schemes of bio-energy production in the EU and other OECD regions are not only costly, but also have limited impacts on reducing greenhouse gases and improving energy security (OECD, 2008 a).

5.4.3 POLICY INSTRUMENTS

Besides climate policy in the context of the UNFCCC there is a range of other EU policies with significant impacts on climate change mitigation in agriculture. Those with the strongest link are energy policy, environment policy (water, air, soil) and agricultural policy.

INTEGRATING AGRICULTURE IN THE EU EMISSION TRADING SYSTEM?

Emission trading systems (ETS) intend to create incentives for investment in emission reduction projects and use price mechanisms to promote abatement on the supply side. In a communication from January 2007 (EU Commission, 2007 b) the EU Commission suggested to strengthen the ETS and extend the scheme to other GHG and sectors. These suggestions have been further elaborated in a legislative proposal (EU Commission, 2008 a) to amend the current ETS-directive. Yet, in that proposal the Commission explicitly excludes the agricultural sector from further extension of the ETS and does not allow for credits from carbon sinks (LULUCF projects). The major reason for this is that agricultural emissions are very difficult to monitor which is a fundamental prerequisite for inclusion of a sector into cap-and-trade and crediting approaches. Instead, the commission suggests, in a proposal for the so-called “effort sharing decision” (EU Commission, 2008 b), to cut overall emissions of sectors not yet included in the ETS by 10 % from 2005 levels by 2020.

The new ETS Directive includes post-2012 CO_2 and N_2O emissions from the production of N-fertilizer (nitric acid and ammonia). The extended scope on N-fertilizer production would increase agricultural production costs. Higher prices for N-inputs could be an incentive for farmers to make use of more efficient nutrient management practices.

ENERGY POLICY (OBJECTIVE FOR BIOFUELS)

A major concern of EU energy policy is energy security. The biomass action plan (EU Commission, 2005) intends to more than double the use of biomass in heating, electricity and transport by 2010 to reduce imports of fossil fuels. In 2007, the Commission proposed further targets, with a 20 % target for all renewables by 2020 (EU Commission, 2007 b) and 10 % for biofuels. These targets have been confirmed in the “climate change and renewable energy packet” of January 2008. The target for biofuels has been challenged and heavily criticized by stakeholders and NGOs, because of possible negative impacts on sustainability goals connected with biofuels. To address these concerns the Commission intends to introduce sustainability standards for bio-energy crops and biofuels.

ENVIRONMENT POLICY: WATER QUALITY, AIR QUALITY, SOIL CONSERVATION

A climate change mitigation strategy in European agriculture should be part of a wider policy approach towards sustainable agriculture and rural development, consistent with related goals in environment policy and development policy. This wider policy approach includes

- Water quality: The Nitrate Directive aims to protect water bodies against nitrate pollution from agricultural sources. It was adopted in 1991. In 2002, all member states transposed it into national law, but it still lacks full implementation and proper application. The Water Framework Directive (WFD, entering into force in 2005) was designed to improve the management of water bodies and to achieve "good chemical and ecological status" of all water bodies until 2015. Member states have identified river basin districts, set up monitoring programs and are currently working on management plans and programs. The implementation of the Water Framework Directive (WFD) is highly relevant for mitigation strategies, as wetland soils contain large amounts of organic matter and the management of wetlands determines their function as a carbon source or sink.

- Air quality (EU health and environmental objectives): In 2005, the EU defined health and environmental objectives to improve air quality and set emission targets for main pollutants. This includes reductions of NO_x and NH_3. NO_x and NH_3 emissions are interconnected with N_2O emissions via N-fluxes. They have the same sources, and instruments to reduce these air pollutants have direct impacts on climate change mitigation.
- Soil directive: A recent Commission's proposal (EU Commission, 2006) addresses the problem of soil degradation and erosion. Member states would be obliged to identify areas of risk for erosion, organic matter decline, compaction, salinization and landslides, and to take measures to reduce these risks. One major concern addressed by the soil directive is low organic matter content of cultivated soils. Therefore, its successful implementation could be a central part of a mitigation strategy.

