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Chapter 6

Assessing Transformation Pathways

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Chapter 6: Assessing Transformation Pathways

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Executive Summary

Stabilizing greenhouse gas concentrations will ultimately require large-scale transformations in human societies, from the way that we produce and consume energy to how we use the land surface. A natural question in this context is what will be the "transformation pathway" toward stabilization; that is, how do we get from here to there? The topic of this chapter is transformation pathways.

The chapter is motivated by three questions. First, what are the near-term and future choices that define transformation pathways, including the goal itself, the emissions pathway to the goal, technologies used for mitigation, the nature of international coordination, and mitigation policies? Second, what are the key decision-making outcomes or characteristics of different transformation pathways, including the magnitude and distribution of economic costs and the implications for other societal priorities such as food security, energy security, sustainable development, and other environmental priorities? Third, what are the key uncertainties that influence choices and outcomes, including economic growth, population growth, technological change, and social and political change?

The synthesis in this chapter relies heavily on an expanded literature on transformation pathway scenarios since AR4. This literature includes a substantial increase in the number of scenarios exploring: low stabilization goals such as 450 ppmv CO_2-e; overshoot emissions trajectories with and without carbon dioxide removal (CDR) technologies; fragmented, delayed, and constrained near-term international action on mitigation; and the implications of variations in technology cost, performance, and availability. The literature also includes a small but growing set of scenarios and research exploring the linkage between mitigation and other societal priorities, an increasingly sophisticated treatment of the role of land use in mitigation, and scenarios exploring non-market approaches to mitigation.

The conclusions regarding baseline scenarios today are largely consistent with those from AR4. Without explicit efforts to reduce emissions, assuming continued economic growth at a global level, and taking into account current potential future technology options and remaining fossil resources, evidence strongly suggests that GHG concentrations will exceed 450 ppmv CO_2-e before 2030 *[Medium Confidence]* and will exceed 850 ppmv CO_2-e by 2100 *[Medium Confidence]*. Absent a dramatic change in regional economic growth patterns in which economic growth in non-OECD countries stagnates, emissions from the non-OECD countries will be larger than those from the OECD countries over the coming century *[High Confidence]*.

Meeting ambitious goals such as 450 ppmv CO_2-e by the end of the century will require a dramatic change to energy systems and the use of the global land surface that is decidedly at odds with both long-term trends and those since the publication of AR4. In an idealized approach to mitigation, in the sense of minimizing the total, long-term global macroeconomic costs of mitigation, all countries would begin mitigation immediately, mitigation would be undertaken where it is least expensive, emissions reductions would be allocated over time in a way that minimizes the total cumulative cost over time, and no important mitigation technologies (e.g., nuclear power, bioenergy, carbon dioxide capture and storage) would be removed as options because of potential adverse consequences. In such an idealized context, meeting a goal of 450 ppmv CO_2-e by 2100, allowing for CO2-e concentrations to exceed this goal in the interim, would call for a reduction in global emissions below 2010 levels of 15% to over 50% in 2030 and 40% to almost 80% in 2050 *[High Confidence]*; and anywhere from a moderate increase to roughly a tripling of low-carbon energy above 2010 levels in 2030 and from a tripling to a seven-fold increase by 2050 *[High Confidence]*. Under these idealized conditions, global macroeconomic costs over the century could be limited to a reduction in important economic indicators such as GDP or personal consumption of less than 4%, assuming a discount rate of 5% *[Medium Confidence]*. The variation in these characteristics depends heavily on the presence of carbon dioxide removal (CDR) technologies and the degree of overshoot the long-term goal. Virtually all of these scenarios include at least a temporary overshoot of the long-term concentration goal and an associated chance of exceeding 2 degrees at some point beyond 2050 on the order of 40%. Maintaining concentrations below 550 ppmv CO_2-e or less stringent goals would lesson emissions reductions, reduce the requirement for low-carbon energy, and reduce macroeconomic costs by roughly ½ to 1/3 *[Medium Confidence]*.

The expanded literature also includes a large number of scenarios that meet these and other long-term stabilization goals while undertaking mitigation over the next several decades that is either less pervasive or less aggressive than called for in an idealized, cost-minimizing implementation pathway. Although more limited near-term mitigation lowers near-term requirements for transformation, it relies on future decision-makers undertaking a more rapid and costly future transformation. Such delays can dramatically increase the costs of mitigation particularly for ambitious goals such as 450 ppmv CO2-e, often several-fold, depending on the nature of the near-term action. *[High Confidence].* Sufficient delays – for example, delaying global action beyond 2030 – can render ambitious mitigation levels such as 450 ppmv CO2-e by 2100 physically infeasible without substantial overshoot along with negative global emissions in the second half of the century using BECCS or other CDR technologies *[High Confidence]*. Indeed, many integrated models cannot produce scenarios that meet a concentration of 450 ppmv CO_2 by 2100 even with overshoot when there is a delay in global emissions reductions or delays by a large component of the world's emissions (e.g., the OECD countries or the non-OECD countries) beyond 2030.

In general, scenarios indicate that there is flexibility to focus regional strategies on particular combinations of technologies that best fit local conditions, leaving particular technologies out of the mitigation portfolio, with only modest increases in macroeconomic costs *[High Confidence]*. However, macroeconomic costs will be substantially higher if substantial elements of the portfolio are left off the table or if prospects for emerging technologies are less than hoped. Studies show that macroeconomic costs under broadly pessimistic assumptions about technology would increase the costs of reaching 450 ppmv CO2-e by the end of the century by as much as four times to more than an order of magnitude and the costs of reaching 550 ppmv CO2e several fold, even assuming an idealized implementation *[Medium Confidence]*. The option to deploy CDR technologies such as BECCS is particularly valuable in ambitious scenarios, such as 450 ppmv CO2-e, as well as when mitigation over the next several decades is delayed, because such approaches to mitigation require dramatic reductions or even negative global emissions beyond mid-century. In recent multi-model scenarios, many models could not produce scenarios leading to 450 ppmv CO2-e by 2100 without BECCS, and the global macroeconomic costs for those that could was increased in the absence of CCS by 50% to over four-times *[Medium Confidence]*.

Because total emission in the non-OECD countries are expected to be larger than those in the OECD countries over the rest of the century, the total quantity of emissions reductions required from the non-OECD countries will need to be larger over the this period as well to meet a 450 ppmv CO2-e or a 550 ppmv CO2-e goal, unless the OECD countries are able to produce net negative emissions in total *[High Confidence]*. However, this does not mean that the actual financial burden will be higher in the non-OECD countries. Burden-sharing regimes can break the link between mitigation undertaken in particular countries and the costs borne by those countries.

Recent research has begun exploring the potential impacts of different solar radiation management (SRM) approaches. While theoretically, the use of solar radiation management (SRM) technologies have the potential to counteract some aspects of anthropogenic climate change (for example by reducing surface air temperatures), the literature suggests that these approaches are associated with a complex mix of benefits and risks. As the assessment is still beset with uncertainty, high-confidence statements are currently not possible.

Although measures of macro-economic costs such as GDP losses or changes in total personal consumption have been put forward as key deliberative decision-making factors, these are far from the only characteristics of transformation pathways that matter for making good decisions. Transformation pathways involve a range of impacts that link to other national and societal priorities such as energy and food security, sustainable development, the distribution of economic costs, local air pollution and other environmental factors associated with different technology solutions (e.g., nuclear power, coal-fired CCS), and economic competitiveness. Recent research has begun to explore these impacts and suggests a range of positive co-benefits of mitigation; however, it also suggests potential risk tradeoffs and, collectively, does not yet provide a definitive statement on the balance between positive and negative side-effects *[Medium Confidence]*..

Despite the advances in scenario development since AR4, several avenues of inquiry remain unanswered. Important future research directions include the following: more scenarios pursuing temperature stabilization rather than concentration goals; more scenarios that include feedbacks from a changing climate, including those on energy and land use systems critical for mitigation; expanded treatment of the benefits and risks of SRM options; expanded treatment of co-benefits and risk trade-offs of mitigation pathways, including their embedding in a wider sustainable development context; improvements in the treatment and understanding of mitigation options in end use sectors in scenarios; and more sophisticated treatments of land use and land used based mitigation options in scenarios.

6.1 Introduction

6.1.1 Framing and Evaluating Transformation Pathways

Stabilizing greenhouse gas concentrations at any level will ultimately require deep reductions in greenhouse gas emissions. Net CO_2 emissions, in particular, must eventually be brought to or below zero. Emissions reductions of this magnitude will require large-scale transformations in human societies, from the way that we produce and consume energy to how we use the land surface. The more ambitious the stabilization goal, the more rapid this transformation must occur. A natural question in this context is what will be the transformation pathway toward stabilization; that is, how do we get from here to there?

The topic of this chapter is these transformation pathways. The chapter is motivated by three questions. First, what are the near-term and future choices that define transformation pathways, including, for example, the goal itself, the emissions pathway to the goal, technologies used for mitigation, the nature of international coordination, and mitigation policies? Second, what are the key decision-making outcomes of different transformation pathways, including the magnitude and distribution of economic costs and the implications for other societal priorities such as food security, energy security, sustainable development, and other environmental priorities? Third, what are the key uncertainties that influence choices and outcomes, including economic growth, population growth, technological change, and social and political change?

Two concepts that emerge from the literature on transformation pathways are particularly important for framing any answers to these questions. The first of these is there is no single pathway to stabilization of greenhouse gas concentrations at any level. Instead, the literature elucidates a wide range of transformation pathways. Choices will govern which pathway is followed. These choices include, among other things, the long-term stabilization goal, the timing of the path to meet that goal, the degree to which concentrations might temporarily overshoot the goal, the technologies that will be deployed to reduce emissions, the degree to which mitigation is coordinated across countries, the policy approaches used to achieve these goals within and across countries, the treatment of land use, and the manner in which mitigation is meshed with other national and societal priorities such as energy security and sustainable development. Indeed, particularly given lack of knowledge today about how many important forces might evolve – for example, economic growth, population growth, technological change, and social and political change

– it is not surprising that the literature sketches out a wide range of often very different possible transformation pathways.

The second key concept is that transformation pathways can be distinguished from one another by a range of outcomes or characteristics. Every pathway is distinct in a range of important ways. Weighing the characteristics of different pathways is the way in which deliberative decisions about transformation pathways would be made. Although measures of macro-economic costs have often been put forward as key deliberative decision-making factors, these are far from the only characteristics about transformation pathways that matter for making good decisions. Transformation pathways inherently involve a range of tradeoffs that link to other national and societal priorities such as energy and food security, sustainable development, the distribution of economic costs, local air pollution, and other environmental factors associated with different technology solutions (e.g., nuclear power, coal-fired CCS), and economic competitiveness.

A question that is often raised about particular stabilization goals and transformation pathways to those goals is whether the goals or pathways are "feasible". In many circumstances, there are clear physical constraints that can render particular long-term goals physically impossible. For example, if mitigation is delayed sufficiently and carbon dioxide removal (CDR) options are not available, a goal of reaching 450 ppmv CO2-e by the end of the century will be physically impossible (Note that in the bulk of this chapter, CDR technologies are not meant to include afforestation, which is addressed independently of CDR options such as bioenergy coupled with CCS (BECCS)). However, in many cases, statements about feasibility are bound up in subjective assessments of the degree to which other characteristics of particular transformation pathways might influence the ability of, or desire of, human societies to follow them. Important characteristics include macro-economic costs, social acceptance of new technologies that underpin particular transformation pathways, the rapidity at which social and technological systems would need to change to follow particular pathways, political feasibility, and linkages other national priorities.

6.1.2 New transformation scenarios since AR4

Since AR4, the integrated modelling community has produced a range of new transformation pathway scenarios that sketch out different possible approaches to mitigation. Major advances include the scenarios exploring the following: low stabilization goals such as 450 ppmv CO_2-e; overshoot emissions trajectories with and without carbon dioxide removal (CDR) technologies; fragmented, delayed, and constrained near-term international action on mitigation; and the implications of variations in technology cost, performance, and availability. The literature also includes a small but growing set of scenarios and research exploring the linkage between mitigation and other societal priorities, an increasingly sophisticated treatment of the role of land use in mitigation, and scenarios exploring non-market approaches to mitigation. Among these, two particularly important categories are scenarios for the discussion in this chapter with less than idealized international policy structures and scenarios with limits on technology cost, performance, or availability. These categories of scenarios are discussed in more detail below.

6.1.2.1 Non-idealized international implementation scenarios

At the time of AR4, the majority of transformation scenarios were based on the assumption of perfect "where", "when", and "what" flexibility; that is, the assumption that mitigation is undertaken where and when it is least expensive and an appropriate balance is struck between mitigation of different GHGs. The economic principle underlying these scenarios is the imposition of a global price on carbon that reaches across countries and permeates all economic sectors within countries. This might be achieved through permit trading schemes or carbon taxes.

However, the reality of international strategies for mitigation, at least in the near-term, is one of different countries taking on different actions at different times, with some countries reducing emissions more quickly than others. The research community has produced a large set of these "non-idealized" scenarios that explore this space since AR4. These can be broadly categorized into two categories, which are often combined in scenarios. One category is "fragmented" action scenarios. In these scenarios, certain countries take action more aggressively than others (see EMF 22, ADAM, and a range of individual papers). These scenarios may still focus on meeting a long-term goal from the start, meaning that early actors are focused on this goal and must take on more near-term emissions mitigation than the later entrants or less aggressive actors to meet these goals; however, the distribution of action across countries is not consistent with least-cost mitigation at least in the near-term. In the long-term, these scenarios may converge toward a single global carbon price as in the cost-minimizing scenarios, or they may remain fragmented throughout the century.

The second category is "constrained-reduction" scenarios (EMF 27, AMPERE, LIMITS, and a range of individual papers). In these scenarios, the ambition and character of near-term mitigation is fixed for a pre-determined period of time. This time period is typically one to four decades into the future, but some studies extend the constrained-reduction period through the end of the century. The constrained-reduction period may also be characterized by a fixed pattern of fragmented action. The global mitigation level during this period is typically chosen to be less than what would minimize costs associated with meeting a 450 ppmv CO_2-e goal, so in this sense, they represent limited near-term ambitions relative to a 450 ppmv CO2-e goal. When the constrained-reduction period is completed, countries react and attempt to meet a specified long-term goal, if it is still possible. They may at this point behave optimally to meet the long-term goal or follow a fragmented policy regime moving forward. The goal of these constrained-reduction scenarios is to test out the long-term implications of following a particular pathway, particularly in the near-term, that may not be consistent with a more ambitious long-term goal. A special category of these constrained-reduction scenarios are "global delay" scenarios in which the constrained reduction in the near-term is no mitigation at all.

6.1.2.2 Limited Technology Scenarios

Research to AR4 had emphasized the importance of technology in constraining the costs of mitigation. A range of individual papers had made initial explorations of this space for more than a decade before AR4. Since AR4, however, a range of new studies have emerged including large model intercomparison studies, that have focused on the implications of limitations on technology cost, performance, availability on the cost and other characteristics of ambitious stabilization goals such as 450 ppmv CO2-e. This includes EMF 27, ADAM, RECIPE, ROSE, AMPERE, and LIMITS. In many cases, these studies have simply assumed that particular technologies, such as CCS or nuclear power, may not be available. In others, they have put constraints on resource supplies, for example the supply of bioenergy. In others, they have called for variations in cost and performance of different technologies. Many have also explored the implications of energy intensity improvements.

6.1.3 Guide to this chapter

Actions to mitigate climate change are the result of choices. For decision makers to deliberate on choices today, they must understand the possible pathways to meet different concentration stabilization levels, the implications of these pathways for the many criteria by which they might be evaluated, and the linkage between actions today and the choices that will be present tomorrow. These are the organizing topics of this chapter. Within this framing, the remaining sections discuss the following specific topics: the tools that are used to project transition pathways (Section 6.2); the baseline, or no-policy, projections of worlds without climate action that are used as the starting point for development of transformation pathways (Section 6.3.1); the broad suite of emissions pathways that might lead to different stabilization levels (Section 6.3.2); the various characteristics of these pathways including energy system transformations (Section 6.3.4), transformations in land use and land use change (Section 6.3.5), associated economic costs (Section 6.3.6), technological and societal changes (Section 6.5), risks and links to other societal priorities (Section 6.6 and Section 6.7); the degree to which actions today influence the options to follow particular transformation pathways in the future (Section 6.4); and the linkage between the high-level, long-term perspective in this chapter and nearer-term, bottom-up sectoral analyses (Section 6.8). Section 6.9 briefly discussed CDR and solar radiation management options in the context of transformation pathways. Section 6.10 identifies important gaps in the current literature.

6.2 Tools of analysis

6.2.1 Key characteristics of integrated assessment models

The transformation pathway scenarios highlighted in this chapter were generated primarily by large-scale, integrated models that can project transformation pathways to mid-century and beyond. These models are designed to capture many of the most important interactions among technologies, relevant human systems (e.g., energy, agriculture, the economic system), and important physical processes associated with climate change (e.g., the carbon cycle).

All of the models share some common traits. First, these models use economics as the criteria for decision making. This may be implemented in a variety of ways, but it fundamentally implies that the models tend toward the goal of minimizing costs to achieve whatever outcome they are tasked with, unless they are specifically constrained to behave otherwise. In this sense, the scenarios tend towards normative descriptions of the future, simulating what should happen from an economic perspective as much as what will happen. To this end, the models typically assume competitive market behavior, meaning that factors such as non-market transactions, information asymmetries, and market power influencing decisions are not effectively represented. Second, these models focus on a long-term and often global perspective that integrates various human and natural systems. This degree of spatial, sectoral, and temporal coverage is crucial for maintaining internal consistency when exploring long-term, cross-sectoral transformations. However, maintaining a long-term, integrated, and often global perspective involves tradeoffs in terms of the detail at which key processes can be represented, ranging from economic cycles to the operation of electric power systems important for the integration of solar and wind power. Finally, these models are not built to capture many social and political forces that can influence the way the world evolves (e.g., shocks such as the oil crisis of the 1970s). Instead, key forces such as population, baseline GDP or labor productivity growth, and technological change are typically inputs to the models.

Beyond these similarities, modeling approaches to generate transformation pathways can be very different, and these differences can have important implications for the variation among scenarios that emerge from different models. In what follows, we highlight key differences in model structure and their potential implications for model results in this chapter. When examining difference in model characteristics, it is important to distinguish between model parameter assumptions and model structure choices. We omit a comprehensive discussion of model parameter assumptions given limited space and since these assumptions have more straightforward implications for model outcomes than model structure choices.

Economic coverage and interactions: Models differ is in terms of the degree of detail with which they represent the economic system and the degree of interaction they represent across economic sectors. *Full-economy* models (e.g., general equilibrium models) represent interactions across all sectors of the economy, allowing them to capture ripple effects from the imposition of a carbon policy and generate an overall impact on economic growth. *Partial economy* models, on the other hand, take economic activity as an input that is unresponsive to policy or other changes such as those associated with improvements in technology. Because full-economy models include feedbacks to the entire economy, costs should be higher in these models than in partial-economy models. On the other hand, full-economy models may include more possibilities for substitution in sectors outside of those represented in partial-economy models, and this would tend to reduce costs.

Foresight: *Perfect foresight* models (e.g., intertemporal optimization models) optimize over time, so that all future decisions are taken into account in today's decisions. In contrast, *recursive dynamic* models make decisions at each point in time based only on the information in that time period. In general, perfect foresight models would be likely to allocate emissions reductions more efficiently over time than recursive dynamic models, which should provide for lower costs and potential differences in emissions trajectories and rates of technology deployment.

Representation of trade: The ease of reaching the stabilization target is inversely related to how easy it is for goods to flow across regions. Models assuming goods are homogeneous and traded at one world price (Heckscher-Ohlin) or assuming one global producer (quasi-trade) will result in lower cost to meet a stabilization target because perfect substitutability of goods across regions is assumed. On the other end of the spectrum, models assuming a preference for domestic goods over imported goods (Armington) or models without explicit trade across regions (e.g., models with import supply functions) will typically result in higher cost of reaching the stabilization target. More generally, many models include trade only in carbon permits and basic energy commodities. These models are not capable of exploring the full nature of carbon leakage that might emerge from mitigation policies, and particularly those associated with fragmented international action.

Model flexibility: The *flexibility* of models describes the degree to which they can change course. In each of these cases, the more flexible the economy is, the lower the economic cost of achieving a stabilization target. There are a number of model assumptions that have implications for how easily an economy can reach a stabilization target or respond to a carbon tax: (1) how easily capital can be reallocated across sectors; (2) how easily the economy is able to substitute across energy technologies; (3) whether fossil fuel resource constraints exist and how easily the economy can extract resources. The complexity of the different factors influencing model flexibility makes clear delineations of which models are more or less flexible difficult. Evaluation of model flexibility is an area of current research (see Kriegler et al., submitted).

Sectoral, regional, technology, and greenhouse gas detail. In general, reaching a stabilization target or imposing a carbon tax will be more costly in a model with more sectoral, regional, or technology detail since it is more difficult to reallocate factors of production to less carbon intensive sectors, regions, or technologies. Models with one monolithic economic sector are implicitly assuming that inputs to production (e.g., capital and labor) can move freely across subsectors. Adding sectoral detail reduces this mobility. The same flexibility story applies when we consider regional detail. Reallocation of factors across regions is easier if there is only one global region. Similarly, less energy detail would imply more substitutability across energy types. Lastly, more GHG detail in the model can result in two counteracting effects. First, including non-CO_2 gases would mean there would be another source of abatement options to meet a specific stabilization target. This will lower the cost of abatement. However, including non-CO_2 gases would mean that a policy targeting emissions (both CO_2 and non-CO_2) would be more costly than a policy just targeting CO_2 emissions.

Representation of Technological change. Models can be categorized into two groups with respect to technological change. On one end of the spectrum, models with *exogenous technological change* take technology as an input that evolves independently of policy measures or investment decisions. These models provide no insight on how policies may induce advancements in technology. On the other end of the spectrum, *induced technological change* or *endogenous technological change* allowing for some portion of technological change to be influenced by deployment rates or investments in R&D. Models featuring endogenous technical are valuable for understanding how the pace of technological change might be influenced by mitigation policy actions.

6.2.2 Overview of the scenario ensemble for this assessment

The synthesis in this chapter is based on a large set of new scenarios produced since AR4. The majority of these scenarios were produced as part of multi-model comparisons focused on low-stabilization goals, delayed participation, technology limitations, and other key issues attending transformation pathways. Most model intercomparison studies produce publicly available databases that include many of the key outputs from the studies. Although crucial for our understanding of transformation pathways, these intercomparison exercises are not the only source of information on transformation pathways. A range of individual studies have been produced since AR4, largely assessing transformation pathways in ways not addressed in the model intercomparison exercises. For the purposes of this assessment, an open call was put forward for modelers to submit scenarios not included in the large model intercomparison databases. These scenarios, along with those from many of the model-intercomparison studies, have been collected in a database that is used extensively in this chapter. This database is available at … [Note to reviewers: This database remains under construction and will be made available upon completion of the Final Draft. In the meantime, databases are publicly available for several of the key model intercomparison exercises.]

6.2.3 Uncertainty and the interpretation of large scenario ensembles

The interpretation of large ensembles of scenarios from different models, different studies, and different versions of individual models is a core component of the analysis of transformation pathways in this chapter. Indeed, many of the tables and figures represent ranges across models.

This interpretation must be handled carefully. There is an unavoidable ambiguity in interpreting these ensembles in the context of uncertainty. On the one hand, scenarios generated from these models and explored in this chapter do not represent a random sample that can be used for formal uncertainty analysis. Each scenario was developed for a specific purpose. Hence, the collection of scenarios included in this chapter does not necessarily comprise a set of “best guesses.” In addition, many of these scenarios represent sensitivities, particularly along the dimensions of future technology availability and the timing of international action on climate change, and are therefore highly correlated. Indeed, most of the scenarios assessed in this chapter were generated as part of model intercomparison exercises which impose specific assumptions, often regarding long-term policy approaches to mitigation, but also in some cases regarding fundamental drivers like technology, population growth, and economic growth. In addition, some modeling groups have generated substantially more scenarios than others, introducing an arbitrary weighting of scenarios. At the same time, however, with the exception of pure sensitivity studies, the scenarios were generated by experts making informed judgements about how key forces might evolve in the future and how important systems interact. Hence, although they are not explicitly representative of uncertainty, they do provide real and often clear insights about uncertainty. In scenario ensemble analyses such as the one in this chapter, it therefore is important to acknowledge the tension between the fact that the associated scenarios are not truly a random sample with explicit information on uncertainty and the fact that much of the variation among the scenarios results from our lack of knowledge about key forces that might shape the future. The synthesis in this chapter does not attempt to resolve the ambiguity associated with ranges of scenarios, and instead focuses simply on articulating the most robust and valuable insights that can be extracted even given this ambiguity.

6.2.4 Interpretation of model inability to produce particular scenarios

A question that is often raised about particular stabilization goals and transformation pathways is whether the goals or pathways are “feasible.” Scenarios generated from integrated models can be helpful in informing this question by providing information about key elements of transformation pathways that might go into assessments of feasibility, such as rates of deployment of energy technologies, rates of reductions in global and regional emissions, macro-economic costs, financial transfers among regions, and links to other societal priorities such as energy security or energy prices. However, beyond cases where physical laws might be violated to achieve a particular scenario, these integrated models cannot determine feasibility in a broad, absolute sense.

This is an important consideration when encountering situations where models are incapable of producing scenarios. Many models have been unable to achieve particularly aggressive stabilization goals such as those associated with meeting 450 ppmv CO2-e targets, particularly under challenging technological or policy constraints. In some cases, this may be due to the violation of real physical laws, the most common of which is when the cumulative carbon budget associated with meeting a long-term goal is exceeded without options to remove carbon from the atmosphere. More often than not, however, model failures arise from pushing models beyond the boundaries that they were built to explore, for example, rates of change in the energy system that exceed what the model can represent, or carbon prices sufficiently high that they conflict with the underlying computational structure. Indeed, in many cases, one model may be able to produce scenarios while another will not. For this reason, this chapter highlights those situations where models were unable to produce scenarios.

Unfortunately, this type of result can be difficult to fully represent in a literature review, because, outside of model intercomparison studies intended explicitly to identify these circumstances, only scenarios that could actually be produced (as opposed that could not be produced) are generally published. Whether certain circumstances are underrepresented because they have been under-examined or because they have been examined and the scenarios failed is a crucial distinction, yet one that it is currently not possible to fully report. And model failures can bias results in important ways, for example, the costs of mitigation, because only those models producing scenarios can provide estimated costs (Tavoni and Tol, 2010). Hence, although these model failures cannot generally be taken as an indicator of feasibility in an absolute sense, they are nonetheless valuable indicators of the challenge associated with achieving a particular scenario and a potential source of bias in results.

6.3 Climate stabilization: Concepts, costs and implications for the macroeconomy, sectors and technology portfolios, taking into account differences across regions

6.3.1 Baseline scenarios

6.3.1.1 Introduction to baseline scenarios

Baseline scenarios are projections of greenhouse gas emissions and their key drivers, including growth in population, economic output, energy demand, and technology availability, as they might evolve in a future in which no explicit actions are taken to reduce greenhouse gas emissions. Baseline scenarios play the important role of establishing the projected scale and composition of the future energy, economic, and land use systems as a reference point for measuring the extent and nature of required mitigation for a given physical stabilization target. Accordingly, the resulting estimates of mitigation effort and costs in a particular stabilization scenario are always conditional upon the associated baseline. Although the range of emissions pathways across baseline scenarios in the literature is broad, it may not represent the full potential range of possibilities. There has been comparatively little research formally constructing or eliciting subjective probabilities for comprehensive ranges of the key drivers of baseline emissions in a country-specific context. As discussed in Section 6.2, although the range of assumption used in the literature conveys some information regarding modellers' expectations about how key drivers might evolve and the associated implications, several important factors limit its interpretation as a true uncertainty range.

6.3.1.2 Baseline emissions from fossil fuels and industry

Global baseline emissions of CO2 from fossil and industrial sources are projected to continue to increase throughout the 21st century (Figure 6.1). Although most baseline scenarios project a deceleration in emissions growth, especially compared to the rapid rate observed in the past decade, none is consistent in the long-run with the pathways in the two most stringent RCP scenarios (2.6 and 4.5), with the majority falling between the 6.0 and 8.5 pathways. Some projections appear to under-estimate current and very near-term emissions, most likely due to inconsistencies in calibration and data sources (Chaturvedi et al., 2012). In the longer term, global fossil and industrial CO2 emissions projections for 2050 range from only slightly higher than current levels (in scenarios with intentionally aggressive assumptions about energy intensity decline) to nearly triple current levels.

A common characteristic of all baseline scenarios is that the majority of emissions over the next century occur in those regions currently outside the OECD (Figure 6.2). This group consists of the Former Soviet Union as well as China, India, Brazil, South Africa, Indonesia and other developing countries throughout Asia, Latin America, and Africa, plus international bunker fuel emissions. Because of its large and growing population and rates of economic growth relatively faster than the industrialized OECD countries, this group of regions is projected to have the dominant share of world energy demand over the course of the next century.[1] While the range of emissions projected in the OECD remains roughly constant (a few models use higher growth projections), nearly all growth in future baseline emissions is projected to occur in the non-OECD countries. It is important to note that while a baseline by construction excludes explicit climate policies, management of non-climate challenges, particularly in the context of sustainable development, will likely impact baseline greenhouse gas pathways. Many of these policy objectives (but likely not all) are taken into account in integrated assessment model baselines, such as reductions in local air pollution and traditional biomass use and fuel-switching more generally away from solids towards refined liquids and electricity. Section 6.6 provides more details on this issue.

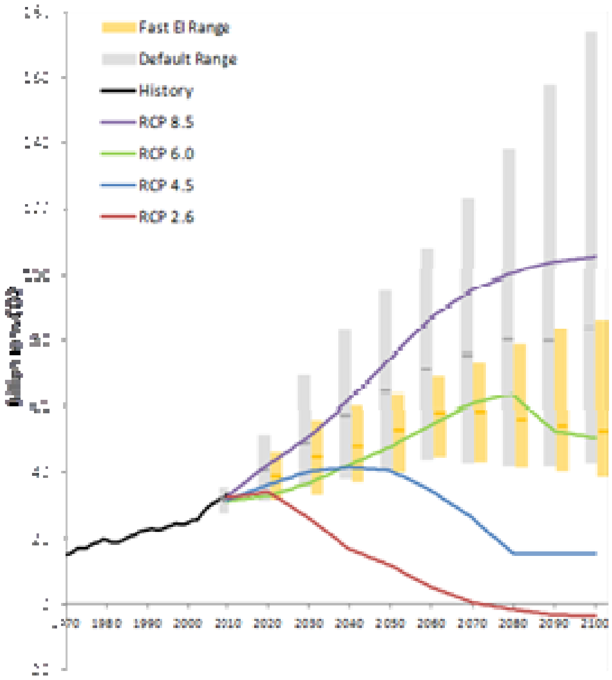

Figure 6.1. Global fossil and industrial CO2 emissions in recent baseline scenario literature with default growth assumptions (grey range) and accelerated energy intensity decline (gold range) compared to historic data and RCP scenarios (Van Vuuren, Stehfest, et al., 2011).

6.3.1.3 Baseline emissions from land use change and terrestrial sequestration

Baseline projections for global land-related carbon emissions and sequestration are made by a smaller subset of models, and due to difficulty of observation are subject to greater historical uncertainty than fossil and industrial emissions (Pan et al., 2011; Houghton et al., 2012). Recent baseline projections for land-related CO2 emissions span a broad range, including significant variation in the past decade (Figure 6.3). As in AR4, most projections suggest declining annual net

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[1] Although the regional definitions employed by integrated assessment models vary considerably, most allow a separation of projections into the OECD group and the non-OECD group. Some of the range of variation in reported 2010 emissions reflects differences in regional definitions.

CO2 emissions in the long run. In part, this is driven by technological change, as well as projected declining rates of agriculture area expansion, which, in turn, is related to the expected slowing in population growth. However, unlike AR4, none of the more recent scenarios projects growth in the near-term. There is also somewhat larger range of variation later in the century, with some models projecting a stronger net sink starting in 2050. There are few reported projections of baseline global land-related N_2O and CH_4 emissions. However, those that are available project increasing emissions over time. Cumulatively, land CH_4 emissions are projected to be 44 to 53% of total CH_4 emissions through 2030, and 41 to 59% through 2100, and land N_2O emissions 85 to 89% and 85 to 90% respectively.

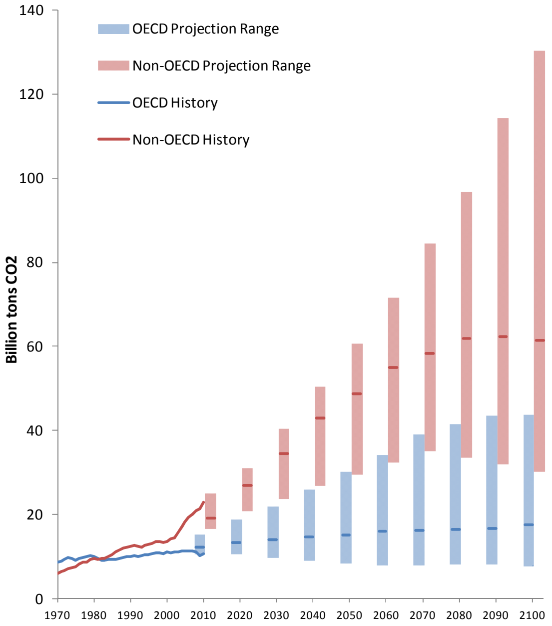

Figure 6.2. Fossil and industrial CO2 emissions projections for OECD (blue range) and non-OECD (red range) in recent baseline scenario literature compared to history [TSU: reference missing]

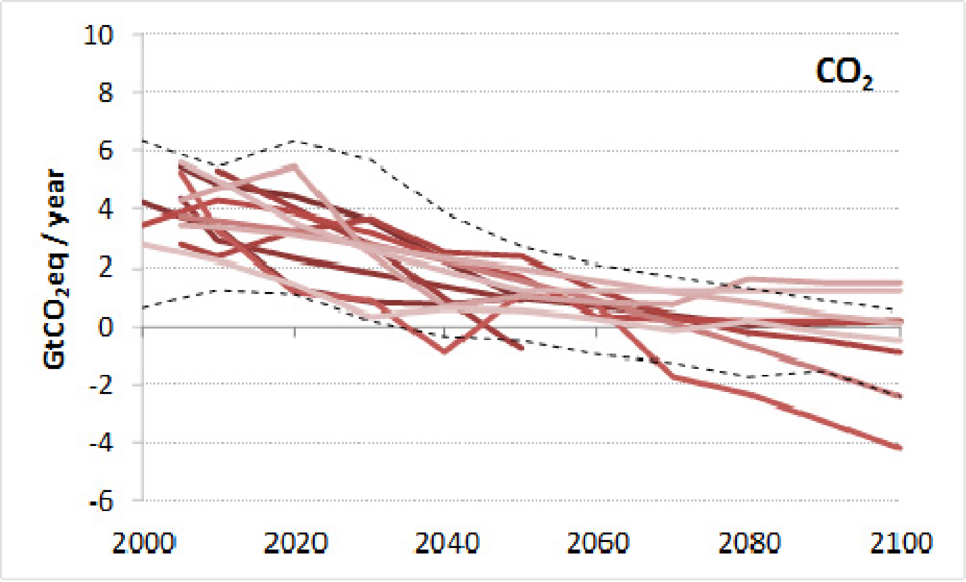

Figure 6.3. Post-AR4 baseline land net CO2 annual projected emissions (GtCO2eq/year). Dotted lines are AR4 min and max. Models only represented once and most recent projections published used. Sources: AR4 (Fisher et al., 2007), post-AR4 (Kriegler et al., Submitted; Clarke et al., 2009a).

