INTERGOVERNMENTAL PANEL ON climate change
Working Group III – Mitigation of Climate Change

Chapter 6

Assessing Transformation Pathways

Chapter:	6	
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Executive Summary

Stabilizing greenhouse gas concentrations will 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" towards stabilization; that is, how do we get from here to there? The topic of this chapter is transformation pathways. The chapter is primarily 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 and sectors contributing to mitigation, the nature of international coordination, and mitigation policies? Second, what are the key characteristics of different transformation pathways, including the rates of emissions reductions and deployment of low-carbon energy, the magnitude and timing of aggregate economic costs, and the implications for other policy objectives such as those generally associated with sustainable development? Third, how will actions taken today influence the options that might be available in the future? As part of the assessment in this chapter, data from over 1000 new scenarios published since AR4 were collected from integrated modelling research groups, many from large-scale model intercomparison studies. In comparison to AR4, new scenarios, both in this AR5 dataset and more broadly in the literature assessed in this chapter, consider more ambitious concentration goals, a wider range of assumptions about technology, and more possibilities for delays in global mitigation and fragmented international action.

Atmospheric concentrations in baseline scenarios collected for this assessment (scenarios without additional efforts to constrain emissions) all exceed 450 ppm CO2-e by 2030 and lie above the RCP 6.0 concentration pathway in 2100 (770 ppm CO2-e in 2100); the majority lie below the RCP 8.5 concentration pathway in 2100 (1330 ppm CO2-e in 2100) *(high confidence)***.** The scenario literature does not systematically explore the full range of uncertainty surrounding development pathways and possible evolution of key drivers such as population, technology, and resources. However, the baseline scenarios do nonetheless strongly suggest that absent explicit efforts at mitigation, cumulative CO2 emissions since 2010 will exceed 700 GtCO2 by 2030, 1,500 GtCO2 by 2050, and potentially well over4,000 GtCO2 by 2100.

Scenarios can be distinguished by the long-term concentration level they reach by 2100; however, the degree to which concentrations exceed (overshoot) this level before 2100 is also important *(high confidence)***.** The large majority of scenarios produced in the literature that reach roughly 450 ppm CO2-e by 2100 are characterized by concentration overshoot facilitated by the deployment of carbon dioxide removal (CDR) technologies. Many scenarios have been constructed to reach roughly 550 ppm CO2-e by 2100 without overshoot. Scenarios with more overshoot exhibit less mitigation today, but they often rest on the assumption that future decision-makers deploy CDR technologies at large scale. An assessment in this chapter of geo-physical climate uncertainties consistent with the dynamics of Earth System Models assessed in WGI found that the likelihood of exceeding temperature goals this century increases with peak concentration levels, which are higher in overshoot scenarios.

All major-emitting regions make substantial reductions from their baseline CO2-e emissions over the century in scenarios that bring GHG concentrations to 550 ppm CO2-e or below by 2100 (*high confidence*). In most scenarios collected for this assessment that reach concentrations between 530 and 580 ppm CO2-e by 2100, global CO2-e emissions are reduced by more than 50%, and in some cases by more than 100%, by the end of the century relative to 2010 levels. CO2-e Emissions are brought to zero or below by 2100 in the majority of the scenarios reaching concentrations between 430 and 480 ppm CO2-e by 2100. In large part because baseline emissions from the non-OECD countries are projected to outstrip those from the OECD countries, the total CO2-e reductions from baseline occurring in the non-OECD countries are larger than in the OECD countries, particularly in scenarios that cost-effectively allocate emissions reductions across countries. Emissions peak earlier in the OECD countries than in the non-OECD countries in these cost-effective scenarios.

Bringing concentrations to 550 ppm CO2-e or below by 2100 will require large-scale changes to global and national energy systems, and potentially the use of land; these changes are inconsistent with both long- and short-term trends (*high confidence*)**.** Accelerated electrification of energy end use, coupled with decarbonization of the majority of electricity generation by 2050 and an associated phase out of freely-emitting coal generation, is a common feature of scenarios reaching roughly 550 ppm C02-e or less by 2100. Scenarios suggest that applications currently using liquid fuel are more costly to decarbonize than electricity and may be the last sectors to be decarbonized for deep CO2 emissions reductions (*high confidence*). Scenarios articulate very different changes in the land surface, reflecting different assumptions about land use costs, the potential of large-scale bioenergy production, and the potential for afforestation and reduced deforestation. Studies indicate a large potential for energy use reductions, but also demonstrate that these reductions will not be sufficient to constrain GHG emissions.

Estimates of the aggregate economic costs of mitigation vary widely, but increase with stringency of mitigation *(high confidence).* Most scenario studies collected for this assessment that are based on the idealized assumptions that all countries of the world begin mitigation immediately, there is a single global carbon price applied to well-functioning markets, and key technologies are available, estimate that reaching 430-480 ppm CO2-e by 2100 would entail global consumption losses of 1% to 4% in 2030, 2% to 6% in 2050, and 2% to 12% in 2100 relative to what would happen without mitigation. To put these losses in context, studies assume increases in consumption from four-fold to over ten-fold over the century without mitigation. Costs for maintaining concentrations at around 550 ppm CO_2-e are estimated to be roughly 1/3 to 2/3 lower. Substantially higher and lower cost estimates have been obtained based on assumptions about less idealized policy implementations, interactions with pre-existing distortions, non-climate market failures, or complementary policies. (Limits on technology and delayed mitigation are discussed below.)

Effort-sharing frameworks could help address distributional issues and decouple regional mitigation investments from financial burdens, but would be associated with significant international financial transfers (*medium confidence*)**.** Without transfers across regions, cost-effectively allocating emissions across countries would yield an uneven distribution of mitigation costs. Scenarios indicate this would lead to higher relative costs in developing economies as well as to many fuel exporters. Studies estimate that the financial transfers to ameliorate this asymmetry could be on the order of hundred billions of USD per year before mid-century to bring concentrations to roughly 450 ppm CO2-e in 2100.

Emissions through 2030 will have strong implications for the challenges of, and options for, bringing concentrations to between 430 and 530 ppm CO2-e by the end of the century *(high confidence)*. The vast majority of cost-effective scenarios leading to 2100 concentrations between 430 ppm CO2-e and 530 ppm CO2-e are characterized by 2030 emissions roughly between 30 GtCO2-e and 50 GtCO2-e. Scenarios with emissions above 55 GtCO2-e in 2030 are predominantly driven by delays in mitigation. These scenarios are characterized by substantially higher rates of emissions reductions from 2030 to 2050, a larger reliance on carbon dioxide removal (CDR) technologies in the long term, and higher transitional and long term economic impacts. Due to these challenges, many models with 2030 emissions in this range could not produce scenarios reaching 430 to 480 ppm CO2-e in 2100. Studies confirm that delaying mitigation through 2030 has substantially larger influence on the subsequent challenges of mitigation than do delays through 2020.

The availability of key technologies and improvements in the cost and performance of these technologies will have important implications for the challenge of achieving concentration goals *(high confidence)***.** Many models in recent multi-model comparisons could not produce scenarios reaching approximately 450 ppm CO2-e by 2100 with broadly pessimistic assumptions about key mitigation technologies. Large-scale deployment of CDR technologies in particular is relied upon in many of these scenarios in the second-half of the century. For those models that could produce such scenarios, pessimistic assumptions about important technologies for decarbonising non-electric energy supply increased discounted global mitigation costs of reaching roughly 450 ppm and 550 ppm CO2-e by the end of the century significantly, with the effect being larger for more stringent goals. The studies also showed that reducing energy demand can potentially decrease mitigation costs significantly.

Mitigation efforts will influence the costs of meeting other societal objectives. Recent studies indicate that climate policies significantly reduce the costs of reaching energy security and/or air quality objectives *(medium evidence, high agreement)*. The associated economic implications for these objectives are not taken into account in most scenario studies. Sectoral studies suggests that the number of co-benefits for energy end use mitigation measures outweighs the number of the adverse side-effects, whereas the evidence suggests this is not the case for all supply side measures *(medium evidence, high agreement)*. The overall welfare implications associated with these additional objectives have not been assessed thoroughly in the literature.

There is only limited evidence on the potential of geoengineering by CDR or solar radiation management (SRM) to counteract climate change, and all techniques carry risks and uncertainties *(high confidence)***.** A range of different SRM and CDR techniques have been proposed, but no currently existing technique could fully replace mitigation or adaptation efforts. Nevertheless, many low greenhouse gas concentration scenarios rely on two CDR techniques, afforestation and biomass energy with carbon capture and storage (BECCS), which some studies consider to be comparable with conventional mitigation methods. SRM could reduce global mean temperatures, but with uneven regional effects, for example on temperature and precipitation, and it would not address all of the impacts of increased CO2 concentrations, such as ocean acidification. Techniques requiring large-scale interventions in the Earth system, such as ocean fertilization or stratospheric aerosol injections, carry significant risks. Although proposed geoengineering techniques differ substantially from each other, all raise complex questions about costs, risks, governance, and ethical implications of research and potential implementation.

Despite the advances in our understanding of transformation pathways since AR4, many avenues of inquiry remain unanswered. Important future research directions include the following: development of a broader set of socioeconomic and technological storylines to support development of scenarios; scenarios explicitly pursuing a wider set of climate goals including those related to temperature change; more mitigation scenarios that include impacts from, and adaptations to, a changing climate, including energy and land use systems critical for mitigation; expanded treatment of the benefits and risks of CDR and SRM options; expanded treatment of co-benefits and risk trade-offs of mitigation pathways; improvements in the treatment and understanding of mitigation options and responses in end use sectors in transformation pathways; and more sophisticated treatments of land use and land used based mitigation options in mitigation scenarios .