COMMON AGRICULTURAL POLICY (CAP)

Some of the existing CAP instruments, although designed for other purposes, do already promote mitigation as a side effect, others lead to higher emissions. Instruments that promote mitigation are e. g. agri-environment measures (AEM), certain payments for modernization of agricultural holdings and machinery, and cross compliance (CC) obligations. Current instruments that counteract mitigation are coupled payments for livestock, export subsidies for animal products and indirect incentives for conversion of grassland to cropland. Most decoupled payments are still insufficiently linked to environmental standards.

The Common Agricultural Policy has recently undergone an assessment ("health check"). The original goal was to adjust the CAP to meet new challenges in the fields of climate change, renewable energies, water management and biodiversity. However, as the health check has led to little additional funding for these new priorities and has not set mandatory objectives for emission reduction or CO_2 removals, it is not to be seen as a general shift in rural development measures towards mitigation of climate change. Full use of the mitigation potential in the agricultural sector would require a general screening of existing instruments. Further and more fundamental reform of the CAP, possibly including a phase-out of direct payments, may be forthcoming with the beginning of the new programming period from 2014 onwards. This would be the appropriate time to fully integrate mitigation measures into the CAP and to reduce current incentives for GHG emissions. AEM could be clearly targeted for climate change mitigation with a result-oriented approach.

OTHER MARKED-ORIENTED INSTRUMENTS

TAXATION AND LEVIES: Similar to an emission trading system, a tax or levy on emission-intensive inputs or emissions would promote sustainable production and emission abatement. An EU-wide taxation of nitrogen has often been proposed by environmental NGOs to tackle the problem of nitrate leaching. It has never been realized at EU level, although in some European countries different nitrogen taxation policies are (or have been) in place. Taxation schemes may be applied to mineral fertilizers, N-surplus at the farm level, number of livestock units, or external feedstuff. This would have to be in addition to the inclusion of N-producers in EU ETS, as this inclusion only covers emission during the production process but not emission during use of fertilizers.

CARBON LABELING addresses the issue from the demand side: As the "carbon footprint" of food products varies widely (von Koerber et al. 2007), consumption and dietary patterns (demand side) significantly influence the mitigation potential of the agricultural sector (supply side). Information and awareness-raising on the consumer side offers opportunities for a marked-oriented approach towards a climate-friendly agriculture and food chain (von Witzke, Noleppa 2007).

6 RECIPE FOR THE LOW-CARBON TRANSITION

RECIPE (Report on Energy and Climate Policy in Europe) set out with the ambition to further our scientific understanding of the economics of decarbonization. The following questions where addressed:

- How does the overall mitigation effort translate into reductions in the various end-use sectors?
- How will mitigation costs change if some key low-carbon technology options are unavailable?
- How does the global mitigation effort affect the distribution of income among world regions?
- What are the effects of a delay or incomplete participation in a global agreement, and how can an international carbon pricing regime be constructed over time?

For tackling these questions, RECIPE combined a top-down model comparison with detailed bottom-up analyses. Three state of the art climate-energy-economy models, embodying harmonized socio-economic assumptions but diverging visions of future technological developments, were employed to generate a set of self-consistent scenarios of possible low-carbon pathways. Experts identified challenges and opportunities in individual key sectors as well as the appropriate mix of policy instruments to bring about the changes that have to take place in the global economy. The result is a list of key ingredients, a ‘recipe’, needed to accomplish the low-carbon transition.

THE CHALLENGE

The challenge is to avoid dangerous climate change while minimizing mitigation costs and creating co-benefits. Absent climate policy, RECIPE projects that carbon emissions will result in atmospheric concentrations between 730 ppm and 840 ppm CO_2, corresponding to a **GLOBAL MEAN TEMPERATURE INCREASE OF 3-7°C** above pre-industrial levels. Several tipping points in the Earth system (e.g. melting of the Greenland ice-shield) are likely to be crossed if emissions continue to rise. Hence, the G8 and other major economies aim at stabilizing warming around **2°C** above pre-industrial levels.

RECIPE indicates what level of climate stabilization could be feasible at what cost. Costs are expressed in ‘gross’ terms, i.e. they do not reflect the benefits of avoided climate change. A 450 ppm CO_2 stabilization target implies a medium likelihood of reaching the 2°C target. The **GLOBAL COSTS** of reaching this target in terms of discounted welfare losses range between 0.1 % and 1.4 % relative to baseline levels. More ambitious stabilization levels result in both better chances to safeguard the 2°C target and higher mitigation costs. Stabilizing CO_2 concentrations at 410 ppm costs between 0.7 and 4 %.