6.3.1.4 Baseline radiative forcing projections

As a result of projected increasing emissions, radiative forcing from all sources continues to grow throughout the century in all baseline scenarios (Figure 6.4), exceeding the target stabilization level of 3.7 W/m2 (which corresponds to 550 CO2-e) between 2040 and 2050, while the 2.6 W.m2 level (which corresponds to 450 CO2-e) is surpassed between 2020 and 2030. Forcing in the baseline grows at a roughly linear rate of 0.5 W/m2 per decade across all literature scenarios, with the dominant share from CO2 (Figure 6.5). There is significant variation in the reported current level of total forcing, primarily due to differences in the highly uncertain contribution of aerosols and other non-gas agents, but likely also due in part to differences in calibration data sources (see WG1 report for a detailed assessment of estimates of current forcing levels). All of the baseline scenarios reviewed here include improvements to technology, which are often quite substantial. Thus there is strong evidence that, conditional on rates of growth assumed in the literature, technological change in the absence of explicit policy intervention is not sufficient to bring about stabilization of greenhouse gas concentrations.

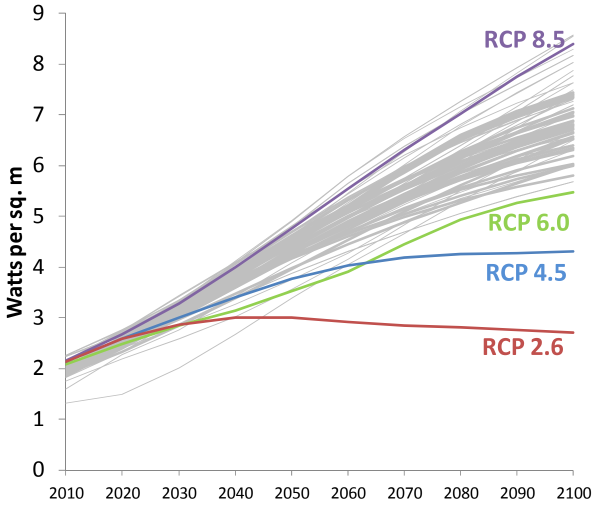

Figure 6.4. Total radiative forcing in baseline scenario literature compared to target stabilization levels associated with the RCP scenarios.

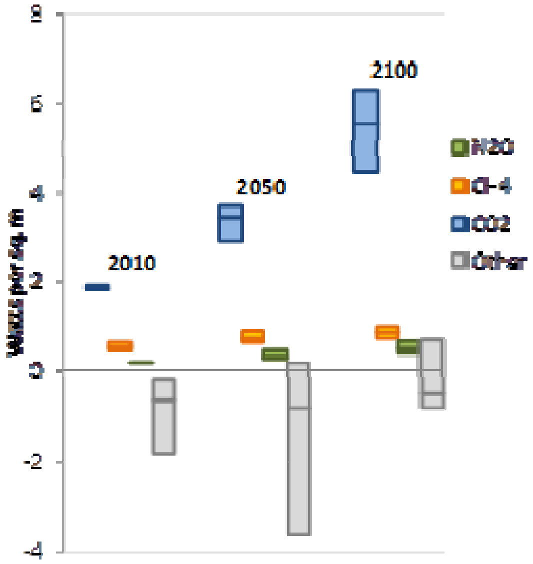

Figure 6.5. Median and range of baseline radiative forcing by component. Other includes other gases and non-gas forcing agents. [Authors: Not update since FOD due to database currently missing component level RF for most models]

6.3.1.5 The drivers of baseline energy-related emissions

The wide range of baseline fossil and industrial emissions paths seen in the literature, while not suggestive of the full uncertainty range, reflects different assumptions across the modelling community on certain key parameters. Figure 6.6 highlights this decomposition for four major regions, which include two post-industrialized economies experiencing relatively slow growth and two emerging economies with much more rapid growth, and provides a good synopsis of the factors driving variation in model baseline (see Blanford et al., 2012). There is comparatively little variation across model scenarios in projected population growth, with many models relying on recent reference projections from the United Nations in which global population growth slows and stabilizes between 9 and 10 billion by 2100 (UN, 2010) However, there is substantial variation in the projections of per capita income and energy intensity, particularly in China and India. All models assume increasing per capita income and declining energy intensity, thus the relative strength of these two opposing effects, which is embodied by per capita energy, plays the most important role in determining the growth of emissions in the baseline. The carbon intensity of energy is projected in most baseline scenarios to change little over time. Although there are a few exceptions in which renewable energy sources become competitive without policy incentives (usually due to a combination of aggressively declining technology costs and steeply rising fossil fuel prices driven by scarcity), most models project the current share of fossil-based energy to persist. In a few baseline scenarios, the fossil mix becomes more carbon intensive, for example due to replacement of conventional petroleum with heavier oil sands or coal-to-liquids technology.

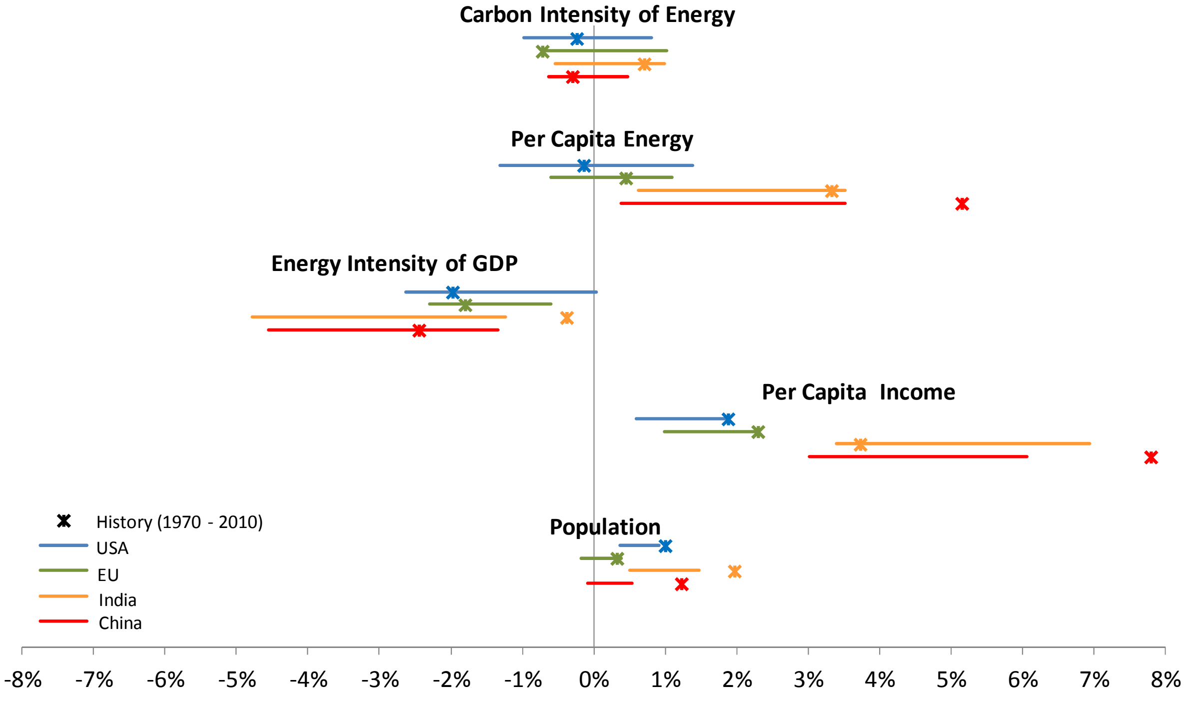

Figure 6.6. Range of average annual growth rates between 2010 and 2050 for Kaya decomposition indicators in baseline scenario literature.

Changes in aggregate energy intensity over time in baseline model scenarios are the net result of several individual trends, including both improvements in end-use energy efficiency of technology and structural changes in the composition of energy demand. Structural changes can work in both directions: there may be increased demand for energy-intensive services such as air-conditioning as incomes rise, while on the production side of the economy there may be shifts to less energy-intensive services as countries become wealthier. Although increasing energy intensity has been observed for some countries during certain stages of development, the net effect is usually negative, and in general energy intensity has declined consistently over time (see Chapter 5). Both technological and structural change can be driven by changes in energy prices, but to a significant extent both are driven by other factors such as technical progress and changing preferences with rising incomes. Most integrated assessment models are able to project structural and technical change only at an aggregate level, although some include explicit assumptions for certain sectors. The possible evolution of baseline energy demand and emissions in buildings, industry, and transportation is discussed below in Section 6.8 and in the respective sectoral chapters.

6.3.2 Emissions trajectories, concentrations and temperature in transformation pathways

6.3.2.1 Linking between different metrics of stabilization scenarios

The majority of long-term scenarios in the literature currently focus on the consequences of reaching long-term concentration goals (partly inspired by the formulation of article 2 in the UNFCCC). Hence, the discussion in this chapter also mostly focuses on concentration stabilisation scenarios. It is important to note, however, that concentration stabilisation scenarios are only one type of scenarios. Other mitigation scenarios include scenarios focused on specific policy formulations (e.g. the G8 target of 50% emission reduction in 2050), temperature goals, and cost-benefit analysis (see box 6.1).

Among long-term scenarios, there are important differences that complicate comparison. For one, some scenarios include all relevant forcing agents, while others are based on intermediate metrics, such as forcing from the Kyoto gases or CO2-only forcing. In addition, many scenarios express long-term climate goals in terms of cumulative emissions, often because these models do not include coupled representations of the carbon cycle or other relevant physical processes. A third distinction is whether the pathways exceed the long-term radiative forcing goal before decreasing to meet that goal (overshoot scenarios) or whether radiative forcing never exceeds the long-term goal (not-to-exceed scenarios).

To provide a comprehensive overview in this assessment, some generic relationships have been used to group scenarios based on their relative stringency. The key parameter used for the binning is the 2100 radiative forcing level, as it forms a pivotal parameter between mitigation action and climate change. In order to include scenarios that did not report full forcing, forcing levels have been linked to other goals such as the forcing of Kyoto gases and the cumulative CO2 budgets. This is an imperfect mapping: in reality there is substantial uncertainty about the relationship between cumulative CO2 emissions and forcing levels (see for instance Figure 6.2). The scenario categories (Table 6.1) have been chosen to capture, among others, the four RCPs (Moss et al., 2010; van Vuuren, Edmonds, et al., 2011). One key finding already captured in Table 6.1 is that there has been a substantial increase in the number of low-stabilization-goal scenarios since AR4. At that time, only 6 scenarios were in included in Category 1.

Box 6.1. Cost Benefit Analysis Scenarios

In the transformation pathways discussed in this chapter, mitigation is typically examined independent from impacts and adaptation. Indeed, as noted in Section 6.1, the vast majority of the studies on transformation pathways reviewed in this chapter have been conducted assuming little or no climate impacts on underlying human and natural systems. (A discussion of the possible biases introduced when impacts and adaptation responses are omitted from transformation pathways is provided in Section 6.3.3) The primary way that impacts and adaptation have been considered in mitigation analysis is in the context of cost-benefit analysis. Cost-benefit studies (e.g. Tol, 1997; Nordhaus and Boyer, 2000; Hope, 2008) balance the economic implications of mitigation and climate damages to identify the optimal trajectory of emissions reductions that will maximize total welfare over time. It is important to note that cost-benefit analysis is one framework of analysis, but not the only one (Bradford, 1999; Barrett, 2008; Keller et al., 2008). Risk assessment is also often used in order to determine overall targets. The transformation pathways explored in this chapter are mostly designed in a cost-effectiveness framework. One important characteristic of cost-benefit analyses is that the bulk of the research is conducted using highly-simplified models without the structural detail necessary to explore the nature of energy system or agricultural and land use transitions that are the focus of this chapter. (A theoretical discussion of cost-benefit analysis, including IAMs that have conducted these analyses, can be found in both Chapters 2 and 3.)

Table 6.1: Categories of scenarios and the approach to comparing across scenarios with different long-term goals.

	Radiative forcing	*CO2-eq Conc*	*CO2 budget (2000-2100)*	*RCP*	*No of scenarios*	*2100 CO2 conc.*	*Indicative 2100 temp above pre-industrial*
	W/m^2	*Ppm*	*GtCO$_2$*		*Number*	*Ppm*	*^{o}C above pi*
Cat 0.	<2.3	<425	<1050	Too few memembers (6) – results were not used.			
Cat 1.	2.3-3	425-485	1050-1550	RCP2.6	140	375-420	1.3-1.7
Cat 2.	3-3.5	485-535	1550-2000		48	400-450	1.7-2.2
Cat 3.	3.5-4	535-585	2000-2500		85	450-495	2.0-2.4
Cat 4.	4-5	585-710	2500-3500	RCP4.5	22	490-590	2.3-3.0
Cat 5.	5-6.8	710-1000	3500-5500	RCP.6	78	630-760	3.0-4.0
Cat 6.	>6.8-	>1000-	>5500-	RCP8.5	36	>800	>4

Note: The first and third column has been used to categorize the scenarios (in addition Kyoto gas forcing was used set a criteria +0.2 W/m2 compared to full forcing). The number of scenarios provides information on the robustness of the results (the number of models will be added in the next version). It does not at all indicate a likelihood of a certain target, nor does it represent the importance of target over another. Although a fixed emission budget was chosen here to link the CO2 budget and forcing categories, the relationship is uncertain in reality. The CO2 concentration range is derived from the IAM model results (10-90th percentile). The temperature outcomes, in contrast, have been derived from the MAGICC model runs. Further in this Chapter we will further present information on the relationship with climate parameters (see also Chapter 6 and 12 of Working Group 1). The table can only represent scenarios meeting a certain target and not “infeasible scenarios”. Tavoni and Tol (2010) have earlier shown that this can be important. Therefore, where relevant in this chapter we have tried to account for this.

6.3.2.2 The timing of emissions reductions: the influence of technology, policy, and overshoot

A crucial question with respect to long-term emission reductions is the timing of emission reductions associated with meeting different targets (Figure 6.7; Figure 6.8; Table 6.2). As Figure 6.7 shows, there are wide emission bands for the different categories defined in Table 6.1. There are several reasons for this. Models differ, among other things, in technology representations, socioeconomic drivers, and the relative valuation of future versus current costs (discounting). This implies that they will make different trade-offs across time and across different gases. Several recent studies have tried to look into the main causes of differences and to develop diagnostic variables to qualify different models (Kriegler et al., submitted; van Vuuren, Lowe, et al., 2009).

Until recently, most studies have focussed on cost-minimizing allocation of emissions over time. Since AR4, scenario studies have increasingly focused on the consequences fragmented international action and related delays in emission reduction (see Riahi et al., Submitted; Clarke et al., 2009a; Vliet et al., 2012; Kriegler and et al., 2013; Rogelj et al., 2013; Tavoni and al., 2013) (see also Section 6.1.2.1). Table 6.2 shows that there is a clear relationship between short-term emission reductions and the long-term target for idealized implementation scenarios (see Section 6.4 for more on this topic). In order to reach ambitious long-term goals, rapid emission reductions between 2020/2030 and 2050 would be needed, often several times the rate than experienced historically. Table 6.2

summarizes the emission profile trajectories by highlighting the relationship between short-term emission reductions and the long-term target (see Section 6.4 for more on this topic).

Three considerations figure heavily in the emissions profile over time. One of these is the option to overshoot. Overshoot scenarios allow for concentration to temporarily exceed the long-term target, allowing for less mitigation in the near-term (Wigley, 2005; Meinshausen et al., 2006). Such scenarios may benefit from inertia in the climate system (Den Elzen and Van Vuuren, 2007; Nusbaumer and Matsumoto, 2008). The vast majority of scenarios meeting a goal of 450 ppmv CO2-e by the end of the century rely on overshoot pathways. It is important to note that severe overshoots may have consequences for (transient) climate change (Section 6.3.2.5).

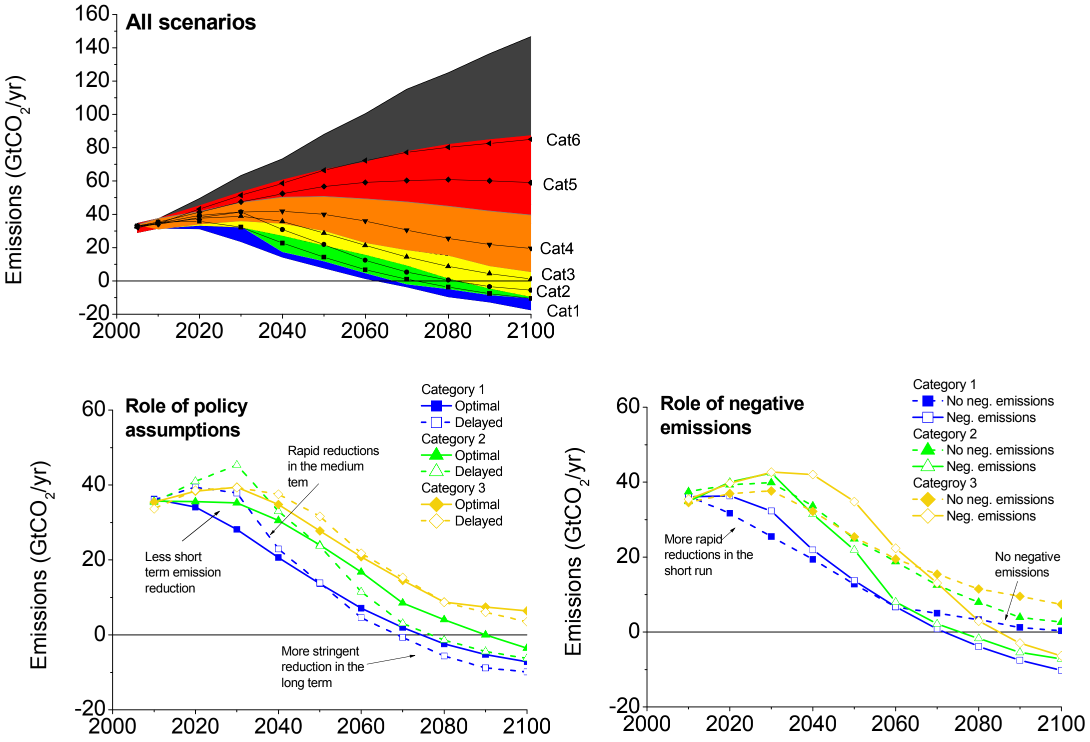

Figure 6.7. CO2 emission pathways of the various categories. The upper-left figure shows 10-90th percentile of the scenarios included in Table 6.1(bands) and the means of each group (lines). The bottom figures only shows the means of each group (category 1-3). The left panel distinguishes between the scenario is based on an optimal policy response, while the right panel indicates whether a scenario includes negative emissions.

The second consideration is technology. Technology mitigation portfolios can have an important influence the timing of emissions reductions. The most noteworthy example is the inclusion of CDR technologies and the consequences for overshoot strategies (Figure 6.7). CDR technologies include a wide range of options, including those often regarded to be part of standard mitigation strategies such as biomass energy with carbon storage (BECCS) and reforestation as well as options such as ocean iron fertilization, biomass burial, and direct air capture (some of these technologies are discussed in more detail in Section 6.8). While BECCS and afforestation are now included in many IAM models, other CDR techniques are now mostly excluded, with some exceptions (Dowlatabadi and Morgan, 1993; Keith et al., 2006b; Keller et al., 2008). It is important to realize that the availability of BECCS is uncertain, largely because of constraints with respect to the use of CCS (both technical and societal) and biomass supply (Van Vuuren et al., 2013).

The important consequences of net negative emissions from BECCS for emission profiles is illustrated in Figure 6.7 and in a range of other studies (Van Vuuren et al., 2007; Edenhofer et al., 2010; Azar et al., 2010; van Vuuren and Riahi, 2011; Tavoni and Socolow,, 2012). Net negative emissions occur in scenarios in the second half of the century, and these allow for more modest 2020 and 2050 emission reductions. For instance, the category I scenarios with net negative emissions show a small emission increase in 2020, while scenarios without net negative emissions have a reduction of 15% (see Section 6.4 for more on this topic). The importance of BECCS within the current scenario literature can also be illustrated by the fact that nearly all scenarios that reach lowest emission targets heavily rely on the use of BECCS.

Table 6.2: Characteristics of scenario categories (emissions compared to 2005)

	Full range			Optimal scenarios		
	2020	2030	2050	2020	2030	2050
	Emissions level (2005 = 100)					
Category 1	110 (95-125)	98 (72-135)	44 (23-63)	100 (89-112)	82 (69-109)	40 (24-52)
Category 2	120 (102-128)	126 (100-149)	67 (37-94)	104 (95-115)	103 (80-118)	70 (40-76)
Category 3	115 (101-125)	119 (99-139)	88 (65-114)	112 (97-120)	115 (94-131)	81 (48-107)
Category 4	116 (104-127)	127 (110-144)	122 (93-155)			
Category 5	126 (117-138)	145 (128-163)	173 (144-204)			
Category 6	132 (113-151)	157 (123-193)	203 (140-269)			

Note: The scenario categories are based on Table 6.1 (covering the same set of scenarios). The optimal scenarios allow for full flexibility with respect to the timing of emission reductions and the allocation across gases, regions and sources. The year 2005 was chosen as emission base year as 2000, 2005 or 2010 are most commonly used as base year in model runs.

Beyond negative emissions, technology portfolio choices – for example, constraining the use of particular low-carbon supply options – can also have implications for the emissions trajectory. However, these implications are less pronounced (see Kriegler et al., Submitted; Riahi et al., Submitted). In general, limiting the use of particular low-carbon supply technologies will make deep emissions reductions relatively more challenging than more modest reductions (Section 6.3.4). Since deep emissions reductions take place in the future, this tends to push more emissions reductions toward the near-term to delay the time at which the very deep reductions are required (Van Vliet et al., Submitted) .

The third consideration is policy structure. In fragmented regimes, total global mitigation is pushed toward the future and near-term emissions reductions will be undertaken more heavily in a limited set of countries. These scenarios, as well as constrained ambition scenarios (See Section 6.1.2.1), including global delay scenarios, have higher 2020 and sometimes 2030 emission reductions than cost-minimizing trajectories, this is compensated for by reducing emissions more rapidly in the 2010-2050 period (Figure 6.1) followed more a further decline after 2050. Constrained ambition, and delay scenarios in particular, rely more heavily on the use of BECCS.

The contribution of different regions is directly related to the nature of international policy structure. Figure 6.8 shows the average emission of different regions for each of the scenario categories. The contribution of all regions is required in order to achieve long-term targets as even reducing Annex-1 regions to zero, would not be enough to reach ambitious climate targets. The distribution of emission targets across regions, burden sharing, and associated mitigation costs are discussed further in Section 6.3.6 .

All-in-all, these results show that the decision on timing of emission reduction is a complex one. It needs to be formulated in terms of (societal) trade-off between the risks related to long-term climate change, expectation about the potential to reduce emissions in the short-term, expectations about the emission reduction potential in the long-term in particular with so-called negative emission technologies, the risks associated with relying on specific long-term technologies and the risk of overshoot.

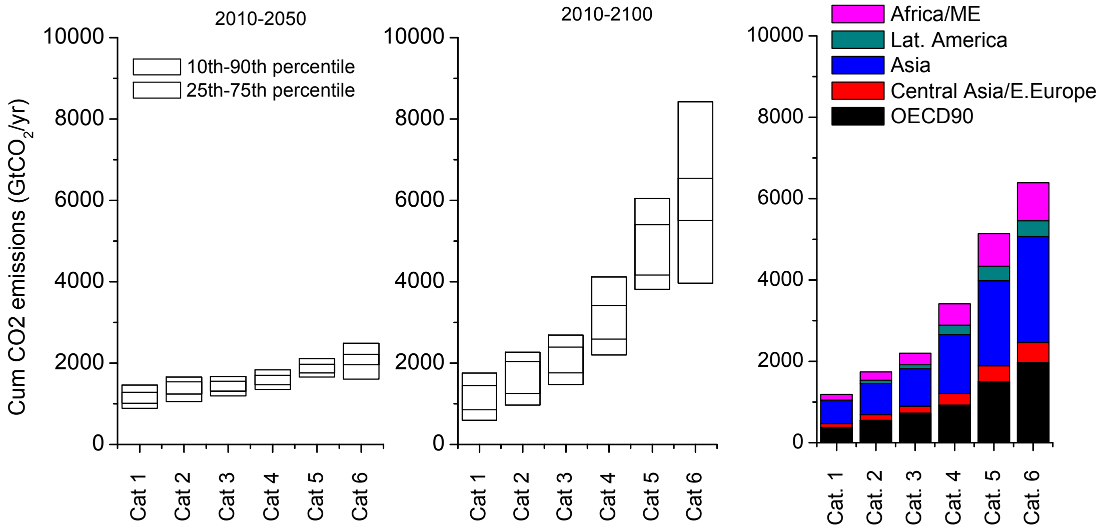

Figure 6.8. Cumulative CO2 Emissions 2100-2050 and 2100-2100 (left and middle panel; 10-90th percentile and 25-75th percentile) and cumulative emissions by region (mean).

FAQ 6.1. Is it possible to bring climate change under control given where we are and what options are available to us? What are the implications of delaying action or limits on technology options?

The answer depends on what is meant by “under control”. There are many possible goals for climate for climate mitigation, including GHG concentration goals and temperature goals, and each of these goals could be expressed as near-term or long-term. A common goal is to keep global temperature change from exceeding 2 degrees. Because of uncertainty in the underlying climate science, it is not possible to know with certainty how much global emissions must be reduced to meet this goal. Nonetheless, many researchers have used the notion of a 450 ppmv CO2-e concentration goal as a proxy for the 2 degree goal. This goal is possible given the options available to us today. Were all countries of the world to take aggressive action to meet this goal, it would require a change to the way that we produce and use energy, and possibly in the crops we grow, that is decidedly at odds with our history. For example, supplies of low-carbon energy – energy from nuclear power, solar power, wind power, hydroelectric power, bioenergy, and fossil resources with carbon dioxide removal – might need to increase five-fold or more over the next forty years. Net CO2 emissions would need to be almost completely eliminated by the end of the century. If we were to delay emissions reductions or to reduce mitigation less in the near-term than what might be called for to meet this goal, it will call for increasingly dramatic reductions in the future and may only be possible with the large-scale use of unproven carbon-dioxide removal technologies.

6.3.2.3 The role of CO_2 emissions from land use change

Currently about 15% of global emissions originates from land-use change. Without climate policy, this share is expected to decrease (see Section 6.3.1). Land CO_2 reductions can be over 100% of baseline emissions from the expansion of forests for sequestration. Including also non-CO_2 gases, Rose et al. (2012b) found that all land-related strategies (agriculture, forestry, bioenergy) contributed 20 to 60% of total cumulative abatement to 2030, and still 15 to 45% to 2100. The trends in LUC CO_2 emissions in mitigation scenarios differ strongly across studies and models. Key factors are whether options to reduce emissions are actually considered, the representation of bio-energy and whether mitigation policies indeed cover also land-use related strategies (Rose et al, (in review; 2012b) and Popp et al (in review) provide an overview of the dynamics included in several IAMs).

Decreases in land use change CO_2 emissions will reduce the pressure to reduce emissions from fossil fuel and industrial sources. The relationship between total cumulative CO_2 emissions from fossil and industrial sources and land-use CO_2 emissions is not straightforward (Figure 6.9). Several model studies show that land-use change related CO_2 emissions are reduced as part of mitigation strategies, and reductions increase at a decreasing rate with policy stringency. However, other models show little relationship (mostly because options to reduce land-use emissions have not been considered) or increasing LUC CO_2 emissions result from increasing bio-energy use (Van Vuuren et al., 2007; Searchinger et al., 2008; Wise et al., 2009b; Melillo et al., 2009). Wise et al. (2009b) illustrate how the assumptions on the ability to control land-use related CO_2 emissions result in dramatically increasing or decreasing LUC emissions within a single model framework. All-in-all, scenarios suggest a substantial cost-effective, and possibly essential, mitigation role for land in transformation. However, policy implementation of large-scale land-related mitigation will be challenging and actual implementation will affect costs and net benefits (Lubowski and Rose, 2013). See Section 6.3.5 for discussion of land mitigation policy coordination and implications.

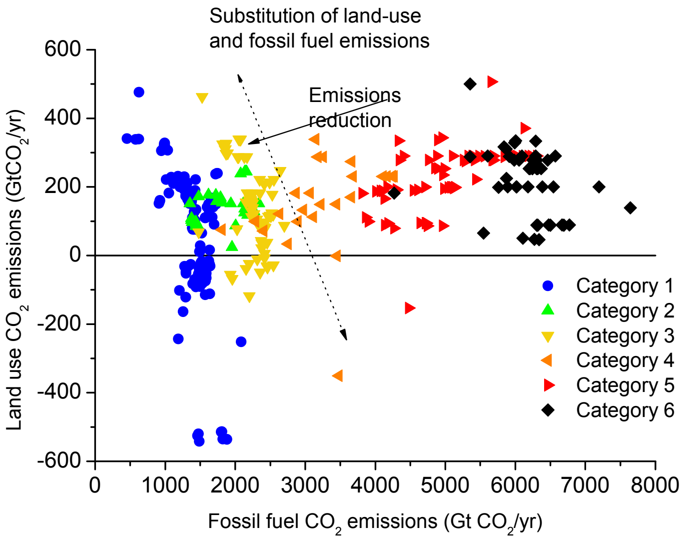

Figure 6.9. Land use and fossil fuel and industrial CO2 emissions in stabilisation scenarios (cumulative emission 2010-2100) (Categories based on Table 6.1)

6.3.2.4 Non-CO2 GHGs and other radiatively important substances

Reducing non-CO_2 greenhouse gases can be an important part of the reduction portfolio. Figure 6.10 shows that non-CO_2 emissions are in general substantially reduced going from Category 6 to Category 1. The increase in emissions in Category 6 is, however, less than for CO_2, which is mostly caused by the fact that agricultural activities (as a cause of a substantial share of the non-CO_2 emissions) are expected to grow less rapidly than energy use (the main driver of CO_2 emissions). Most studies expect that in the short run, there are many low-cost options to reduce non-CO_2 gases (compared to CO_2). In the long run, however, emission reductions are expected to be severely constrained by several hard to mitigate sources such as livestock and emissions associated with fertilizers resulting in lower reduction rates than for CO_2 (Figure 6.10; see also Lucas et al. (2007)).

Land CH_4 reductions were 20 to 40% of total CH_4 reductions, and land N_2O reductions 56 to 82% of total N_2O (Kriegler et al., Submitted; van Vuuren et al., 2007). Land reductions of N_2O are a larger share of total reductions through 2030 and 2050, than 2100, implying that land-related mitigation is more important in the nearer-term for some models. Land-related N_2O reductions are over half of total N_2O reductions, but only a fifth or less of baseline land emissions, suggesting that models are cost-effectively keeping N_2O emissions. For f-gases, the less ambitious mitigation scenarios expect a very rapid growth of emissions. For the lowest categories, this emission growth is significantly reduced, but emissions are not reduced further than the 2005 emission level.

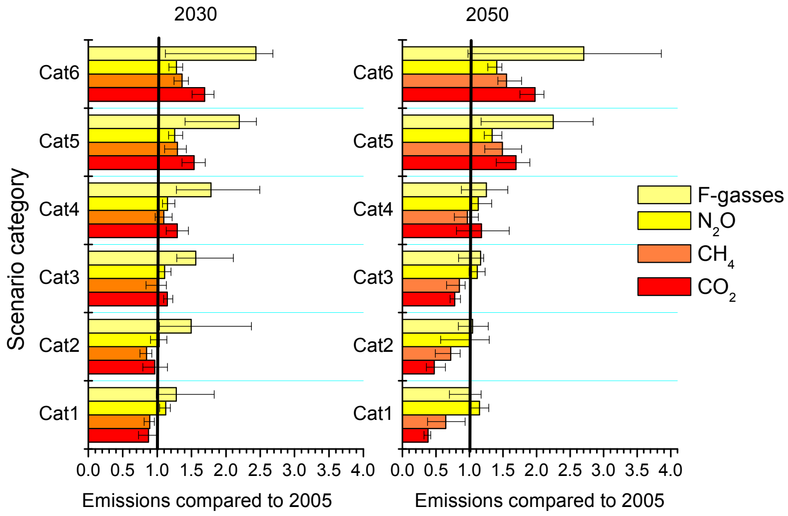

Figure 6.10. Emissions reductions in greenhouse gases in 2030 and 2050 across scenarios. (full AR5 scenario database). Bars indicate mean across the scenarios. Uncertainty range the 10-90th percentile.

The methods used to determine the substitution among different gases (substitution metrics) have an important influence on emission reduction strategy. This includes the allocation of reduction efforts across different gases, the overall timing and the global and regional costs. In most current climate policies, emission reductions are allocated on the basis of Global Warming Potentials (GWPs) for a time of horizon of 100 years. Many models use this approach as well. (In Chapter 3, an overview of the impact of emission metrics in relation to objectives of climate policies is provided; Chapter 8 of the Working Group 1 report discusses the physical aspects of substitution metrics.) A number of different ways to allocate emissions across climate forcers have been suggested including the use of metrics based on the physical properties, but also cost optimization in economic models. A key point is that ideally metrics are formulated based on the overall objectives of climate policy (see for instance Fuglestvedt et al., 2003; Manning and Reisinger, 2011; Tol et al., 2012). Manne and Richels (2001) and Van Vuuren et al. (2006) illustrate how metrics may lead to rather different mitigation strategies and discuss how this relates to the overall objective of climate policy (see also Tol et al. (2012)). The work of Manne and Richels (2001) specifically showed that costs-optimisation under a long-term climate target leads to postponing of reductions of short-lived gases (most notable CH4) compared to the use of a static GWPs measure (Shine et al., 2007 address the same issue based on a physical approach). Some literature published in response suggested that the impacts on overall, global costs, however, would be small, certainly compared to the advantage of allowing for a multi-gas strategy (see Aaheim et al., 2006; Johansson et al., 2006). Recently, several papers looked into the current policy discussion on alternative "physics"-based metrics, including updated GWP values and the use of alternative GTP values (either dynamic or static, i.e. changing over time or integrated over a certain time period) (Van den Berg et al., Submitted; Smith et al., 2012; Reisinger et al., 2012; Azar and Johansson, 2012). In general, these studies confirm that the choice of metrics is critical for the timing of CH4 emission reductions (within the Kyoto basket) but have not a strong impact on overall costs. The impact of using GWP values from the AR4 report (instead of SAR) has very little impact even on the timing of CH4 reductions. The use of dynamic GTP values, however, is likely to have a large influence on timing, with again the emissions reductions of short-lived gases being postponed (see previous references). This effect, however, depends also on the mitigation options and associated costs for CH4 as well. At the moment, very little literature exists on the impact of the choice of metrics on regional costs in the context of international climate regimes. Economic costs are likely to be larger for some regions with relatively high shares of CH4 emissions.

Considerable discussion exists on the optimal timing of reducing short-lived climate forcers including CH4, ozone and some aerosols (black carbon) (see also WG1). While part of the different short- and long-lived climate forcers originate from the same activities (e.g. fossil fuel combustion), this is not always the case. Abatement of short-lived gases is often driven primarily by non-climate benefits such as air pollution control, but sometimes also by considerations regarding economic efficiency. However, they have little impact on long-term stabilisation goals. For the latter, it will be required to reduce long-lived forcing to zero. While some literature suggest that it is attractive to postpone emission reduction of short-lived forcers (for instance, as they do not contribute to long-term targets) (Berntsen et al., 2010; Myhre et al., 2011), it also been argued that near term reduction of these forcers could slow down climate change already in the short-run and also reduce air pollution (black carbon and ozone precursors such as CH4) (Shine et al., 2007; UNEP and WMO, 2011). Quite some literature has emerged recently on the consequences of climate policy on emissions of air pollutants and the potential trade-offs and synergies that are involved (Rose, Kriegler, et al., in review; McCollum, Krey, et al., 2013). Although research is still going on in looking to the issue of allocation across gases from different angles, an important factor will be political decisions on the importance of short- and long-term climate change. A similar strain of research is to see whether air pollution policies can be formulated in such a way that it does not work against climate policy (i.e. optimisation of sulphur emission reduction in time, as function of other gases) – and whether indirect impacts of climate policy on aerosol emissions can be optimised in time.