6.1 Introduction

6.1.1 Framing and Evaluating Transformation Pathways

Stabilizing greenhouse gas concentrations at any level will require deep reductions in greenhouse gas emissions. Net global 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 primarily 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 and sectors contributing to 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 international distribution of economic costs and the implications for other policy objectives such as those associated with sustainable development? Third, how will actions taken today influence the options that might be available in the future?

Two concepts 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 emissions pathway 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 policy objectives such as sustainable development.

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

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 to a large enough degree and carbon dioxide removal (CDR) options are not available (see Section 6.9), a goal of reaching 450 ppm CO2-e by the end of the century can be physically impossible. 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 economic implications, 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 objectives. A primary goal of this chapter is illuminate these characteristics of transformation pathways.

6.1.2 New transformation scenarios since AR4

Since AR4, the integrated modelling community has produced a range of new transformation pathway scenarios. Major advances include an increase in the number of scenarios exploring the following: low concentration goals such as 450 ppm CO_2-e; overshoot emissions trajectories with and without CDR technologies; a variety of international mitigation policy configurations including fragmented action and delays in 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 policy objectives, an increasingly sophisticated treatment of the role of land use in mitigation, and scenarios exploring non-market approaches to mitigation. Two particularly important categories for the discussion in this chapter are non-idealized international implementation scenarios 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 idealized assumption that mitigation is undertaken where and when it is least expensive. Such “idealized implementation” scenarios assume the imposition of a global price on carbon that reaches across countries, permeates all economic sectors within countries, and that rises over time in a way that will minimize discounted economic costs over a long-period of time, typically through 2100. These are often referred to as “cost-effective” scenarios, because they lead to the lowest aggregate global mitigation costs under idealized assumptions about the functioning of markets and economies (See Section 6.3.6). However, the reality of international strategies for mitigation is one of different countries taking on mitigation at different times and using different and independent implementation approaches. Responding to this reality, the research community has produced a large set of “non-idealized” international implementation scenarios for reaching long-term concentration goals. Often, but not always, non-idealized implementation is focused on the coming decades, with a transition toward idealized implementation in the long run. In addition to individual papers (for example, Richels et al., 2007; Edmonds et al., 2008), Luderer et al., 2013, ERL paper; Roegelj et al., 2012; van Vliet et al., 2012), there have been a number of multi-model projects exploring non-idealized implementation scenarios (Table 6.1). This chapter relies heavily on those multi-model studies.

Table 6.1: Multi-model studies exploring non-idealized international implementation

Multi-Model Study	**Description**
EMF 22 (Clarke et al., 2009a)	Delayed participation (fragmented action) scenarios in which OECD countries begin mitigation immediately; Brazil, Russia, India, and China begin after 2030; remaining countries begin after 2050. Scenarios meet various 2100 concentration goals, with and without overshooting the concentration goal.
EMF 27 ((Blanford et al., 2014), (Kriegler et al., 2014c))	Delayed and limited participation scenario with Annex I adopting 80% emissions reductions until 2050, non-Annex I adopting a global 50% emissions reduction by 2050 after 2020, and resource exporting countries not undertaking emissions reductions.
AMPERE ((Kriegler et al., 2014a) (Riahi et al., 2014)	Two studies: AMPERE WP2 focused on delayed action scenarios with the world following moderate action until 2030, and adopting long-term concentration goals thereafter. AMPERE WP3focused on delayed participation scenarios with EU27 or EU27 and China acting immediately and the remaining countries transitioning from moderate policies to a global carbon pricing regime (without mitigation goal) between 2030 and 2050..
LIMITS ((Kriegler et al., 2014b; Tavoni et al., 2014)	Delayed action scenarios with the world following two levels of moderate fragmented action through 2020 or 2030, and adopting two long-term concentration goals thereafter. Three different effort-sharing schemes are considered.
RoSE ((Luderer et al., 2013a)	Delayed action scenarios with the world following moderate fragmented action in the near term and adopting a long-term concentration goal after 2020 or 2030.

Note: The EMF27, AMPERE, LIMITS and ROSE studies also included scenarios of moderate fragmented action throughout the 21st century without the goal of meeting any specific long-term concentration.

There are a number of ways that scenarios may deviate from the idealized implementation, but two are most prominent in the new literature. One set of scenarios includes those in which near-term mitigation is inconsistent with – typically less than – what would be called for to minimize the discounted, century-long costs of meeting a long-term goal such as 450 ppm CO2-e by 2100. These scenarios are intended to capture the implications of “delayed action” or “delayed mitigation” or “constrained near-term ambition”. Mitigation is not undertaken “when” it would be least expensive. The other set of scenarios includes those in which the price on carbon is not consistent across countries. Some countries reduce emissions more aggressively than others, particularly in the near-term, so that mitigation is not undertaken “where” it is least expensive. These scenarios are intended to capture the implications of “fragmented action” or “delayed participation”. Non-idealized international implementation scenarios may include one or both of these deviations.

6.1.2.2 Limited Technology Scenarios

Scenario research prior to AR4 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 meeting concentration goals such as 450 ppm CO2-e by 2100. This includes EMF 27 (Krey et al., 2014; Kriegler et al., 2014c), ADAM (Edenhofer et al., 2010), RECIPE (Luderer et al., 2011; Tavoni et al., 2012), and AMPERE (Riahi et al., 2014).. In many cases, these studies have simply assumed that particular technologies, such as CCS or nuclear power, may not be available. In others, studies 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 end use improvements. In addition, a number of individual research papers and reports have explored this space, typically constrained to a single model model (Kim et al., 2000; Richels et al., 2007; Calvin et al., 2009a; van Vliet et al., 2009; Krey and Riahi, 2009; Riahi et al., 2012a; Luderer G et al., 2013; Rogelj et al., 2013b). Many more individual studies were conducted prior to AR4.

6.2 Tools of analysis

6.2.1 Overview of integrated modeling tools

The long-term scenarios assessed in this chapter were generated primarily by large-scale, integrated models that can project key characteristics of transformation pathways to mid-century and beyond. These models represent many of the most relevant interactions among important human systems (e.g., energy, agriculture, the economic system), and often represent important physical processes associated with climate change (e.g., the carbon cycle). Other approaches to explore transformation pathways include qualitative scenario methods and highly-aggregated modeling tools, such as those used for cost-benefit analysis (see Box 6.1 on cost-benefit analysis). These other approaches provide a different level of quantitative information about transformation pathways than scenarios from large-scale integrated models.

All integrated models share some common traits. Most fundamentally, integrated models are simplified, stylized, numerical approaches to represent enormously complex physical and social systems. They take in a set of input assumptions and produce outputs such as energy system transitions, land use transitions, economic effects of mitigation, and emissions trajectories. Important input assumptions include population growth, baseline economic growth, resources, technological change, and the mitigation policy environment. The models do not structurally represent 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, the implications of these forces enter the model through assumptions about, for example, economic growth and resource supplies. The models use economics as the basis 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 the aggregate economic costs of achieving mitigation outcomes, unless they are specifically constrained to behave otherwise. In this sense, the scenarios tend towards normative, economics-focused descriptions of the future. The models typically assume fully-functioning markets and competitive market behavior, meaning that factors such as non-market transactions, information asymmetries, and market power influencing decisions are not effectively represented. Maintaining a long-term, integrated, and often global perspective involves tradeoffs in terms of the detail at which key processes can be represented in integrated models. Hence, the models do not generally represent the behaviour of certain important system dynamics, such as economic cycles or the operation of electric power systems important for the integration of solar and wind power, at the level of detail that would be afforded by analyses that the focus exclusively on those dynamics.

Beyond these and other similarities, integrated modeling approaches can be very different, and these differences can have important implications for the variation among scenarios that emerge from different models. The following paragraphs highlight a number of key differences in model structure. To provide insight into the implications these tradeoffs, potential implications for aggregate economic costs are provided as examples, when appropriate.

Economic coverage and interactions. Models differ 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 explore and understand ripple effects from, for example, the imposition of a mitigation policy, including impacts on overall economic growth. *Partial economy* models, on the other hand, take economic activity as an input that is unresponsive to policies or other changes such as those associated with improvements in technology. These models tend to focus more on detailed representations of key systems such as the energy system. All else equal, aggregate economic costs would tend to be higher in full-economy models than in partial-economy models because full-economy models include feedbacks to the entire economy. 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 aggregate economic 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 aggregate costs.

Representation of trade. Models differ in terms of how easy it is for goods to flow across regions. On one end of the spectrum are models assuming goods are homogeneous and traded easily at one world price (Heckscher-Ohlin) or that there is one global producer (quasi-trade). On the other end of the spectrum are 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). In general, greater flexibility to trade will result in lower aggregate mitigation costs because the global economy is more flexible to undertake mitigation where it is least expensive. More generally, many partial equilibrium 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. Model flexibility is not a single, explicit choice for model structure. Instead, it is the result of a range of choices that influence, for example, how easily capital can be reallocated across sectors including the allowance for premature retirement of capital stock, how easily the economy is able to substitute across energy technologies, and whether fossil fuel and renewable 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 and characterization of model flexibility is an area of current research (see Kriegler et al., 2013b). Greater flexibility will tend to lower mitigation costs.