The **REGIONAL DISTRIBUTION** of welfare losses depends on (1) domestic abatement costs, (2) effects related to shifts in energy prices and energy trade volumes, and (3) the allocation of emission rights. In general, India and other developing countries tend to benefit from emission allocation schemes envisaging long-term equalization of per capita emissions rights, while emission allocations based on GDP shares would be disadvantageous. In contrast, Europe, the USA, and other industrialized countries fare better with GDP-based allocations, while per capita convergence results in higher costs. Rent transfers through an international carbon market increase in proportion to the carbon price. Technological innovation and stabilization of investors’ expectations can contribute to lower carbon prices, thereby reducing both the value of the allowances to be distributed and the potential for distributional conflicts between nations.

BOX 6-1
A LOW-CARBON TRANSITION FRAMEWORK FOR EUROPE

The Directives under the EU Climate and Energy Package provide for 20 % emission reduction by 2020 relative to 1990. The effort increases to 30 % in case of comparable efforts by other major emitters. Moreover, they set a binding target for renewable energy generation of 20 % of primary energy consumption to be reached by 2020. Europe's next step should be to launch a societal deliberation for developing a long-term trajectory for the transition towards a low-carbon economy by 2050, comprising for example legally binding reduction targets. Redirecting current investment flows is of paramount importance for the size of the final mitigation bill. Regulators should therefore provide:

1. **AN INSTITUTIONAL FRAMEWORK** that regularly monitors progress of individual Member States against the transition path into a decarbonized economy. This enhances accountability and credibility of government policy, thus allowing firms to shift investment and corporate strategy towards low carbon projects, technologies and sectors. The UK's Climate Change Act could serve as a blueprint for Europe's transition framework.

2. **A STRENGTHENED EU ETS,** that (i) expands its temporal reach along a trajectory consistent with the EU's fair share of reaching the 2°C target and extends coverage post 2020 to additional sectors where this enhances long-term predictability to low-carbon investors, (ii) clearly defines opportunities for low-carbon investments in Europe by limiting CDM use as the EU emission reduction target is increased to 30% as part of international deal, and (iii) reduces investment uncertainty and perverse incentives from free allocation by exploring international cooperation and other options to address leakage concerns in sectors considered at risk of leakage.

3. **A RAPID AND ROBUST IMPLEMENTATION OF THE EU RENEWABLES DIRECTIVE.** RECIPE indicates that renewables will play a central role in any future low-carbon energy mix. The Renewables Directive allocates national objectives and the guidance on reporting expects Member States to characterize technology mix and complementing policies. Effective use of renewable power from intermittent sources will require flexible power market design integrating energy, transmission and balancing markets and the demand side, tailored network expansion, and financial mechanisms like feed-in tariffs that address policy risk. The Commission has to negotiate stringent compliance mechanisms so as to enhance the credibility of the national targets.

4. **UP-SCALED RD&D FUNDING,** in particular for transportation and power generation technologies that are compatible with full-scale decarbonization of the EU's energy system. Regulators should expand research grants and support demonstration projects for immature technologies. In this light, the EU CCS Directive is a laudable starting point but innovative renewable energy technologies deserve more attention.

5. **NON-MARKET BASED POLICIES** as a complement to carbon pricing preventing a further build-up of emission intensive capital. RECIPE shows that conventional coal-fired capacities without CCS are phased out prior to 2020 under a cost-efficient stabilization path. In presence of inertia in utility investment behavior, regulators should evaluate additional policies which limit the use of coal without CCS.

6. **SUPPORT FOR DEVELOPING COUNTRIES** in their transition to low-carbon growth.

> This requires technical assistance and capacity building, technology cooperation and public finance to contribute to incremental costs at a scale suitable for the challenge, including dedicated auction revenue from the EU ETS and from carbon pricing in international aviation and shipping.

Domestic regulations of this kind would enhance Europe's credibility in international climate negotiations while also lowering future costs of climate stabilization. RECIPE indicates that even if the introduction of climate policy is delayed in other parts of the world, Europe will enjoy a first mover advantage when unilaterally implementing stringent mitigation measures. The window of opportunity to prevent dangerous climate change at bearable cost is narrow and closing. Without a Europe taking the lead by demonstrating the feasibility of effective climate governance, the global community is likely to miss this window of opportunity.