6.3.2.5 The link between concentrations, radiative forcing (CO2-equivalent concentrations), and temperature

For policy-making the linkage between different emission pathways and climate targets is of key importance. WG1 explores how the so-called representative concentration pathways (RCP) lead to different climate impacts. Here, we would like to use this information also in relation to the larger scenario context discussed in this Chapter. Therefore, we use the MAGICC results[2] that are discussed in WG1, (see Schaeffer et al., in review; Meinshausen et al., 2011). Panel B in Figure 6.11 compares the GCM results for the RCPs as reported by WG1 to the outcomes of MAGICC showing that the results seem to be consistent. The different emission categories discussed in this chapter correspond to different levels of expected warming. Uncertainty, however, plays a key role as illustrated by wide range of different temperature outcomes shown in Figure 6.11. The climate system itself has a considerable contribution to this uncertainty (Figure 6.11). In fact, up to 2040 or so the uncertainty ranges of the various scenario categories strongly overlap. In the literature various approaches have been put forward to deal with these uncertainties. For instance, various studies have attempted to relate different targets by using either probabilistic relationships between forcing and temperature, expressing temperature targets in terms of a probability with which a particular temperature might be exceeded (Meinshausen, 2006; Schaeffer et al., 2008; Zickfeld et al., 2009; Allen et al., 2009; Meinshausen et al., 2009; Ramanathan and Xu, 2010; Rogelj et al., 2011). While the probability of category 1 not overshooting the 2°C target is around 60%, the probability of category of 2 is about 40-50%. All other categories have a probability of substantially below 50%. In terms of the delay

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[2] MAGICC is also used in WG1 – which makes the results comparable to those presented in WG1. Moreover, in the next draft we also intend to use the emulator developed on the basis of CMIP ESM/GCM model results.

scenarios discussed here (Figure 6.11), the results indicate that the latter result in a considerably higher rate of temperature increase in the next decades. This also translates into a much higher probability of temporarily exceeding the 2oC target. For the long-term (2100), however, the different scenarios might converge based on the emission trajectory assumed.

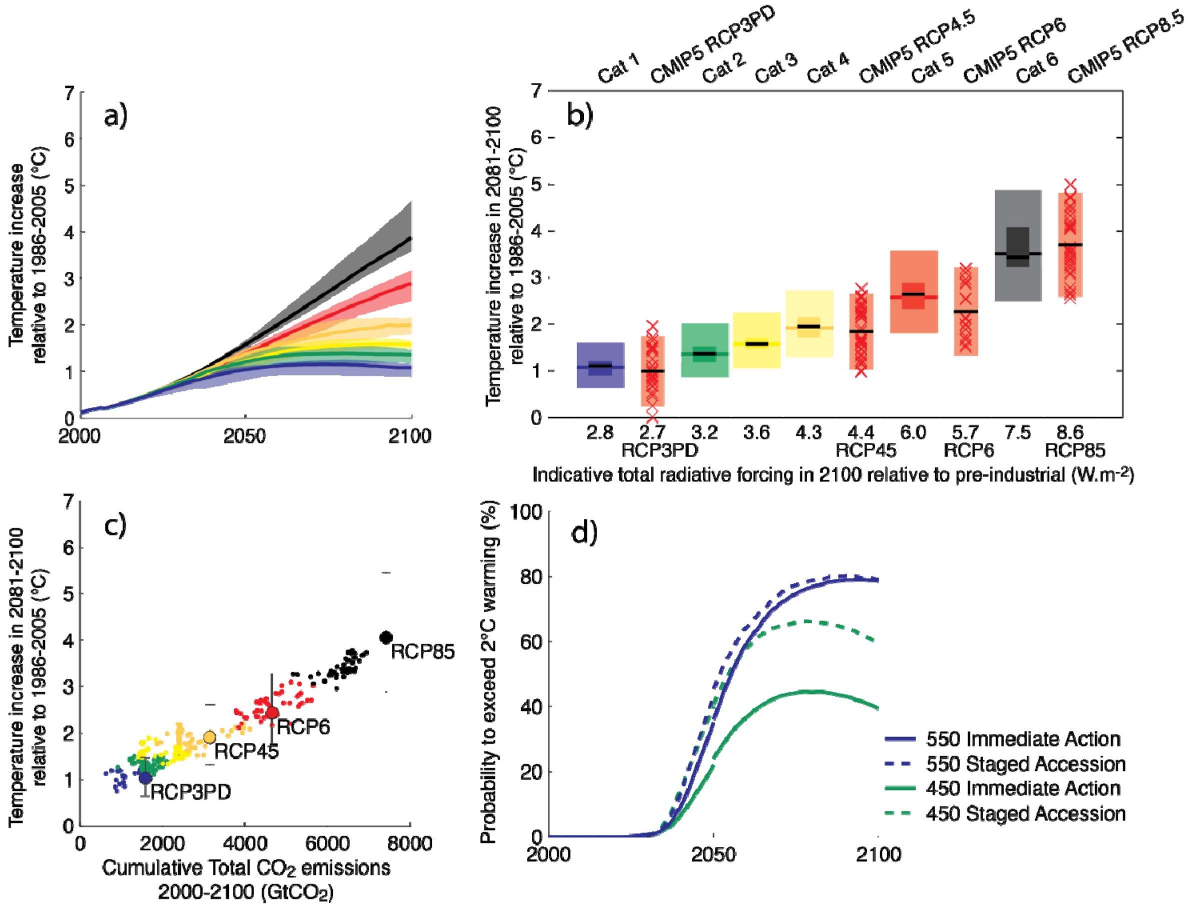


Figure 6.11. Calculated temperature level for the scenario categories and for the Representative Concentration Pathways as calculated by Earth System Models. **Panel a** shows temperature increase relative to 1986-2005 as calculated by MAGICC (the range represents scenario uncertainty; for climate system uncertainty only median values are shown). **Panel b** shows 2081-2100 temperature levels according to the MAGICC calculations for the scenario categories and the RCP runs as reported by different GCM models represented by individual markers (see WG1) and overall mean and 90% uncertainty ranges. The ranges for the MAGICC results show both the scenario uncertainty (inner bars) and the climate/carbon cycle uncertainty (outer bars). **Panel c** shows relationship between cumulative CO2 emissions in the 2000-2100 period and 2081-2100 temperature levels calculated by MAGICC. **Panel d** indicates the difference between immediate action scenarios and staged accession scenarios (taken directly from Schaeffer et al., 2013).

Another option to control the increase of climate radiative forcing is by directly altering the radiative forcing by techniques now called Solar Radiation Management (SRM) (see also Working Group 1 report). Section 6.9 provides a brief overview of key benefits and risks associated with these options. These options are not often explored in IAM model analysis (cf. Goes et al., 2011; Moreno-Cruz and Keith, 2012). Reasons include that SRM technologies are only in a very preliminary stage of development and that decisions regarding SRM typically involve an assessment of risks versus benefits, instead of an assessments of costs (Barrett, 2008). Clearly, the use of SRM would imply that relationships between greenhouse gas emissions and radiative forcing that underlies much of the discussion of literature so-far would (at least partly) be broken, which means that a much wider range of emission scenarios could still be consistent with a certain forcing level than indicated so-far. The potential use of SRM has also implications when considered in conjunction with the uncertainties in the climate systems. Because SRM can be implemented quickly (decades) whereas reduction in carbon dioxide concentrations takes place on century-timescales it might, in principle, be implemented after key uncertainties might be reduced (see Keller and McInerney, 2008; Van Vuuren and Stehfest, 2013) Lorentz et al., 2012). This attribute of SRM makes it a potentially valuable instrument for managing climate risk even if the costs and damages of SRM were comparable to the costs of mitigation and the damages of climate change (Moreno-Cruz and Keith, 2012). However, SRM may entails many risks that are, at this time, deeply uncertain as discussed in Section 6.9 .

6.3.3 Treatment of impacts and adaptation in transformation pathways

Although the importance of considering impacts and adaptation responses when assessing the optimal level of mitigation in a cost-benefit framework is obvious, it is less obvious what role impacts and adaptation have in transformation pathways. Mitigation, impacts and adaptation are interlinked in several important ways and should, ideally, be considered jointly in the context of achieving stabilization targets. In the vast majority of cases, however, the transformation pathways discussed in this chapter do not consider these linkages, and is considered a major gap in the transformation pathways literature. Major efforts are now underway to incorporate impacts and adaptation into transformation pathways, but these efforts must overcome a range of challenges, including the sectoral and regional character of impact and adaptation in highly-aggregated models and a desperate lack of data and empirical evidence on impacts and adaptation required for model calibration. In interpreting these pathways, it is therefore important to ask how they would be different were they to include the effects of impacts and adaptation.

Omitting climate impacts and adaptation responses from transformation pathways is likely to lead to biased results for three main reasons. First, climate impacts could limit the effectiveness of emissions mitigation options. For instance, thermal cooling requirements for thermal power plants could be effected by reduced precipitation, or climate change could impact biofuel crop productivities. Unfortunately, the set of modeling studies that explore these issues is limited (Fisher-Vanden et al., 2011), so there is insufficient evidence today to draw broad conclusions about how the omission of impacts and adaptation responses would alter the results reviewed in this chapter. Second, adaptation responses to climate change could themselves alter emissions from human activities, potentially requiring deeper, or perhaps less stringent, cuts in emissions to reach atmospheric stabilization targets. For example, a warmer climate is likely to lead to higher demand for air conditioning (Mansur et al., 2008) which will lead to higher emissions if this increased electricity demand is met by electric power generated with fossil fuels. On the other hand, this will be balanced by reductions in heating demand, which would lower emissions. Further, because electricity is relatively easier to decarbonize than solid, liquid, or gaseous fuels, changing in heating and cooling demands could reduce the economic costs of mitigation. Climate change will also change the ability of the terrestrial biosphere to take up carbon. Again, there is a limited number of studies that account for changes in baseline emissions resulting from climate change (Bosello et al., 2010b; Eboli et al., 2010; Anthoff et al., 2011). Finally, mitigation strategies will need to compete with adaptation strategies for scarce investment and R&D resources. This will also lead to higher abatement costs. A number of studies account for competition for investment and R&D resources. In cost-benefit modeling studies like de Bruin et al (2009) and Bosello et al (2010a, 2010b), adaptation and mitigation are both decision variables and compete for investment resources. Competition for investment resources is also captured in studies measuring the economic impacts of climate impacts, but rather than competing with mitigation investments, competition is between investment in adaptation and consumption (Bosello et al., 2007) and other capital investments (Darwin and Tol, 2001). Some simulation studies that estimate the economic cost of climate damages add adaptation cost to the cost of climate impacts and do not capture crowding out of other expenditures (Hope, 2006). No existing study, however, examines how this crowding out will affect an economy’s ability to invest in mitigation options to reach stabilization targets. The scenarios discussed in this chapter also do not account for crowding out and therefore could underestimate the cost of meeting stabilization targets.

6.3.4 Energy Sector Technology Transitions

6.3.4.1 Low-carbon energy supply along transformation pathways

The fundamental transformation required in the energy sectors to meet long-term concentration goals is a potentially dramatic decrease in the use of freely-emitting fossil fuels. This decrease is a natural consequence of the limits placed on GHG emissions associated with long-term goals, and the primary role that energy sector CO_2 places in those emissions. Although the relationship between allowable GHG or even CO_2 budgets is quite strong, some flexibility in the limits on the use of freely-emitting fossil energy associated with different long-term goals remain, due to differences in the carbon content of the various fossil fuels (e.g., natural gas has a lower carbon content per unit of energy than coal); the potential to achieve negative emissions by utilizing bioenergy with CCS, which allow for greater emissions of freely-emitting fossil energy; differences in the timing of mitigation among scenarios; and representations of physical systems such as the carbon cycle.

It is important to note that the reduction in freely-emitting fossil fuels is not necessarily equal to the reduction in fossil fuels more generally, because fossil resources can be used in combination with CCS to serve as a low-carbon energy source (right panel in Figure 6.12). This means that the total use of fossil fuels (left panel in Figure 6.12) can exceed that for just the freely emitting fossil fuels. It is worthwhile noting that scarcity of fossil fuels alone will not be sufficient to stabilize atmospheric GHG concentrations at levels that compatible with stringent stabilization targets (e.g., the 2°C target) (McCollum, Bauer, et al., 2013a).

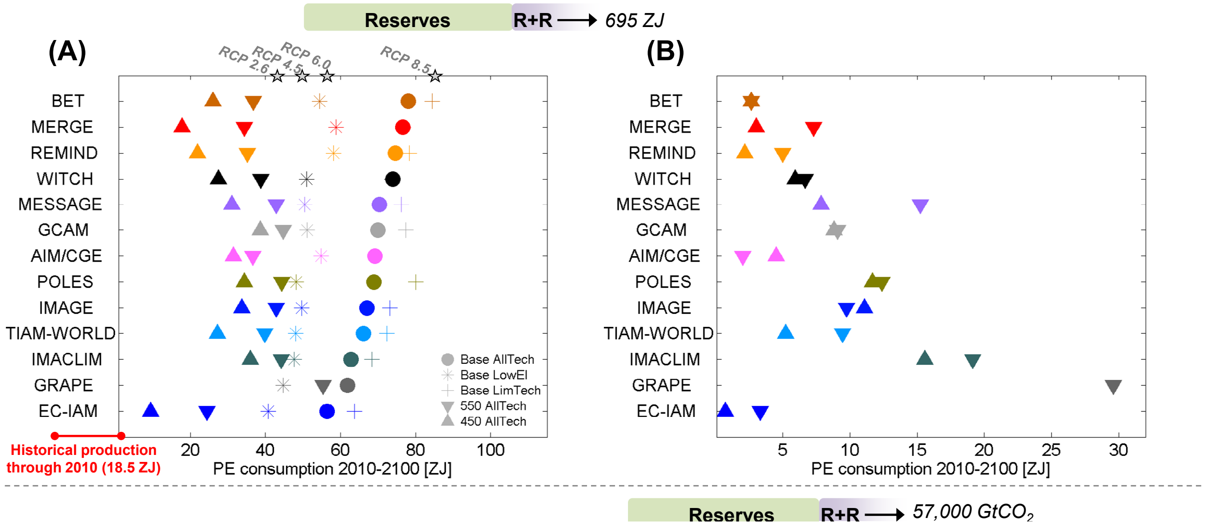


Figure 6.12. Cumulative global consumption of fossil fuels and cumulative global emissions of CO2 across models participating in the EMF27 modeling intercomparison (full-century models only). **Panel A** shows all fossil fuels (coal, oil, and natural gas combined) for five different scenarios; **Panel B** only those fossil fuels used in combination with CCS in the two climate policy scenarios (450 AllTech, 550 AllTech). EMF27 model results are compared to the four RCP scenarios (Van Vuuren, Edmonds, et al., 2011), and to the lower/upper fossil reserves and resources estimates ("R+R" = reserves + resources). (Source: McCollum et al. (2013a))

To accommodate this reduction in freely-emitting fossil fuels, any transformation of the energy system relies on a combination of three high-level strategies: (i) decarbonisation of energy supply, (ii) an associated switch to low-carbon energy carriers such as decarbonized electricity or hydrogen and biofuels in the end-use sectors to profit from the decarbonisation of the supply system, and (iii) the reduction of energy demand. The first two of these can be represented in terms of the carbon intensity of energy. The last can be imperfectly illustrated in terms of energy intensity of GDP, energy per capita, or other indexed measures of energy demand.

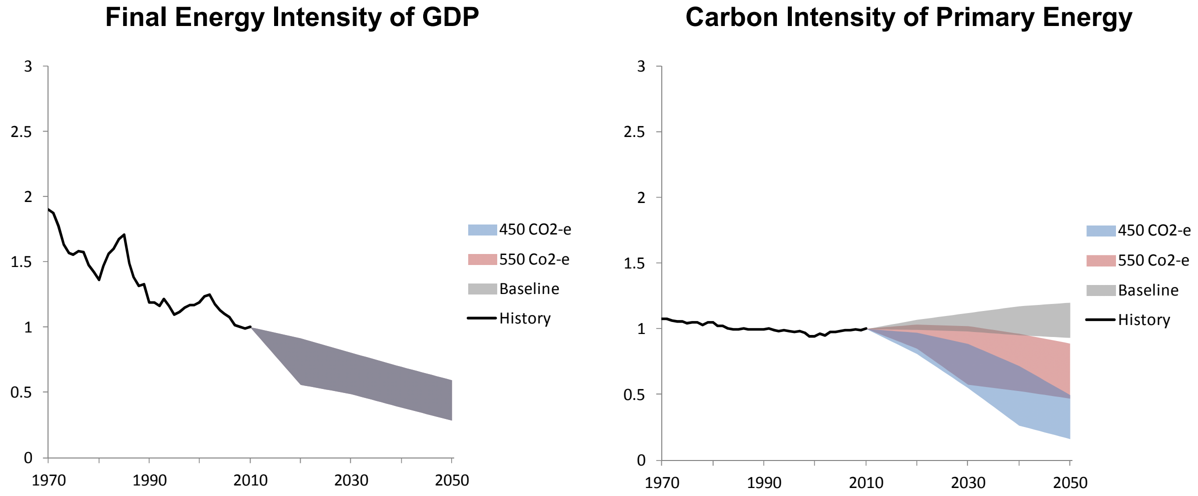


Figure 6.13. Evolution in final energy intensity (left panel) and carbon intensity of primary energy (right panel) along transformation pathways.

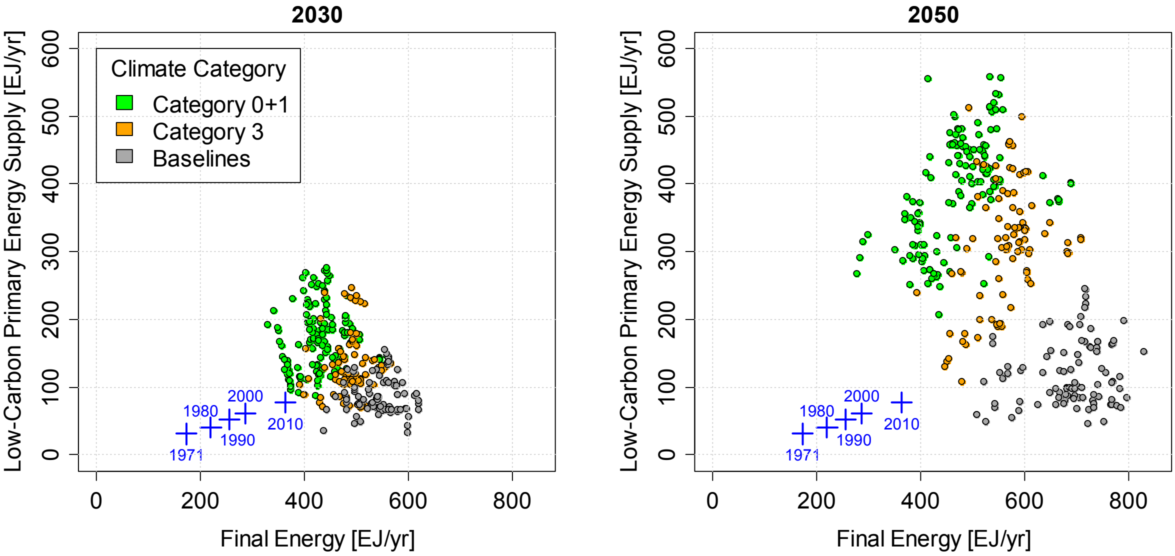
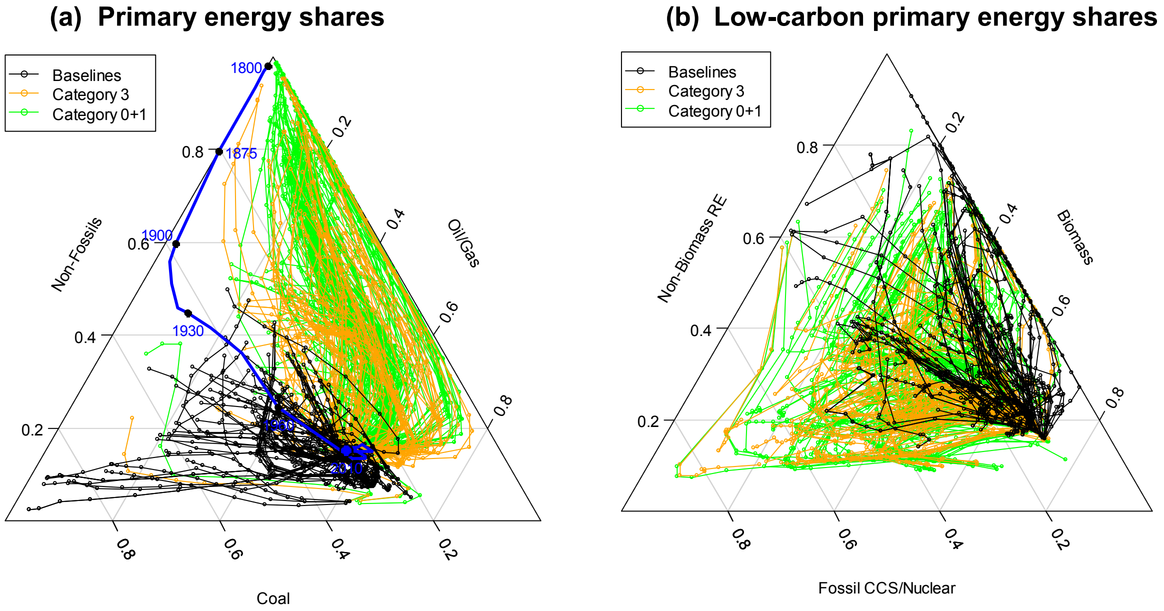


Figure 6.14. Global low carbon primary energy supply (direct equivalent) vs. total final energy use in the reviewed long-term transformation pathways by 2030 and 2050 assuming a cost-minimizing mitigation profile over the near-term. The colour coding is based on categories of climate stabilization as defined in Section 6.3.2 (Sources: Scenario data from AR5 scenario database, historical data from IEA (2012a))

The transformation pathway literature suggests that the first of these two (carbon intensity of energy) will make the largest break from past trends in the long-run on pathways toward stabilization (Figure 6.13). To some degree, this result in scenarios could be attributed to assumptions about the flexibility to achieve end use energy reductions relative to decarbonization of supply in integrated models, about which there is a great deal of uncertainty (see Section 6.8 for a further discussion). However, this result is also a natural consequence of the fact that, although energy use reduction is fundamental to mitigation, the ultimate potential for end use reduction is limited; some energy will always be required to provide energy services. This means that a long-term strategy for carbon mitigation must ultimately focus on producing low-carbon energy and switching from emitting to non-emitting fuels in end uses if deep emissions reductions are to be achieved (See also Figure 6.16 and the discussion below regarding the temporal relationship between energy reduction and fuel switching in end uses).

This decarbonization of the energy supply will require a dramatic scale-up of low-carbon energy supplies. The deployment levels of low carbon energy technologies are substantially higher than today in the vast majority of scenarios, even under baseline conditions, but in particular so for the most stringent climate stabilization scenarios of climate categories associated with meeting 450 ppmv CO2-e or more stringent goals. These scenarios indicate that, assuming a cost-minimizing mitigation profile, a scale up of anywhere from a modest increase to upwards of three times today's low carbon energy in 2030 is consistent with a 450 ppm CO2e goal. A scale up of anywhere from roughly a tripling to over seven times today's levels in 2050 is consistent with this same goal (Figure 6.14). The degree of scale up depends critically on the degree of overshoot, which allows emissions reductions to be pushed into the future.

The degree of this scale also depends crucially on the degree that final energy use is altered along a transformation pathway. Final energy demand reductions will occur both in responses to higher energy prices brought about by mitigation as well as by approaches to mitigation focused explicitly on reducing energy demand. When taking into account the level of total final energy use, it becomes clear that higher low carbon energy technology deployment tends to go along with higher final energy use and vice versa (Figure 6.14). Hence the relative importance of energy supply and demand technologies varies across transformation pathways (Riahi et al., 2012a).


(a) Primary energy shares

(b) Low-carbon primary energy shares

Figure 6.15. Primary energy (a) and low-carbon primary energy shares (b) by technology cluster in different transformation pathways between 2010 up to 2100. Notes: Consecutive dots show the development in the future in 10-year steps where the black lines correspond to baseline scenarios, orange to climate category 3 scenarios and green to climate category 0+1 scenarios. The colour coding is based on categories of climate stabilization as defined in Section 6.3.3. (Sources: AR5 scenario database, historical data from Grubler (2008) and IEA (2012a))

Different technologies compete for the provision of low carbon energy (Figure 6.15b). Moving from baselines to climate category 3 and further to category 0 and 1, the role of fossil energy (coal and hydrocarbons) decreases across scenarios (Figure 6.15a). At the same time, the degree to which this is accomplished depends to a large degree on the models and the assumptions used to generate scenarios. The role of the individual low-carbon energy supply options as shown in Figure 6.15b crucially depends on assumptions made on the future availability, cost and performance of technologies (Kim et al.; Krey et al., Submitted; Tavoni et al., 2012), fossil and renewable energy resources (Luderer et al.; McCollum, Bauer, et al., 2013a), and CO2 storage potentials and system integration constraints (Fischedick et al. 2011; Krey and Clarke 2011). For example, some pathways maintain roughly equal shares of biomass, non-biomass RE, and fossil CCS and nuclear energy, while other pathways tend to heavily rely on non-biomass RE. A more detailed discussion of the contribution of individual energy supply technologies to the future energy system can be found in Chapter 7.

A major advance in the literature since AR4 is the assessment of scenarios with limits on available technologies or variations in the cost and performance of key technologies. These scenarios are intended as a rough proxy for various non-economic obstacles faced by technologies. Many low-carbon supply technologies, such as nuclear power, CO2 storage, hydro or wind power, face public acceptance issues and other barriers that may limit or slow down their deployment (see Section 6.8). In general, these scenarios demonstrate the simple fact that reductions in the availability and/or performance or an increase in costs of one technology will necessarily result in increases in the use of other options. The more telling result of these scenarios is that limits on the technology portfolio available for mitigation can substantially increase the costs of meeting long-term goals. Indeed, many models cannot produce scenarios leading to 450 ppmv CO_2-e when particularly important technologies are removed from the portfolio. This topic is discussed in more detail in Section 6.3.6 .

6.3.4.2 Energy end use sectors along transformation pathways

As noted above, end use sectors play two critical roles in climate mitigation: fuel switching to allow the use of more low-carbon fuels and energy use reduction. Both are important elements of a technology strategy. A key question is the relative timing of each of these. Virtually all scenarios indicate meaningful reductions in energy demand as an economically-efficient element of mitigation. In particular in the short-term (2020-2030) when the supply system is still heavily reliant on fossil fuels (and thus very carbon intensive) the contribution of energy intensity reductions (measured as final energy use per unit of GDP) outweighs the contribution of decarbonisation of energy supply (measured as the fossil fuel and industrial CO_2 emissions per unit of primary energy) as shown in Figure 6.16. This dynamic indicates several factors. One is that fuel switching takes time to take root as a strategy, because there is little incentive to switch, say, to electricity early on when electricity may still be very carbon intensive. As electricity decreases in carbon intensity through the use of low-carbon energy sources, then there is an increasing incentive to increase its use. A second factor is that there may be low-cost demand reduction options available in the near-term, although there is limited consensus on the costs of reducing energy demand (see Section 6.8). Hence, transformation scenarios sketch out an evolving character in the end use sectors with an initial focus on energy reductions and an increasing focus on fuel switching over time. Of importance, these trends can be very regional in character. For example, the value of fuel switching will be higher in countries that already have low-carbon electricity portfolios.

Regardless of the exact roles of demand reduction and decarbonisation, a transition to a low carbon energy system requires a switch from carbon-intensive (e.g. direct use of coal, oil and natural gas) to low-carbon energy carries (most prominently electricity, but also heat and hydrogen) in the end-use sectors in the long-run (Figure 6.17a). It should be noted that there is generally an autonomous increase in electrification in baseline scenarios that do not assume any climate policies which is reflecting a trend toward more convenient grid-based fuels due to higher affluence (Nakicenovic et al., 1998; Schäfer, 2005). With increasing stringency of the climate target, the share of electricity in final energy use significantly increases beyond the baseline level (Figure 6.17a). Because electricity generation can be decarbonized at relatively modest extra costs (compared to other fuels), electrification of the end-use sectors is a way of reducing GHG emissions from the entire energy system (Figure 6.17b) (Edmonds et al., 2006; Sugiyama, 2012). There are, however, significant differences across the end-use sectors – transportation, buildings and industry – that will be discussed in Section 6.8.

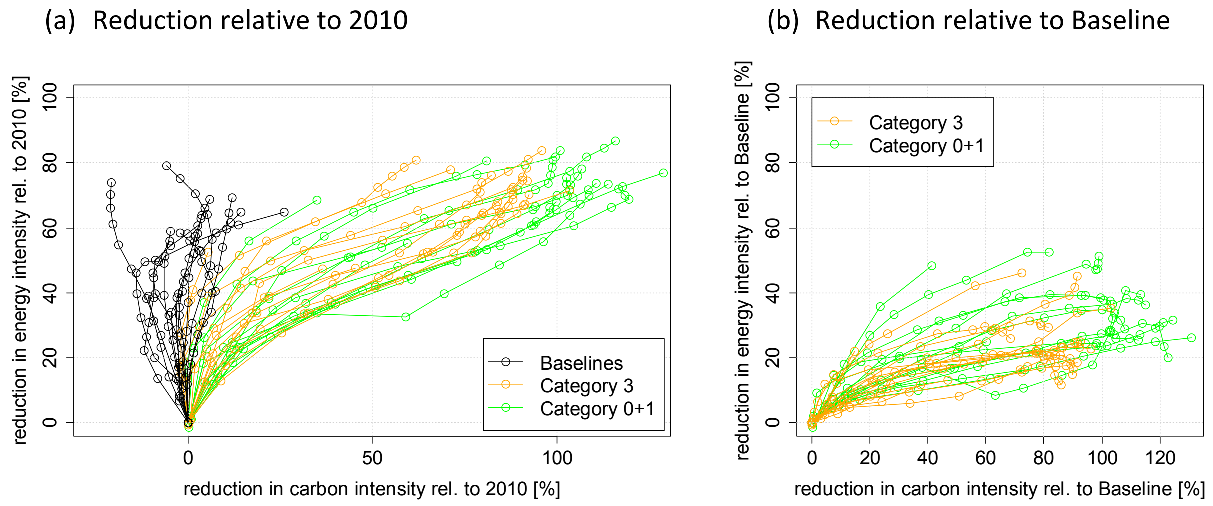


Figure 6.16. Development of carbon intensity vs. final energy intensity reduction (a) relative to 2010 in selected baseline, 550 and 450 ppm CO2-e stabilization scenarios and (b) relative to Baseline in the same 550 and 450 ppm CO2-e stabilization scenarios. The colour coding is based on categories of climate stabilization as defined in Section 6.3.2 . [Authors: Please see note in the introduction regarding the preliminary nature of the AR5 scenario dataset.]

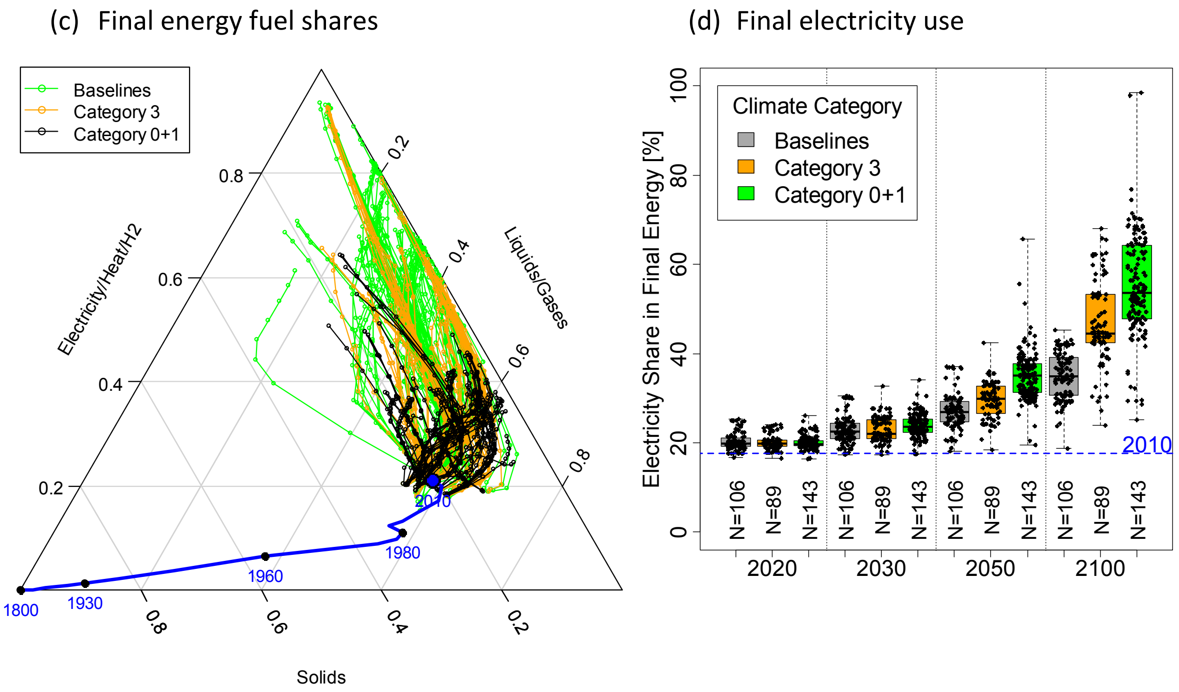


Figure 6.17. Final energy shares for three different groups of energy carriers – solids, liquids and gases, electricity, heat and hydrogen – between 2010 up to 2100 (a) and total final electricity use (b) in transformation pathways from different climate categories. Notes: In panel (a) consecutive dots show the development in the future in 10-year steps where the black lines correspond to baseline scenarios, orange to climate category 3 scenarios and green to climate category 0+1 scenarios. The colour coding is based on categories of climate stabilization as defined in Section 6.3.2 . (Sources: AR5 scenario database, historical data from Grubler (2008) and IEA (2012a))

FAQ 6.2. What are the most important technologies for mitigation? Is there a silver bullet technology?

Researchers have known for a long time that reducing GHG concentrations will require a portfolio of options. No single option is sufficient to reduce GHG concentrations and eventually eliminate net CO2 emissions. Options include a range of energy supply options such nuclear power, nuclear power, solar power, wind power, hydroelectric power, bioenergy, and fossil resources with carbon dioxide removal. Reductions in energy end use will be valuable to reduce the need for low-carbon energy supplies. And a range of technologies, from heat pumps to electric cars, will be needed to allow the use of low-carbon fuels in buildings, industry, and transportation. Halting deforestation and encouraging an increase in forested land will help to halt or reverse land use change CO2 emissions. Furthermore, there are opportunities to reduce non-CO2 emissions from land use and industrial sources. All of these must be deployed to some degree to stabilize GHG concentrations, and a portfolio approach that is tailored to local circumstances and takes into account other local priorities such as energy security or local air pollution will dramatically reduce the costs of mitigation. At the same time, it is also true that meeting ambitious concentration goals will not be possible without unproven carbon dioxide removal technologies if emissions mitigation is too modest over the coming decades. In this scenario, carbon dioxide removal technologies are less a “silver bullet” than a “backstop”.

6.3.5 Land and stabilization

Transformation pathway scenarios suggest a substantial cost-effective, and possibly essential, mitigation role for land in transformation (Section 6.3.2), with baseline land emissions and sequestration an important uncertainty (Section 6.3.1). However, this transformation is challenging due to the regional scale of deployments and implementation issues, including institution and program design, land-use and regional policy coordination, emissions leakage, biophysical and economic uncertainties, and potential non-climate social implications. Recent literature suggests that these factors will affect land-related mitigation opportunities and net mitigation benefits.

6.3.5.1 Land use in idealized implementation scenarios

Climate change mitigation may have profound impacts on the land surface. Changes in the land surface over the coming decades through the end of the century and beyond will result from a confluence of factors, some of which are largely associated with economic growth and others of which are heavily influenced by mitigation itself. These include (1) the demand for food and other products from land such as forest products and the improvements in technology for these purposes, (2) the demand for land for growing urban environments, (3) the demand for protected lands for environmental, aesthetic and economic purposes, (4) the demand for bioenergy, particularly in the context of mitigation, and (5) the desire to store carbon in land by reducing deforestation, encouraging afforestation, and changing management as part of a mitigation regime. Only a small set of models are currently capable of exploring these interactions; the development of fully integrated land use models is a major area of integrated model development.