Sectoral, regional, technology, and greenhouse gas detail. Models differ dramatically in terms of the detail at which they represent key sectors and systems. These differences influence not only the way that the models operate, but also the information they can provide about transformation pathways. Key choices include the number of regions, the degree of technological detail in each sector, which GHGs are represented and how, whether land use is explicitly represented**,** and the sophistication of the model of Earth system process such as the carbon cycle. Some models include only CO2 emissions, many do not treat land use change and associated emissions, and many do not have submodels of the carbon cycle necessary to calculate CO2 concentrations. In addition, although the scenarios in this chapter were generated from global models which allow for the implications of mitigation for international markets to be measured, regional models can provide finer detail on the implications for a specific region's economy and distributional effects. The effects of detail on aggregate mitigation costs are ambiguous

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, models with *endogenous technological change* (also known as *induced technological change*) allow for some portion of technological change to be influenced by deployment rates or investments in R&D. Models featuring endogenous technological change 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 number of models has increased and model functionality has significantly improved since AR4, allowing for a broader set of scenarios in the AR5 ensemble. The majority of these scenarios were produced as part of multi-model comparisons. 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 <insert URL of WG III AR5 Scenario Database> [The WG III AR5 Scenario Database will be published with the report.] A summary of the models and model inter-comparison exercises that generated the scenarios referenced in this chapter can be found in Annex II.10.

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 assessment of transformation pathways in this chapter. Indeed, many of the tables and figures represent ranges of results across models all of these dimensions.

There is an unavoidable ambiguity in interpreting ensemble results in the context of uncertainty. On the one hand, the scenarios assessed 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 a weighting of scenarios that can be difficult to interpret. 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 our lack of knowledge about key forces that might shape the future (Fischedick et al., 2011; Krey and Clarke, 2011). 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 given this ambiguity. However, wherever possible, scenario samples are chosen in such a way as to reduce bias, and these choices are made clear in the discussion and figure legends.

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” (see Section 6.1). 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, aggregate economic costs, financial transfers among regions, and links to other policy objectives such as energy security or energy prices. However, beyond cases where physical laws might be violated to achieve a particular scenario (for example, a 2100 carbon budget is exceeded prior to 2100 with no option for negative emissions), these integrated models cannot determine feasibility in an 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 concentration goals such as those associated with meeting 450 ppm CO2-e goals, 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. Frequently, however, instances of model infeasibility 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, and model improvements over time may result in feasible scenarios that previously were infeasible. Hence, although these model infeasibilities cannot generally be taken as an indicator of feasibility in an absolute sense, they are nonetheless valuable indicators of the challenge associated with achieving particular scenarios. For this reason, whenever possible this chapter highlights those situations where models were unable to produce scenarios.

Unfortunately, this type of result can be difficult to fully represent in an assessment, 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. Model infeasibilities 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).

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

6.3.1 Baseline scenarios

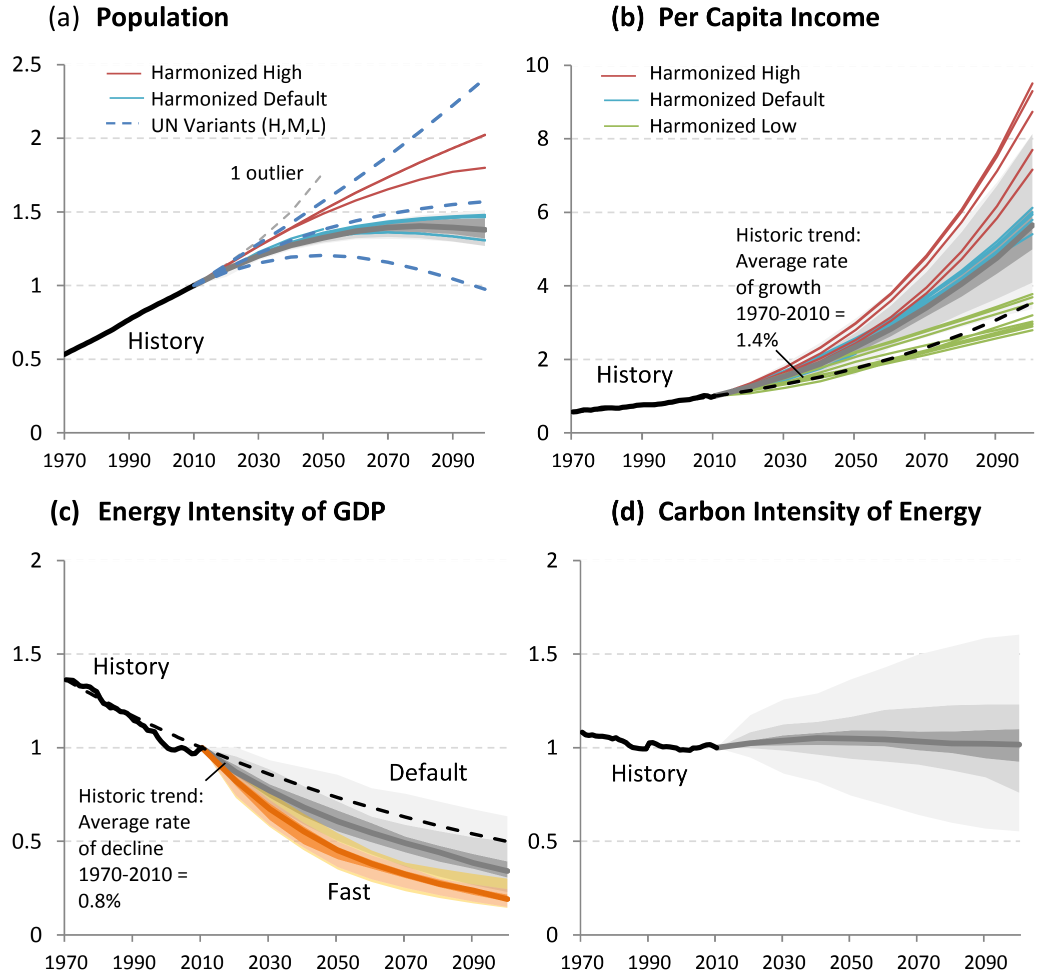
6.3.1.1 Introduction to baseline scenarios

Baseline scenarios are projections of greenhouse gas emissions and their key drivers 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 climate goal. Accordingly, the resulting estimates of mitigation effort and costs in a particular mitigation 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, and this remains an important research need for scenario development. As discussed in Section 6.2 , although the range of assumptions 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. An important distinction between scenarios in this regard is between those that are based on modelers' "default" assumptions and those that are harmonized across models within specific studies. The former can be considered a better, although still imperfect, representation of modelers' expectations about the future, while, as is discussed below, the latter consider specific alternative views that in some cases span a larger range of possible outcomes.

6.3.1.2 The drivers of baseline emissions of energy-related emissions

As discussed in Chapter 5, the drivers of the future evolution of energy-related emissions in the baseline can be summarized by the terms of the Kaya identity: population, per capita income, energy intensity of economic output, and carbon intensity of energy. At the global level, baseline projections from integrated models are typically characterized by modest population growth stabilizing by the end of the century, fast but decelerating growth in income, a decline in energy intensity, and modest changes in carbon intensity with ambiguous sign (Figure 6.1).


(a) **Population**

(b) **Per Capita Income**

(c) **Energy Intensity of GDP**

(d) **Carbon Intensity of Energy**

Figure 6.1. Global Baseline Projection Ranges for Kaya Factors. Scenarios harmonized with respect to a particular factor are depicted with individual lines. Other scenarios depicted as a range with median emboldened; shading reflects interquartile range (darkest), 5th – 95th percentile range (lighter), and full extremes (lightest), excluding one indicated outlier in population panel. Scenarios are filtered by model and study for each indicator to include only unique projections. Model projections and historic data are normalized to 1 in 2010. GDP is aggregated using base-year market exchange rates. Energy and carbon intensity are measured with respect to total primary energy. Sources: UN (2012), Heston et al (2012), World Bank (2013), BP (2013), JRC/PBL (2012), IEA (2012a) (2012), WG III AR5 Scenario Database (Annex II.10).

There is comparatively little variation across model scenarios in projected population growth, with virtually all modelling studies relying on central estimates (UN, 2012). One exception is the RoSE project (Bauer et al., 2013b; Calvin and al., 2014; De Cian and al., 2014) (that explicitly considers high population scenarios, as well as the storyline beneath the RCP 8.5 scenario. Among the majority of default population projections there are some minor differences across models, for example the extent to which declining rates for certain regions in coming decades are incorporated. On the other hand, there is substantially more variation in model projections of per capita income, with a few scenarios harmonized at both the low and high ends of the range, and energy intensity, for which two studies (AMPERE and EMF27) specified alternative “fast” decline baselines. Still, the inter-quartile range of default assumptions for both indicators is narrow, suggesting that many scenarios are based on a similar underlying narrative. Models project a faster global average growth rate in the future as dynamic emerging economies constitute an increasing share of global output. Energy intensity declines more rapidly than in the past, with an especially marked departure from the historical trend for “fast” energy intensity decline scenarios. Carbon intensity, typically viewed as a model outcome driven by resource and technology cost assumptions, is projected in most baseline scenarios to change relatively little over time, but there are exceptions in both directions. Declining carbon intensity could result from rapid improvements in renewable technologies combined with rising fossil fuel prices. Conversely, the fossil share in energy could rise with favourable resource discoveries, or the fossil mix could become more carbon intensive, for example due to replacement of conventional petroleum with heavier oil sands or coal-to-liquids.