CARBON PRICING

Establishing a credible long-term pricing regime for GHG emissions is the most important ingredient of an efficient climate policy framework. At the international level, regulators could establish a **GLOBAL CARBON MARKET** stepwise by linking regional systems bottom-up. In a top-down fashion, countries can implement national economy-wide caps and implement corresponding domestic mitigation policies, and trade corresponding emissions rights at government level (as embodied in the Kyoto Protocol). The latter approach enables timely negotiations over regional levels of effort but has the drawback of flawed efficiency of government trading. Therefore, it can be complemented – or substituted – by bottom-up linking of emerging OECD cap-and-trade schemes operating at the entity level.

Developing countries can join this carbon market step-by-step with suitable trading mechanisms for different countries and sector trading mechanisms substituting the current CDM in an intermediate period. These approaches should be complemented by other mechanisms of international cooperation, including technology cooperation, and use of public finance to support developing countries in their implementation of low-carbon development strategies. Thus institutional capacity and experience with climate policies is developed that can be the basis for a future participation of developing countries in a global carbon market.

Though the need for carbon markets is indisputable, RECIPE highlighted significant **UNCERTAINTY** over future carbon prices and mitigation cost. Both hinge critically on (1) innovation and the availability of low-carbon alternatives to conventional fossil fuels, (2) flexibility of substituting emissions-intensive activities in the energy-economic system, and (3) the ability of policy-makers to stabilize investors' confidence via credibly committing to long-term carbon pricing regimes.

COMPLEMENTARY MEASURES

On its own, carbon pricing is not sufficient. Distortions specific to technology markets exist which recommend to employ extra policy instruments to supplement carbon pricing. National **TECHNOLOGY SUPPORT** policies can be targeted at different levels of the innovation chain. First, innovation policies such as publicly funded R&D programs, direct capital grants and subsidies, and technology demonstration provide incentives to engage in research and development. Second, policies for technology adoption include growing initial markets, providing non-financial support during commercialization, and creating an encouraging business environment by removing regulatory barriers. To deal with uncertainties regarding future technology development, R&D and demonstration projects can help to increase knowledge of technological opportunities. A diversified technology portfolio provides insurance against the risk that certain technologies might perform worse than expected.

From an **INTERNATIONAL PERSPECTIVE**, individual countries can create synergies and reap economies of scale by engaging jointly in R&D and coordinating national R&D efforts. For developing and emerging countries which exhibit rapidly growing energy demand and CO_2 emissions, and which already are or will soon be among the world's largest emitters, leapfrogging and technology sharing can be accelerated through provisions with regards to intellectual property rights and financial mechanisms that could either be part of a comprehensive post-2012 agreement on climate change or be channeled through external funds. Therefore, the global carbon market should be complemented by a technology agreement where countries agree to enhance their low-carbon technology effort, including a burden-sharing arrangement for public R&D expenditures, coordination mechanisms to avoid the duplication of work, and technology sharing arrangements.

TECHNOLOGIES

RECIPE indicates that renewable energy technologies and carbon capture and storage (CCS) are **INDISPENSABLE OPTIONS** for keeping mitigation costs low. Biomass and nuclear power play less important roles. Mitigation costs will rise if either CCS is excluded as a mitigation option or the amount of renewables employed is fixed at its business-as-usual level. For nuclear power and biomass, the respective cost increase is of a much lower magnitude. In terms of limiting mitigation costs, the economic value of including renewable energies in a portfolio of mitigation options is highest when looked at over the course of the century as benefits from technological learning can be best realized in the long term. While the focus of our model exercise was on energy supply technologies, improvements in energy efficiency deserve attention, as they can provide additional flexibility in case that certain energy technologies fail to unfold their expected potential.

All mitigation technologies involve trade-offs between positive and negative **SIDE EFFECTS**. For CCS, there is the danger that stored carbon leaks from storage sites. The production of biomass can result in additional emissions of N_2O (a highly potent GHG formed from the nitrogen contained in fertilizers), destroy natural carbon sinks, and have adverse impacts on biodiversity and food prices. Hydropower may have detrimental effects in terms of destroying human habitats and ecosystems. Other renewables suffer from their intermittent availability which poses serious challenges for their large-scale integration in power grids. For nuclear energy there are risks of accidents, still unresolved problems related to the deposal of radioactive waste and concerns about proliferation. Possible ancillary benefits of alternative (non-fossil) sources of energy include reducing ambient air pollution, increasing energy security, involving local communities and providing employment opportunities from which people in developing countries can probably benefit the most.