Scenarios indicate that the combination of these forces can result in very different projected landscapes relative to today, even in baseline scenarios (e.g., Figure 6.18). For instance, Popp et al. (in review) evaluate three models, and show that projected 2030 baseline changes from today alone vary sharply across models in all regions (Figure 6.18), with projections exhibiting growth and reductions in non-energy cropland (e.g., Asia), and both energy cropland growth and not (e.g., Asia, OECD, Reforming Economies). Furthermore, different kinds of land are converted when baseline cropland expands (e.g., ME & Afr).

Mitigation generally induces greater changes than in baseline scenarios, but even in idealized implementation scenarios, there are very different potential transformation visions. Overall, it is difficult to generalize on regional land cover effects of mitigation. For the same scenario, some models convert significant acreage, some do not. Some lose pasture acreage, others gain, and others have no change. Some models convert food cropland (possibly shifting it elsewhere), others sustain it. Some of the results are attributable to specific assumptions, such as fixed pasture acreage, prioritized food provision, land availability constraints for energy crops, including/excluding afforestation options. Others are more subtle results of combinations of modeling assumption and structure, such as land productivity & heterogeneity, yield potential, land production options, and land conversion costs.

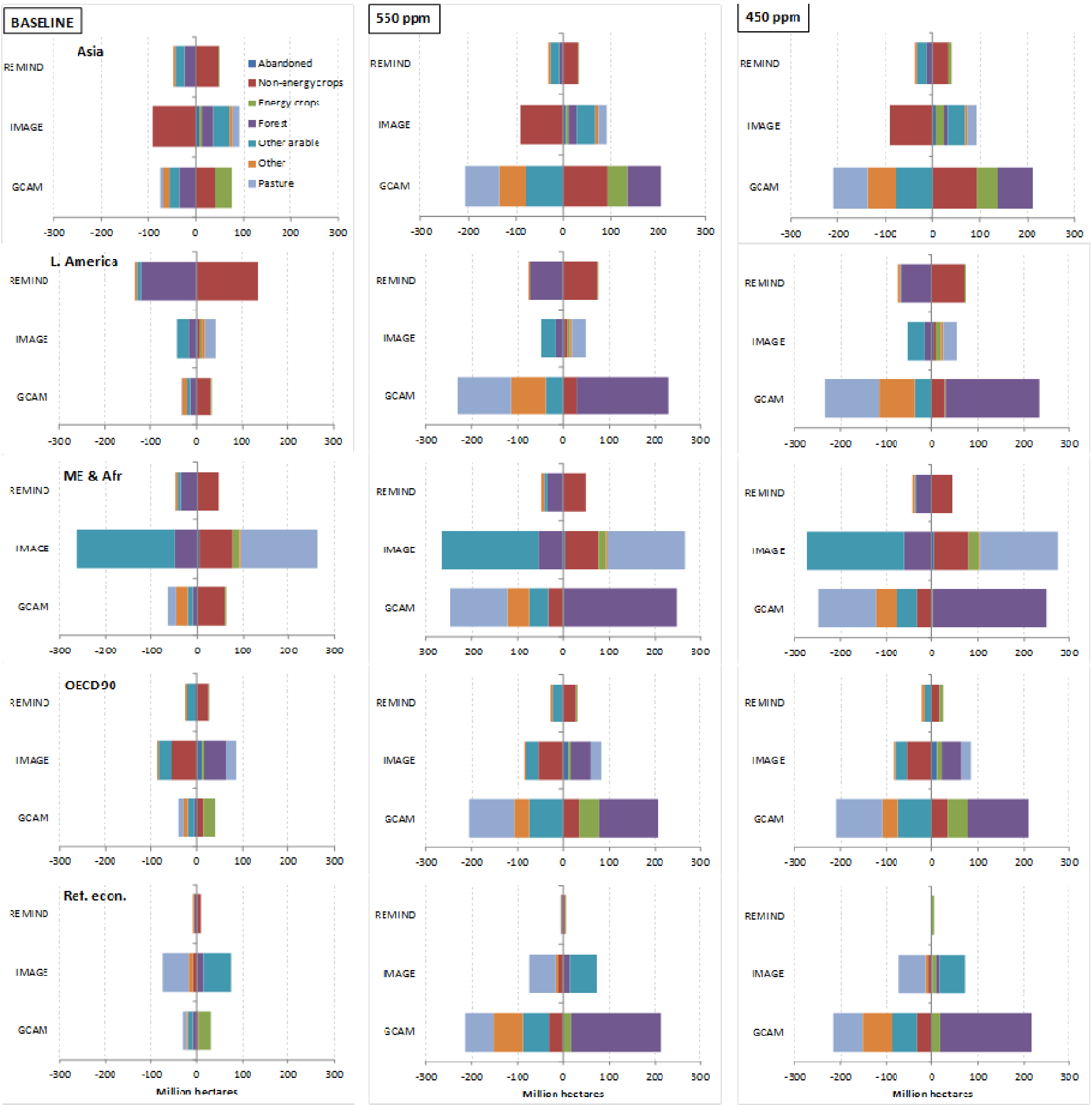


Figure 6.18. Regional land cover change by 2030 from 2005 from three models for baseline (left) and idealized implementation 550 ppm (center) and 450 ppm (right) scenarios. Source: EMF-27 Study (see Popp et al., in review).

Nonetheless, a common characteristic of climate policy scenarios is an expansion of energy cropland in many regions in order to support the production of bioenergy. Less consistent is the response of forest land. Some models exhibit only a modest change in forest land. In contrast, others exhibit a very strong forest land expansion by 2030 (see the GCAM results in Figure 6.18). This result largely derives from important differences in approaches to incorporating land carbon in the mitigation regime. In Figure 6.18, GCAM includes an explicit price incentive, related to carbon price, to store carbon in land, which serves to encourage afforestation. In contrast, REMIND has an avoided deforestation option, and IMAGE constrains land conversion. Both of these protect existing forests, but neither encourages afforestation. In other studies, Melillo et al (2009) protect existing natural forests based on profitability and Popp et al (2011) impose conservation policies that protect forest regardless of cost. The explicit pricing of land carbon incentive in GCAM (see also Wise et al (2009b)), leads to substantial expansion in forest land. Such forest expansion results in the largest land use sink associated with transformation pathways (see Section 6.2.2). There is relatively modest additional land conversion in the 450 scenarios compared to the 550 scenarios, a result consistent with the declining mitigation role of land-related mitigation with policy stringency (6.3.1).

6.3.5.2 Bioenergy

To understand bioenergy's transformation role, it is important to understand bioenergy's role within the energy system. (Rose et al., 2012a) found bioenergy contributing up to 15% of cumulative primary energy over the century during stabilization (see Chapter 7 for more detail on bioenergy's role in energy supply). Figure 6.19 shows more recent annual results for idealized implementation scenarios. Modern bioenergy is projected to provide 0 to 100 EJ in 2030, 15 to 225 EJ in 2050 and 80 – 320 EJ in 2100. The scenarios project increasing deployment of, and dependence on, bioenergy with tighter climate change targets, both in a given year as well as earlier in time. By 2050, bioenergy represents up to 30% of total primary energy, and as much as 45% by 2100 (Figure 6.19). Shares of total primary energy increase under climate policies due to both increased deployment of bioenergy and shrinking energy systems.

Bioenergy's share of total regional electricity and liquid fuels could be significant. However, there is no single vision about where biomass is projected to be cost-effectively deployed within the energy system, due in large part to uncertainties about relative technology options and costs over time. Some models prefer to use biomass for electricity, while others prefer to use if for biofuels, as well as hydrogen. For idealized participation, scenarios projected up to 35 percent of global regional electricity from biopower by 2050, and up to 70 percent of global regional liquid fuels from biofuels by 2050 (Rose et al., 2012a).

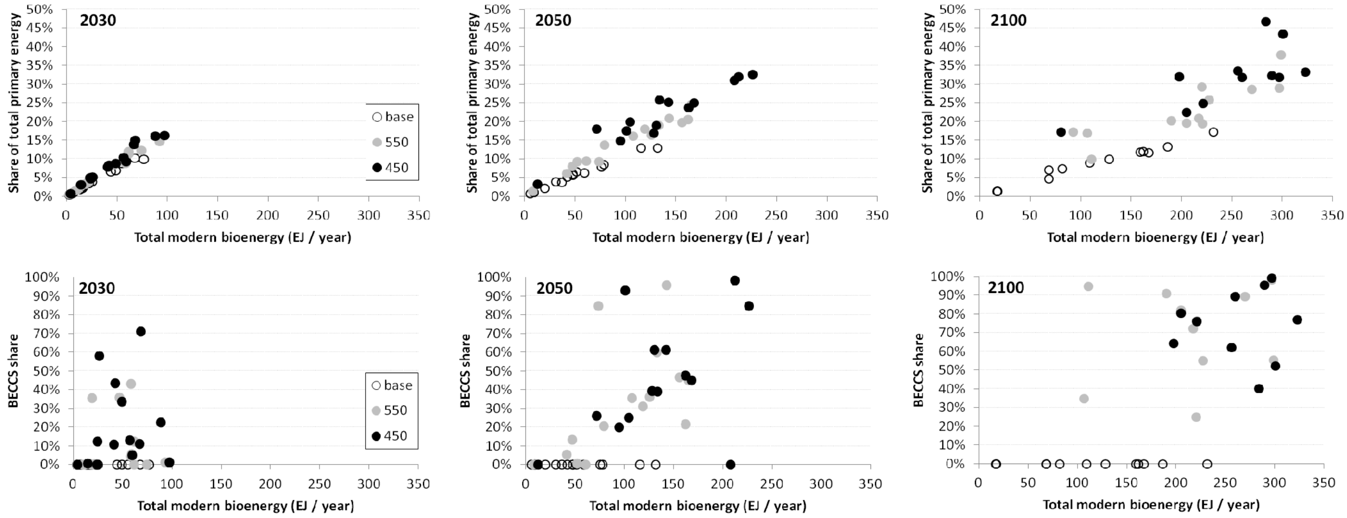


Figure 6.19. Annual global modern biomass primary energy and BECCS share of modern bioenergy in baseline, 550 ppm, and 450 ppm scenarios in 2030, 2050, and 2100. Notes: All scenarios shown assume idealized implementation. Three models project to 2050, the rest project to 2100. Also, some models do not include BECCS technologies and some do not model more than biopower bioenergy options (Source: Rose et al.).

A particularly important issue with respect to bioenergy is the availability and use of BECCS. BECCS features prominently when it is included in scenarios (Figure 6.19). As noted in Section 6.3.2 , BECCS could be very valuable for getting to lower targets, and as an overshoot response technology that even affects the degree of overshoot. In models that include BECCS technologies, BECCS is deployed in greater quantities and earlier in time the more stringent the climate policy. For instance, in Figure 6.19 BECCS reaches 60-70% of modern bioenergy by 2030; 20% to almost 100% and 40% to almost 100% by 2050 and 2100 respectively

Two additional insights are worth noting. First, the availability of BECCS technologies could affect biomass demand. In scenarios without CCS available, global biomass demand decreased in the first half of century and increased in the second half of the century, for a net increase in bioenergy cumulatively over the entire century. Finally, some integrated models are cost-effectively trading-off lower land carbon stocks and increased N_2O emissions for the long-run climate change management benefits of bioenergy ((Rose et al.; Popp et al., in review).

Regionally, models universally project that the majority of biomass supply for bioenergy and bioenergy consumption will occur in developing and transitional economies. For instance, 45-95% of global bioenergy primary energy is projected from non-OECD countries in 2050, and 60-90% in 2100, including bioenergy with CCS (Rose et al.). Developing and transitional regions are also projected to be the home of the majority of agricultural and forestry mitigation.

6.3.5.3 Non-idealized policy implementation – policy coordination and design

Coordination between land mitigation policies, regions, and activities over time will affect forestry, agricultural, and bioenergy mitigation potential and net GHG effectiveness. Most transformation scenarios assume idealized implementation, with immediate, global, and comprehensive availability of land related mitigation options, and no uncertainty, risk, or transactions costs (For a discussion of these issues, see Lubowski and Rose, 2013). In these cases, models are assuming a global terrestrial carbon stock incentive or a global forest protection policy, as well as global agriculture mitigation policies and incentives for agriculture/forestry biomass feedstocks for bioenergy displacement of fossil fuel based energy. Interactions between regions and mitigation options through land and commodity markets imply that there are potential leakage and societal distributional implications with partial policies. Altogether, there is likely less available mitigation potential in the near-term, and possibly unavoidable negative emissions consequences associated with getting programs in place.

The literature has begun exploring more realistic fragmented policy contexts and identifies a number of policy coordination issues. Three concerns figure most prominently. First, of primary concern for mitigation are the policy structures that would mediate the competition between land-based mitigation options. Across mitigation technologies, there is competition between energy crops and forest carbon strategies (e.g. Wise et al., 2009b; Melillo et al., 2009), and avoided deforestation and afforestation (Rose and Sohngen, 2011). Conversely, forest management and afforestation are synergistic (Rose and Sohngen, 2011). A fundamental question that arises is how will these incentives be balanced? Increased bioenergy incentives without terrestrial carbon stock incentives or global forest protection policies (Wise et al., 2009b; Popp, Hascic, et al., 2011; Reilly et al., 2012). Melillo et al. (2009) suggest a large potential for land use change emissions with large-scale deployment of cellulosic energy crops. These studies have analyzed the implications of ignoring land conversion emissions with energy crop expansion. All find higher land conversion emissions, resulting in the need for deeper emissions reductions in the fossil and industrial sectors and increased total mitigation costs. The land conversion leakage comes primarily in the form of displacement of pasture, grassland, and natural forest. There is also food cropland conversion. However, bioenergy deployment and land-use implications vary notably across models due to differences in modeling assumptions and structure. Wise et al. (2009b) project significantly more bioenergy and energy crop land expansion. Melillo et al (2009) project only slightly more bioenergy and similar energy cropland area with price induced agricultural land management intensification. Popp et al. (2011) project slightly more bioenergy, but significantly more energy crop land. Recall that there can be important differences in the land carbon policies modelled (discussed above). There are also differences across studies in the stringency of the climate policy modeled. Analysis by

Calvin et al. (Submitted) finds that forest protection policies could need to be extensive. In their model, they need to protect 90% of the world's forests to prevent deforestation from increased energy crop demand. Note that providing energy crops, especially while protecting terrestrial carbon stocks, could result in a significant increase in food prices, potentially further exacerbated if expanding forests.

The second major concern is the nature of land use changes and land-use change emissions leakage under fragmented participation. In addition to the leakage associated with coordinating mitigation activities, staggered adoption of land mitigation policies will likely have leakage implications. The analyses noted above assume the ability to globally protect or incentivize forest carbon stocks. A few studies have evaluated the implications of staggered forest carbon incentives—across regions and forest carbon activities. For instance, land CO2 emissions increases of 4 and 6 GtCO2/year in 2030 and 2050 respectively have been estimated from scenarios with staggered global regional climate policies that include forest carbon incentives (Calvin et al. 2009). And, fragmented and delayed forest carbon policy could even accelerate deforestation. For example, Rose and Sohngen (2011) project 60-100 GtCO2 of leakage by 2025 with a carbon price of $15/tCO2 rising 5% per year. Regional mitigation supply costs are also affected by regional participation/non-participation, which has heterogenous effects on regional opportunity costs for mitigation due to relative differences in the structure of regional production (Golub et al., 2009).

Finally, the type of incentive structure is likely to matter. Transformation scenarios assume that all emissions and sequestration changes are priced (similar to capping all emissions). However, mitigation, especially in agriculture and forestry, may be sought through voluntary markets. Thus, there are incentives for mitigation activities, but emissions of non-mitigation activities can increase without penalty and reduce the net mitigation benefit of mitigation activities (Rose et al., 2013).

6.3.6 The macroeconomic costs of transformation pathways

6.3.6.1 Overview of macroeconomic costs

Emissions mitigation requires explicit efforts to reduce greenhouse gas emissions that would not otherwise be taken. Mitigation actions will therefore require a range of changes, including behavioural changes and the use of alternative technologies that can decrease economic output and the consumption of goods and services by individuals. These potential macroeconomic costs of mitigation are generally estimated against a counterfactual baseline scenario without climate policy; that is as the change from what would have happened without any mitigation efforts. Most of these estimates focus only on a constrained set of direct market effects and do not take into account important ancillary costs or benefits of mitigation actions, such as health benefits from reduced air pollution or changes in landscapes (see Section 6.6). Further, these costs are only those of mitigation; they do not capture the benefits of reducing greenhouse gas concentrations and limiting climate change. It is against these benefits of mitigation that the potential costs of mitigation must ultimately be weighed.

A wide range of methodological issues attend the estimation of macroeconomic cost in integrated models, including: the metric used to measure of costs (for example, "equivalent variation", "compensating variation", GDP losses, consumption losses, and area of the marginal abatement cost function); the representation of the economy and the energy system and agricultural system in particular; and the method used to sum costs over time (i.e., the method used for discounting costs).(For more discussion on methods for issues in estimating macroeconomic costs, see Chapter 3 and the annex on metrics and methodologies). Projections of key driving forces such as population, technology, and economic growth along with the associated baseline emissions projections add an additional layer of uncertainty to cost estimates. In addition, macroeconomic costs may be influenced by assumptions about the future cost, performance, and availability of mitigation technologies, the nature of international participation in mitigation, and the policy instruments used to reduce emissions (e.g., carbon taxes, tradable permits, regulatory policies such as renewable portfolio standards).

Because models provide different metrics of macroeconomics costs, results from models with different cost metrics must necessarily be mixed in the analysis of results. For consistency, results in this section are presented preferentially in terms of consumption losses, GDP losses, and area under the marginal abatement cost function (See Chapter 3 and the Metrics and Methodologies Annex for more discussion of economic cost metrics). To maintain consistency regarding the value of costs in the future relative to those of today, all costs are summed over time using a 5% discount rate. Lower discount rates would tend to put more weight on costs in the future; higher discount rates would tend to put more weight on near-term costs (see Chapter 3 for more discussion of discounting).

6.3.6.2 Global macroeconomic costs of climate stabilization in idealized implementation scenarios

A valuable benchmark for exploring the macroeconomic costs of mitigation is the assumption of an idealized approach in which mitigation is undertaken where and when it is most effective and in which there are no explicit limits on the deployment of particular mitigation technologies. Such an idealized scenario is achieved by assuming the existence of a ubiquitous price on carbon in well-functioning markets that is applied across the globe in every sector of every country (this could be achieved either through a global carbon price or emissions trading with assuming transparent markets and no transaction costs), and that rises over time at a rate that minimizes the discounted cost of mitigation. Regardless of its likelihood, this scenario is valuable in that it leads to a low-cost approach to mitigation and therefore serves as a benchmark against which other scenarios with non-idealized policy structures or limits on technology might be compared. It is therefore taken as a starting point in this section. It is important to note that although idealized mitigation scenarios provide low cost estimates, they do not necessarily provide least-cost estimates. In practice, the ubiquitous carbon price may interact with other existing policies such as regulatory policies, technology, and energy policies, any revenue generated from carbon markets may interact with existing revenue structures. A carbon price combined with policies directly addressing these other factors could result in higher or even lower economic costs.

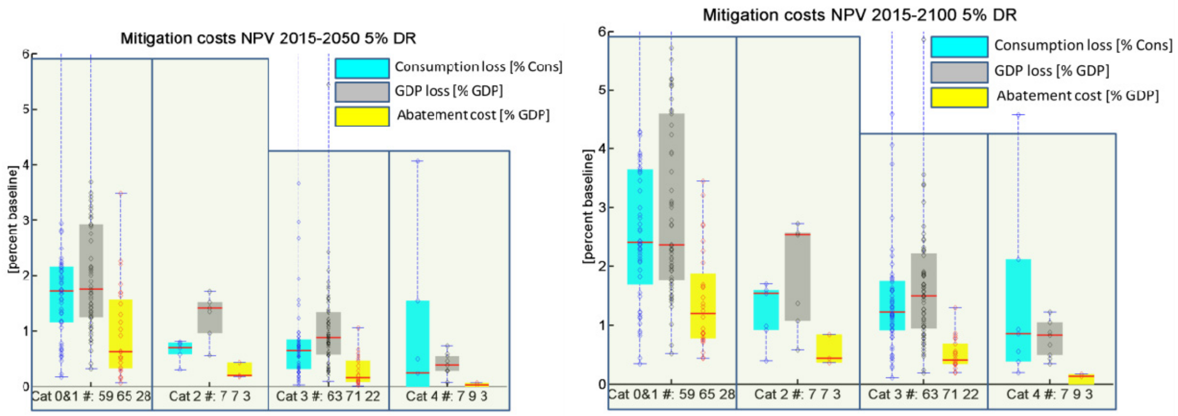


Figure 6.20. Global mitigation costs of idealized implementation scenarios as reported in the AR5 database. Costs are expressed as a fraction of aggregate production – or in the case of consumption losses – consumption in the baseline. Left panel shows net present value costs until 2050 and right panel until 2100. Boxplots show range (whiskers), 25 to 75 percentile (box) and median (red line) of scenario samples. Sample size is indicated at the bottom. GDP and consumption losses are drawn from almost identical samples of general equilibrium model results. Abatement costs are drawn from a complementary sample of partial equilibrium model results. One model reports substantially higher costs than 6% (see text). Preliminary results subject to update of the AR5 scenario database and sampling choices.

In the large majority of mitigation studies, net present value consumption losses are estimated to be below 4% across all climate target categories (see Figure 6.20). An important caveat to this result is that it does not account for a potential sampling bias due to the fact that high cost models may have reported pathways towards low stabilization targets to a lesser degree (see discussion of model failures in Section 6.2, and Tavoni and Tol, 2010). The increase of mitigation costs with increasing target stringency is still clearly visible. The 16th to 84th percentile range of estimated consumption losses for Category 3 (mostly 550 ppm CO2e scenarios) is 0.6-2% (Median: 1.2%) over the period 2015-2100, and increases to 1.1-3.9% (Median: 2.4%) for Category 0&1 (mostly 450 ppm scenarios). Percentage costs until 2050 are 30-40% lower, reflecting the fact that losses rise faster than production and consumption with time.

Due to the pattern of increasing costs over time, net present value costs are highly sensitive to the choice of discount rate. They reduce by up to a factor of two when choosing a discount rate of 8% instead of 5%, and they double to triple when adopting a discount rate of 1%. Abatement costs tend to be lower than full economic costs, but share the same sensitivity to the discount rate.

Cost ranges across all models and scenarios do not fully depict the increase in costs with mitigation stringency, because they do not control for the model and study used to create the cost estimates. It is therefore instructive to look at the cost increases projected by individual models in a given study (Figure 6.21). The net present value of mitigation costs more than doubles for most scenarios when moving from 550 ppm CO2e to 450 ppm CO2e (Category 1) stabilization.

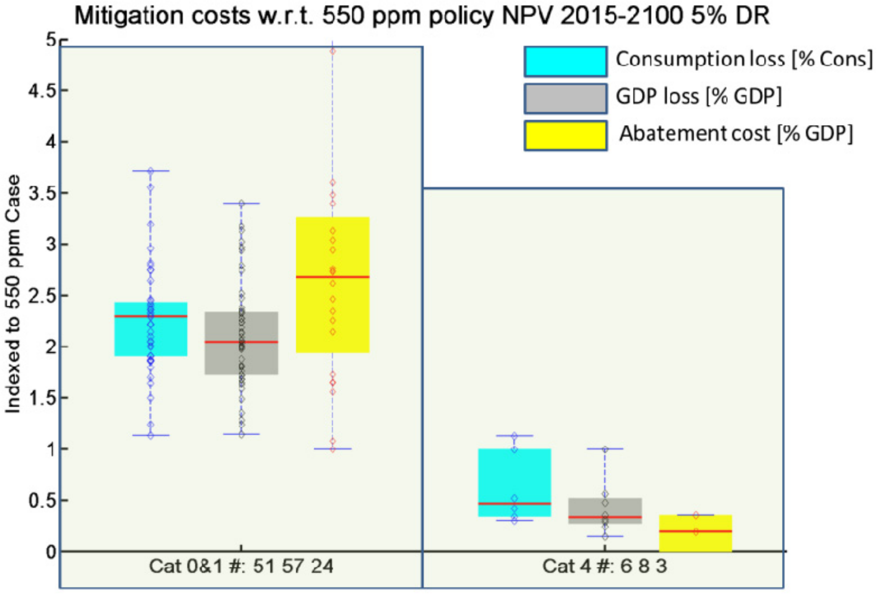


Figure 6.21. Global mitigation cost increases relative to reference level of climate stabilization (Category III = 1) for the period2010-2100 See figure caption 6.11 for further explanation. Preliminary results subject to update of the AR5 scenario database and sampling choices.

The variation of cost estimates for individual climate categories can be attributed to many factors. These include model structure, underlying socioeconomic drivers such as population and economic growth, assumptions about technology cost and performance, resources and international trade, assumptions about energy demand and assumptions about residual emissions in the energy sector. Further efforts to better understand the sources for differences in cost estimates are an important research area (Kriegler et al., submitted). However, it is also important to acknowledge the resulting uncertainty, because it highlights the fact that not only are the benefits of climate mitigation uncertain, so are the costs.

It is possible to control for several key sources of uncertainty by relating mitigation costs to cumulative emissions reductions from baseline emissions for different model types (Figure 6.22). As mitigation reaches roughly 80% of baseline emissions, mitigation costs rise more steeply. However, there are noticeable differences in the cost increases between different model types. Thus, to the extent that different model types represent different classes of assumptions about the flexibility to substitute carbon intensive energy technologies with low carbon energy technologies, this substitutability is a key determinant of mitigation costs, Since different models have different such capabilities for deep emissions reductions, the spread in cost estimates also increases with mitigation stringency. In other words, scenarios indicate greater consensus regarding the nature of mitigation costs at lower stabilization levels than those at higher levels. This increase in variation reflects the challenge associated with modelling energy and other human systems that are dramatically different than those of today.

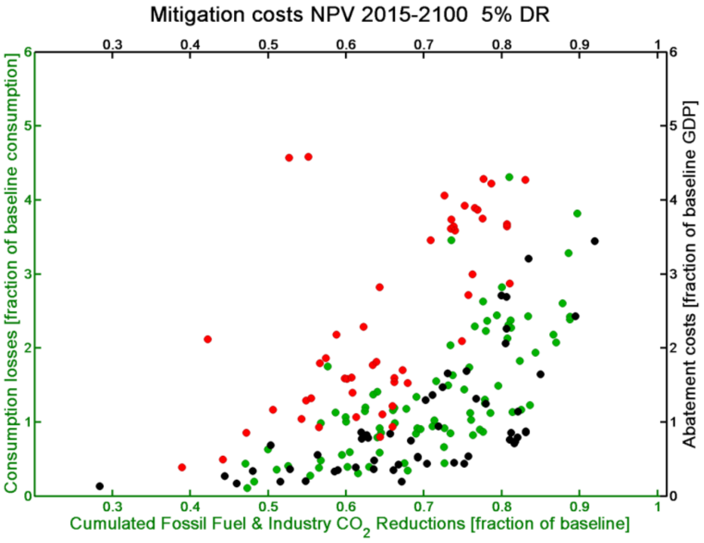


Figure 6.22. Global mitigation costs as a function of cumulative CO2 emissions reduction from fossil fuel combustion and industry (fraction of cumulated baseline emissions) over the period 2010-2100. Mitigation costs are reported in NPV consumption losses (green and red dots) for general equilibrium (GE) models or abatement costs (black dots) for partial equilibrium models. Red dots describe the subclass of computable GEs plus one intertemporal GE with more limited substitutability of energy technologies. Preliminary results subject to update of the AR5 scenario database.

Assumptions about the policy environment can be another important driver of costs even though all scenarios assumed idealized implementation frameworks. For example, one model with an emphasis on market imperfections, infrastructure lock-ins and myopia reports consumption losses roughly four times higher for pure carbon pricing policies. This model produces costs below 6% if additional policies such as infrastructure policies and revenue recycling are assumed in addition to carbon pricing (Waisman et al., 2012).

6.3.6.3 The implications of technology portfolios for global macroeconomic costs

Because technology will underpin the transition to a low-carbon economy, the availability, cost, and performance of technologies will exert an influence on macroeconomic costs. Several multi-model studies, EMF27 (Kriegler et al., Submitted), ADAM (Knopf et al., 2009; Edenhofer et al., 2010), AMPERE (e.g. Riahi et al., Submitted), and RECIPE (Luderer et al., 2011; Tavoni et al., 2012) have explored the influence of technology availability, cost, and performance. In addition, a number of individual research papers and reports have explored this space, typically constrained to a single model (Kim et al., 2000; Richels et al., 2007; Calvin, Edmonds, et al., 2009; van Vliet et al., 2009; Krey and Riahi, 2009; Riahi et al., 2012a).

A precise understanding of the implications of technology availability on costs is confounded by several factors. One issue is that the sensitivities among technologies are not necessarily comparable across models or scenarios. Some models do not represent certain technologies such as BECCS in the first place and therefore do not show a strong reaction in policy costs if the options are restricted, but might instead have difficulties in achieving tighter stabilization targets regardless (Krey et al., Submitted). In addition, assumptions about cost and performance can vary across models, even within a single, multi-model study. In addition, many limited technology scenarios are characterized by frequent model failures (see the fraction of models able to meet a particular goal with different technology combinations for EMF 27 at the bottom of Figure 6.23) (see Section 6.2.4 regarding interpretation of model failures).

Nonetheless, all of these analyses confirm that mitigation costs are heavily influenced by the nature of the available mitigation technologies. In addition, these studies indicate that the influence of technology on costs generally increases with increasing stringency of the climate target (see, for example, Figure 6.23). In general, limited technology portfolios have not led to many model failures for the 550 ppmv CO2-e scenarios. However, at the tighter, 450 ppmv CO2-e constraint, many models could not produce scenarios with limited technology portfolios, particularly when assumptions preclude the use of BECCS, which is disproportionately valuable in 450 ppmv CO2-e scenarios.

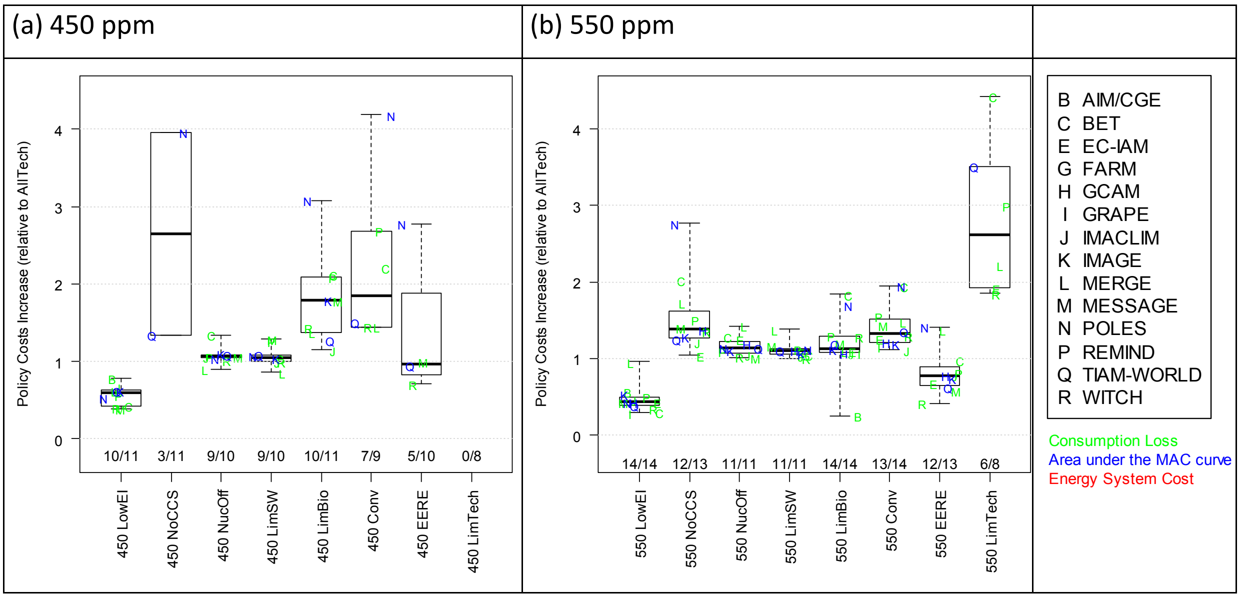


Figure 6.23. Relative mitigation cost increase in case of technology portfolio variations compared to the default (AllTech) technology portfolio under a 450 ppm (a) and a 550 ppm (b) CO2-equiv stabilization target from the EMF27 study. The numbers at the bottom of both panels indicate the number of models that attempted the reduced technology portfolio scenarios and how many in each sample were feasible. The conventional (Conv) scenario combines pessimistic assumptions for bioenergy and other RE with availability of CCS and nuclear and the higher energy intensity pathway and the energy efficiency and renewable energy (EERE) case combines optimistic bioenergy and other RE assumptions with a low energy intensity future and non-availability of CCS and nuclear. LimTech refers to a case in which essentially all supply side options are constrained and energy intensity develops in line with historical records in the baseline. (Krey et al., Submitted; Kriegler et al., Submitted)

The response in mitigation costs varies to some degree by technology, however, the ranges reported by the different models tend to strongly overlap (Figure 6.23), reflecting the general variation of mitigation costs across models as discussed in the previous section (cf. Fisher et al. (2007)). As noted above, the unavailability of CCS tends to be associated with the most significant cost increase (Krey et al., Submitted; Edenhofer et al., 2010; Tavoni et al., 2012) for several reasons: (i) CCS is a versatile technology which can be combined with electricity, synthetic fuel and hydrogen production from several feedstocks and in energy-intensive industries (e.g. cement, steel), (ii) CCS can act as bridge technology that is compatible with existing fossil-fuel dominated supply structures, and (iii) the combination of biomass with CCS can serve as a valuable CDR technology (see Section 6.2.2).

Bioenergy shares some of these characteristics with CCS. It can be applied in various sectors of the energy system, including for the provision of liquid low-carbon fuels for transportation, and it can be used as a CDR technology when combined with CCS. In contrast, those options that are largely confined to the electricity sector (e.g., wind, solar and nuclear energy) tend to show a lower value, because there are a number of low-carbon electricity supply options available that can generally substitute each other.

Demand-side technologies also demonstrate an important influence on the costs of mitigation. For example, in EMF27, reductions in the energy intensity pathway led to substantial reductions in the costs of mitigation. It should be noted, however, that the costs for implementing this more energy efficient future have not been taken into account by all models, leading to a potential downward bias of these estimate. Demand side measures are important not just for reducing energy consumption, but also for facilitating the use of low-carbon fuels. For example, Riahi et al. (2012a) and Kyle and Kim (2011) show that allowing electricity or hydrogen in transportation lowers mitigation costs by opening up additional supply routes to the transportation sector (see Section 6.8 for more on this topic).

6.3.6.4 The implications of fragmented international participation and constrained near-term mitigation for global and regional macroeconomic costs

A wide range of individual model studies (Keppo and Rao, 2007; Edmonds et al., 2008; Clarke et al., 2009a; Tol, 2009; van Vliet et al., 2009; Richels et al., 2009; Bosetti, Carraro, and Tavoni, 2009b; Calvin, Patel, et al., 2009b; Krey and Riahi, 2009; Jakob et al., 2012) and multi-model studies (the RECIPE project, the RoSE Project (Kriegler et al., Submitted), the EMF 22 Study (Clarke et al., 2009b), and the AMPERE study) have shown that the timing and the rate of international participation in climate mitigation will have a significant effect on the global economic costs of achieving climate stabilization policies. There is no definitive study of the implications of fragmented action or constrained reductions, because there is an infinite number of possible such scenarios, and different studies explore different possibilities. Nonetheless, this research has consistently demonstrated (1) that limited emissions reductions by all or only a portion or all countries of the world can substantially increase the macroeconomic costs of meeting long-term goals, and (2) that cost increases are most severe for the most ambitious climate goals. The additional costs are a trade-off between higher mid-term emissions and the more rapid and aggressive mitigation effort needed in the future to make up for delays in the present. The extent cost increase depends on the nature of the non-idealized mitigation regime, whether the climate target can be overshot, the availability of CDR technologies, and to the discounting of future versus present losses.