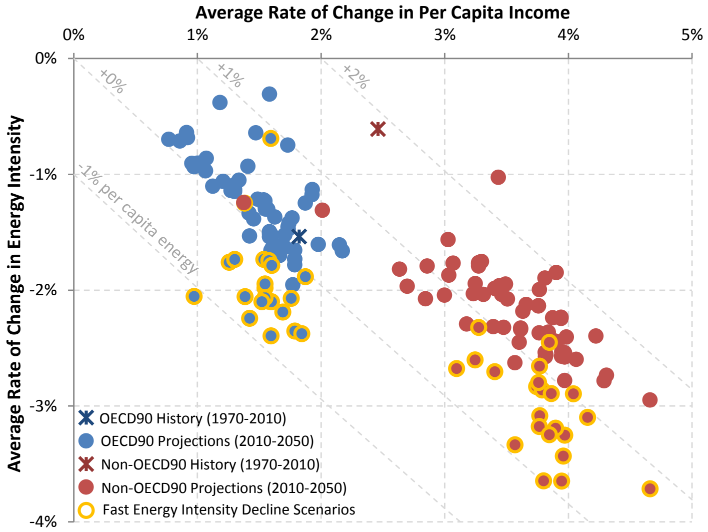


Figure 6.2. Average rates of change between 2010 and 2050 in baseline scenarios for per capita income and energy intensity of GDP in OECD90 and Non-OECD90. Yellow outlines reflect fast energy intensity decline scenarios. 62 of 77 unique default intensity scenarios and 22 of 24 unique fast intensity scenarios are plotted. Omitted are scenarios without OECD90 break-out. Sources: UN (2012), Heston et al (2012), World Bank (2013), BP (2013), WG III AR5 Scenario Database (Annex II.10).

While all models assume increasing per capita income and declining energy intensity, broad ranges are projected and high uncertainty remains as to what rates might prevail. Most models describe income growth as the result of exogenous improvement over time in labour productivity. The processes of technological advance by which such improvement occurs are only partially understood. Changes in aggregate energy intensity over time are the net result of several trends, including both improvements in the efficiency of energy end-use 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 industries as countries become wealthier. Although increasing energy intensity has been observed for some countries during the industrialization stage, the net effect is usually negative, and in general energy intensity has declined consistently over time. Both efficiency improvements and structural change can be driven by changes in energy prices, but to a significant extent both are driven by other factors such as technological progress and changing preferences with rising incomes. Most integrated models are able to project structural and technological change only at an aggregate level, although some include explicit assumptions for certain sectors (Sugiyama et al., 2014).

Because of limited variation in population and carbon intensity projections, the relative strength of the opposing effects of income growth and energy intensity decline, which is summarized by changes in per capita energy, plays the most important role in determining the growth of emissions in the baseline scenario literature (see Blanford et al., 2012). Assumptions about the evolution of these factors vary strongly across regions. In general, rates of change in population, income, energy intensity, and per capita energy are all expected to be greater in developing countries than in currently developed countries in coming decades, although this pattern has not necessarily prevailed in the past 40 years, as non-OECD countries had slower energy intensity decline than OECD countries (Figure 6.2). Among default energy intensity scenarios, assumed rates of change appear to be positively correlated between income and energy intensity, so that equivalent per capita energy outcomes are realized through varying combinations of these two indicators. The harmonized shift in the energy intensity decline rate leads to very low per capita energy rates, with global per capita energy use declining in a few cases (Figure 6.3). Projected emissions are essentially the product of per capita energy and carbon intensity projections, with most variation in future emissions scenarios explained by variation in per capita energy; the highest emissions projections arise from instances with high levels in both indicators (Figure 6.3).

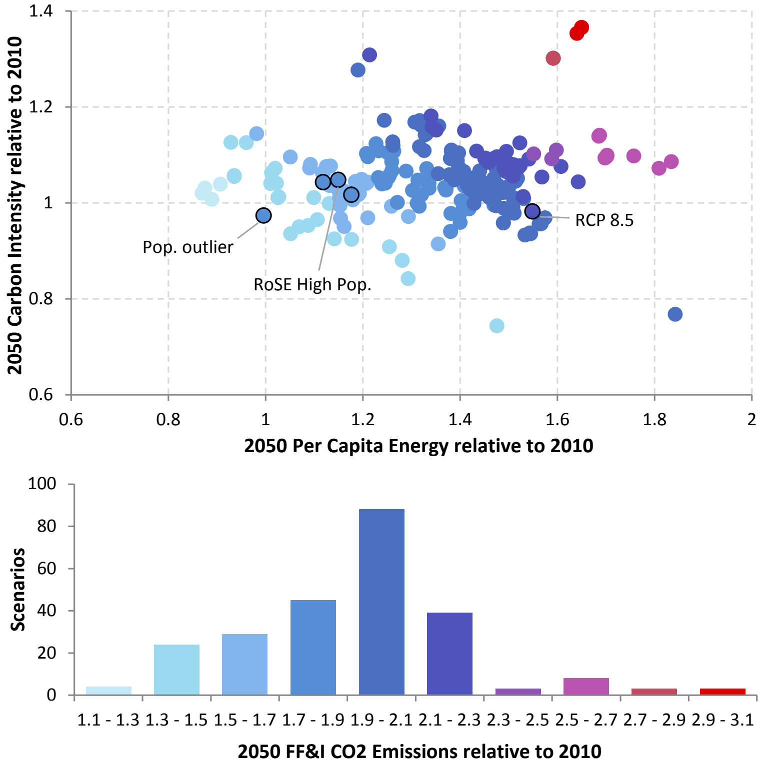


Figure 6.3. Indexed change through 2050 in carbon intensity of energy and per capita energy use in baseline scenarios. Color reflects indexed 2050 fossil fuel and industrial (FF&I) emissions according to key in bottom panel showing histogram of plotted scenarios. For default population projections, emissions are correlated with chart position; exceptions with high population are noted. Source: UN (2012), BP (2013), JRC/PBL (2012), IEA (2012a), WG III AR5 Scenario Database (Annex II.10).

6.3.1.3 Baseline emissions projections from fossil fuels and industry

Based on the combination of growing population, growing per capita energy demand, and a lack of significant reductions in carbon intensity of energy summarized in the previous section, global baseline emissions of CO2 from fossil fuel and industrial (FF&I) sources are projected to continue to increase throughout the 21st century (Figure 6.4a). 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 (see IPCC (2013), Chapter 12 for a discussion of the RCP study). The RCP 8.5 pathway has higher emissions than all but a few published baseline scenarios. Projections for baseline FF&I CO2 emissions in 2050 range from only slightly higher than current levels (in scenarios with explicit assumptions about fast energy intensity decline) to nearly triple current levels.

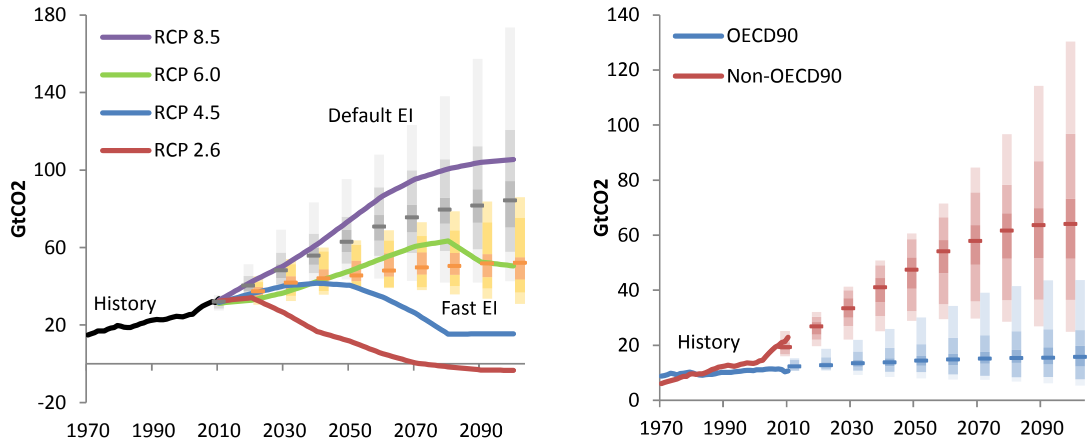


Figure 6.4. Global fossil fuel and industrial (FF&I) CO2 emissions with default growth assumptions (grey range) and fast energy intensity decline (gold range) (a) and for OECD90 vs. Non-OECD90 (b) in baseline scenarios. Scenarios are depicted as ranges with median emboldened; shading reflects interquartile range (darkest), 5th – 95th percentile range (lighter), and full extremes (lightest). Absolute projections are subject to variation in reported base year emissions arising from different data sources and calibration approaches (Chaturvedi et al., 2012). Some of the range of variation in reported 2010 emissions reflects differences in regional definitions. Sources: WG III AR5 Scenario Database (Annex II.10), JRC/PBL (2012), (van Vuuren et al., 2011c).

A common characteristic of all baseline scenarios is that the majority of emissions over the next century occur among non-OECD90 countries (Figure 6.4b). Because of its large and growing population and projected rates of economic growth relatively faster than the industrialized OECD90 countries, this region is projected to have the dominant share of world energy demand over the course of the next century. While the range of emissions projected in the OECD90 region remains roughly constant (a few models have higher growth projections), nearly all growth in future baseline emissions is projected to occur in the non-OECD90 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 baseline scenarios, 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.