The transformation of the global energy system will fundamentally alter **INVESTMENT PATTERNS**. RECIPE suggests that investments in fossil fuel based energies not equipped with CCS should be phased out rapidly, while investments in CCS and renewables need to be scaled up significantly. For the policy scenario, RECIPE projects investments in low-carbon technologies to amount to about 0.2% to 1% of world GDP over the course of the 21st century. This corresponds to US$ 1200 billion of additional (i.e. above baseline) investments in mitigation technologies by the middle of the century. The largest part would be targeted at renewable energy sources and CCS. Investments in conventional fossil fuel based sources of energy generation would fall by US$ 300 to 500bn. Private sector involvement will be crucial to raise investments in clean energy technologies above their historical peak of US$ 150bn in 2007. Credible long-term climate policies facilitates such investments by increasing certainty about future market volumes and profitability of low-carbon technologies and providing incentives for early movers to establish technological leadership in this sizeable market. The projected developments have important repercussions for investments in extractive industries, the agricultural sector, and commodity markets in general.

POWER GENERATION

RECIPE projects that the power sector will account for the bulk of the mitigation effort, particularly in the near-term. Under climate policy intervention, the generation mix will be almost fully decarbonized at the latest by mid-century. Since many other sectors will increase their use of electricity as energy input, decarbonization in the power sector gains strategic importance. European power generation increased by 30 % from 1990 to 2006. RECIPE suggests that European power demand can continue to rise (2-3-fold until 2100) even in the stabilization scenarios. Since the power sector is characterized by long-lived and capital-intensive infrastructure, it will be in the focus of near-term low-carbon investments. Most low-carbon power generation technologies have significant potential for cost reductions if appropriate incentives are put in place to encourage their development and diffusion.

Market failures in the R&D chain provide a strong rationale for additional policy instruments. Feed-in tariffs have the advantage of providing a high investment certainty which underscores the effectiveness of this approach in particular in early technology development stages. At later stages, tradable quotas incentivize competition across renewables. Regulators should facilitate grid access for renewable energy sources and remove regulatory barriers such as overly long planning procedures.

TRANSPORT

Final energy consumption in the European transport sector increased by 26 % from 1990 to 2003, mainly due to road transport (both passenger and freight). RECIPE projects that demand will continue to grow throughout the century even in policy scenarios (2-3-fold until 2100) as will CO_2 emissions without policy intervention. GDP growth, removal of trade barriers, cost reduction and a shift to faster transport modes are the main drivers for growth.

The future development of low-carbon technologies in the transport sector is highly uncertain. In the short-term, research and development should thus be given highest priority in order to assess the viability of alternative options (e.g. electrification, hydrogen and advanced biofuels). Policies promoting the use of biofuels should take into account the well-to-wheel energy efficiency and greenhouse gas emissions of the production of these fuels. For the transport sector to contribute to ambitious long term targets in an economically efficient manner, inclusion of transport into emissions trading is necessary but not sufficient. Regulators should employ a combination of complementary policy tools addressing specific market failures and consumer behavior (e.g. transport-reducing spatial planning, the provision of public transport systems and mandatory fuel efficiency standards).

INDUSTRY

Without policy intervention, the industry sector's energy consumption will be dominated by fossil fuels, in particular coal. In the presence of climate policy more electricity is used and the energy mix is decarbonized in accordance with the power sector's generation mix. The industry sector holds significant possibilities for energy efficiency improvements. In Europe, initial emissions reductions are likely to hinge on improvements to existing installations as only few new installations are scheduled for construction in the mid-term. After 2020 a new capital turnover cycle is expected to unfold in Europe. This dynamic has to be taken into account when implementing a carbon constraint for the industrial sector.

Asymmetric carbon prices bear limited risks of carbon leakage for some sectors, including cement, iron and steel, aluminum, refineries and fertilizers. There are three short-term options to tackle carbon leakage issues that need to be carefully weighted to limit distortions to the carbon price signal and other negative side effects: (i) border adjustments, (ii) free allowances for industries at risk and (iii) investment support for efficiency improvements. In the long-term, comparable carbon prices across sectors internationally e.g. by means of an international cap-and-trade regime is the first best tool for addressing leakage concerns.