The longer the delay in cost-effective mitigation and the smaller the proportion of emissions included in a climate regime, the higher the costs and the more challenging it becomes to meet any long-term goal. For example, EMF22 (Clarke et al., 2009b) compared a full cooperation scenario with a fragmented action scenarios in which BRICs and other developing countries joining the coalition in 2030 and 2050 respectively. Only two of 10 participating models could produce a 450 ppmv CO2-e overshoot scenario under these delay assumptions (see Section 6.2.4 for a discussion of interpretation of situations in which models cannot produce particular scenarios), and global macroeconomic costs over the century were more than doubled in these two scenarios (Figure 6.24). Only half of the models were capable of producing a 550 ppmv CO2-e not-to exceed scenario under the delay assumptions, and costs were increased by 50% to more than double. All but one model was able to produce the 550 ppmvCO2-e scenario with overshoot, and costs for those models were 25% to 75% higher than under idealized implementation.

When fragmented action applies only to the next several decades or if the deviation from cost-minimizing reductions in constrained reduction scenarios is more modest, the increase in macroeconomic costs can be more easily compensated for. However, even in such cases, deferral of cost-effective action exacerbates the challenges of stabilization and increases macro-economic costs

(Luderer et al.; Kriegler and et al., 2013). For example, the AMPERE project (Riahi et al., Submitted) explored the implications of two constrained reduction emissions pathways through 2030 that are roughly consistent with a 550 ppmv CO2-e goal on the on the cost of meeting a 450 ppmv CO2-e goal. Two out of eight models could not meet the 450 ppmv CO2-e goal with the less ambitious 2030 target, and costs ranged from between a modest increase to more than doubling for the remaining models. Under a more ambitious 2030 goals, costs were as high as 60% above those in the cost-minimizing scenario.

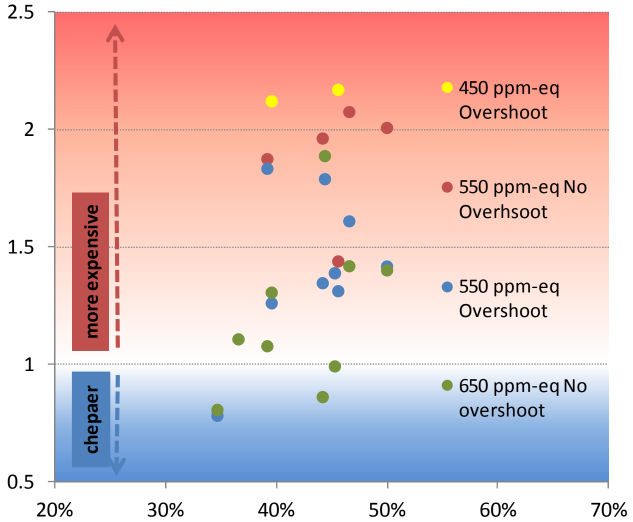


Figure 6.24. The economic implications of partial cooperation under four different climate targets. The x axis shows the fraction of CO2 emissions covered by the international climate policy in the period 2020-2050. The y axis shows the ratio of the global policy costs in the partial cooperation scenarios with respect to same ones under full cooperation. Blue and red colours identify areas in which policy costs respectively increase or decrease as a result of partial cooperation. Policy costs are calculated as GDP losses or Area under MAC in net present value terms (at 5% discounting). Source: elaboration on the EMF22 data base (Clarke et al., 2009a).

A separate set of analyses have pursued constrained reduction scenarios that do not focus on meeting a specific long-term goal. Rather than showing the increase in macroeconomic costs of meeting long-term goals, these studies show that deviating from the idealized implementation can lead to concentrations well above 450 ppmv CO2 and similar targets (Blanford et al., 2013; e.g. Kriegler and et al., 2013 (EMF27)).

In general in fragmented action scenarios, the increased costs of partial cooperation fall on early actors. However, costs can also increase for late entrants (Clarke et al., 2009a; Jakob et al., 2012) (Figure 6.25). Late entrants benefit in early periods from lower mitigation; however, if long-term goals are truly to be met, they must act extraordinarily quickly once they begin to take action. This rapid action can more than compensate for the reduced costs from limited near-term mitigation, and would increase the maximum policy costs over time for all major regions (see Figure 6.25). The degree to which the late entrants costs might increase with delayed participation depends on the extent of carbon intensive technologies and infrastructure put in place during the period during which they undertake limited reductions and the speed at which emissions must be reduced after they begin to reduce emissions more aggressively. Indeed, in the face of a future mitigation commitment it is optimal to anticipate emissions reductions, reducing the adjustment costs of confronting climate policy with a more carbon intensive capital stock (Bosetti, Carraro, Massetti, et al., 2009; Richels et al., 2009).

Fragmented international architectures can also have negative impacts in terms of environmental effectiveness, since non-signatory countries might increase emissions compared to the case with no agreement in place. Non-harmonized carbon policies would impact international trade and globally integrated energy markets. The resulting "carbon leakage" has been shown to be potentially significant (Gurney et al., 2009; Böhringer et al., 2010). Moreover, leakage can also occur in agricultural sectors and generate substantial additional emissions from land use change (Wise et al., 2009b). However, changes in relative prices would also affect the incentives to carry out innovation, leading to a counterbalancing induced-technology effect, which reduces carbon leakage (Di Maria and Werf, 2007).

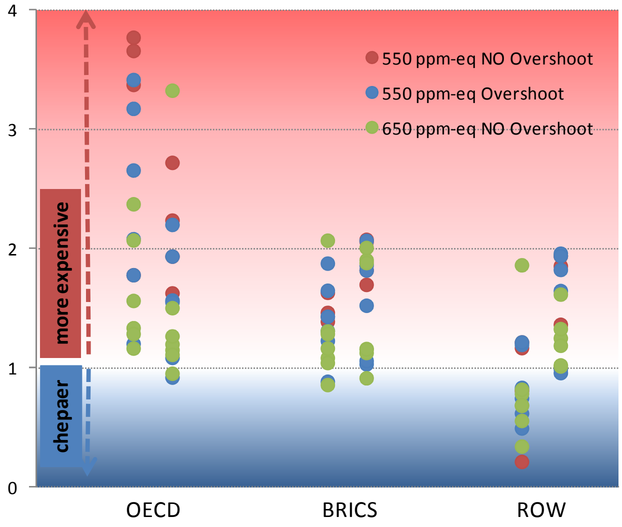


Figure 6.25. Impact of partial cooperation for 3 representative regions (OECD, BRICS and Rest Of the World). The y axis shows the ratio of GDP losses between partial and full participation scenarios. Blue and red colours identify areas in which policy costs respectively increase or decrease as a result of partial cooperation. Costs are calculated both in NPV terms (left bars) and as maximum losses over time (right bars). In the partial cooperation scenarios, OECD join immediately the climate policy, BRICs in 2030 and other DCs in 2050. Source: EMF22

6.3.6.5 The implications of Policy Implementation for Macroeconomic Costs

There are a variety of national and international policy instruments for tackling GHG mitigation, including carbon taxes, emissions trading schemes, standards and technology-support policies (see chapter 3 for taxonomy).Economic analysis has long demonstrated that the way to minimize the costs of mitigation is to undertake mitigation where and when it is least expensive (Montgomery, 1972). This implies that policies be both flexible and comprehensive. The most economically-efficient climate policy remains a be broad-based cap-and-trade policy or carbon tax in the absence of other distortions (Goulder and Parry, 2008). In general, the discussion of the costs of transformation pathways thus far, has assumed such an approach. Even scenarios with fragmented or constrainted near-term emissions reductions have typically assumed an efficient, full-economy carbon prices for all countries undertaking mitigation.

However, real-world approaches may very well deviate from this least-cost approach. For example, some policies may only address particular sectors, such as power generation, while excluding others; other policies may regulate the behavior in a sectors, for example through renewable portfolio standards or fuel economy standards; still other policies may prohibit intertemporal decision making (for example, banking and/or borrowing of emission permits issued at different periods of time may not be allowed). Approaches that exclude sectors or regulate reductions by sector will have higher costs than those that give a consistent incentive for mitigation across the full economy (Paltsev et al., 2008).

A wide range of recent studies have explored this space. This includes full-scale mutli-model comparison studies, including EMF 22 (Böhringer et al., 2009), EMF 24 (Fawcett et al., 2013), and EMF 28 (Knopf et al., Submitted); and it also includes an extensive set of individual papers. All of these studies corroborate both that instruments with limited coverage or regulate the quantities of reductions among sectors will increase costs, particularly for deep reductions where coverage and flexibility are most important. For example, a survey of results reported by OECD (2009) indicates that exempting energy-intensive industries increases mitigation costs for achieving 550 ppm stabilization by 50% in 2050, and that excluding non-CO2 GHG emissions increases the mitigation costs for the 550 ppm stabilization by 75% in 2050. EMF 22 (Böhringer et al., 2009) find that differential prices for ETS and non-ETS emissions in the EU and the inclusion of a renewable portfolio standard could double the mitigation costs for the EU 20-20-20 goal. Wise et al. (2009b) found that the failure to include land use change emissions in climate policy could double global carbon prices in a 450 ppmv CO_2 scenario.

It is important to note that climate policies will always interact with pre-existing policy structures, and these interactions can both increase or decrease policy costs. For example, Babiker et al (2004) shows that emission trading may lead to a decrease in welfare for some countries due to change in terms-of-trade effects (that is, when prices of exported and imported goods change). Paltsev et al (2007) show that pre-existing distortions (e.g., energy taxes) can greatly increase the cost of a policy that targets emission reduction.

FAQ 6.3. How much would it cost to bring climate change under control?

The broader socio-economic implications of mitigation go well beyond economic costs such as GDP losses. Transition pathways involve a range of tradeoffs that link to other national and societal priorities such as energy and food security, sustainable development, the distribution of economic costs, local air pollution and other environmental factors associated with different technology solutions, and economic competitiveness. Nonetheless, macroeconomic costs are an important criterion for evaluating transformation pathways and can serve as one indicator of the level of difficulty associated with particular transformation pathways. There is great uncertainty about the global macroeconomic costs of mitigation arising from limits to our methodologies, uncertainty about the future, and different measure even of economic costs. If policies were to be implemented in the most cost-effective way possible, and all countries of the world were to begin reducing emissions shortly, studies indicate that meeting a 450 ppmv CO2-e goal by century's end would entail a reduction in key macroeconomic measures such as global GDP or the amount global consumers can spend of 2% to 4% over the full century. However, if policies are not implemented effectively, mitigation is delayed, or important technologies are not made available, global economic costs could be many times higher.

6.3.6.6 Regional macro-economic costs and burden-sharing regimes

The costs of climate change mitigation will not be identical across countries. (Hof et al., 2009; Clarke et al., 2009b; Edenhofer et al., 2010; Luderer, DeCian, et al., 2012; Blanford et al., 2013; Tavoni and al., 2013). This is influenced by the nature of international participation in mitigation, allowance allocations, and transfer payments.

In the idealized setting of a universal carbon price leading to reductions where they would be globally most efficient, the costs of mitigation would vary substantially across countries and regions if transfer payments are not made (Figure 6.26). A robust result of modeling studies is that, in the absence of transfer payments, OECD costs would be lower than the global average, Latin America would be on average around the global mean, and that other regions would face costs higher than the global mean (Clarke et al., 2009b; Tavoni and al., 2013).

The variation in regional costs can be attributed to a several factors. First of all, costs are heavily dependent on baseline emissions (see Section 6.3.6.2). These emissions are expected to be larger in the developing regions than the developed regions (see Section 6.3.1). Baseline emissions depend on more than the population and the size of a country's economy; they also depend on the level of energy and carbon intensities. Developing countries are generally characterized by higher energy and carbon intensities due to the structure of economies in economic transition: this induces a higher economic feedback for the same level of mitigation (Luderer, DeCian, et al., 2012). Second, though often difficult to quantify, emission abatement potential varies across regions. For example, the uncertainty surrounding the potential of biomass related mitigation is evident by the large spread in the emission reductions projected to take place in Latin America, with the highest estimates yielding cumulative emissions reductions well above 100% (due to CO2 removal). Finally, domestic abatement is only one determinant of policy costs, since international markets would interact with climate policies (Leimbach et al., 2010). For some regions –notably the fossil energy exporting countries- higher costs would also originate from unfavourable terms of trade effects of the climate policy (OECD, 2008; Luderer, Bosetti, et al., 2012; Blanford et al., 2013), while some regions could experience increased bio-energy exports (i.e. Russia and Latin America,(Persson et al., 2006; Wise et al., 2009a; Leimbach et al., 2010).

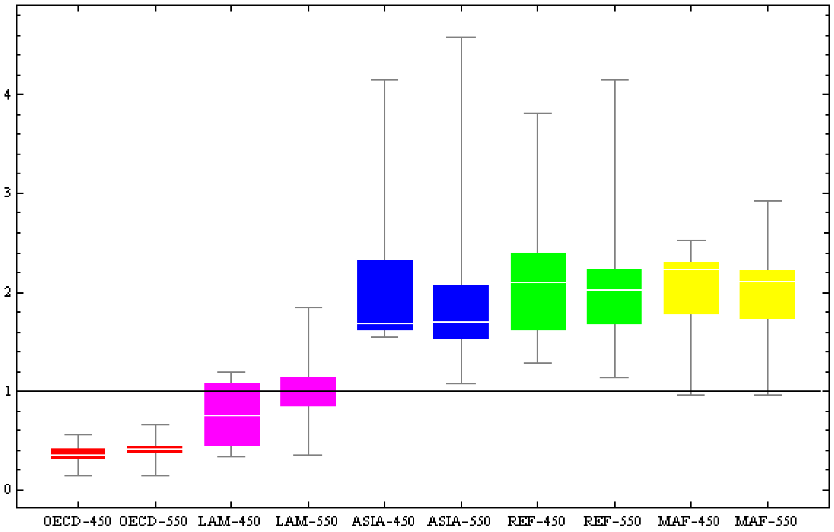


Figure 6.26. Regional distribution of policy costs relative to the global average (indicated by the line at 1). Costs are displayed for 5 macro-regions for both a 450 ppm-eq and 550 ppm-eq stabilization target, in a first best setting with complete participation, uniform carbon pricing, and no transfer payment across region. Costs are computed in NPV at 5% d.r. Box plots indicate variations across models (median, 25% and 75%, and maximum and minimum). Source: EMF27 DB.

A crucial consideration in the analysis of the macroeconomic costs of mitigation is that the mitigation costs borne in a region can be separated from who pays those costs. The creation of endowments of emission allowances and the possibility to freely exchange them in an international carbon market allows for this separation. This suggests that the choice of the initial allocation of allowances would not change the globally efficient level of regional abatement, but that it would determine the degree to which abatement costs are borne within a given country or financed through the sale (or purchase) of allowances or other financial transfers.

Many studies have analysed regional emission allocations or requirements for emission reduction targets and time of participation in international climate mitigation regimes or emission allocation approaches according to equity principles (see Chapter 4.2.1.2) and related costs to achieve different concentration stabilization or temperature targets (for an overview on allocation approaches or proposals, see den Elzen and Höhne (2008, 2010). The broad spectrum of proposals can be categorised in seven categories, dependant on which of the four equity principles they apply to (Table 6.3).

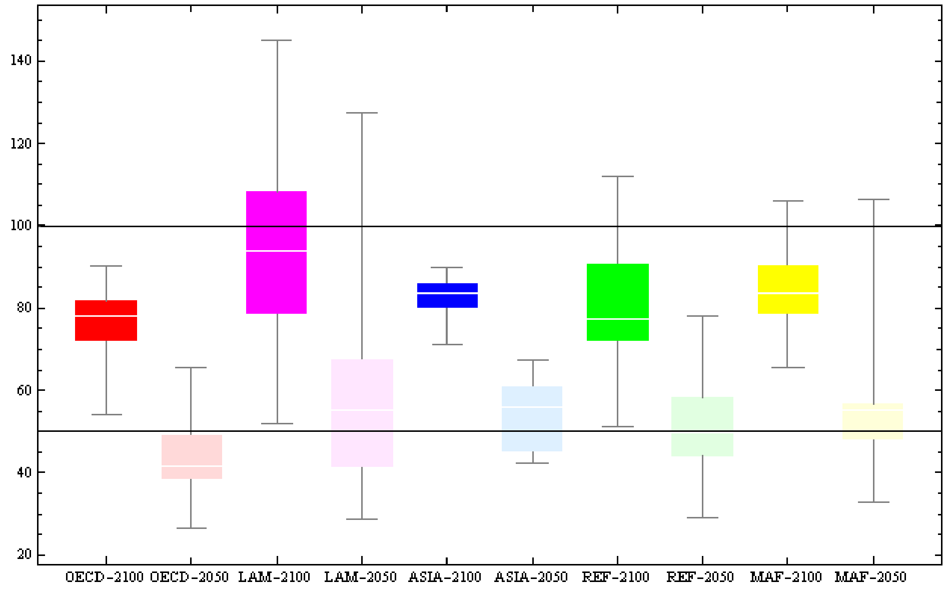


Figure 6.27 Regional distribution of the relative mitigation effort in a first best 450 ppm-eq policy. Mitigation is calculated as reductions from BAU of both cumulative CO2 emissions till 2100 (dark colors) and till 2050 (light colors). The two lines indicate cumulative emissions reductions of 50% and 100%. Values above 100% can be achieved with negative emissions. Box plots indicate variations across models (median, 25% and 75%, and maximum and minimum). Source: EMF27

Comparing these indicators between regimes and studies is quite complex because studies explore different regional definitions, timescales, starting points for calculations, and measurements to assess emission allowances such as CO2 only or as CO2-equivalent (see Höhne et al.). The range of results for a selected year and stabilization level is relatively large due to the fact that it depicts fundamentally different effort sharing approaches and other varying assumptions of the studies. Nonetheless, it is possible to provide some general comparison and characterization of these studies (Table 6.3, Figure 6.28 and Figure 6.29).

The results indicate that even within specific categories of effort sharing, the range of allowances can be substantial. Often it is the way the equity principle is implemented that to a large extent determines the outcome, not necessarily the equity principle itself. For some effort sharing categories, the ranges are smaller because only a few studies were found.

The results also demonstrate that distributional impacts differ significantly with underlying criteria for effort sharing, despite the ranges within a category. For the OECD90 region for example, proposals in the category “Responsibility, capability, need” and those based on “Carbon budgets” lead to relatively high reductions, and can assign even negative allowances. In comparison, proposals based on reduction potential lead to relatively stringent reductions for e.g. the ASIA region, as they assume significant mitigation potential in that region irrespective of responsibility and capability in that region (see also Figure 6.26).

The choice of the stabilization level is significant for the resulting level of emission allowances in regions. Indeed, for many regions, the choice of the stabilization level is of equal or larger importance for resulting emission allowances than the choice of the effort sharing approach. For the low concentration levels under any effort sharing approach analysed here, allowances in OECD90 and EITs are a fraction of today’s emissions in 2050, and allowances for Latin America and Asia are below 2010 emission levels in 2050. For higher stabilization scenarios most studies show a significant decline in allowances for OECD90 and EITs by 2050. Most studies show a decline in allowances for the Latin America region, mostly increasing for the Africa and Middle East region and an inconsistent picture for ASIA.

Table 6.3: Categories of effort sharing proposals [Data collection is in progress, we make all efforts to get a balanced amount of studies in all categories. We expect additional studies from recent modelling comparisons. Not all mentioned studies are included in the dataset used below as they may not have been provided in sufficient detail.]

Categories	**Responsibility**	**Capability**	**Equality**	**Potential**	**Description**	**Studies**	
						No	**References**
Responsibility	X				Concept first directly proposed by Brazil in the run-up of the Kyoto negotiations (UNFCCC, 1997), without allocations. Allowances quantified by only a few studies.	2	Den Elzen et al. (2005); Den Elzen and Lucas (2005)
Capability		X			Frequently used for allocation relating reductions or reduction costs to GDP or human development index (HDI).	4	Den Elzen and Lucas (2005); Knopf et al. (2011); Jacoby et al. (2009); Miketa and Schrattenholzer (2006)
Equality			X		A multitude of studies provide allocations based on immediate or converging per capita emissions (e.g. Agarwal and Narain, 1991; Meyer, 2000). Later studies refine the approach using also per capita distributions within countries (e.g. Chakravarty et al., 2009);	21	Böhringer and Welsch (2006); Bows and Anderson (2008); Chakravarty et al. (2009); Criqui et al.(2003); Den Elzen and Lucas (2005); Den Elzen and Meinshausen (2006); Den Elzen et al.(2005; 2008); Edenhofer et al. (2010); Hof et al. (2010); Höhne and Moltmann (2008, 2009); Knopf et al.(2009, 2011); Kuntsi-Reunanen and Luukkanen (2006); Nabel et al.(2011); Miketa and Schrattenholzer (2006); Peterson and Klepper (2007); Onigkeit et al. (2009); Van Vuuren et al. (2009; 2010)
Potential				x	Modelling studies often use "equal marginal abatement cost" as a reference case for cost globally effective mitigation. Also approaches based on sectors such as the Triptych approach (ref) or sectoral approaches consider as basic principle the reduction potential. Finally also studies using equal percentage reductions, also called grandfathering, are placed in this category.	10	Böhringer and Welsch (2006); Böhringer and Löschel (2005); Den Elzen and Lucas (2005); Den Elzen et al. (2008); Groenenberg et al. (2004); Hof and Den Elzen (2010); Höhne and Moltmann (2008); Höhne et al. (2005); Peterson and Klepper (2007); Van Vuuren et al.(2009);
Responsibility, capability and need	X	X			Recent studies used explicitly responsibility and capability as a basis, e.g. Greenhouse Development Rights (Baer et al., 2008); (Winkler et al., 2011)	4	Baer et al. (2008); Baer (2013); Höhne and Moltmann (2008, 2009); Winkler et al. (2011) (2011)[181](2011)(2011)
Carbon budget	X		X		Several studies allocate equal cumulative per capita emission rights based on a global carbon budget, combining the principles of responsibility and equality. Studies diverge on how they assign the resulting budget for a country to individual years	4	Bode (2004); Nabel et al. (2011); Jayaraman et al. (2011); Schellnhuber et al. (2009)
Staged approaches	X	X	X	X	A suite of studies propose or analyse approaches, where countries take differentiated commitments in various stages. Categorisation to a stage and the respective commitments are determined by indicators using all four equity principles.	15	Bosetti and Frankel (2012); Criqui et al. (2003); Den Elzen and Lucas (2005); Den Elzen and Meinshausen (2006); Den Elzen et al. (2007; 2008, 2012); Ekholm et al. (2010a); Hof et al.(2010); Höhne and Moltmann (2008, 2009); Höhne et al.(2005, 2006); Knopf et al. (2011); Vaillancourt and Waaub (2004)

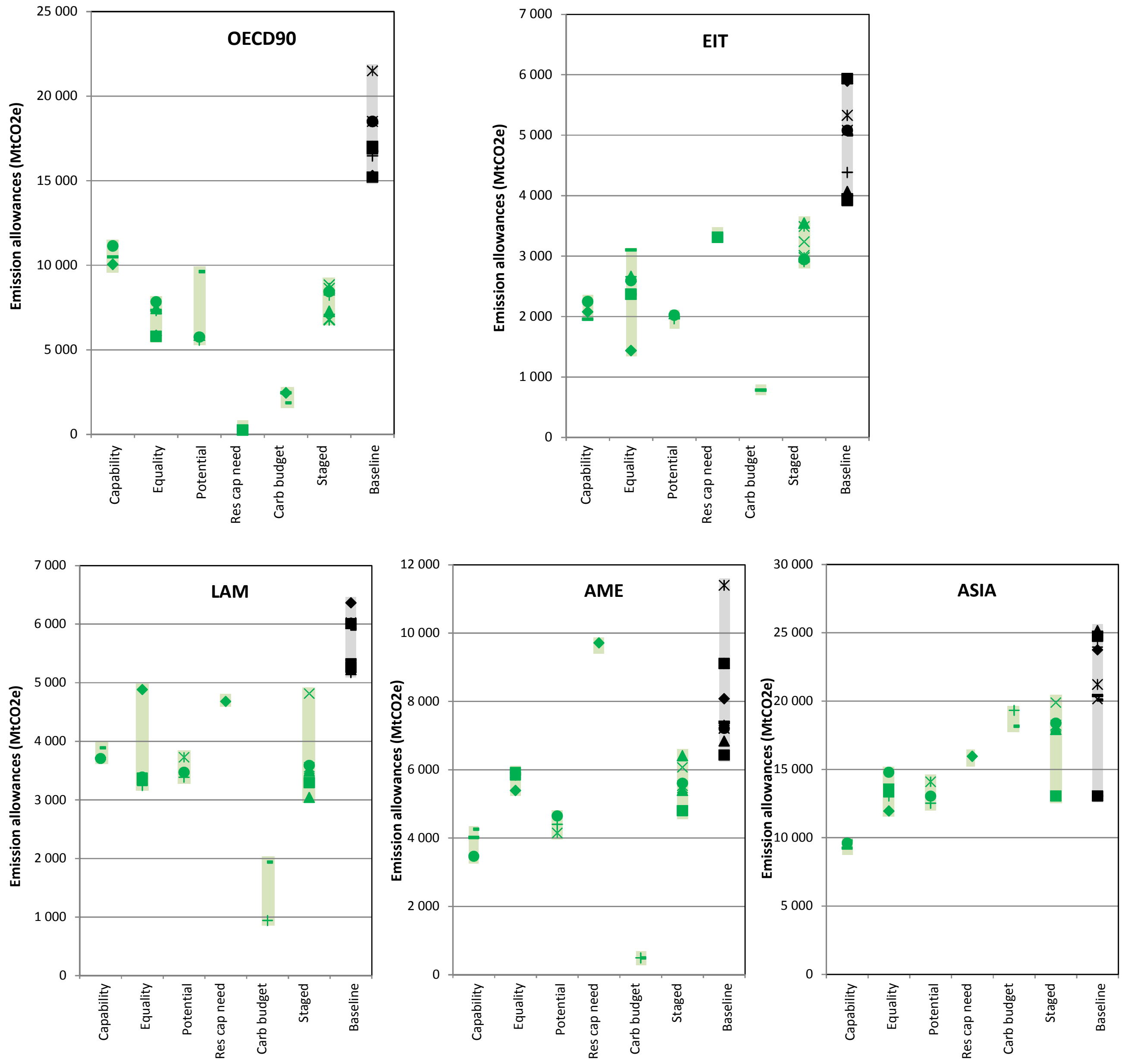


Figure 6.28. Emission allowances by effort sharing category for RCP 2.6, i.e. 425-475 ppmCO2e, compared to BAU emissions in 2030 in MtCO2e (including all GHG and all sectors). [Authors: All data preliminary and subject to review]

Especially for low stabilization levels, the effort sharing approaches differ in the extent to which they incentivise financial transfers between countries. If the allocation based on "Potential" is taken as the comparison point for globally cost effective reductions, any approach with higher allocations would mean that a country could possibly sell emission allowances on the international carbon market, if they would reduce towards reduce towards their cost effective level. An approach with lower allocations would mean that the country could possibly buy emission allowances for compliance if they reduce towards reduce towards their cost-effective level, and they could gain from the lower costs on other countries. Such financial transfers could be particularly high for some regions for the categories "Carbon budget" and "Responsibility, capability and need" in general and for "Staged approaches" for some of studies.

Only in some cases, effort sharing approaches allocate more allowances than the base line emissions. In general this applies only to the higher stabilization levels and recent years. For example, it could apply for ASIA and LAM until 2020 or AME until 2030 for some approaches.

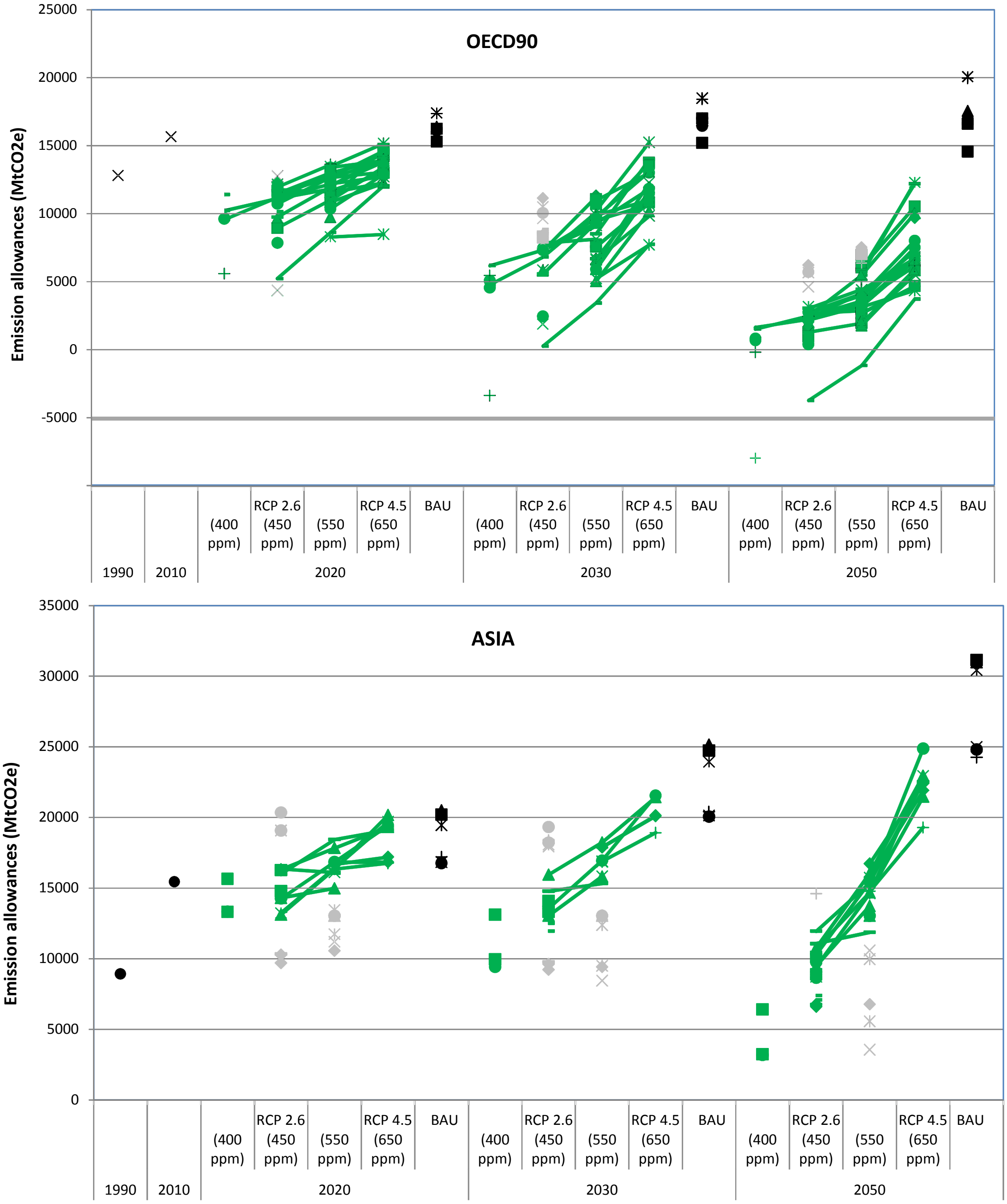
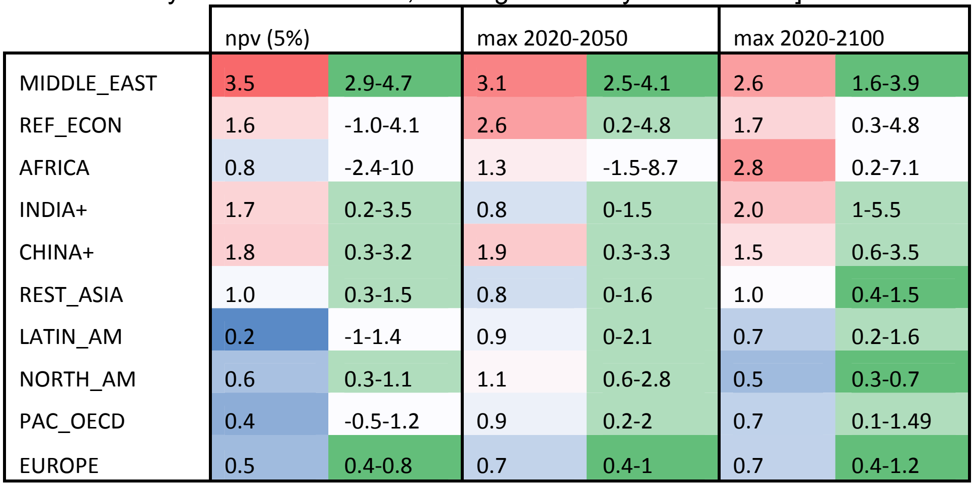


Figure 6.29. Emission allowances for studies that considered various concentration levels (green) or for a single level (grey) in comparison to 1990 and 2010 emissions and BAU emissions in 2020/2030/2050 (black) for the OECD and Asia as example in MtCO2e (including all GHG and all sectors). [Authors: All data preliminary and subject to review]

The creation of endowments of emissions allowances would generate payment transfers across regions in a global carbon market. These transfers depend on the regional abatement opportunities, the distribution of allowances, and the climate stabilisation target. Multi model studies indicate that the size of the carbon market would be significant in relation to the global mitigation reduction, on the order of hundred billions of U.S. dollars per year before mid-century (Clarke et al., 2009b;

Luderer, DeCian, et al., 2012; Tavoni and al., 2013). For some regions, financial flows would be on the same order of magnitude as the investment requirements for emissions reductions (McCollum and al, 2013). The direction of the transfers is determined to a large extent by the type of burden sharing scheme: allocations tending to a convergence in per capita emission allowances would entail side payments from the OECD towards some developing countries in the first part of century, though not necessarily beyond that (Tavoni and al., 2013), Optimal transfers can also be devised as a way to provide the right economic incentives to regions to participate in international climate agreements. When accounting for the strategic behaviour of the various regions and countries, the literature suggests that climate coalitions which are self-enforcing and stable can indeed be effective only in the presence of significant compensatory payments across regions (Finus et al., 2003; Nagashima et al., 2009; Bréchet et al., 2011). Transfers would also occur in case that different regional social costs of carbon were equalized to maximize efficiency (Landis and Bernauer, 2012).