6.3.1.4 Baseline emissions from land use change and non-CO2 gases

Baseline projections for global land-related carbon emissions and sequestration are made by a smaller subset of models, and due to observation difficulties are subject to greater historical uncertainty than FF&I emissions (Pan et al., 2011; Houghton et al., 2012). Baseline projections for land-related CO2 emissions reflect base year uncertainty and suggest declining annual net CO2 emissions in the long run (Figure 6.5a). In part, projections are driven by technological change, as well as projected declining rates of agriculture area expansion, a byproduct of decelerating population growth. Though uncertain, the estimated contribution of land-related carbon over the coming century is small, with some models projecting a net sink late in the century. For non-CO2 greenhouse gases, the contribution in CO2-equivalent terms is larger with projected emissions increasing over time (Figure 6.5a). Along with fugitive methane and a few industrial sources, land-related activities are projected to be a major driver of non-CO2 emissions, accounting for roughly 50% of total CH_4 emissions and 90% of N_2O emissions. Total CO2-e emissions are projected as the sum of FF&I CO2, land-related CO2, and non-CO2 (Figure 6.5b), with FF&I CO2 constituting around 80%.

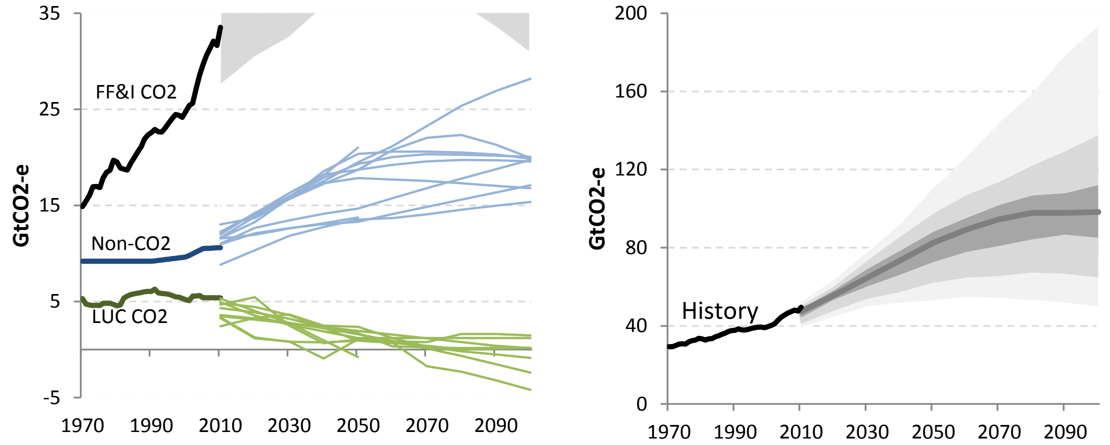


Figure 6.5. Global CO2-equivalent emissions by component (a) and total (b) for baseline scenarios. Land use change (LUC) CO2 and Non-CO2 projections are shown for individual models from EMF27. FF&I CO2 projections are depicted in detail above; the range is truncated here. Total CO2-e emissions are shown for all baseline scenarios with full coverage, depicted as a range with median emboldened; shading reflects interquartile range (darkest), 5th – 95th percentile range (lighter), and full extremes (lightest). Sources: WG III AR5 Scenario Database (Annex II.10), JRC/PBL (2012), IEA (2012a).

6.3.1.5 Baseline radiative forcing and cumulative carbon emissions

The emissions pathways for all of the emissions from the scenarios collected for this assessment were run through a common version of the MAGICC model to obtain estimates of CO2-e concentrations (Section 6.3.2). As a result of projected increasing emissions in the scenarios, radiative forcing from all sources continues to grow throughout the century in all baseline scenarios, exceeding 550 CO2-e (3.7 W/m2) between 2040 and 2050, while 450 CO2-e (2.6 W/m2) is surpassed between 2020 and 2030 (Figure 6.6a). Again, the majority of baseline forcing scenarios fall below the RCP 8.5 path but above RCP 6.0. Total forcing projections include the highly uncertain contribution of aerosols and other non-gas agents, which are based on scenario emissions for those models that project emissions of these substances and median forcing estimates in the MAGICC *model for those that do not (see Section 6.3.2). Due to variation in driver assumptions, which may not* reflect true uncertainty, baseline scenarios could lead to a range of long-term climate outcomes, with cumulative carbon emissions from 1751 to 2100 reaching between 1.5 and 3 TtC (Figure 6.6b). Noting that all of the baseline scenarios reviewed here include improvements to technology throughout the economy, there is strong evidence that, conditional on rates of growth assumed in the literature, technological change in the absence of explicit mitigation policies is not sufficient to bring about stabilization of greenhouse gas concentrations.

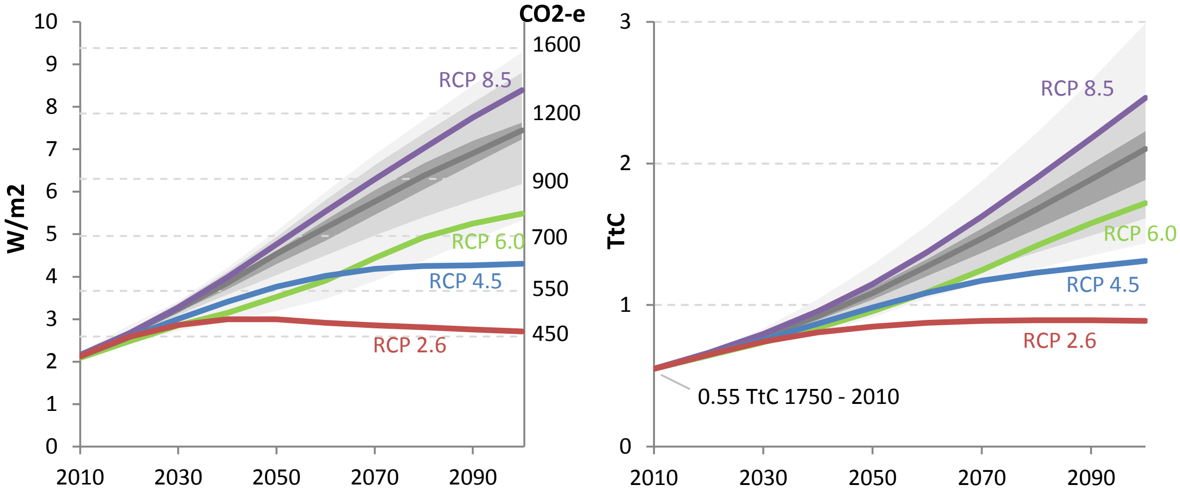


Figure 6.6. Total radiative forcing (a) and cumulative carbon emissions since 1751 (b) in baseline scenario literature compared to RCP scenarios. Forcing was estimated ex post from models with full coverage using MAGICC with median assumptions. Secondary axis in (a) expresses forcing in CO2-e concentrations. Scenarios are depicted as ranges with median emboldened; shading reflects interquartile range (darkest), 5th – 95th percentile range (lighter), and full extremes (lightest). Sources: WG III AR5 Scenario Database (Annex II.10), Boden et al. (2013), Houghton (2008), (van Vuuren et al., 2011a).

6.3.2 Emissions trajectories, concentrations and temperature in transformation pathways

6.3.2.1 Linking between different types of scenarios

There are important differences among long-term scenarios that complicate comparison between them. One difference is the nature of the goal itself. The majority of long-term scenarios focus on reaching long-term radiative forcing or greenhouse gas concentration goals. However, scenarios based on other long-term goals have also been explored in the literature. This includes scenarios focused on specific policy formulations (e.g. the G8 goal of 50% emission reduction in 2050 (G8, 2009) or the pledges made in the context of (UNFCCC, 2011a; b)), those based on cumulative emissions goals over a given period, those based on prescribed carbon prices, and those resulting from cost-benefit analysis (see Box 6.1 for a discussion of cost-benefit analysis scenarios). A second important difference is that some scenarios include all relevant forcing agents, while others only cover a subset of gases or focus only on CO_2. Finally, some scenarios allow concentrations to temporarily exceed long-term goals (overshoot scenarios), while others are formulated so that concentrations never exceed the long-term goal (not-to-exceed scenarios).

Box 6.1. Cost Benefit Analysis Scenarios

Cost-benefit studies (e.g. Tol, 1997; Nordhaus and Boyer, 2000; Hope, 2008) monetize the impacts of climate change and then balance the economic implications of mitigation and climate damages to identify the optimal trajectory of emissions reductions that will maximize total welfare. There are other frameworks of analysis for considering impacts as well (Bradford, 1999; Barrett, 2008; Keller et al., 2008). For example, risk assessment is also often used in order to determine overall goals. A theoretical discussion of cost-benefit analysis, including models that have conducted these analyses, can be found in both Chapters 2 and 3. One important characteristic of cost-benefit analyses is that the bulk of research in this domain has been conducted using highly-aggregate models that do not have the structural detail necessary to explore the nature of energy system or agricultural and land use transitions that are the focus of this chapter. For this reason, they are not assessed in this chapter. In contrast, the scenarios explored here rely on more detailed integrated models and have been implemented in a cost-effectiveness framework, meaning that they are designed to find a least-cost approach to meeting a particular goal, such as a concentration goal in 2100. Additionally, the scenarios and models described in this chapter typically examine mitigation independent from potential feedbacks from climate impacts and adaptation responses. A discussion of studies that do incorporate impacts into their assessment of transformation pathways, and a characterization of how these feedbacks might affect mitigation strategies, is provided in Section 6.3.3).