AGRICULTURE

For agriculture, a range of mitigation options is available at low, zero or even negative costs but considerable non-price-related barriers exist. Due to potentially high transaction costs in emission monitoring, an expansion of the emission trading system to the agricultural sector seems inappropriate. A climate change mitigation strategy in the European agriculture sector should be part of a wider policy approach towards sustainable agriculture and rural development, consistent with related goals in environment policy and development policy.

TIME TO ACT

RECIPE conveys an encouraging core message: avoiding dangerous climate change is possible and it can be achieved at moderate cost. One should not underestimate the positive implication of this finding. Yet action is urgent. The **WINDOW OF OPPORTUNITY** to achieve climate stabilization is narrow and closing. Delaying the implementation of a global carbon pricing regime until 2030 renders the 450 ppm stabilization scenario infeasible. If global action starts in 2020, climate stabilization will be feasible but world consumption losses over the 21st century will rise by at least 46 %. Cost will also rise if emerging economies do not participate in a global effort to mitigate their emissions growth. Ultimately, the size of the stabilization bill primarily depends on today's decision-makers and their willingness to agree on an ambitious global climate agreement as an successor of the Kyoto Protocol. Leaders should keep that in mind when they gather in Copenhagen.

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ABBREVIATIONS

°C	degree Celcius
AAU	Assigned Amount Unit
AEM	agri-environment measure
AR4	Fourth Assessment Report
AUS	Australia
BAU	business as usual
BECCS	bioenergy with carbon capture and storage
bn	billion / 10^9
BREF	Best Reference Document
C&C	contraction and convergence
CAIT	Climate Analysis Indicators Tool
CAP	Common Agricultural Policy
CC	cross compliance
CCS	Carbon Capture and Storage
CDC	common but differentiated convergence
CDM	Clean Development Mechanism
CGE	computable general equilibrium
CH_4	methane
CHN	China
CMCC	Centro Euro-Mediterraneo per i Cambiamenti Climatici
CIRED	Centre International de Recherche sur l'Environnement et le Développement
CO_2	carbon dioxide
CO_2eq.	carbon dioxide equivalent
EC	European Commission
ECCP	European Climate Change Programme
EJ	exajoule / 10^{18} Joule
ENSO	El-Niño-Southern Oscillation
EEA	European Environmental Agency
ETS	emissions trading scheme
EU	European Union
EU-15	European Union with 15 Member States
EU-27	European Union with 27 Member States
EUR	Europe
FAO	Food and Agriculture Organization
FEEM	Fondazione Eni Enrico Mattei
GDP	Gross Domestic Product
GHG	greenhouse gas
g/vkm	gram per vehicle kilometer
Gt	gigatons / 10^9 tons
HFC	hydrofluorocarbon
ICAP	International Carbon Action Partnership
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMO	International Maritime Organization
IND	India
IPCC	Intergovernmental Panel on Climate Change
IPPC	Integrated Pollution Prevention and Control
JI	Joint Implementation
LULUCF	land use, land use change and forestry
Mt	megatons /10^6 tons
MRV	monitoring, reporting and verification
N_2O	nitrous oxide
NAMA	National Appropriate Mitigation Action
NGO	non-governmental organization
NH_3	ammonia
NO_x	mono-nitrogen oxide
OECD	Organization for for Economic Co-operation and Development
PIK	Potsdam Institute for Climate Impact Reseach
PFC	perfluorcarbon
ppm	parts per million
R&D	Research and development
R-AI	rest of Annex-I
R-NAI	rest of non-Annex-I
RD&D	Research, Development and Deployment
RECIPE	Report on Energy and Climate Policy in Europe
RGGI	Regional Greenhouse Gas Initiative
SF_6	sulfur hexafluoride
SRES	Special Report on Emissions Scenarios
t	ton
TAR	Third Assessment Report
tn	trillion / 10^{12}
TWh	terawatt hour / 10^{12} watt hours
UBA	Federal Environmental Agency (Germany)
UK	United Kingdom
ULCOS	Ultra-low CO_2 Steelmaking
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USD	United States Dollar
WBGU	German Advisory Council on Global Change
WCI	Western Climate Initiative
WGD	Water Framework Directive
WRI	World Resources Institute
WTO	World Trade Organization
WWF	World Wide Fund For Nature