Table 6.4: Policy costs relative to the global average for an allocation scheme of convergence to equal per capita by mid-century, for a 450 ppm-eq stabilization target, three cost metrics (Net Present Value at 5% discount rate, and maximum in the periods 2020-2050 and 2020-2100), and 10 representative regions. Red colouring is used for costs above global average (e.g. >1) and blue colouring for below the global average (e.g. <1). White, light green and dark green colours indicate low, medium and high reliability as measured by the agreement across models, and report min-max ranges. Source: LIMITS DB (Tavoni and al., 2013). [AFRICA=countries of Sub-Saharan Africa; CHINA+=countries of centrally-planned Asia (primarily China): EUROPE countries of Eastern and Western Europe ;INDIA+ countries of South Asia (primarily India); LATIN_AM: countries of Latin America and the Caribbean; MIDDLE_EAST countries of the Middle East; NORTH_AM countries of North America (primarily the United States of America and Canada); PAC_OECD: countries of the Pacific OECD (Organisation for Economic Co-operation and Development); REF_ECON:countries from the Reforming Economies of Eastern Europe and the Former Soviet Union; REST_ASIA other countries of Asia.] [Low reliability is defined when the coefficient of variation across models is higher than 1; medium reliability between 0.5 and 1; and high reliability lower than 1.]



	npv (5%)		max 2020-2050		max 2020-2100	
MIDDLE_EAST	3.5	2.9-4.7	3.1	2.5-4.1	2.6	1.6-3.9
REF_ECON	1.6	-1.0-4.1	2.6	0.2-4.8	1.7	0.3-4.8
AFRICA	0.8	-2.4-10	1.3	-1.5-8.7	2.8	0.2-7.1
INDIA+	1.7	0.2-3.5	0.8	0-1.5	2.0	1-5.5
CHINA+	1.8	0.3-3.2	1.9	0.3-3.3	1.5	0.6-3.5
REST_ASIA	1.0	0.3-1.5	0.8	0-1.6	1.0	0.4-1.5
LATIN_AM	0.2	-1-1.4	0.9	0-2.1	0.7	0.2-1.6
NORTH_AM	0.6	0.3-1.1	1.1	0.6-2.8	0.5	0.3-0.7
PAC_OECD	0.4	-0.5-1.2	0.9	0.2-2	0.7	0.1-1.49
EUROPE	0.5	0.4-0.8	0.7	0.4-1	0.7	0.4-1.2

The transfers associated with different burden sharing schemes have a direct impact on the regional distribution of climate policy cost. These costs are sensitive to the given allocation scheme, especially for developing countries; and they are highly dependent on the concentration stabilisation target (Russ and Criqui, 2007; den Elzen et al., 2008; Edenhofer et al., 2010; Ekholm et al., 2010b; Luderer, DeCian, et al., 2012) (See Table 6.4 and Figure 6.30). For example, allocating CO2 permits on a per capita basis from 2050 onwards for a 2C compatible climate objective does not necessarily balance the uneven regional distribution of policy costs observed in the uniform tax case. For some regions, there is little agreement across models. For example, emerging economies like China could incur in relatively high expenditures (Den Elzen et al., 2012; Johansson et al., 2012), though this

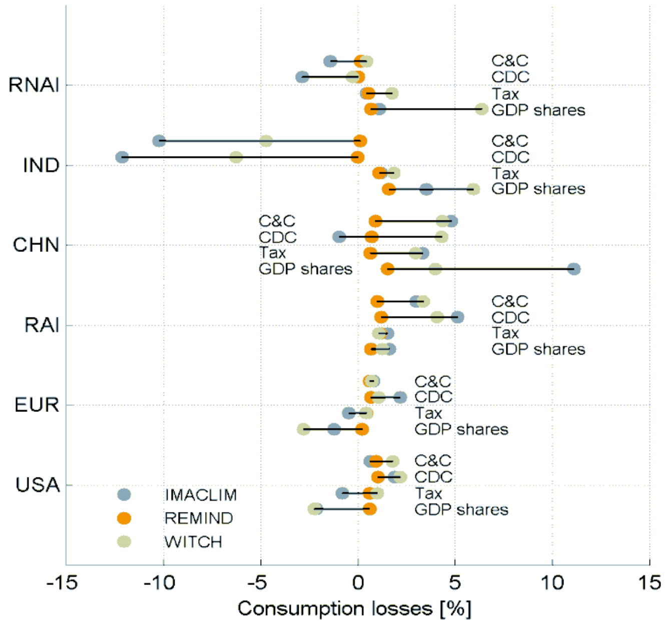


Figure 6.30. Policy costs for different allocation schemes (C&C=Contraction and Convergence, CDC=Common but differentiated Convergence, Tax=Uniform Carbon Tax, GDP Shares= equal emission right of emission per unit of GDP) from the RECIPE project for a 450 ppm-CO2 stabilization target, for key regions.

would change when cumulative past emissions are also accounted for (Jiahua, 2008; Ding et al., 2009; He et al., 2009). Effort sharing schemes would yield a more equitable cost distribution between countries (Ekholm et al., 2010b).

Box 6.2. LDCs issues reflected by Chap. 6 of WGIII contribution to AR5

[TSU COMMENT TO REVIEWERS: Boxes highlighting further LDC-specific issues are included in other chapters of the report (see chapter sections 1.3.1, 2.1, 7.9.1, 8.9.3, 9.3.2, 10.3.2, 11.7, 12.6.4, 16.8) and a similar box may be added to the Final Draft of chapters, where there is none in the current Second Order Draft. In addition to general comments regarding quality, reviewers are encouraged to comment on the complementary of individual boxes on LDC issues as well as on their comprehensiveness, if considered as a whole.]

Along the various transformation pathways, in the IAM literature, developing countries are required to make larger emissions reductions than developed countries. This has obvious implications on mitigation costs, finance, and burden sharing. The IAM literature does not provide detailed analysis of LDCs because of data and information deficits pertaining to the situation and the modeling of the specific features and characteristics of developing countries in general and LDCs in particular. Based on the limited available literature, the contribution of LDCs to future GHG emissions is negligible due to the current small size of its emissions and their lower growth rates compared to other developing countries GHG emissions, with available estimates from IAM literature suggesting emissions from LDCs growing by less than 50% compared to more than 100% for the emerging developing countries between 2000 and 2100 (Calvin, Patel, et al., 2009b). Nonetheless, the mitigation challenges and tradeoffs involved are particularly significant for LDCs given their ambitions for economic growth, poverty alleviation, and sustainable development on one hand and their limited means for mitigation in terms of technology and finance on the other hand.

The transformation pathways literature has also indicated the need for large deployment of low carbon technologies, particularly those that result in negative emissions such as Biomass Energy with

Carbon Storage (BECC) and Reforestation to achieve low stabilization goals. Land use related emissions, for example, are projected to contribute along the various transformation pathways 14-72% of total cumulative emissions abated by 2050 with bioenergy contributing 20-40% of total primary energy in 2100. These abatement patterns imply significant challenges for developing countries in general and LDCs, where large land-use abatement potentials lie, in particular. IAM models surveyed in the chapter universally project the majority of bioenergy primary energy will occur in developing economies (60-75% in non-OECD in 2050). The 550 ppm scenarios assessed by EMF-27 reported estimates for bioelectricity shares in total electricity in the range 0-26% for LDCs compared to 0-11% for OECD and biofuel shares in total liquid fuels in the range 0-73% for LDCs compared to 0-31% for OECD in 2050. No doubt, these projections lay ahead critical challenges and uncertainties for LDCs when taking into account issues related to large scale deployment, institutions and program design, non-climate social implications, and potential impacts on sustainable development.

The transformation pathways literature related to burden sharing and mitigation distributional implications in LDCs is relatively scarce. The food-mitigation tradeoffs literature (e.g. Reilly et al., 2012) tends to suggest negative impacts for poor developing countries because of the high share of their incomes spent on food. The literature on societal risks along transformation pathways (e.g. Liang and Wei, 2012) showed mitigation might increase rural-urban gap and deteriorate the living standards of large sections of the population in developing countries exacerbating over time. In contrast the sustainable development literature seems to suggest that policy and measures aligned to ‘development’ and ‘climate’ objectives can deliver substantial co-benefits and help avoid climate risks in developing countries. The assessment of regional cooperation 2010-2030 for South Asia showed that climate benefits plus non-climate co-benefits of coordinated energy investment in the region can add nearly 1% of regional GDP annually (Shukla et al., 2009).

Finally, the literature related to trade spillover impacts from mitigation policies have suggested certain risks for LDCs in the form of induced factor mobility, unemployment, and international transport related impacts on food and tourism sectors (Nurse, 2009; ICTSD, 2010). In particular the International Centre for Trade and Sustainable Development (ICTSD) 2010 study on trade impacts of regulating GHG emissions from international transport reported GDP losses for LDCs and Small Islands developing States (SIDS) in the range 0.2-1.8% due to reduction of maritime trade between these countries and EU.

Downscaling of IAM Modeling to the level of LDCs specifics and strengthening the links to other national and societal priorities are two primary areas for improvements. National priorities such as sustainable development, poverty eradication, national security, urban pollution and other non-climate environmental goals are major drivers of national policies and actions in LDCs. Similarly, the implications of different transformation pathways and mitigation strategies will be judged on their links to these priorities. Future research in this direction would be valuable for future assessments.

6.4 Integrating long- and short-term perspectives

6.4.1 Near-term actions in a long term perspective

Stabilizing atmospheric concentrations of greenhouse gases and radiative forcing is a long-term endeavour. Whether a particular long-term stabilization target will be met, and what the costs and other implications will be of meeting it, will depend on decisions to be made and uncertainties to be resolved over many decades in the future. For this reason, the transformation to atmospheric stabilization is best understood as a process of sequential decision-making and learning. The most relevant decisions are those that must be made in the near-term with the understanding that new information and opportunities for strategic adjustments will arrive often in the future, but largely beyond the reach of those making decisions today. An important question for decision makers today is therefore how near-term decisions will influence which transformation pathways could be followed by future decision makers. Some decisions may maintain a range of future options, while others may constrain the future set of options for stabilization and approaches to stabilization.

6.4.2 Near-term emissions and long-term transformation pathways

A key outcome of current decision-making will be the level of near-term global emissions. The option to maintain total forcing below a target is only definitively foreclosed when physical factors ensure the threshold will be crossed (which due to inertia in these systems may occur before the threshold itself is reached). Due to uncertainty in several of these factors (e.g. carbon cycle, non-gas forcing contributions), the extent of future emissions at which a forcing target will be exceeded cannot be stated with precision (see WGI for more on this topic). Additional inertia in socioeconomic systems will in practice likely foreclose the option not to exceed a target sooner, but this type of inertia can in principle be overcome at a cost and its characterization in models varies widely. Moreover, when a long-term goal is formulated in terms of a targeted end-of-century forcing level which can be exceeded in the meantime (so-called “overshoot” targets), and especially when a CDR technology is assumed to be available, essentially any target can be achieved regardless of the near-term path by shifting emissions reductions to the future. Thus the question is most suitably framed not in absolute terms of preserving or foreclosing particular targets but rather in terms of articulating the consequences for future decision-makers and societies that spring from today’s choices.

Model scenarios are typically designed to find the least-cost pathway to meet a long-term target, in some cases under specific constraints, such as the timing and extent of international participation and the availability of certain technologies. Overall, models show a broad range of near-term emissions that could be consistent with a particular long-term target (Figure 6.31). This is partly based on underlying variation across models in factors such as baseline growth, mitigation costs, trade-offs between sectors such as energy and land-use, and the evolution of non-CO2 gases and non-gas forcing agents. However, the effects of certain scenario characteristics can be discerned. Figure 6.31 distinguishes near-term pathways in published long-term scenarios by the definition of the target, the implementation of delayed participation constraints, and the availability of a negative emissions technology.

In general, emissions pathways through 2030 are lower for more stringent targets, where a target is more stringent when it (a) culminates in a higher forcing level at the end of the century (the basis for the Climate Category assignment); (b) does not allow for overshoot during the century; or (c) is applied to forcing from Kyoto gases only (as in Clarke et al., 2009a), omitting the likely net negative (though uncertain) offset from non-gas forcing agents. Pathways with delayed participation tend to be higher than pathways with full participation from the beginning: any participating countries compensate partially during the initial phase, but the global pathway is shifted in time, resulting in steeper reductions later to meet the target (see Clarke et al., 2009a). Conversely, restricting the availability of a negative emissions technology (which otherwise would be employed further in the future) leads to lower near-term pathways. Keith et al (2006b) show that in an optimal decision framework with climate sensitivity uncertainty the existence of CDR technologies alters near term strategy even though net emissions are not negative until after 2100. Still, there is considerable overlap between categories owing to inter-model differences in the more general factors listed above.

Figure 6.31(a) shows scenario results for long-term targets in the range of 450 CO2-e. There are very few observations of not-to-exceed scenarios; current forcing is already near that level. Particularly when the target is applied to only Kyoto gases, only drastic and immediate global cuts can achieve it. When overshoot is allowed but a negative emissions technology is not available (now or in the future), near-term emissions decline from 2010 levels in all published scenarios. There are no published scenarios depicting a pathway returning to 450 CO2-e by century’s end without a negative emissions option when delayed participation is imposed. The vast majority of published 450 CO2-e scenarios involve overshoot during the century and include a negative emissions technology. Of these, the highest involve delayed participation constraints and have continued growth in energy-related CO2 emissions reaching as high as 50 GtCO2 in 2030. At the same time, many scenarios under the same conditions show steep reductions from current levels. Figure 6.31 (b) shows results for 550 CO2-e scenarios. Because the target is less proximate, some growth in emissions can occur in not-to-exceed pathways, of which more are published. There is significant overlap between the range of pathways for the two target categories, particularly when comparing the 450 CO2-e overshoot range assuming the availability of a negative emissions technology to the 550 CO2-e not-to-exceed range, suggesting that in the near-term these pathways are roughly interchangeable (Kriegler et al., Submitted; Blanford et al., 2013).

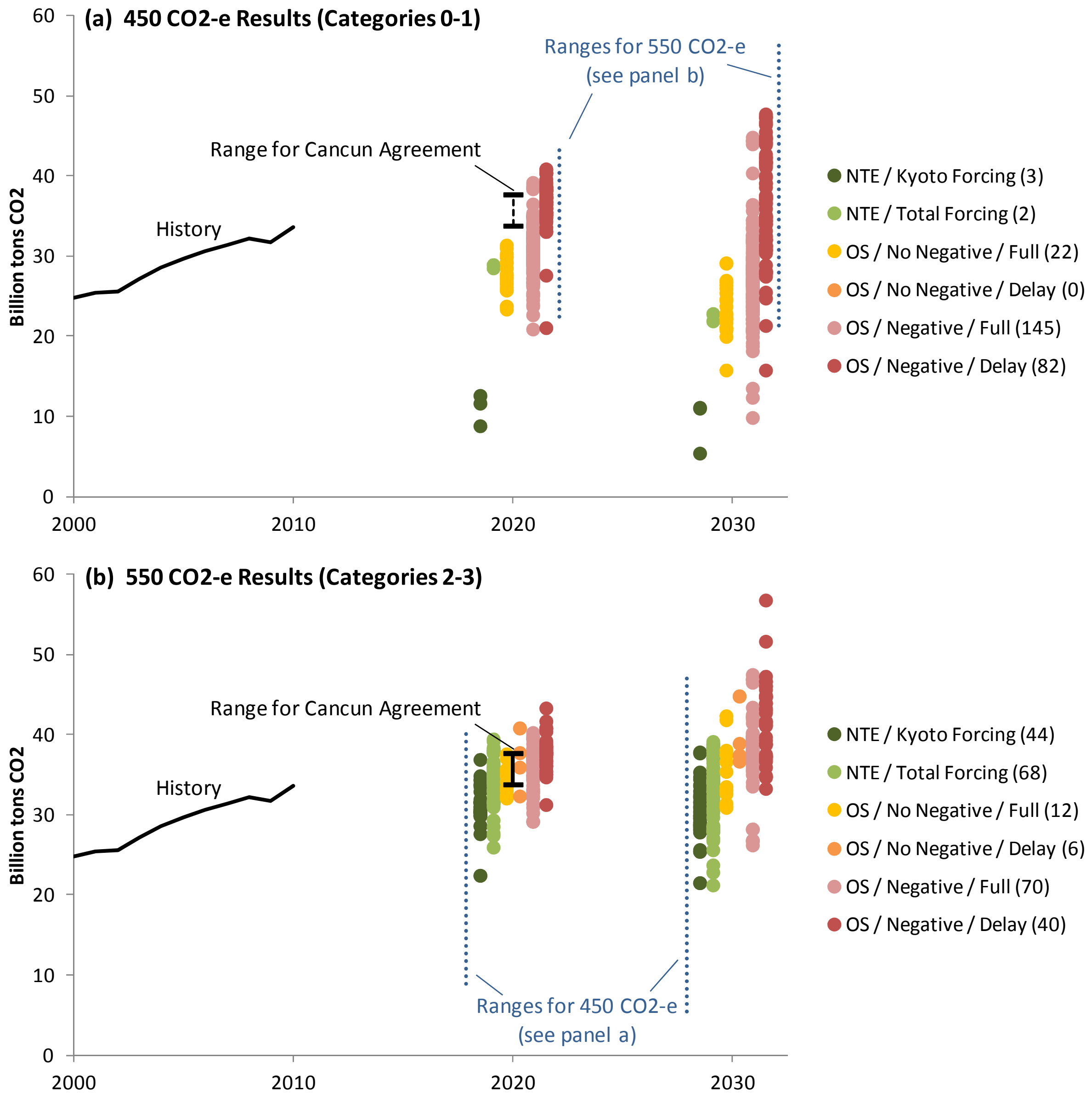


Figure 6.31. Near-Term Global Emissions (FFI) from Scenarios Achieving Long-Term Targets of (a) 450 CO2-e (Categories 0-1) and (b) 550 CO2-e (Categories 2-3). Individual model results are indicated with colors referring to scenario classification as not-to-exceed (NTE) vs. overshoot (OS); CO2 equivalence in terms of Kyoto gas contributions or total contributions to forcing; availability of a negative emissions technology; and timing of international participation (full vs. delay). Number of reported results is shown in legend (254 total for 450 CO2-e, 240 total for 550 CO2-e).

An important indicator for the implications of near-term emissions pathways for long-term goals is the number of models that cannot produce scenarios under a given set of circumstances (see Section 6.2 for a discussion of model solution failures and their interpretation). Unfortunately, this type of result is difficult to represent in a literature review, because in general only scenarios that could actually be produced are published. Whether certain circumstances are underrepresented because they have been under-examined or because they have been examined and the scenarios failed is a crucial distinction, yet one that it is currently not possible to fully report. However, several multimodel studies have attempted systematically to explore the ability of models to produce scenarios under particular constraints. In the EMF 27 multi-model study, (Clarke et al. (2009a)) only five out of 10 models were able to meet a 450 CO2-e target allowing for overshoot before 2100 with full participation, and only two of 10 models found the overshoot 450 CO2-e target feasible when delayed action by some participants was imposed. In the AMPERE project (Riahi et al., Submitted), only two of five models could produce scenarios returning forcing to 450 CO2-e by 2100 with constrained reductions through 2030. Moreover, as shown in Figure 6.31(a), no model has produced such a scenario without a negative emissions technology, although again it is difficult to assess how many have tried, as this information is not reflected in the scenario database . Several individual modeling team studies have also explored this space, and have found situations in which they could not reach solutions for more ambitious targets and delayed action or constrained technology, including O'Neill et al. (2010), Edmonds et al. (2008) and Edmonds et al. (2013).

Figure 6.31 also shows the range of global emissions associated with implementation of the 2020 commitments under the Cancun agreement (cite AMPERE protocol). This range is higher than any published scenario consistent with a not-to-exceed 450 CO2-e target, and higher than any consistent scenario with a 450 CO2-e overshoot target if CDR technologies are not available. The Cancun range corresponds most closely to the published range of 450 CO2-e scenarios with fragmented or constrained reductions and CDR options. Alternatively it appears to be consistent with a 550 CO2-e target under most circumstances, although most not-to-exceed pathways to this target indicate lower emissions levels.

6.4.3 The importance of near-term technological investments and development of institutional capacity

While it is clear that some mitigation effort in the near-term is crucial to preserve the option of achieving low stabilization targets, whether these targets are met in the long-run depends to a greater extent on the potential for deep emissions reductions several decades from now. Thus efforts to begin the transformation toward stabilization must also be directed toward developing the technologies and institutions that will enable deep future emissions cuts rather than exclusively on meeting particular near-term targets. The way in which countries begin low-carbon technology deployment and mitigation policies may well turn out to be quite different from the approach that proves out best in the long run. The benefit of beginning to create and improve technologies today and to develop institutional capacity is that it creates opportunities to make early and mid-course corrections.

The likelihood of a unified global policy for greenhouse gas mitigation is low for the near future. Rather, the expectation is that a "mosaic" of national and regional policies will emerge over the years to come. Individual countries will bring different views and values to bear on their decisions, which will likely lead to a wide variety of policy approaches, some more economically-efficient than others. Flexible market-based policies with maximal sectoral and geographic coverage are most likely to deliver emissions reductions at the lowest economic cost (see Section 6.3.6.5). Although the added cost of inefficient policies in the near-term may be smaller than in the long-term when mitigation requirements will be much larger, their implementation now may lead to "institutional lock-in" if policy reform proves difficult. Thus a near-term focus on developing institutions such as domestic and international emissions trading markets (as in the European Union's ETS), as well as political structures to manage the large capital flows associated with carbon pricing, could provide substantial benefitis in the coming decades when mitigation efforts reach their full proportions.

R&D investment to bring down the costs of low-emitting technology options and early deployment of mitigation technologies to improve long-term performance through learning-by-doing are among the most important steps that can be taken in the near-term. R&D investments are relevant for bringing down the costs of known low-carbon energy alternatives to the current use of predominantly fossil fuels, to develop techniques that today only exist on the drawing board, or generate new concepts that have not yet been invented. Early deployment of climate change mitigation technologies can lead to both incremental and fundamental improvements in their long-term performance through the accumulation of experience or learning-by-doing. Climate policy is essential for spurring R&D and learning-by-doing, because it creates commitments to future greenhouse gas emissions reductions that create incentives today for investments in these drivers of technological innovation, and avoid further lock-in of long-lived carbon-intensive capital stock.

Even if policies requiring emissions reductions are not implemented immediately, market participants may act in anticipation of future action. Commitments to emissions reductions in the future will create incentives for investments in mitigation technologies today, which can serve both to reduce current emissions and avoid further lock-in of long-lived carbon-intensive capital stock and infrastructure (Bosetti, Carraro, and Tavoni, 2009a; Richels et al., 2009).

6.5 Integrating technological and societal change

Technological change occurs because existing technologies are constantly subject to change and because new technologies incessantly succeed and replace older ones. Various steps can be discerned in the life of a technology, from invention through innovation, demonstration, commercialization, diffusion and maturation (see e.g. Grübler et al., 1999). All these phases involve complex interactions between technological and societal change and developments. The remainder of this section summarises what the literature says about the role of efforts to spur innovation in transformation pathways and how processes of technological and societal change are integrated and accounted for in these pathways.

6.5.1 Integrating technological and societal change

Although technological change has received extensive attention and analysis, a clear systematic understanding has so far proven elusive. Nonetheless, it is broadly accepted that both investments in R&D and the accumulation of experience through learning-by-doing play important roles in the mechanisms behind technological change. Other related phenomenon include effects like automation and economies-of-scale. It is broadly recognised that these main drivers of technological innovation are complementary yet inter-linked (e.g., Sagar and van der Zwaan, 2006).

The development and deployment of new energy technologies is central to climate stabilization, since established fossil fuel based energy supply will need to be replaced by new low-carbon energy techniques. The costs of climate policies are significantly influenced by the rate and direction of technological change (Kriegler et al., Submitted; Kemfert and Truong, 2007; Richels and Blanford, 2008; Blanford, 2009; Kyle et al., 2009; Wang et al., 2009; Bosetti, Carraro, Massetti, et al., 2009) and the discussion in Section 6.3.6.3). The importance of technological change raises important questions about the best way to improve the technologies needed for deep emissions reductions and the degree to which current efforts in this regard are adequate to the upcoming challenge. Important questions also surround the appropriate timing of investments in technological change relative to efforts to reduce emissions. Regardless of modeling approaches, however, virtually all transformation scenarios assume that technology will improve significantly over time, especially for technologies with a large potential for advancement (see e.g. van der Zwaan et al., Submitted). There is generally more agreement about cost and performance improvements for mature technologies than for many emerging technologies upon which transformation pathways may depend (McCollum et al., Submitted).

Most of the scenarios developed since the 1970s for energy and climate change analysis embed exogenous assumptions about the rate of technical change, but only since the late 1990s has the effect of induced innovation been considered in the energy and climate policy models used for the development of these scenarios (Messner, 1997; van der Zwaan et al., 2002). This is because empirical evidence of the magnitude of such effects was limited (Popp, 2006b). Now, empirical data on technical change is being progressively incorporated into computational models for the integrated assessment of climate change (Fisher-Vanden, 2008), though unsettled issues include proper accounting for the opportunity costs of climate-related knowledge generation, treatment of knowledge spillovers and appropriability, and the empirical basis for parameterizing technological relationships. (Gillingham et al., 2008)

The strand of literature which deals with innovation and climate change suggests that the benefits of technological change are sufficiently high to justify upfront investments and support in innovation and diffusion of low carbon mitigation options. Studies that have specifically looked at the role of investments in innovation and diffusion in energy efficiency and clean energy – and on how these are induced by policy – suggest that current rates of investment are too low. For example, an average increase between 3 and 6 times from current clean energy R&D expenditures, has been suggested to be the optimal one to achieve climate stabilization. This corresponds to investment rates in clean energy R&D in the next few decades in the range of 50-100 Billion USD per year (Bosetti, Carraro, Massetti, et al., 2009; IEA, 2010; Marangoni and M. Tavoni, 2013). The R&D gap is particularly important given that investments in OECD countries have been decreasing as a share of total national R&D budgets, which currently stands at about 4%. This gap would need to be directed to a well-diversified portfolio of investments, but especially to advanced transportation, which currently faces the steeper marginal costs of abatement.

The two-way relation between mitigation and innovation raises the question of what would be the proper policy intervention aimed at reducing CO2 emissions. The influence of induced technical change on the optimal program of mitigation depends on both the rate and direction of the innovation process, which drives the feedback loop (Sue Wing, 2006). The modelling literature of endogenous technical change indicates that relying solely on innovation policies would not be sufficient to achieve climate stabilization (Bosetti et al., 2011). On the other hand, climate policies such as carbon pricing could induce significant technological change, provided the policy commitment is credible, long term and sufficiently strong (Popp, 2006a; Bosetti et al., 2011), while at the same time materialising emission reductions. This suggests that the implementation of mitigation policies is an important driver of the cost, and thus the feasibility, of additional mitigation in the future, but does not necessarily rule out the need for specific policies aimed at incentivizing R&D investments. Indeed, the joint use of R&D subsidies and climate policies has been shown to generate further benefits, in the order of 10-30% (D. Popp, 2006; V. Bosetti et al., 2011). Thus, the combination of R&D subsidies and CO2 emission constraints is optimal, since climate-specific R&D instruments can step up early innovation and ultimately reduce mitigation costs (Gerlagh et al., 2009), although R&D subsidies could raise the shadow value of the CO2 because of the rebound effect from stimulating innovation (Otto and Reilly, 2008).

The imperfections and externalities in the knowledge markets provide the strongest rationale for subsidizing research or development, or in the absence of such a policy mechanisms, to increase the level of carbon pricing (Golombek and Hoel, 2008; Hart, 2008; Greaker and Pade, 2009; Heal and Tarui, 2010; De Cian and Tavoni, 2012). In this cases, carbon taxes above the Pigouvian levels or which differ across regions can be welfare enhancing because they address the underprovision of R&D. Innovation has also an impact on carbon leakage, with the potential for reducing it, due to positive spillovers of clean energy technologies (Maria and Van der Werf, 2008).

The unequivocal call for clean energy innovation policies can be somewhat questioned, however, when all inventive activities, including also endogenous technical progress for ‘‘dirty’’ inputs, are accounted for. In such cases, the overall effect of a climate policy on innovation might not be straightforward, since clean energy R&D can crowd out other inventive activities, and result in lower welfare (Goulder and Mathai, 2000). The degree of substitutability between input of production has been shown to drive the final result (Otto et al., 2008; Acemoglu et al., 2009; Carraro et al., 2010).

Innovation is also found to play an important role when accounting for uncertainty about future climate response, technological performance and policy implementation (Loschel, 2002; Bohringer and Löschel, 2006; Baker and Shittu, 2008; Bosetti and Tavoni, 2009). Innovation can provide hedging against uncertainty, since the required investments are relatively smaller than the physical one required for mitigation technologies.

6.5.2 Integrating societal change

Managing a transition towards a low carbon society involves more than simply creating new and better technologies. Ultimately, technologies are embedded in human societies, and social and institutional systems are necessarily both an “obstacle” and a “support” to conduct the dramatic changes associated with many transformation pathways. Changes in the social determinants of individual and collective decision-making are complex and not amenable to the sorts of modelling techniques that were used to generate the long-term transformation pathways reviewed in this chapter. Yet, these changes are necessarily implied by transformation scenarios.

In the short run, before deep emissions reductions are undertaken, mitigation policies may be focused more on regulatory options. However, in the long run, all transformation pathways ultimately require either an implicit or explicit price on carbon that will allow emissions to be undertaken across the economy. There are a number of obstacles to carbon pricing policies. One is industrial competition under uneven carbon constraints. The impact of a carbon price differs widely across sectors because of the heterogeneity of their energy intensity of the turnover of their capital stock. In case of asymmetry of carbon constraints, the risks of carbon leakages are then an argument for not imposing significant carbon prices on the energy intensive industry (Houser et al 2008, Smale & al 2006, Fischer & al 2011, Monjon & al 2011, Demailly & al 2008). A second obstacle is the uneven impacts on household’s purchasing power which is one major cause of failures in adopting a carbon tax. The low middle classes are indeed specifically hurt by significant increases of energy prices especially when they are totally dependent from automobile for their daily travels because they live in remote areas, in low density cities or in urban suburbs (Combet et al 2010, Grainger et al 2010). Both experiences of successful introduction of carbon taxes (Sterner 1994, Wier 2005) and of failure (Deroubaix 2006) show that the introduction of significant carbon pricing demands a social consensus to use a carbon tax as a component of a larger reform of fiscal systems which allow for indirect compensatory transfers through the reduction of other taxes or specific devices for the most vulnerable segments of society. Guivarch (2011) shows that they have to be complemented by policies apt to upgrade the adaptability of labour force to changing conditions.

Beyond explicit carbon policy structures, the use of new technologies requires both new institutional structures to manage the technology as well as lifestyle changes to accept new technology. The capacity of mitigation policies to trigger investments in low carbon technologies is limited by the risks supported by industry. Risk-averse firms try and prevent to face sunk-costs in case their expectations do not realize and do not adopt technologies by merit order in function of their levelized costs. This problem is analysed in economic literature on decision under uncertainty (Kahneman and Tversky 1979), Pyndick 1982, 1987). Hallegatte et al. (2008) show the importance of the difference in investment rules in a managerial economy (Roe 1994) and a shareholder economy (Jensen 1986). Hadjilambrinos (2000) and Finon (2009, 2012) show how differences in regulatory regimes may explain differences in technological choices in the electricity industries. Grübler (2010) show how institutional rigidities may lead to technological de-learning. Historically, political and institutional pre-conditions to changing decision routines to setting up organisational skills explains why countries with similar dependence on oil imports adopted very different responses to oil shocks (Hourcade, Kostopoulou 1994). Institutional structures must be available to manage new infrastructures such as those associated with large quantities of intermittent resources on the electric grid, CO2 transport and storage, dispersed generation or storage of electricity, or nuclear waste and materials. Another critical sector is agriculture and food production. Mitigating these trends has huge implications on both the price of land and the policies that govern the location of human settlements.

In addition to institutional structures, individuals within a society must accept the new technologies that they use. A long literature on the energy efficiency gap articulates a difference between perceived economic incentives for energy efficiency and actual consumer behaviour. Issues include reliability of technologies, maintenance, quality of the end-use service, comfort and time, information failures, property rights like the tenant/landlord problem, behavioral characteristics and their differentiation per level of income.

More generally, large-scale changes in the build environment will require large-scale societal change. Recent modeling exercises captured for example the trade-off between commuting costs and housing costs and their impact on the urban sprawl and the mobility needs (Gusdorf et al 2007, 2008). They show that the price of real estate is a driver of mobility demand as powerful as gasoline prices. A vision of the consolidated impact of urban forms on energy consumption (transportation, heating and air-conditioning) can be derived from meta-analysis of urban forms (Leck 2006).

6.6 Sustainable development, and transformation pathways, taking into account differences across regions

Averting the adverse social and environmental effects of climate change is fundamental to sustainable development (WCED, 1987). Yet, climate change is but one of many challenges facing society in the twenty-first century. Others include, for instance, providing universal energy access to the world's poorest; limiting air pollution, health damages, and water impacts from energy and agriculture; alleviating energy security concerns; minimizing energy-driven land use requirements and biodiversity loss; and maintaining the security of food supplies (see Chapter 4). A complex web of interactions and feedback effects links these various energy challenges, or rather sustainability objectives.

The assessment of scenario literature points towards potential policy choices related to climate change mitigation options. Beyond consideration of macroeconomic costs, regional conditions etc., these choices will be based on impacts on other societal objectives and on the availability of non-climate policies that may affect mitigation efforts.[3] Implementation of climate policies may therefore adequately be described within a multi-objective framework and may be aligned with other societal priorities in order to maximize synergistic effects and to avoid trade-offs (see Chapter 15). But since the relative importance of different objectives differs among various stakeholders and may change over time, transparency on the multiple effects that accrue to different actors at different points of time is important (see also Chapter 4).

This section attempts to summarize the growing literature on possible "co-benefits" and "adverse side effects" with respect to climate change mitigation. In doing so, a multi-objective perspective is taken and focus is given to scenario studies that have conducted integrated assessments of the various energy challenges. For a low-carbon society would ideally be compatible with a number of societal priorities for sustainable development (Skea and Nishioka, 2008).

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[3] The net welfare effect is then the sum of the monetized impacts (some positive, some negative) in other dimensions (see Section 3.5.3).

6.6.1 Co-benefits and risks of mitigation options: Synthesis of sectoral information and linkages to transformation pathways

While the scientific literature makes very clear that a variety of policies and measures exist for mitigating climate change, the impacts of each of these options along other, non-climate dimensions have received much less attention. To the extent these "climate mitigation side-effects" are positive, they can be deemed "co-benefits"; if adverse, they imply "risks" with respect to the other non-climate objectives. Table 6.5 provides an aggregated overview of the co-benefits and risks that could potentially be realized if certain types of mitigation options are enacted in different sectors: side-effects resulting from energy supply-side transformations (i.e., upstream reduction of carbon intensity of fuels and capture technologies); via technological and behavioural changes in the transport, buildings, and industry end-use sectors (i.e., downstream reduction of carbon intensity through fuel switching to low-carbon alternatives and of energy use through decreasing energy intensity and structural/activity changes); and via modified agriculture, forestry, and land use practices. These co-benefits and risks can be classified by the nature of their impact: economic, social, or environmental. Other types of impacts are also possible and are highlighted in the table where relevant.

Whether or not any of these co-benefits and risks actually materialize, and to what extent, will be highly case- and site-specific, as the side-effects will depend importantly on local circumstances and the scale, scope, and pace of implementation, among other factors. Measures undertaken in an urbanized area of the industrialized world, for instance, may not yield the same impacts as when enacted in a rural part of a developing country. In some cases completely opposite side-effects might even result. Such detailed considerations are not reflected in Table 6.5, which is meant to give an aggregated sense for the potential of co-benefits and risks throughout the world when stringent climate mitigation policies are in place. Local and national considerations are instead taken up explicitly by each of the respective sectoral chapters (see Chapters 7-12). Note that in addition to the *qualitative* information on potential side-effects summarized below, Table 6.5 also provides *quantitative* information for each sector regarding the potential for technology deployment, GHG mitigation, and demand reduction that can be feasibly achieved by 2050. These figures come from both IAM scenario analyses (see earlier parts of this chapter) and detailed sectoral studies (see Chapters 7-12).

The compilation of sectoral findings in Table 6.5 documents a large number of co-benefits and a small number of risks for demand side options (transport, buildings, and industry). This may provide incentives for installing demand side options beyond their mitigation potential in an effort to manage the risks of climate change mitigation. Any unit of energy saved avoids the risk of supplying this energy. However, no single category of options is completely devoid of risk.[4] For instance, by contributing to a phase-out of conventional fossil fuels (thereby reducing carbon intensity of energy supply or 'fuel switching'), nearly all mitigation options have major health and environmental benefits for society (owing to significant reductions in both outdoor and indoor air pollution). Local and sectoral employment gains and improved security of energy supply at the national level (e.g. resource efficiency, import dependency, exposure to energy price volatility) offer additional examples of robust co-benefits across a wide range of mitigation options. Another clear message gleaned from Table 6.5 is that energy efficiency and conservation to reduce energy intensity (either through technological or structural/behavioural means) are the only general-purpose mitigation options that can lead to co-benefits in all sectors. Moreover, while nearly all mitigation options for reducing carbon and energy intensity have higher up-front investment requirements, their often lower operating costs (and sometimes even life-cycle costs)[5] can contribute to reduced energy costs for consumers. Yet, it should be noted that an important barrier to the implementation of clean fuels

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[4] For a discussion of differing priorities of objectives across stakeholders, please refer to sections 3.7.1 and 4.X.