Despite these differences, it is necessary for the purposes of assessment to establish comparability across scenarios. To this end, scenarios assessed here have been grouped according to several key parameters (Table 6.2) (for more detail on this process, see the Methods and Metric Annex). The main criterion for grouping is the radiative forcing level in 2100, expressed in full-forcing CO2-e concentrations. (Full radiative forcing here includes greenhouse gases, halogenated gases, tropospheric ozone, aerosols and albedo change). Radiative forcing levels are often used as goal in scenarios, and the RCPs have been formulated in terms of this indicator (Moss et al., 2010; van Vuuren et al., 2011b). The scenario categories were chosen to relate explicitly to the four RCPs. A similar table in AR4 (Table 3.5) presented equilibrium values rather than 2100 values. Equilibrium values (as presented in AR4) and 2100 concentration and temperature values (as presented in this report) cannot easily be compared given the wide range of possible post-2100 trajectories and the lags in the physical processes that govern both. In particular, equilibrium values assume that concentrations stay constant after 2100, while many scenarios in the literature since AR5 show increasing or decreasing concentrations in 2100. Thus, it is more appropriate to focus on 21st century values to avoid relying on additional assumptions about post-2100 dynamics.

Another issue that complicates comparison across scenarios is that the earth system components (e.g. the carbon cycle and climate system) of integrated models can vary substantially (van Vuuren et al., 2009b). Hence, similar emissions pathways from different models may arrive at different 2100 CO2-e concentration levels and climate outcomes. To provide consistency in this regard across the scenarios assessed in the scenario database for AR5 (Annex II.10), and to facilitate the comparison with the assessment in WG1, the variation originating from the use of different model was removed by running all the scenarios in the database with at least information on Kyoto gas emissions through a standard reduced-form climate model called MAGICC (see Meinshausen et al., 2011ac; b; Rogelj et al., 2012). For each scenario, MAGICC was run multiple times using a distribution of earth system parameters, creating an ensemble of MAGICC runs. The resulting median concentration from this distribution was used to classify each scenario (see Section 6.3.2.6 for more on this process and a discussion of temperature outcomes). This means that the concentration information reported here does not reflect uncertainty by earth system components, unless mentioned otherwise, and it also means that the concentrations may differ from those that were originally reported in the literature for the individual models and scenarios.

The consistency of the MAGICC model version used here and the more comprehensive general circulation models used in the Working Group 1 report (Stocker et al., 2013) is discussed in Section6.3.2.6 , where it was also used to produce probabilistic temperature estimates. The CO2-e concentration in 2010 is 400 ppm CO2-e based on the parameters used in this version of MAGICC.

In order to compare scenarios with different coverage of relevant substances or goals, a set of relationships was developed to map scenarios with only sufficient information to assess Kyoto gas forcing or with information only on cumulative CO2 budgets to the full forcing CO2-e concentration categories (Table 6.2 and Method and Metrics Annex). Scenarios that extend to the end of the century were mapped, in order of preference, by Kyoto gas forcing in 2100 or by cumulative CO2 budgets from 2011 to 2100. In addition, scenarios that only extend to mid-century were mapped according to cumulative CO2 budgets from 2011 to 2050. These mappings allows for a practical, though still imperfect, means to compare between scenarios with different constructions.

The categories leading to CO2-e concentration above 720 ppm contain mostly baseline scenarios and some scenarios with very modest mitigation policies (Figure 6.7). The categories from 580-720 ppm

CO2-e contain a small number of baseline scenarios at the upper end of the range, some scenarios based on meeting long-term concentration goals such as 650 ppm CO2-e by 2100, and a number of scenarios without long-term concentration goals but based instead on emissions goals. There has been a substantial increase in the number of scenarios in the two lowest categories since AR4 (Fisher et al., 2007a). The RCP2.6 falls in the 430-480 ppm CO2-e category based on its forcing level by 2100. A limited number of studies (Rogelj et al 2013a,b; Luderer et al, 2013) have explored emissions scenarios leading to concentrations below 430 ppm CO2-e by 2100. These scenarios were not submitted to the AR5 database.

Table 6.2: Definition of CO2-e concentration categories used in this assessment, the mapping used to allocate scenarios based on different metrics to those categories, and the number of scenarios that extend through 2100 in each category. [Note: This table shows the mapping of scenarios to the categories; Table 6.3. shows the resulting characteristics of the categories using this mapping. The table only covers the scenarios with information for the full 21st century. The mapping of scenarios based on 2011-2050 cumulative total CO2-e emissions is described in the Methods and Metrics Annex.]

CO_2 equivalent concentration in 2100 (based on full radiative forcing)[1]		*Secondary categorisation criteria*[2]			*No of scenarios extending through 2100*	
CO2-e Concentration (ppm)	*Radiative forcing (W/m^2)*	*Kyoto gas only CO2-e concentration in 2100 (ppm)*	*Cumulative total CO_2 emissions 2011-2100 (GtCO2)*	*Corresponding RCP*[3]	*Total*	*With Overshoot Greater than 0.4 W/m^2*
430 – 480	2.3 – 2.9	450-500	< 950	RCP2.6	114	72
480 – 530	2.9 – 3.45	500-550	950 – 1500		251	77
530 – 580	3.45 – 3.9	550-600	1500 – 1950		198	22
580 – 650	3.9 – 4.5	600-670	1950 – 2600	RCP4.5	102	8
650 – 720	4.5 – 5.1	670-750	2600 – 3250		27	0
720 – 1000	5.1 – 6.8	750-1030	3250 – 5250	RCP.6	111	0
>1000	> 6.8	1030-	> 5250	RCP8.5	160	0

[1] Scenarios with information for the full 21st century were categorised in different categories based on their 2100 full radiative forcing/CO2-e concentration level (including greenhouse gases and other radiatively active substances).

[2] If insufficient information was available to calculate full forcing, scenarios were categorized, in order of preference, by 2100 Kyoto gas forcing or cumulative CO_2 emissions in the 2011-2100 period. Scenarios extending only through 2050 were categorised based on cumulative CO_2 emissions in the 2011-2050 period. Those scenarios are not included in this table. (See the Methods and Metrics Annex for more information.)

[3] The column indicates the corresponding RCP (Representative Concentration Pathway) falling within the scenario category based on 2100 equivalent concentration.

This mapping between different types of scenarios allows for roughly comparable assessments of characteristics of scenarios, grouped by 2100 full forcing CO2-e concentration, across the full database of scenarios collected for AR5 (Table 6.3.). The cumulative CO_2 budgets from 2011 to 2100 in each category in Table 6.3 span a considerable range. This range is results from the band width of concentration levels assigned to each category, the timing of emission reductions, and variation in non-CO_2 emissions, including aerosols. Although this leads to a wider range than for the scenarios used in WG1 (SPM Figure 10), the central estimates are very consistent. (Temperature results are discussed in Section 6.3.2.6).

An important distinction between scenarios is the degree to which concentrations exceed the 2100 goal before decreasing to reach it. Table 6.3. includes subcategories for scenarios in which concentrations exceed their 2100 level by more than 0.4 W/m^2 and scenarios that sometime during the century overshoot the upper concentration level of the category. Both subcategories result in different emission profiles and temperature outcomes compared to those that do not meet these criteria (see Section 6.3.2.6 regarding temperature outcomes).

Table 6.3. Key characteristics of the scenarios categories introduced in Table 6.2. For all parameters, the 10th to 90th percentile of the scenarios are shown[1]. Source: WG III AR5 Scenario Database (Annex II.10)

		CO2 emission budget[2] (GtCO2/yr)			*Concentration (ppm) [3]*		*Temperature (relative to 1850-1870)[3, 4]*			
CO2-e Conc in 2100 (CO2-e)	*Subcategories*	*2011-2050*	*2011-2100*	*CO2-e emissions in 2050 relative to 2010 (%)*	*CO2 in 2100*	*Peak CO2-e*	*2100 Temperature (degrees C)*	*Probability of Exceeding 1.5 degrees C (%)*	*Probability of Exceeding 2 degrees C (%)*	*Probability of Exceeding 2.5 degrees C (%)*
430 – 480	Total range	550-1270	630-1180	31-65	390-435	455-515	1.5-1.8 (1.2-2.3)	53-86	12-37	2-11
	Overshoot <0.4 W/m2	550-1060	630-1180	31-55	390-435	455-485	1.5-1.7 (1.2-2.1)	53-73	12-22	2-6
	Overshoot >0.4 W/m2	910-1270	680-1180	35-65	400-435	490-515	1.6-1.8 (1.3-2.3)	77-86	22-37	6-11
480 – 530	Total range	870-1620	960-1550	43-119	420-460	495-620	1.8-2.2 (1.4-2.9)	81-99	33-84	11-47
	Overshoot <0.4 W/m2	870-1240	960-1490	44-61	425-460	495-545	1.8-2.1 (1.4-2.6)	81-94	33-57	11-22
	Overshoot >0.4 W/m2	1070-1580	1050-1490	47-99	425-460	515-560	1.8-2.1 (1.4-2.7)	86-95	38-62	12-24
	No exceedance of 530 ppm CO2-e	900-1220	1020-1280	43-60	420-440	495-525	1.8-1.9 (1.4-2.4)	82-89	34-43	11-15
	Exceedance of 530 ppm CO2-e	1190-1620	990-1550	51-119	425-460	540-620	1.9-2.2 (1.5-2.9)	93-99	47-84	15-47
530 – 580	Total range	1090-1790	1160-2180	52-123	425-520	535-625	2.1-2.3 (1.7-2.9)	93-99	56-84	20-49
	Overshoot <0.4 W/m2	1090-1490	1410-2180	53-91	465-520	535-570	2.1-2.3 (1.7-2.9)	93-96	56-72	20-35
	Overshoot >0.4 W/m2	1540-1780	1170-2080	99-122	425-505	570-625	2.1-2.2 (1.7-2.9)	96-99	69-84	26-49
	No exceedance of 580 ppm CO2-e	1110-1600	1220-2130	52-98	440-510	535-575	2.1-2.3 (1.7-2.9)	93-96	56-72	20-34
	Exceedance of 580 ppm CO2-e	1510-1790	1160-1970	98-123	425-495	590-625	2.2-2.3 (1.7-2.9)	97-99	75-84	33-49
580 – 650	Total range	1260-1640	1880-2430	68-139	500-540	570-670	2.3-2.7 (1.8-3.4)	96-100	75-93	36-67
650 – 720	Total range	1320-1720	2620-3320	103-131	565-615	645-690	2.6-2.9 (2.1-3.6)	99-100	89-95	60-74
720 – 1000	Total range	1600-1930	3620-4990	128-168	645-775	750-905	3.1-3.7 (2.5-4.7)	100-100	97-100	83-96
>1000	Total range	1840-2320	5350-6950	165-220	815-975	1040-1225	4.1-4.8 (3.3-6.3)	100-100	100-100	99-100

[1] Text in blue shows results of the subset of the scenarios from column one. One subcategory distinguishes scenarios that have a large overshoot (i.e. a maximum forcing during the 21st century that is >0.4 W/m2 higher than the 2100 forcing) from those that do not have a large overshoot. The second set of subcategories shows whether a scenario exceeds the maximum concentration level of its category somewhere before 2100.For categories above 580 ppm CO_2-e, the information in the row "total range" refers to the 10th to 90th percentiles for the total set of scenarios in the category. For the categories below 580 ppm CO_2-ee, the total range is based on the 10th to 90th percentiles of the subcategories (the lowest and highest values from the subcategories).

[2] For comparison of the cumulative CO2 budget results assessed here with those presented in WG1, emissions from 1850 to 2011 are estimated to be about 2035 Gton CO_2.

[3] Estimates of concentrations and climate change are based on MAGICC model calculations using the MAGICC model in a probabilistic mode (see Methods and Metrics Annex). (Meinshausen et al., 2011a; c). The comparison between MAGICC model results and the outcomes of the models used in WG1 is further discussed in Section 6.3.2.6. The likelihood statements are indicative only.

[4] Temperature in 2100 is provided for a median estimate of the MAGICC calculations, which illustrates differences between the emissions pathways of the scenarios in each category. The range of temperature change in the parentheses includes in addition also the climate system uncertainties as represented by the MAGICC model (see 6.3.2.6 for further details).

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

There are wide ranges of emission pathways associated with meeting different 2100 CO2-e goals (Figure 6.7). For all categories below a 2100 CO_2-e concentration of 720 ppm CO2-e, emissions are reduced in the long-run relative to current levels. The decision on timing of emission reductions is a complex one. Model scenarios are typically designed to find the least-cost pathway to meet a long-term goal, in some cases under specific constraints, such as the availability of certain technologies or the timing and extent of international participation. Because models differ in, among others, technology representations and baseline assumptions, there are clear differences in scenario outcomes for the timing of reductions and the allocation of reductions across gases.

Three interrelated factors are particularly important determinants of emissions profiles in the modelling literature: (1) the degree of overshoot, (2) technology options and associated deployment decisions, and (3) policy assumptions. Overshoot scenarios typically entail less mitigation today in exchange for greater reductions later (Wigley, 2005; Meinshausen et al., 2006; den Elzen and van Vuuren, 2007; Nusbaumer and Matsumoto, 2008). Overshooting a long-term concentration goal, however, may lead to higher transient temperature change than in a pathway for which the goal is never exceeded (Section6.3.2.6). Overshoot is particularly important for concentration goals which are close to today's levels. The majority of scenarios reaching 480 ppm CO2-e or below by 2100, for instance, rely on overshoot pathways. Those that do not include overshoot need faster emissions reductions (and associated energy system changes) during the next 1-2 decades (Calvin et al., 2009c).

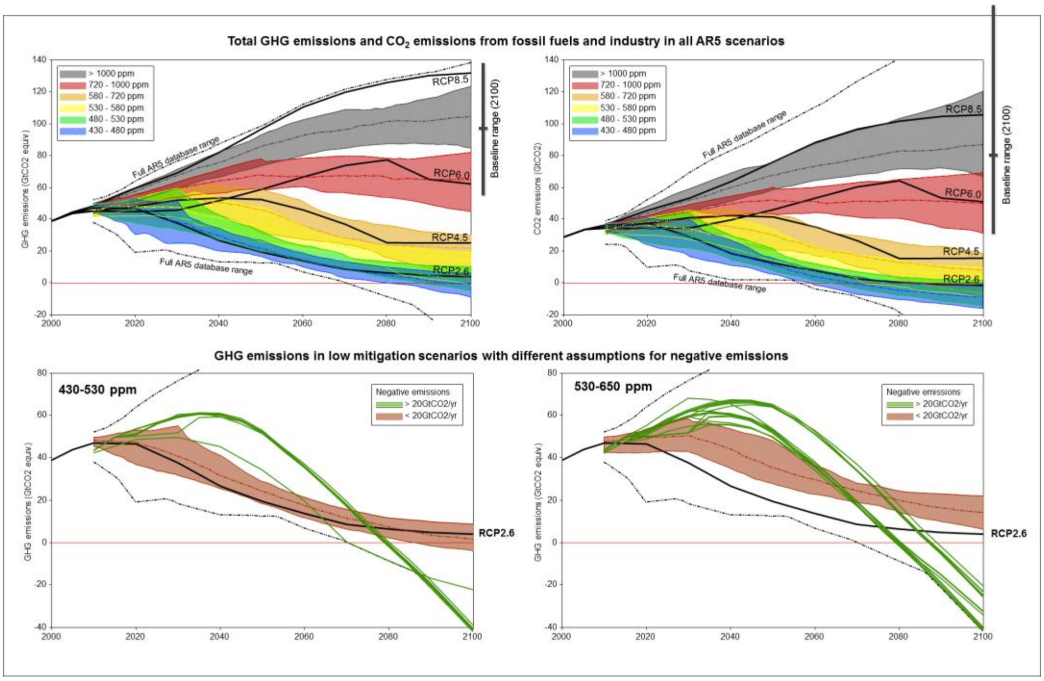


Figure 6.7. Emissions for total CO2 and Kyoto gases for the various categories defined inTable 6.2. The bands indicate the 10-90th percentile of the scenarios included in the database. The solid lines indicate the RCP scenarios. The dotted lines indicate the database range. The black bar on the right indicates the full 2100 range (not only the 10-90th percentile) for baseline scenarios (see Section 6.3.1). The lower panels show for the combined categories 430-530 ppm and 530-650 ppm CO2-e the scenarios with and without negative emissions larger than 20 GtCO2-e/yr. Source: WG III AR5 Scenario Database (Annex II.10).

The second consideration is technology. The most critical set of technologies in this context are CDR technologies, which can be used to generate negative emissions (van Vuuren et al., 2007; Edenhofer et al., 2010; Azar et al., 2010a, 2013; van Vuuren and Riahi, 2011; Tavoni and Socolow,, 2012). In most model studies in the literature, negative emissions are generated via the use of BECCS, and, to a lesser extent, afforestation, though in principle other options could potentially result in negative emissions as well (see Section6.9). CDR technologies have not been applied yet at large scale. The potential of afforestation is limited, and the use of BECCS is ultimately constrained by the potential for CCS and biomass supply (Van Vuuren et al., 2013). CDR technologies have two key implications for transformation pathways. One is that by removing emissions from the atmosphere, CDR technologies can compensate for residual emissions from technologies and sectors with more expensive abatement. The second is that CDR technologies can create net negative emissions flows, which allow faster declines in concentrations in the second half of the century and thus facilitate higher near-term emissions, effectively expanding the potential scope for overshoot. In model comparison studies, many of the models that could not produce scenarios leading to concentrations of roughly 450 ppm CO2-e by 2100, particularly in combination with delayed or fragmented policy approaches, did not include CDR techniques (Clarke et al., 2009a, refs). The vast majority of scenarios with overshoot of greater than 0.4 W/m2 (greater than 20 ppmv CO2-e) deploy CDR technologies to an extent that net global CO2 emissions become negative. Evidence is still mixed whether CDR technologies are essential for achieving very low greenhouse gas concentration goals (Rose et al., 2013). A limited number of studies have explored scenarios with negative emissions larger than 20 $GtCO_2$ per year (lower panels Figure 6.7) as a means to delay emission reductions. However, the majority of studies have explored futures with smaller, but often still quite substantial, contributions of CDR technologies. Technology portfolio assumptions other than CDR technologies (e.g. regarding renewables, CCS, efficiency and nuclear power) can also have implications for emissions trajectories, although these are often less pronounced and may in fact shift mitigation earlier or later (Eom et al.; Rogelj et al., 2012; Riahi et al., 2014); Krey et al., 2014; ((Kriegler et al., 2014c).