[5] See the 'cost and potential' sections in the sector chapters.

Table 6.5: Main co-benefits (green) and risks (red) of selected mitigation options. Column two provides in addition the contribution of the respective mitigation options to reach low stabilization targets. Ranges of baseline scenarios for the year 2050 are compared to the range in low stabilization scenarios (category 1). Co-benefits and risks are case- and site-specific, and depend on local circumstances as well as on the implementation practice (see Tables 7.4, 8.6.2, 9.6, 10.9, 11.9, and 11.A.2 in Chapters 7-11 and the Bioenergy Annex to Chapter 11). The contribution of the mitigation options is thus not an indicator for the realized co-benefits or the magnitude of risks.

Mitigation options				**Non-climate objectives**			
Energy Supply	**Deployment[1]**		**Rate of change[1]**	**Economic**	**Social (including equity)**	**Environmental**	**Other**
	2010	***2050***					
Nuclear replacing coal power	10 EJ/yr	(8-24) *23-50* EJ/yr	(-0.5-2) *2-4* %/yr	Affordability (increases the cost of electricity generation) Energy security (import dependency)	Risk due to (unresolved) long-term waste disposal requirement Risk of large-scale accidents	Health and ecosystem benefits due to reduction of air pollution and mining accidents	Proliferation risk
RES (Wind, PV, CSP, hydro, geothermal, biomass) replacing fossil fuels	62 EJ/yr	(60-131) *166-270* EJ/yr	(0-2) *2.7-3.8* %/yr	Affordability (increases in many cases the cost of electricity generation) Energy security (import dependency)	Local employment and value added at the place of deployment Contribution to (off-grid) energy access and technology transfer to rural areas Risk of conflicts about the siting of plants (mainly wind and hydro) Noise (mainly wind) Displacement (hydro) Risk of food security and interference with subsistence farming (biomass, see AFOLU)	Health and ecosystem benefits due to reduction of most forms of air pollution (excluding biomass) and mining accidents Biomass: water security risk and other ecological impacts, e.g., biodiversity, soil quality etc. (see also AFOLU) Wind: impact on landscape, low water requirements PV: low water requirement Hydro: Risk of loss of habitat and other ecological impacts CSP & hydro: high water consumption Geothermal: water use and pollution	Supply from variable RES requires extra measures to match demand Higher material requirements (e.g. supply of rare earths)
Fossil CCS replacing coal	0 GtCO2 stored	(0-0) *4-10* GtCO2 stored	(0-0) *NA* %/yr	Affordability (increases the cost of electricity generation) Energy security (import dependency, resource efficiency) Possibly less controllable power output (but possibly better compared to variable and unpredictable RES)	Preserves fossil industry jobs, infrastructure and investments Risk of conflicts about the siting of storage facilities and transport pipelines Concern about risk of CO_2 leakage Lock-in effect	Environmental risk of CO_2 leakage Increase of upstream environmental risks due to higher fuel use	
BECCS replacing coal power	0 GtCO2 stored	(0-0) *0-5* GtCO2 stored	(0-0) *NA* %/yr	*See fossil CCS.*	*See fossil CCS. For possible upstream effect of biomass supply, see biomass supply and AFOLU*	*See fossil CCS. For possible upstream effect of biomass supply, see biomass supply and AFOLU*	Innovation risk because feasibility not yet established
Fugitive methane capture and use or treatment	NA	NA	NA	Energy security (potential to use gas in some cases)	Improved occupational safety at coal mines	Health benefits due to reduction of hydrocarbon emissions and hence summer smog	

Transport	**GHG Mitigation & Demand Reduction Potential**	*For possible upstream effects of low-carbon electricity, see energy supply. For possible upstream effects of biomass supply, see biomass supply and AFOLU.*			
Reduction of fuel carbon intensity: e.g. by electrification, biofuels, CNG and other measures	*Scenario ranges for the whole sector:* 1) carbon intensity in the transport sector 2010: 71 gCO2/MJ BL (2050): 61-67 gCO2/MJ Cat 1 (2050): 37-53 gCO2/MJ 2) final energy demand in the transport sector 2010: 93 EJ High (2050): 147-262 EJ Low (2050): 55-132 EJ	Affordability (may increase or reduce costs for consumers and businesses) Energy security (reduction of oil dependency)	Lower exposure to oil price volatility risks Noise reduction (for electrification and fuel cells)	Electrification, hydrogen: Health and ecosystem benefits due to potential large reductions of local urban air pollution in many key pollutants CNG, biofuels: Health and ecosystem benefits are uncertain	Resource risk (e.g. limited supply of battery or fuel cell material inputs, infrastructure for hazardous wastes disposal)
Reduction of energy intensity		Affordability for businesses Energy security (reduction of oil dependency)	Improved transport affordability for households (lower travel costs for the consumer in most cases due to improved engine and vehicle performance efficiency)	Health and ecosystem benefits due to reduced urban air pollution.	
Improve urban form and infrastructure Modal shifts (e.g. from private to public or non-motorized transport)		Improved productivity due to reduced urban congestion and travel times across all modes Energy security (reduction of oil dependency)	More equitable mobility access and safety, particularly in DCs Potentially reduced risks of accidents by provision of safer transport (mainly modal shift) and infrastructure for pedestrians and cyclists	Health and ecosystem benefits due to (i) reduced urban air pollution and (ii) reduced exposures to air pollution Health benefits from shifts to active transport modes	
Journey reduction and avoidance		Affordability (lower fuel and travel costs for the consumer) Improved productivity due to reduced urban congestion and travel times Energy security (reduction of oil dependency)	Improved access and mobility	Reduced land use from transport infrastructure Potential risk of damages to vulnerable ecosystems from shifts to new and shorter routes Health and ecosystem benefits due to reduced urban air pollution	
Buildings	**GHG Mitigation & Demand Reduction Potential**	*For possible upstream effects of fuel switching and RES, see energy supply.*			
Fuel switching, RES incorporation, green roofs, and other measures reducing CI of buildings sector	*Scenario ranges for the whole sector:* 1) carbon intensity in the buildings sector 2010: 29 gCO2/MJ	Affordability (increases in most cases the cost of energy for the consumer) Net employment gains Lower need for energy subsidies Enhanced asset values of buildings	Fuel poverty alleviation in some cases (in residential buildings) Lower exposure to energy price volatility risks Increased productive time for women and children (for switch to non-traditional cooking fuels in residential buildings in DCs)	Health benefits due to: (i) reduced outdoor air pollution, (ii) reduced indoor air pollution (in residential buildings in DCs), and (iii) fuel poverty alleviation (in residential buildings) Reduction of the heat island effect (in cities)	

Efficient equipment Retrofits of existing buildings (e.g. cool roof, passive solar, etc.) Exemplary new buildings	BL (2050): 20-26 gCO2/MJ Cat 1 (2050): 10-18 gCO2/MJ 2) final energy demand in the buildings sector 2010: 113 EJ High (2050): 195-291 EJ Low (2050): 93-159 EJ	Affordability (reduces in most cases the cost of energy for the consumer) Net employment gains Energy security (resource efficiency, power grid reliability, reduction of peak power demand, shifting demand to off-peak periods) Improved productivity (in commercial buildings) Lower need for energy subsidies Enhanced asset values of buildings (for exemplary new buildings and retrofits)	Fuel poverty alleviation in most cases (for retrofits of residential buildings and efficient equipment) Increased comfort (for new buildings and retrofits) Lower exposure to energy price volatility risks Increased productive time for women and children (for replaced traditional cookstoves in residential buildings in DCs)	Health benefits due to: (i) reduced outdoor air pollution, (ii) improved indoor environmental conditions and reduced indoor air pollution (in residential buildings in DCs) (iii) lower indoor infectious disease spread rates (due to better ventilation), and (iv) fuel poverty alleviation (in residential buildings) Reduced impacts on ecosystems, cultivations, materials, etc. Reduced water consumption and sewage production Reduction of the heat island effect (for retrofits & new buildings in cities)	
Behavioral changes reducing energy demand		Energy security (resource efficiency) Lower need for energy subsidies	Lower exposure to energy price volatility risks	Health benefits due to: (i) reduced outdoor air pollution, and (ii) improved indoor environmental conditions Reduced impacts on ecosystems, cultivations, materials, etc.	
Industry	**GHG Mitigation & Demand Reduction Potential**	*For possible upstream effects of low-carbon energy supply (incl CCS), see energy supply. For possible upstream effects of biomass supply, see biomass supply and AFOLU.*			
Reduction of energy intensity through new industrial processes and technologies	*Scenario ranges for the whole sector:* 1) carbon intensity in the industry sector 2010: 57 gCO2/MJ BL (2050): 51-61 gCO2/MJ Cat 1 (2050): 13-31 gCO2/MJ 2) final energy demand in the industry sector 2010: 137 EJ High (2050): 72-204 EJ Low (2050): 216-355 EJ	Affordability (may increase or reduce costs for the consumer) Reduce energy input costs for businesses Energy security (resource efficiency, power grid reliability)	Improved energy access	Reduction of local pollution and associated positive impacts on biodiversity Reduction of water use (e.g for new cement and pulp and paper production technologies)	Innovation risk because feasibility of some technologies not yet established (particularly for SMEs)
Material efficiency of goods, recycling, and product demand reductions		Affordability (reduces costs for the consumer due to longer life of products) Reduction of societal costs of waste disposal Reduction in production costs (for businesses) Reduction in national sales tax revenue in medium term (for product demand reduction and material efficiency)	Reduced threat of displacement from reduced demand for landfill sites Job creation in formal recycling market (potentially for poor in informal waste recycling market) and the service sector Potential short-term reduction in employment (for product demand reduction)	Reduction of local pollution and wastes (e.g. due to low post-consumption waste) Less use of virgin materials/natural resources Health benefits due to reduction of supply-chain accidents Reduced competing demand for land	Innovation risk because feasibility of some technologies not yet established (particularly for SMEs)

AFOLU	GHG Mitigation Potential				
Conservation of existing carbon pools and avoiding emissions (avoided deforestation; agricultural methane/nitrous oxide emissions reductions)	*Scenario ranges for the whole sector:* 1) carbon intensity ranges in 2030 and 2050 (Baselines compared to Category I scenarios)	New source of income for landowners through payment for ecosystem services (PES) or other transfers (for avoided/reduced deforestation (REDD+)) Transaction costs and costs of monitoring and evaluation Increased efficiency of feed conversion and fertilizer use (for CH_4 /N_2O emissions reduction)	Food security due to reduced flexibility of land-use (e.g. for agricultural expansion in case of avoided/reduced deforestation (REDD+)) Food security (for CH_4 emissions reduction) Protection of cultural habitats and recreational areas (for avoided/reduced deforestation) Use of traditional practices and improved animal welfare (for CH_4 emissions reduction)	Ecosystem benefits (water and biodiversity) due to forest conservation, reduced water pollution (for N_2O emissions reduction) More efficient agriculture can increase or decrease pressure for forest conversion→ biodiversity loss /biodiversity conservation	Improvement or diminishing of tenure and property rights at the local level (for indigenous people and local communities) Access to participative agreements
Increase of existing carbon pools (Afforestation/reforestation & additional activities (cropland, forest, & grazing land management, revegetation)		Reduced flexibility of land-use once projects are validated. Diversified sources of income and access to new markets	Competition with other land-uses, food production and water Job creation through new enterprises	Opportunity to use sequestration projects to protect and restore watersheds and other landscapes→ water and biodiversity Competition with water supplies in some instances Monocultures reduce biodiversity Positive impacts on albedo and evaporation	Promote clarification of land tenure Promote participative schemes Concentration on decision making → marginalization of land users
Substitution of biological products for fossil fuels (bioenergy, harvested wood products, etc.)		Diversified sources of income and access to new markets	Can promote forest conversion → biodiversity loss Competition with other land-uses → reduced food production and/or water availability Job creation through new enterprises	Management of watersheds (nutrients, water) → water and biodiversity Environmental damage due to increased use of fertilizers or increased leakage → biodiversity loss, reduced water quality	Promote participative schemes Concentration on decision making → marginalization of land users

1) Scenario ranges for stabilization scenarios of category 1 (italics), and baseline scenarios (in parentheses). Ranges correspond to the interquartile of the distribution from stabilization scenarios assuming a full portfolio with stylized immediate action policy assumptions (P1)

and technologies highlighted in Table 6.5 (some of which are fundamental to societal well-being and sustainable development, see Chapter 4) is their limited availability to those households and firms which have restricted access to capital (see Chapters 7.10, 8.8, 9.8, 10.9, 11.8, and 16).

Moreover, in addition to furthering the achievement of various global targets for sustainability, namely those of the major environmental conventions and the Millennium Development Goals (MDG), climate mitigation can potentially yield positive side-effects in the impacts, adaptation, and vulnerability (IAV) dimensions (see Section 11.7). For instance, decentralized renewable energy systems can help to build adaptive capacity in rural communities (Venema and Rehman, 2007), and sustainable agricultural practices (e.g., conservation tillage and water management) can improve drought resistance and soil conservation and fertility (Uprety et al., 2012).

6.6.2 Transformation pathways studies with links to other societal priorities

As indicated above, the overall nature and extent of the side-effects arising from climate mitigation depends importantly on how (and which of) the various options in Table 6.5 are actually implemented. Indeed, the measures will interact with each other in countless ways, such that the full systems-level welfare impacts for multi-objective decision-making are best viewed from an integrated perspective that permits the full accounting of the impacts of each of the multiple objectives on social welfare (see Section 3.5.3) (Sathaye et al., 2011).[6] Since the Fourth Assessment Report (AR4), a number of recent studies have been conducted to shed light on the macro-level implications of climate mitigation for other societal priorities, including energy access, air pollution and its health impacts, water use, energy security, land use requirements and biodiversity preservation, and international trade. While the majority of these studies focus on two-way interactions (e.g., the effect of climate mitigation on air pollution in a given country or across groups of countries – or vice versa), a few recent analyses have looked at three or more objectives simultaneously. This section attempts to summarize the main conclusions of the transformation pathways literature as it relates to large-scale side-effects from climate mitigation for other policy objectives, or in some cases the other way around.

6.6.2.1 Air pollution and health

Greenhouse gases and pollutant emissions typically derive from the same sources (e.g., power plants, factories, cars), hence mitigation strategies that reduce the use of fossil fuels often result in major cuts in emissions of fine particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and mercury, among other species. A review of 37 peer-reviewed studies by Nemet et al. (2010) – spanning diverse geographies, economic sectors, time horizons, and valuation techniques – concludes that the economic value of air quality co-benefits from climate change mitigation ranges from \$2/tCO_2 to \$196/tCO_2, with a mean of \$49/tCO_2. In fact, co-benefits are found to be larger in developing countries (mean: \$81/tCO_2) than industrialized countries (\$44/tCO_2), a finding that results from the currently higher pollution levels of the former and, thus, the greater potential for improving health in those emerging nations (see also Shukla and Dhar (2011a)).

Although these air quality co-benefits are of a similar order of magnitude as climate mitigation costs, only a handful of global IAM studies take air pollution into account. Rose et al.(2012) review five of the models that do and find that air pollution policies may no longer be binding constraints on pollutant emissions under climate policies of varying stringency. In China, for instance, mitigation efforts leading to radiative forcing of 3.7 W/m^2 (2.8 W/m^2) in 2100 result in SO_2 emissions 15 to 55%

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[6] This poses a significant challenge, since costs of climate mitigation needs to be weighted against multiple benefits for other objectives that are traditionally measured in different units (e.g., health benefits of reduced air pollution in terms of life years saved, or benefits in terms of improved energy security and reliability of energy supply). In addition, weighting the different objectives in a single overall welfare formulation implies subjective choices about the ranking or relative importance of policy priorities. Ultimately, however, the ranking of priorities with respect to different objectives remains a policy variable.

(25–75%) below reference levels by 2030 and 40 to 80 % (55–80%) by 2050. Similarly, Rafaj et al. (2012) calculate that stringent climate policies consistent with achieving the 2°C target would simultaneously lead to near-term (by 2030) reductions of SO_2, NO_x, and $PM_{2.5}$ on the order of 40%, 30%, and 5%, respectively, relative to a baseline scenario. By further exploiting the full range of opportunities for energy efficiency and ensuring access to modern forms of energy for the world's poorest (hence less household air pollution), the near-term air pollution co-benefits of climate mitigation could be even greater: 50% for SO_2, 35% for NO_x, and 30% for $PM_{2.5}$ by 2030, according to a scenario by Riahi et al. (2012b). The latter result is particularly noteworthy since emissions of fine particulate matter cause some of the worst health damages. In fact, the Riahi et al. (2012b) scenario shows that by 2030 stringent climate mitigation can help to reduce globally-aggregated disability-adjusted life years (DALYs) by more than 10 million, a decrease of one-third compared to a baseline scenario. The vast majority of these co-benefits would accrue in today's rapidly developing economies.

6.6.2.2 Energy security

Energy security concerns fall along three distinct dimensions that shape national energy security agendas today: *sovereignty* (relating to geopolitics, power balance in energy trade, and control over energy systems), *robustness* (state of energy infrastructure and physical availability of energy resources), and *resilience* (ability of energy systems to respond to disruptions; associated with the diversity of energy options) (Cherp et al., 2012).

Scenario studies indicate that the co-benefits of climate mitigation for energy security are multi-fold. First, such policies will likely lead to major reductions in global energy trade and, by extension, the import dependency of many countries, thus making national and regional energy systems less vulnerable to disruptions (Costantini et al., 2007; Criqui and Mima, 2012; Jewell, Cherp, Vinichenko, et al., in review; Shukla and Dhar, 2011b). Jewell et al. (in review)for instance, find that in stringent climate policy scenarios global energy trade would be 30-60% lower by 2050 (40-90% by 2100) than in scenarios without such policies. Second, climate policies will lead to much lower extraction rates for fossil resources (Kruyt et al., 2009; McCollum, Bauer, et al., 2013a), which could alleviate energy price volatility given that perceptions of resource scarcity are a key driver of rapid price swings. Third, climate policies would almost certainly result in energy systems with dramatically increased resilience; namely, the diversity of energy sources used in the transport and electricity sectors would rise, both relative to today and to a baseline scenario in which fossils remain dominant (Cherp et al., In review; Jewell, Cherp, and Riahi, in review; Grubb et al., 2006; Riahi et al., 2012b). These developments would make energy systems less vulnerable to various types of shocks and stresses.

Although the act of leaving more fossil resources in the ground has been referred to as an "energy security buffer" (Turton and Barreto, 2006), a risk of global climate mitigation efforts is that such measures have the potential to curtail the export revenues of fossil energy producers, thereby decreasing their "demand security." Whether this would actually happen is not entirely clear: climate policies could in fact favor conventional resources by pricing highly carbon-intensive unconventionals out of the market (Persson et al., 2007). A risk of such developments is that continuing reliance on today's main exporters could contribute to a stagnation, or even an increase, in the geographical concentration of fossil resource production (Cherp et al., In review).

6.6.2.3 Energy access

Roughly a quarter of the world's population lives without access to electricity and nearly a half depends on traditional solid fuels (e.g., unprocessed biomass, coal, or charcoal) for cooking and heating (Pachauri et al., 2012). The majority of these individuals reside in the urban slums and rural villages of the developing world, where climate change impacts are likely to be most acute. Studies have shown that, while the scale of the challenge is tremendous, providing universal energy access would likely result in negligible impacts on, or even a reduction of, GHG emissions globally (PBL, 2012; Riahi et al., 2012b). Moreover, when viewed from the reverse direction (the side-effects of climate mitigation on energy access), there appears to be only one major risk: climate policies that increase energy prices for the world's poor could potentially impair the transition to universal energy access by making energy less affordable (see Table 6.5).

6.6.2.4 Biodiversity preservation

The concept of biodiversity can be interpreted in different ways; measuring it therefore presents a challenge. One indicator that has been used in the IAM literature for assessing the biodiversity implications of global transformation pathways is that of mean species abundance (MSA), which uses the species composition and abundance of the original ecosystem as a reference situation. According to PBL (2012), globally-averaged MSA declined continuously from approximately 76% in 1970 to 68% in 2010 (i.e., a further eight percentage-point loss in the world's biodiversity took place, relative to the undisturbed states of ecosystems). This was mostly due to habitat loss resulting from conversion of natural systems to agriculture uses and urban areas. Climate change is expected to only compound these drivers of biodiversity loss in the future, bringing down global MSA to 60% by 2050 (PBL, 2012). Because such losses will have widespread adverse effects for ecological goods and services, most efforts to mitigate climate change will provide important co-benefits (through avoided biodiversity loss). At the same time, certain mitigation measures, such as reforestation/afforestation efforts and bioenergy production, could impose risks, depending on where and how they are implemented. To the extent new land is required for bioenergy feedstocks, biodiversity could suffer. Even if care is taken to source feedstocks exclusively from agricultural residues and/or crops grown on marginal lands, biodiversity loss could still continue to decline, owing to the promotion of monocultures (see Table 6.5). Clear land management policies and practices will thus need to be enacted in order to guard against such an outcome. Assuming these policies do complement climate mitigation actions, then it appears possible to stabilize average global biodiversity at the 2020/2030 level (MSA = 65%) by 2050 (PBL, 2012). This would prevent more than half of all biodiversity loss projected to occur by mid-century, a target interpreted to be in accordance with the Aichi Biodiversity Targets (CBD, 2010).

6.6.2.5 Water use

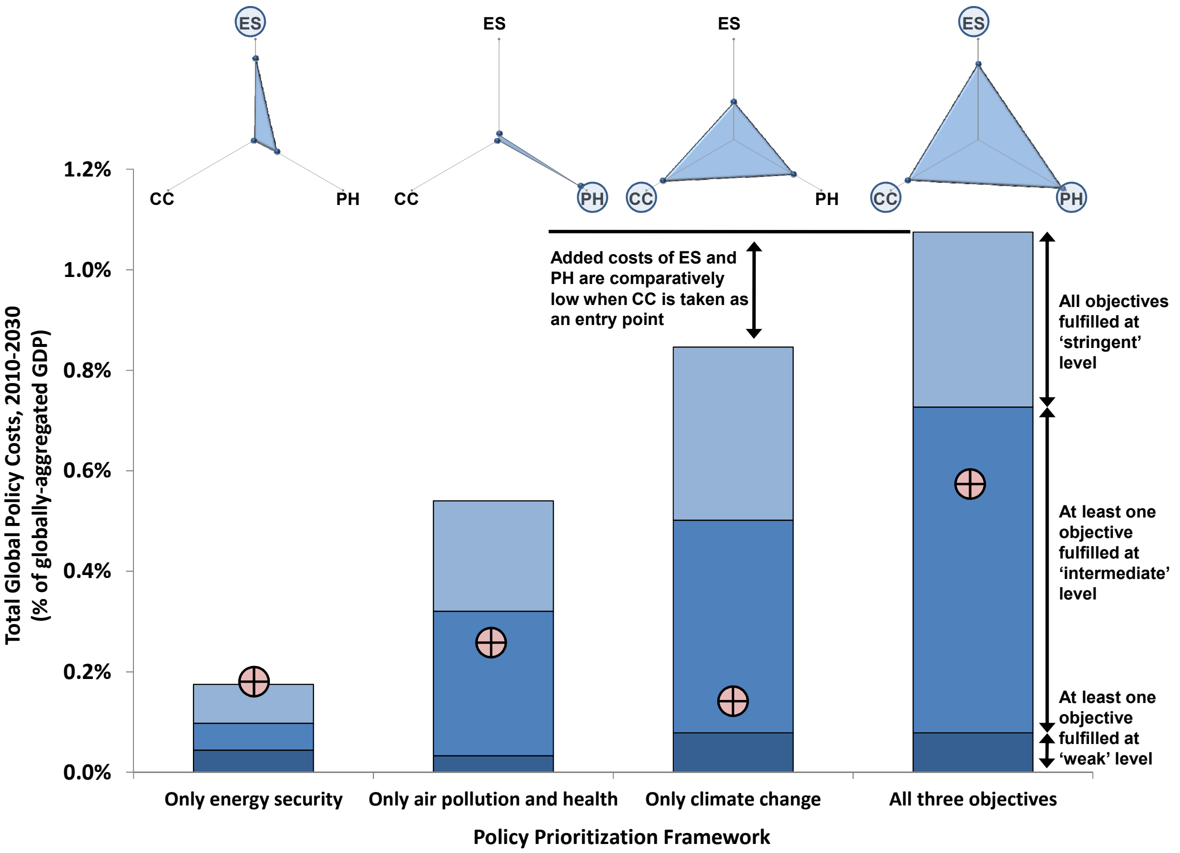
The last decades have seen the world's freshwater resources come under increasing pressure from humanity. Almost three billion people live in water-scarce regions (Molden, 2007), some two billion in areas of severe water stress (demand accounting for >40% of total availability) (PBL, 2012). Water withdrawals for energy and industrial processes (currently 20% globally) and municipal applications (10%) are likely to grow considerably over the next decades, jointly surpassing irrigation (70%) as the primary water user by mid-century (Alcamo and Henrichs, 2002; Shiklomanov and Rodda, 2003; Molden, 2007; Fischer et al., 2007; Shen et al., 2008; Bruinsma, 2011). Increasing demands will only exacerbate the current water problem, given that growth is likely to be greatest in areas already under high stress, such as South Asia. Climate change is expected to affect water supplies in important ways: impacts could be either positive or negative depending on the location (Hanasaki et al.; Hejazi, Edmonds, Clarke, Kyle, Davies, Chaturvedi, Wise, et al., submitted; Silberstein et al., 2012).

Climate change mitigation will have a mixed effect on the future pace of water demand growth. On one hand, the replacement of fossil-fueled power plants, oil refineries, petro-chemical facilities, and factories with certain renewably-powered alternatives (e.g., solar PV and wind power) will reduce freshwater withdrawals for thermal cooling – an important co-benefit (see Table 6.5). On the other hand, there are forms of renewable energy (e.g., hydropower, solar CSP, and especially bioenergy) that could demand a significant amount of water – an important risk trade-off. For bioenergy in particular, the overall effect will depend entirely on implementation practices: which feedstocks are grown, where, and do they require irrigation. Similarly, reforestation/afforestation efforts and attempts to avoid deforestation will impact both water use and water quality, as these measures would lead to changes in land-cover. Net effects could be either positive (Townsend et al., 2012) or negative (Jackson et al., 2005), depending on the local situation.

When accounting for the system dynamics and relative economics between alternative mitigation options (both in space and time), a set of transformational scenario pathways by PBL (2012) indicates that stringent climate mitigation actions, combined with heightened water-use efficiency measures, could potentially contribute to a 25% reduction in total global water demand by 2050, relative to a baseline scenario. This translates to an 8% decline in the number of people living in severely water-stressed regions worldwide (from 3.7 to 3.4 billion in 2050). Hanasaki et al. (in review) and Hejazi et al. (submitted) find the co-benefits from climate mitigation to be of roughly the same magnitude: reductions of 1–4% and 3–5%, respectively, in 2050. Notably, scenario results from Hejazi et al. (submitted) indicate that water scarcity problems could actually be made worse if climate policies fail to include emissions from land use change, as such policies could lead to more intensive production of bio-energy crops.

6.6.2.6 Integrated studies of multiple objectives

Capturing the myriad interactions and linkages between society's varied priorities for sustainable development demands integrated approaches and analysis frameworks. Recent scenario exercises that have looked at multiple objectives in parallel include Bollen et al. (2010), the Global Energy Assessment (McCollum et al., 2011; GEA, 2012; See McCollum, Krey, et al., 2013), PBL (2012), and the Low-Carbon Society pathways (See e.g. Skea and Nishioka, 2008; Shukla and Dhar, 2011b). The former two studies are unique in that they attempt to quantify key interactions in economic terms. Bollen et al. (2010), for instance, develops a set of scenarios using a social welfare optimization approach to assess the costs and benefits of climate, air pollution, and energy security policies, either singularly-focused or in combination. The Global Energy Assessment (McCollum, Krey, et al., 2013) focuses on the same subset of objectives but instead uses normative policy targets and a large ensemble of scenarios to determine ranges of costs for policy packages of varying stringency and form (i.e. a cost-effectiveness approach). The unifying element of these two studies is that they both highlight the advantages of taking an integrated approach to policy, particularly because of the near-term gains that can be realized (for a discussion of the associated increase of incentives for global climate agreements, see Nemet et al., 2010). In other words, owing to synergistic effects, policy goals can be achieved more cost-effectively if the objectives are integrated and pursued simultaneously rather than pursuing them in isolation. This is shown in Figure 6.32, wherein the sum of the three leftmost bars (single-minded policy approaches) is much greater than the rightmost bar (integrated policy approach). As many of these synergies come about through energy efficiency and decarbonization (i.e., reduction of energy and carbon intensity and activity change) climate policy may be seen as a strategic entry point for reaping these benefits. For example, requirements for end-of-pipe pollution control equipment are reduced, as are those for imported fossil fuels. That said, an important conclusion from the comparison of Bollen et al. (2010) and McCollum et al. (2013b) is that such co-benefits will only be realized from efforts to mitigate climate change that are on the more stringent end of the spectrum (e.g., Category 0-1 scenarios); moderate or weak action is simply not enough. Moreover, the co-benefits of stringent climate policies will be much less pronounced if future policies for air pollution and energy security are more aggressive than currently planned.



Fulfillment	**Climate change mitigation (CC)** [climate stabilization categories]	**Air pollution and health** [%-reduction in global health impacts from baseline, 2030]	**Energy security** [global primary energy trade (EJ/yr), 2030]
Stringent	**0 – 1**	**>80%**	**<120**
Intermediate	**2 – 3 – 4**	**25% – 80%**	**120 – 140**
Weak	**5 – 6**	**<25%**	**>140**

Figure 6.32: Costs of achieving societal objectives for energy sustainability under different policy prioritization frameworks. For McCollum et al. (2011) [colored bars], policy costs are derived from an ensemble of more than 600 scenarios and represent the net financial requirements (cumulative discounted energy-system and pollution-control investments, variable costs, and operations and maintenance costs) over and above baseline energy-system development, which itself is estimated at 2.1% of globally-aggregated GDP. For Bollen et al. (2010) [pink circles], policy costs are derived from a set of four distinct scenarios and are calculated as GDP losses (cumulative discounted) relative to a no-policy baseline. Triangular schematics summarize the performance of scenarios that achieve 'stringent' fulfillment only for the objective(s) targeted under the corresponding policy frameworks (axis values normalized from 0 to 1 based on the full range of scenario ensemble outcomes). Sources: GEA (2012), McCollum et al. (2011), Bollen et al. (2010).

Another class of sustainable development scenarios that has received increased attention since AR4 are the Low-Carbon Society (LCS) pathways (Kainuma et al., 2012). In contrast to conventional low-carbon scenarios, which tend to rely on carbon pricing to achieve system-wide transformations, LCS pathways typically assume policies and measures that facilitate life-style changes, green manufacturing processes, and investments into energy-efficient devices, 3R measures, and other targeted technologies (Shukla and Chaturvedi, 2012). An additional distinguishing feature of LCS studies is that their framing and modeling delineate policy roadmaps which simultaneously deliver lower emissions and yield various development and adaptation co-benefits (Shukla et al., 2008).

These co-benefits are neither automatic nor assured, but result from conscious and carefully coordinated policies and implementation strategies. Particular attention is paid to local conditions and short-term needs and objectives (Kainuma et al., 2012). In fact, LCS roadmaps are often developed using back-casting methods that aim to achieve pre-specified targets – not only for climate change – and that consider diverse stakeholder input (Shukla and Chaturvedi, 2012). Similar to other integrated scenario analyses like GEA (McCollum, Bauer, et al., 2013b) and Bollen et al. (2010), which show that stringent climate mitigation policies can act as effective entry points for achieving other societal objectives, LCS assessments indicate that explicit inclusion of these co-benefits in the cost calculation results in a lower "social cost of carbon" (Shukla et al., 2008).

6.7 Risks of transformation pathways

Mitigation will be undertaken within the context of a broad set of societal priorities, existing societal structures, institutional frameworks, and physical infrastructures. The relationship between these broader characteristics of human societies and the particular implications of mitigation activities will be both complex and uncertain. Mitigation will also take place under uncertainty about the underlying physical processes that govern the climate. All of these indicate that there are a range of different risks associated with different transformation pathways. It is important to point out that these relationships need not be negative. In many cases, there may be positive relationships between mitigation and other aspects of human societies (see Section 6.6).

The various risks associated with transformation pathways can be grouped into several categories, and many of these are discussed elsewhere in this chapter. One set of risks is associated with the linkage of mitigation with other societal priorities, such as clean air or energy security, which might be positive or negative. These risks are discussed extensively under the heading of sustainability in Section 6.6 . Another set of risks is associated with the possibility that particular mitigation options might be taken off the table because of perceived negative side effects and the stabilization will prove more challenging that what might have been expected. These issues are discussed extensively in Section 6.3 as well as elsewhere in the chapter. The macroeconomic implications of mitigation cannot be understood with any degree of certainty today, for a wide range of reasons. This issue is discussed in Section 6.3.6 , and as pointed out there, it is important to emphasize that both the economic costs and the economic benefits of mitigation are uncertain. One of the most fundamental risks associated with mitigation is that any transformation pathway may not maintain temperatures below a particular threshold, such as 2°C or 1.5°C above preindustrial levels due to limits in our understanding of the relationship between emissions and concentrations and, more importantly, the relationship between GHG concentrations and atmospheric temperatures. This topic is discussed in Section 6.3.2 .

A broad risk that underpins all the transformation scenarios in this chapter is that every long-term pathway depends crucially not just on actions by today's decision makers, but also by future decision-makers and future generations. Indeed, mitigation must be framed within a sequential-decision making not just because it is good practice, but more fundamentally because decision makers today cannot make decisions for those in the future. A consistent risk is that future decision makers may not undertake the mitigation that is required to meet particular long-term goals. In this context, actions today must be seen as creating or limiting options to manage risk rather than leading to particular goals. This topic is discussed extensively in Section 6.3 and 6.4 through the exploration of both idealized scenarios but also those that undertake particular near-term strategies such as delays in mitigation or mitigation that is intended to extend current ambitions. This issue is particularly important in the context of current scenarios that lead to concentration goals such as 450 ppmv CO_2-e. Virtually all of these scenarios temporarily overshoot the long-term goal and then descend to it by centuries end through increasingly dramatic emissions reductions. When near-term action is not sufficiently limited, this goal can only be met through the use of CDR technologies such as BECCS, putting greater pressure on future decision-makers. While we can articulate these scenarios as being possible in a physical sense, they come with a very large risk that future decision makers will not deign to take on the ambitious action that would ultimately be required.

6.8 Integrating sector analyses and transformation scenarios

6.8.1 The sectoral composition of GHG emissions along transformation pathways

GHG's are emitted by multiple sectors of the economy (Figure 6.33). As noted in Section 6.3.1, energy sector emissions are the dominant source of GHG emissions in baseline scenarios, and they continue to grow over time relative to land-use change CO2 emissions and non-CO2 GHG emissions. Energy supply, and electricity generation in particular, is the largest single source of greenhouse gas emissions (left panel in Figure 6.34). However, if indirect emissions from electricity are allocated to end use sectors, the end-use sectors represent a substantially larger share of total emissions. Indirect emissions are larger than direct emissions in buildings and constitute an important share of industrial emissions.

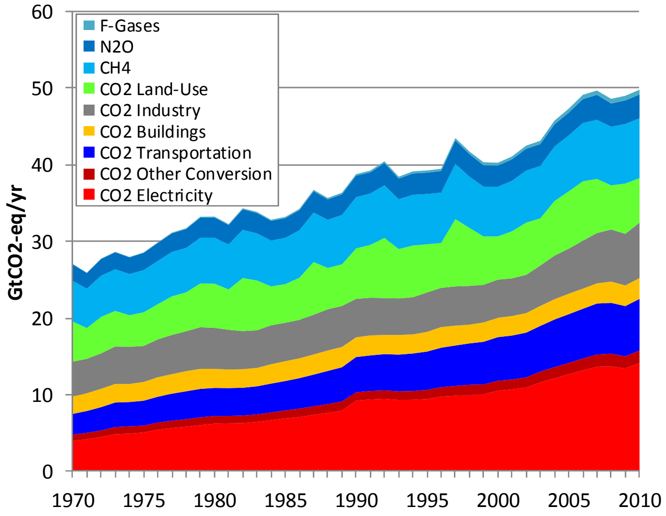


Figure 6.33. Direct CO_2 and CO_2-e emissions across sectors historically (IEA, 2012b; JRC/PBL, 2012)

In mitigation scenarios from integrated models, decarbonization of the electricity sector takes place at a pace more rapid than reduction of direct emissions in the energy end use sectors Figure 6.35. In 450 ppmv CO2-e scenarios, the electricity sector is largely decarbonized by 2050, whereas deep reductions in direct emissions in the end use sectors largely arise toward mid-century and beyond. More so than any other electricity technology, the availability of BECCS and its role as a primary CDR technology has a substantial effect on this dynamic, allowing for energy supply sectors to serve as a negative emissions source by mid-century.

Within the end use sectors, deep emissions in transportation are generally the last to emerge toward the end of the century because there may be fewer options to switch to low-carbon energy carriers in the transportation sector than in the buildings and industrial sectors. (This topic is discussed in more detail below.) In the majority of scenarios, deforestation is largely halted by mid-century, which is also a characteristic of baseline scenarios (see Section 6.3.1). Several scenarios focus on afforestation and reforestation, in which case the land use sector can become a carbon sink by mid-century (see section 6.3.5). In all cases, larger reductions in any single sector reduce the necessary reductions in other sectors and reduce the costs of mitigation.

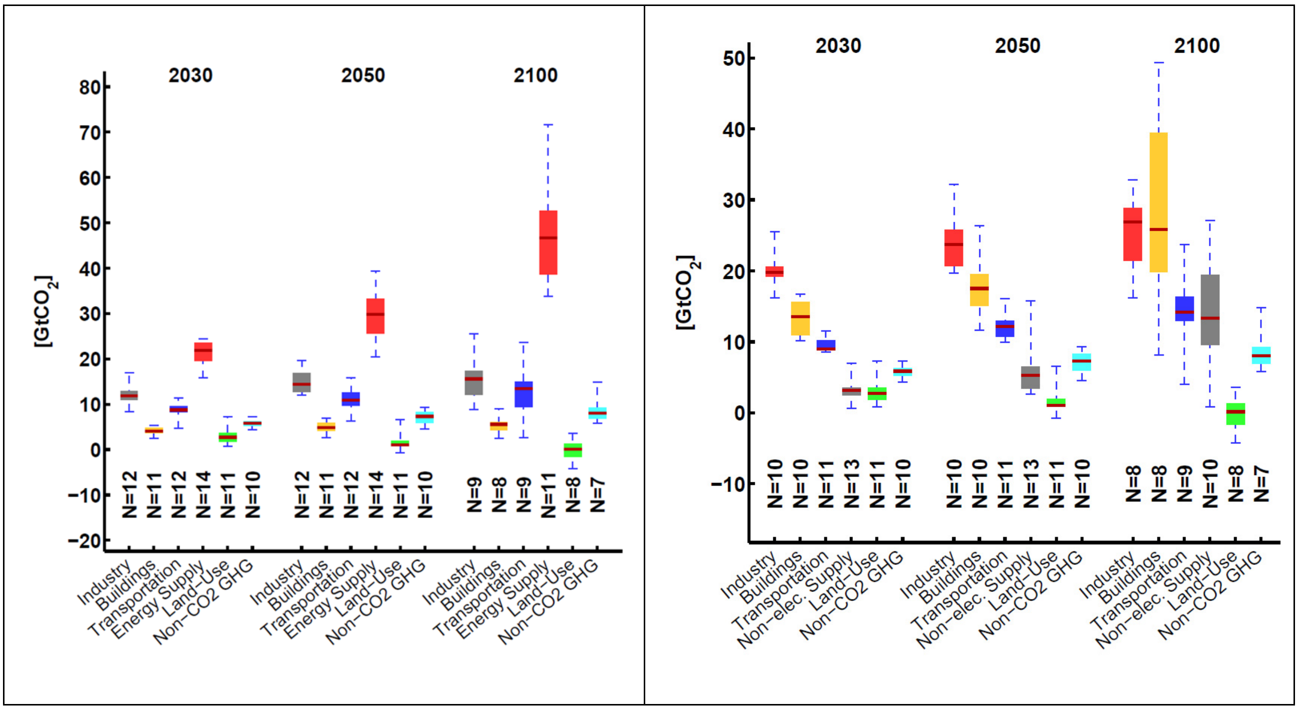


Figure 6.34. Direct emissions of GHGs (left panel) and total emissions of GHGs with electricity emissions allocated to end use sectors (right panel) across sectors in baseline scenarios. Results from the EMF 27 study.

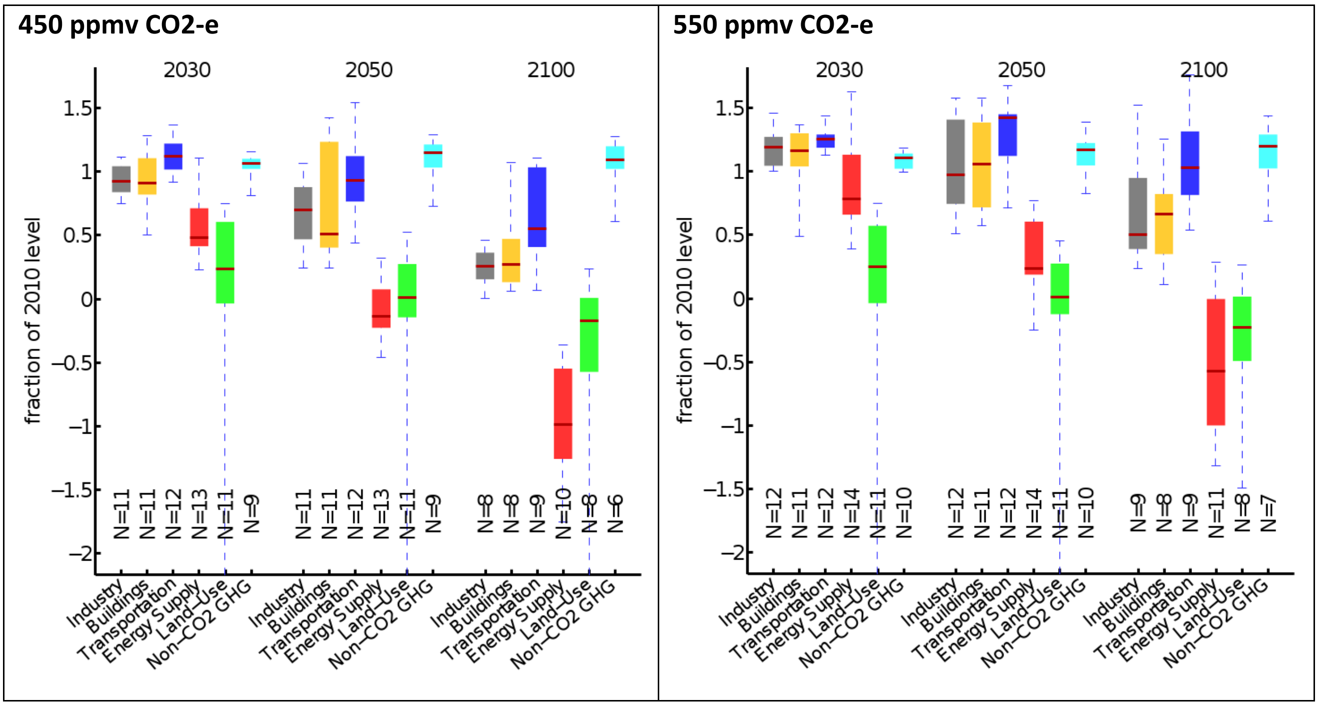


Figure 6.35. Direct CO$_2$ emissions across sectors. The thick black line corresponds to the median, the coloured box to the inter-quartile range (25th to 75th percentile) and the whiskers to the total range across all reviewed scenarios. The blue dashed lines refer to historical data as of 2009 (IEA, 2011a). Scenarios from preliminary AR5 scenario database.

Beyond these high-level characteristics of long-term transformation pathways lies a range of sector and cross-sectoral actions that could or should be undertaken in the near-term. The remainder of this section discusses a number of key strategic decisions for mitigation in the near-term, attempting to synthesize the available evidence from the integrated scenarios discussed in this chapter and the sectoral analyses in Chapter 7 through Chapter 12 and to identify gaps in one or either of these.

6.8.2 Decarbonizing energy supply

Virtually all transformation studies indicate that decarbonization of electricity is a critical element of mitigation strategy; however, there is no general consensus regarding the precise low-carbon technologies that might support this decarbonization. Both sectoral studies and integrated studies have presented a wide range of combinations of renewable energy sources, nuclear power, and CCS-based technologies as both viable and cost-effective. The breadth of different, potentially cost-effective strategies indicates that regional circumstances, including both regional resources and links to other regional priorities (e.g. national security, local air pollution, energy security), will be as important decision-making factors as economic costs. (See Chapter 7 for more discussion of electricity supply options.)

The one exception to this flexibility in electricity supply surrounds the use of BECCS for ambitious climate goals. CDR technologies such as BECCS are fundamental to many deep emissions scenarios, such as those meeting a 450 ppmv CO_2-e goal by the end of the century (see Section 6.3). Most integrated studies use BECCS as the sole proxy for CDR technologies. In this context, the use of BECCS allows the electricity sector to serve as a CO2 sink, reducing the pressure to reduce emissions in end use sectors, and allowing for a more gradual transition in these sectors (Note that electricity emissions can be negative in scenarios with BECCS in Figure 6.35). This lower pressure is often reflected through lower mitigation in transportation, as it is generally the sector with less mitigation possibilities and the use of BECCS provides competition for liquid fuels derived from bioenergy in transportation.

6.8.3 Energy demand reductions and fuel switching in end use sectors

A long-term strategy for carbon mitigation must ultimately focus on switching from emitting to non-emitting fuels if deep emissions reductions are to be achieved in end use sectors. Yet energy reduction is also an important lever for mitigation by reducing emissions from higher-carbon fuels and reducing the need to produce lower-carbon fuels. An important question is therefore the potential for both fuel switching and energy reductions and the relationship between the two.

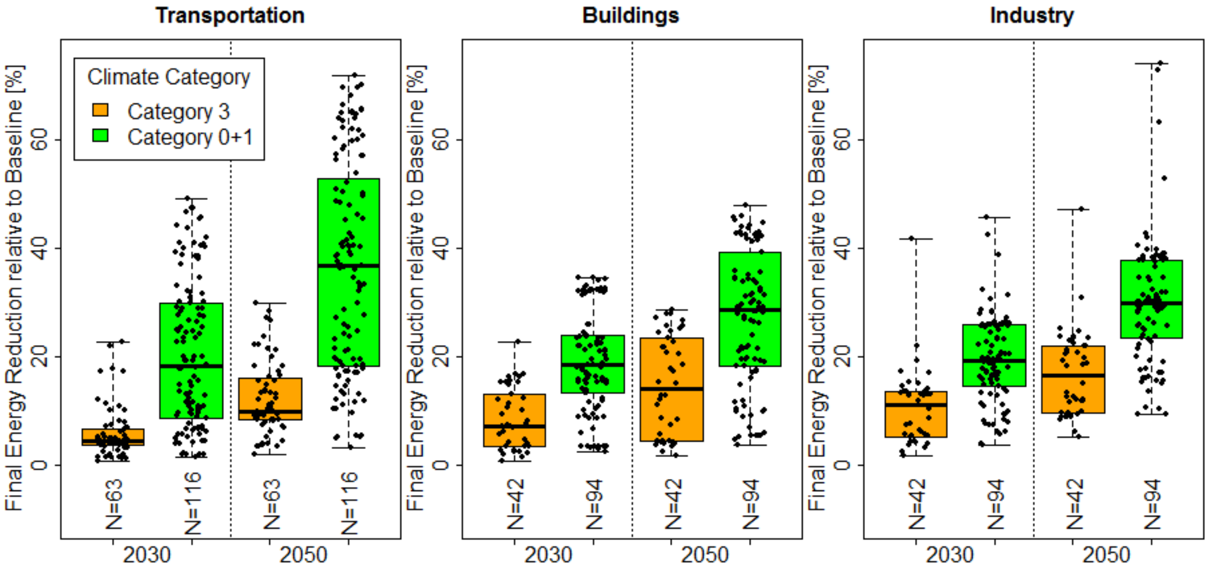


Figure 6.36. Total final energy reduction in the three end-use sectors (buildings, industry and transportation) by 2020, 2030 and 2050 in transformation scenarios from three different climate categories (see Section 6.2.2). The thick black line corresponds to the median, the coloured box to the inter-quartile range (25th to 75th percentile) and the whiskers to the total range across all reviewed scenarios. The blue dashed lines refer to historical data as of 2009 (IEA, 2011b). Scenarios from preliminary AR5 scenario database. [Authors: Final draft will include results from sectoral studies as well.]

In general, integrated models represent end use reduction options at a highly aggregated scale and achieve reductions from baseline emissions based exclusively on the imposition of a carbon price. These studies indicate reductions from baseline on the order of 20% to 40% of baseline energy by 2050 in 450 ppmv CO2 scenarios, with the largest reductions coming in the transportation sector. In contrast, sectoral studies explore options for reduction based on engineering or local details and do so based on cost-effectiveness calculations. Sectoral studies find greater end use reduction potential than do integrated modelling studies. For example, in the transportation sector, sectoral studies include a higher propensity for modal shifts, more compact cities, and greater behavioural changes. It is challenging to compare the potential for energy reductions across studies, because it is very difficult to discern the degree of mitigation that has occurred in the baseline itself in these studies. Therefore any comparisons must be considered approximate at best.

The options for substitution to low-carbon fuels in end uses sectors are bioenergy, electricity, or hydrogen. The potential approaches vary by sector. In general, both sectoral and integrated studies indicate that electricity can relatively easily be used to supply virtually every building energy demand over the long term. For this reason, there is general agreement that electricity can serve as the primary source of building energy, with the remaining fuel supplied by hydrogen or gas from bioenergy. Unlike buildings, there is no single perceived near or long-term configuration for transportation fuels. The majority of studies indicate a continued reliance on liquid and gaseous fuels, supported by an increase in the use of bioenergy up to 2050. However, many also include substantial shares of electricity through, for example, the use of electric vehicles for light-duty transportation, usually during the second-half of the century. And many studies still perceive hydrogen as a potential long-term solution should storage and production challenges be overcome. Similar to the transportation sector, here is no single perceived near or long-term configuration for industrial energy. Some studies indicate a move toward predominant use of electricity whereas others indicate a continued reliance on liquid or solid fuels, again, largely supported through bioenergy.

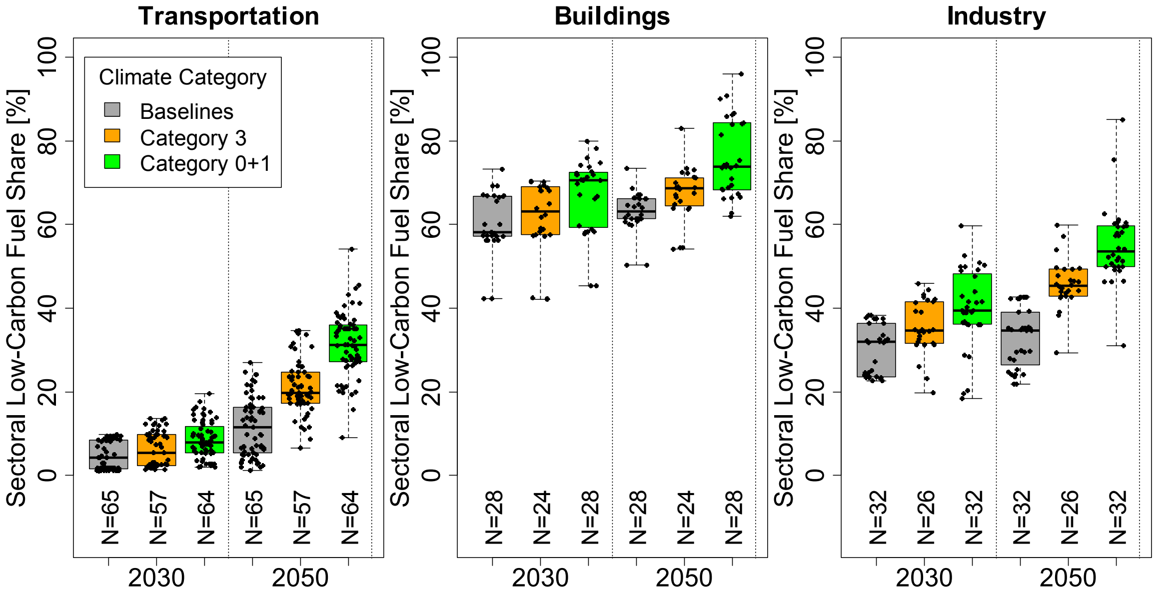


Figure 6.37. Development of final energy fuel shares in the residential and commercial sector, the industrial sector, and the transport sector in the Base, 550 and 450 AllTech cases over time. [EMF 27]

An important consideration is the relative timing and relationship between fuel switching and end use reductions in the end use sectors (comparison of Figure 6.36 and Figure 6.37). The comparison between integrated and sectoral studies is difficult in this regard, because few sectoral studies have attempted to look concurrently at both fuel switching and energy reduction strategies. Instead, the majority of sectoral studies have focused most heavily on energy reduction. To a large degree, this focus on energy reduction arises because sectoral studies are focused on near-term actions for mitigation, and, in the near-term, major fuel sources such as liquid fuels and electricity may have high carbon intensities. In the longer-term, however, these fuel sources will be largely decarbonized along transformation pathways, meaning that energy reductions will not so clearly lead to reductions in indirect emissions (note that this does not mean they do not continue to be important, because they decrease the need for low-carbon energy sources and the associated co-benefits and risks, see Section 6.6). This evolution can be clearly seen through the evolution of direct and indirect emissions over time in end use sectors (Figure 6.38). In 2010, the largest emissions from the buildings sector are the indirect emissions from electricity. This trend continues in baseline scenarios. However, in deep emission reduction scenarios, indirect emissions from electricity are largely eliminated by 2050, and in many scenarios, the electricity sector becomes a sink for CO2 through the use of BECCS. A similar trend can be seen in the industrial sectors. There are only minimal indirect emissions from electricity in the transport sector today and by 2050 in mitigation scenarios. Those scenarios that decarbonize the transportation sector through electrification do so on the backs of a largely decarbonized electricity sector.

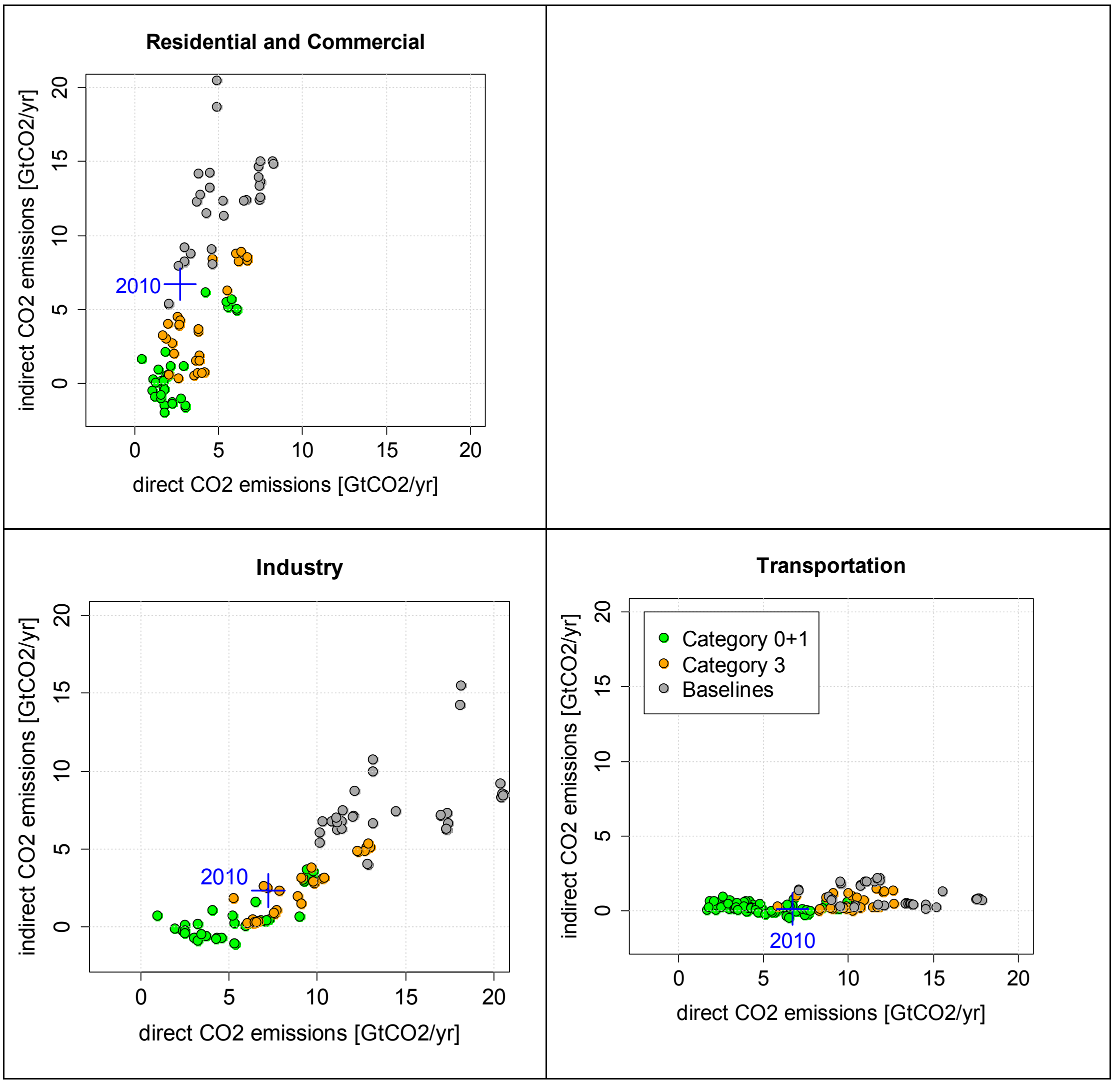


Figure 6.38. Direct and indirect emissions from electricity from end use sectors in 2050.

6.8.4 Options for bioenergy production and for reducing or reversing land use change emissions

As noted in Section 6.3.5 , land use change emissions are largely eliminated by mid-century in most baseline scenarios. And there are major differences in the nature of land use change emissions across mitigation scenarios, with some scenario envisioning a full incorporation of land use emissions into a global regime and large quantities of associated afforestation (Wise et el. 2009) and others envisioning various forest protection or other policies to constrain land use change emissions. The desire to store carbon in land competes with the need for bioenergy to decarbonize the energy system. Since AR4, integrated modelling studies have made significant headway in exploring these interactions, including both the potential for bioenergy and the potential for reducing or reversing land use change emissions, and they have sketched out a range of different potential approaches and land system configurations.

The role of sectoral studies has largely been to explore the nature of policy and social structures to support the sorts of broad changes in land use practices over time. Opportunities and concerns for sustainable development can be of institutional, social, economic, natural asset and health, and technology and infrastructure matters. Implications of transformation pathway scenarios depend to a large degree on how specific areas of land change. While more area remaining covered by natural forests could enhance biodiversity and a range of other ecosystem services, afforestation occurring through large scale plantations can impact biodiversity, water and other ecosystem services negatively. Implications of transformation pathway scenarios that require large land areas for dedicated biomass feedstocks are that food prices could increase if land normally used for food production is devoted to bioenergy. Implications of transformation pathway scenarios that rely heavily on reductions of non-CO_2 GHGs from agriculture depend on whether mitigation is achieved through reduced absolute emissions, or through reduced emissions per unit of agricultural product, and the role of large scale industrial agriculture (large areas of monoculture crops or intensive livestock production potentially damaging ecosystem services).

6.9 Carbon and radiation management and other geo-engineering options including environmental risks

In this section we discuss some of the techniques that can be used for CDR and SRM and the assessment of their effectiveness, costs and possible risks. Both techniques may have considerable implications for the assessment of mitigation strategies as discussed in Section 6.3.2 .

6.9.1 Carbon dioxide removal

A diverse set of methods might enable removal of CO_2 from the atmosphere. These methods vary greatly in their costs, risks to humans and the environment, the potential scalability, as well as in depth of research about their potential and risks. The divergence between techniques is so great that it is very difficult to draw meaningful conclusions about CDR as a whole. The spectrum of CDR techniques may usefully be divided into three categories according to the fate of the stored carbon: (a) ocean waters, (b) land biosphere, (c) geosphere (Stephens and Keith, 2008). It must be noted, however, that other taxonomies may be more relevant for risk assessment and regulatory policy such as the division between encapsulated industrial technologies such as BECCS and direct air capture on one hand and ecosystem manipulation technologies such as biochar and iron fertilization on the other.

The literature indicates that in pursuit of stringent CO_2 emissions reduction, particularly at late stages when much emissions reduction has already been accomplished, CDR could become competitive with further deployment of conventional mitigation, but that a strategy dominated by CDR carries associated environmental and societal risks (cf. Tavoni and Socolow,, 2012). (Note that throughout the chapter, reforestation and afforestation are treated separately from other CDR options such as ocean storage and geologic storage, so CDR refers only to these latter options.)

Ocean storage

It is possible to increase the flux of carbon from the atmosphere into the ocean, for example by deliberately manipulating biogeochemical cycling in the surface ocean. One approach that has received considerable attention in the scientific literature is the addition of iron to the ocean surface in regions in which biological productivity is limited by iron. This can potentially increase ocean surface productivity, which, in turn, potentially increases the export of carbon from the surface to the deep ocean. The net effect would be a decrease in atmospheric carbon dioxide concentrations.

Large-scale experiments in the open ocean have shown that the addition of iron can create short-term increases in biological productivity in the form of algal blooms (Boyd et al. 2007). However the extent of the fertilization effect is highly variable. Surface fertilization alone provides no long-term drawdown of atmospheric carbon dioxide, this requires an increase in the flux of carbon from the surface to the deep ocean. Experimental evidence for increases in the export flux is substantially weaker than evidence for the algal blooms themselves (Boyd et al., 2007).

The maximum achievable net flux (not counting the carbon that is sequestered by iron fertilization and then re-emitted later in the century) appears to be limited to ~0.8 GtC per year averaged over the first hundred years even if iron fertilization was applied in all iron limited regions (Sarmiento et al., 2009). Application of iron fertilization at this scale would entail a large-scale disruption to ecology of the ocean with a wide variety of potential benefits and impacts (cf. Oschlies et al., 2010).

The use of iron fertilization, or for that matter direct injection of CO_2 in the ocean, increases the carbon dioxide flux into the oceans. As a result, this increases the rate of oceanic acidification, though it may decrease surface acidification over the coming century. It is also possible to add alkalinity to the ocean, accelerating the weathering process that will ultimately remove anthropogenic CO_2 from the biosphere. These methods might counteract the acidification of the surface ocean and would provide a form of long-term carbon storage but they are less explored and more expensive (House et al., 2007).

Storage in the terrestrial biosphere

The means by which one might alter the carbon stock in the land biosphere are necessarily diverse as they correspond to the immense diversity of human land-use and of terrestrial ecology. The most prominent methods discussed in the literature include afforestation, alteration of forest management to increase carbon stocks, alteration of farming or grazing practices to increase stocks of soil carbon, and the incorporation of recalcitrant biomass soils either as lignin or as partially combusted biomass (biochar) (Shepherd et al., 2009; Woolf et al., 2010).

Geological storage.

Atmospheric carbon can be captured as pure carbon dioxide either by combusting biomass in a system that captures and purifies resulting CO_2 (BECCS) or by industrial systems that directly capture atmospheric CO_2, often called Direct Air Capture (DAC). In either case the resulting CO_2 could be put into deep underground storage using geological CCS for which the IPCC special report on CCS provides a comprehensive summary. The technology and cost of BECCS are similar to that for coal fired electric power with CCS. There are, however, possible negative impacts associated with the bio-energy production (see Annex to Ch.11 and (Wise et al., 2009b)).

Direct capture of CO_2 from ambient air has been demonstrated at industrial scale only as a pre-treatment for cryogenic air separation, but not as a stand-alone process. Consequently there are no reliable estimates of the cost and performance of DAC if industrial scale technologies were to be developed. The cost estimates using current technologies vary widely from 150$/tCO2 to 1000 $/tCO_2$ (House et al., 2011), with a central estimate on the order of \$600/tCO_2 (Socolow et al., 2011).

Only few papers have assessed the role of DAC in climate stabilization scenarios (Keith et al., 2006a; Pielke Jr, 2009; Nemet and Brandt, 2012; Chen and Tavoni, 2013). These studies generally show that the contribution of DAC can hinge critically on the stringency of the climate target, the costs relative to other mitigation technologies, and assumptions about scalability.

6.9.2 Solar radiation management

One key determinant of the role of SRM in climate policy is that it can act relatively quickly (Shepherd et al. 2009,Swart and Marinova 2010; Keith 2000, Matthews and Caldeira, 2007, Goes et al, 2011). The climate responds to changes in radiative forcing such as those induced by SRM on a timescale of order a decade or less, whereas the climate's response to gradual change in emissions has a longer (order century) timescale. SRM can temporarily and imperfectly mask some of the climate change that arises from the accumulation of long-lived greenhouse gases such as CO_2 (e.g. Bala et al., 2008; Ricke et al., 2010; Irvine et al., 2012). Emissions mitigation necessarily has a much slower impact on climate due to the inertia inherent in the carbon cycle and the economy. Mitigation cannot substantially reduce climate risks on timescales of a few decades. On multidecadal- to century- timescales the reduction in long-lived GHGs can reduce climate risks. Trade-offs between SRM and mitigation can hence have important temporal and intergenerational dimensions (Wigley, 2006; Matthews and Caldeira, 2007; Goes et al., 2011). It is therefore a misconception to think of a simple one-time trade-off between SRM and mitigation.

Scientific understanding and public understanding of SRM is growing rapidly (Shepherd et al., 2009; Mercer et al., 2011). The basic understanding that SRM might be used as a tool to reduce the impacts of anthropogenic climate change dates back to the 1960s (Keith, 2000), but very little scientific research was done until the last half-decade. A crude measure of the rapid growth of knowledge is that the rate of papers related to (and citations to these papers) "geoengineering" has increased by about a factor of 10 in the 5 years ending in 2011 (Mercer et al., 2011). There are now several government-sponsored research programs related to SRM as well as a formal project to systematically compare climate model responses to SRM (Kravitz et al., 2011). As a consequence of this rapid growth in the available literature, any attempt a synthesis will necessarily be incomplete and rapidly outdated.

The effectiveness of SRM in counteracting anthropogenic climate change is inherently limited by the fact that the radiative forcing produced by plausible SRM techniques is substantially different from the radiative forcing from GHGs (Govindasamy and Caldeira, 2000; Robock et al., 2008). It is therefore impossible for SRM to produce a climate response that perfectly compensates for the climate response due to GHG's. Thus while a level of SRM can, in principle, be selected so as to compensate for the effect of GHG's on a single climate variable, such as the globally averaged surface temperature, it cannot do so on all variables at once. For example, if SRM is employed to halt the increase in globally averaged surface temperature over some period during which GHG concentrations rise, then the global hydrological cycle as measured by average evaporation and precipitation rates will decrease. Conversely, if SRM is employed to minimize the acceleration of the global hydrological cycle as the climate warms, then the global mean temperatures are still increasing.

Similarly, a strategy to reduce the change in global mean sea-level can introduce sizeable rates of change in global mean temperature (Irvine et al., 2012) (Irvine et al, 2012). The economic analysis of the role of SRM in the context of climate change policies has produced mixed results (Klepper and Rickels, 2012). SRM appears to be less costly than traditional mitigation options (Barrett, 2008), but whether it is a substitute or a complement to mitigation ultimately depends on the risks associated with its deployment compared to those created by climate change (Goes et al., 2011; Moreno-Cruz and Keith, 2012).

Only a few studies have quantitatively evaluated the extent to which SRM can compensate for some subset of measures of anthropogenic climate change on a regional basis and these studies are often silent on key issues (e.g., the effects of uncertainties). In addition, the results hinge on the assumed SRM strategy. Early studies suggested that SRM may do a poor job at reducing climate impacts, (Robock et al., 2008). Later studies show that (a) SRM cannot accurately reverse GHG driven climate change (discussed in more detail below) and that (b) the divergence can be larger at regional scales compared to the global means basis (Ricke et al., 2010). One study examining the effectiveness of SRM in compensating for temperature or precipitation changes on a regional basis shows that SRM could compensate for the effects of increased GHG on temperature and precipitation patterns reasonably well, even at a regional level. A single (in a mathematical sense optimal given the model assumptions) choice of SRM forcing was able to reduce the population-weighted mean squared deviation in temperature by 99% and in precipitation by 85%. However, both objectives could not be achieved simultaneously (Moreno-Cruz et al., 2012).

Most studies to date have focused on climate variables such as temperature and precipitation, with a few exemptions analyzing metrics such as sea-level rise (e.g. Moore et al., 2010; Irvine et al., 2012). Expanding the analysis to other relevant quantities (e.g., crop productivity or biodiversity) is a key step towards an improved understanding of the effectiveness—or lack thereof—of SRM in reducing climate risks (cf. Robock et al., 2008; Pongratz et al., 2012).

It is useful to distinguish the specific risks that arise as side-effects of generating radiative forcing from the questions discussed above arising from the inability to produce a radiative forcing that precisely counteracts the radiative forcing from GHGs. These risks are strongly dependent on the particular method of SRM employed to generate the radiative forcing. Ozone depletion from the introduction of geoengineering aerosol into the stratosphere is arguably one of the best studied risks. For sulphate aerosols the primary mechanism of action is that additional aerosol reduces NOx concentrations which in turn shifts chlorine from inactive reservoir species to ClO, the species most active in chlorine mediated ozone destruction (Tilmes et al., 2009). The impact of SRM aerosols is mediated by the anthropogenic chlorine loading in the stratosphere, and chlorine loading is decreasing following implementation of the Montréal protocol and related treaties. As a result, the impact of SRM aerosols on chlorine depends on assumptions about the implementation of aerosol SRM. The study of Tilmes et al. (2009) assumes that SRM is implemented to offset most anthropogenic climate change by the decade 2040-2050. This analysis shows that under these conditions ozone loss relative to a “no geoengineering” case would be as much as 10% at polar latitudes with much smaller losses or small gains in mid-latitudes (Tilmes et al., 2009). With geoengineering the resulting ozone concentration would still be significantly higher than current concentrations due to the decline in stratospheric chlorine loading. Overall the study found that large-scale use of geoengineering would delay recovery of the ozone hole by roughly 3 decades (Tilmes et al., 2009).

6.10 Gaps in knowledge and data

The questions that motivate this chapter all address the broad characteristics of possible long-term transformation pathways toward stabilization of greenhouse gas concentrations. The discussion has not focused on today’s global or country-specific technology strategies, policy strategies, or other elements of a near-term strategy. It is therefore within this long-term strategic context that gaps in knowledge and data should be viewed. Throughout this chapter, a number of areas of further development have been highlighted. Several areas would be most valuable to further the development of information and insights regarding long-term transformation pathways.

These include the following: more scenarios pursuing temperature stabilization rather than concentration goals, because temperature stabilization pathways may have a different emissions profile than concentration stabilization scenarios; more scenarios that include feedbacks from a changing climate, including those on energy and land use systems critical for mitigation; expanded treatment of the benefits and risks of SRM options; expanded treatment of co-benefits and risk trade-offs of mitigation pathways, including their embedding in a wider sustainable development context; improvements in the treatment and understanding of mitigation options in end use sectors in scenarios; and more sophisticated treatments of land use and land used based mitigation options in scenarios. In addition, a major weakness of the current integrated modeling suite is that regional definitions are often not comparable across models. An important area of advancement would be to develop some clearly defined regional definitions that can be met by most or all models.

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