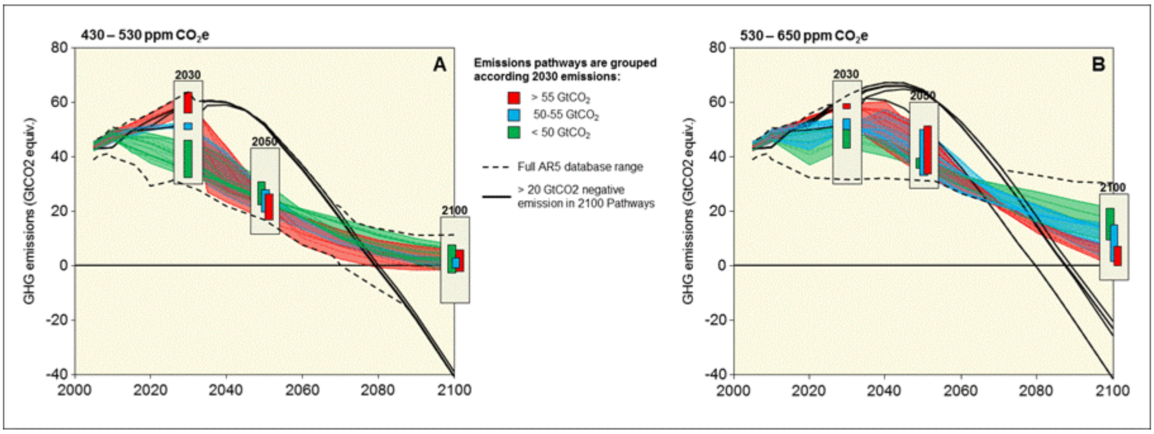


Figure 6.8. Emission pathways from three model comparison exercise with explicit 2030 emissions goals. Mitigation scenarios are shown for scenarios reaching between 430-550ppm CO2-e in 2100 (left) and 530-650ppm CO2-e in 2100 (right). Scenarios are distinguished by their 2030 emissions: <50 GtCO2e by 2030 (green), 50-55 GtCO2e (blue), and >55 GtCO2e (red). Individual emission pathways with negative emissions of > 20 GtCO2/yr in the second-half of the century are shown as solid black lines. The full range of the scenarios in the AR5 database is given as dashed black lines. (source: scenarios from intermodeling comparisons with explicit interim targets (AMPERE: Riahi et al,(2014); LIMITS: Kriegler et al(2014b), ROSE: Luderer et al (2013a) and WG III AR5 Scenario Database (Annex II.10)).

The third consideration is policy structure. Since AR4 scenario studies have increasingly focused on the outcomes of fragmented international action and global delays in emission reduction (Clarke et al., 2009a; Vliet et al., 2012; Rogelj et al., 2013a; Kriegler et al., 2014b; see Riahi et al., 2014; Tavoni et al., 2014). Considering both idealized and non-idealized scenarios, a considerable range of 2020 and 2030 emissions can be consistent with specific long-term goals. Although studies show that low long-term concentration goals could still be met with near term emissions above those in idealized scenarios, initial periods of delay are typically followed by periods rapid reductions in subsequent decades (Kriegler et al., 2014a; Riahi et al., 2014). This has important implications for costs and technology transitions, among other things (see Section 6.3.5). In general, delays in mitigation increase the risk of foreclosing on certain long-term goals and decrease the options for meeting long-term goals (Riahi et al., 2014).

The intersection of these three factors – overshoot, CDR technologies, and delayed mitigation –can be viewed in the context of the implications for emissions pathways over the next twenty years. Emissions pathways over the century can be viewed in terms of the level emissions pass through in 2030 (Figure 6.8). For a given range of forcing at the end of the century, pathways with the lowest levels in 2030 have higher emissions in the long run and slower rates of decline in the middle of the century. On the other hand, high emissions in 2030 leads to more rapid declines in the medium term and lower or eventually net negative emissions in the long-run, with the pattern exaggerated in a few extreme scenarios exploring deployment of CDR of 20 GtCO2/yr or more. (See Section 6.4 for a more thorough discussion of the relationship between near-term actions and long-term goals.) Deeper long-term goals also interact with these factors. For example, scenarios leading to concentrations below 430 ppm CO2-e by 2100 (Rogelj et al 2013a,b; Luderer et al, 2013) feature large-scale application of CDR technologies in the long-term, and most of them have deep emission reductions in the near term.

A final observation is that the characteristics of emissions profiles discussed here are in many cases driven by the cost-effectiveness framing of the scenarios. A more comprehensive consideration of timing would also include, among others, considerations of the trade-off between the risks related to both transient and long-term climate change, the risks associated with specific (long-term) technologies and expectation of the future developments of these technologies, short-term costs and transitional challenges, flexibility in achieving climate goals, and the linkages between emissions reductions and a wide range of other policy objectives (van Vuuren and Riahi, 2011; Krey et al., 2014; Riahi et al., 2014) .

6.3.2.3 Regional roles in emissions reductions

The contribution of different regions to mitigation is directly related to the formulation of international climate policies. In idealized implementation scenarios, which assume a uniform global carbon price, the extent of mitigation in each region depends most heavily on relative baseline emissions, regional mitigation potentials, and terms of trade effects. All of these can vary significantly across regions (van Vuuren et al., 2009a; Clarke et al., 2012; Chen,W et al., 2013; van Sluisveld et. al., 2013; Tavoni et al., 2014). In this idealized implementation environment, the carbon budgets associated with bringing concentrations to between 430 and 530 ppm CO2-e in 2100 are generally highest in Asia, smaller in the OECD, and lowest for other regions (Figure 6.9, left panel). However, the ranges for each of these vary substantially across scenarios. Mitigation in terms of relative reductions from baseline emissions are distributed more similarly between OECD, ASIA and REF across scenarios (Figure 6.10, right panel). The Middle East and Africa (MAF) region and especially Latin America (LAM) have the largest mitigation effort. In absolute terms, the remaining emissions in the mitigation scenarios and the emission reductions are largest in Asia (Figure 6.10, left panel), due to the size of this region. It is important to note that the mitigation costs borne by different regions and countries do not need to translate directly from the degree of emissions reductions, because the use of effort-sharing schemes can reallocate economic costs (See 6.3.6.6).

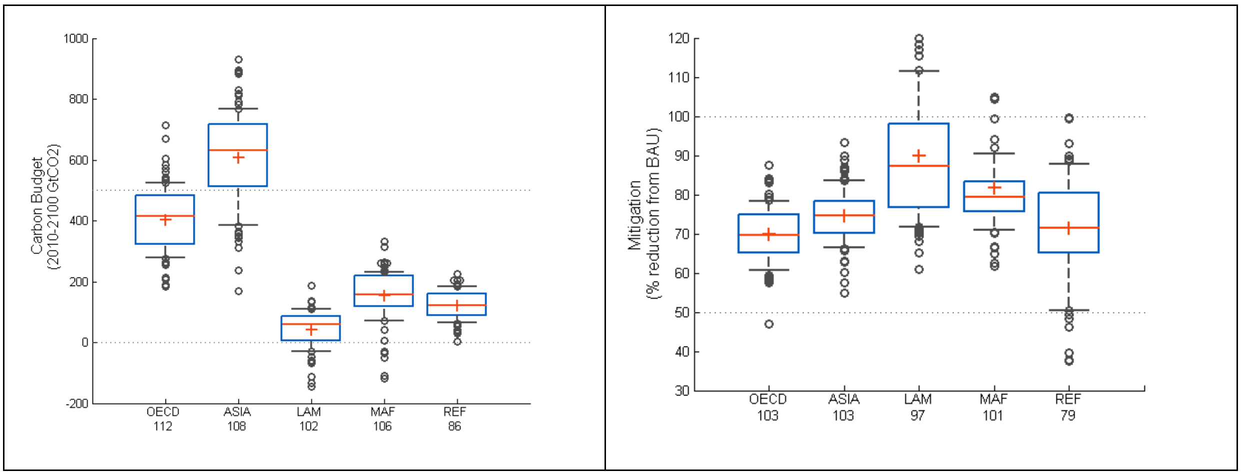


Figure 6.9. Regional carbon budget (left) and relative mitigation effort (right) for 430-530 ppm-e scenarios, based on cumulative CO2 to 2100. Carbon budgets below 0 and relative mitigation above 100% can be achieved via large negative emissions. Box plots indicate mean, median, 25-75th percentiles. Whiskers extend to outliers, shown with dots. The number of scenarios is reported below the regional acronyms. Source: WG III AR5 Scenario Database (Annex II.10), idealized implementation and default technology cases.

The transient emissions reduction implications also vary across regions in idealized implementation scenarios (Table 6.4). In general, emissions peak in the OECD sooner than in other countries with higher baseline growth. Similarly, emissions are reduced in the OECD countries by 2030 relative to today, but they may increase in other regions, particularly the fast-growing Asian and MAF regions.

Deviations from the idealized implementation, either through global delays in mitigation or delays by particular countries or regions, will lead to different regional contributions to emissions reductions. When mitigation is undertaken by a subset of regions, it will have implications on other non-participating countries through energy markets, terms of trade, technology spillovers, and other leakage channels. Multi model ensembles have shown leakage rates of energy related emissions to be relatively contained, often below 20% (Bauer et al.; Böhringer et al., 2012, p. 29; Blanford et al., 2014; Kriegler et al., 2014a). Policy instruments such as border carbon adjustment can effectively reduce these effects further (Böhringer et al., 2012, p. 29). Leakage in land use on the other hand could be substantial, though fewer studies have quantified it (Calvin et al., 2009).

Table 6.4. Regional CO2 emission reductions in 2030 over 2010, and peak year of emissions, for 430-530 and 530-650 ppv CO2-e scenarios. Negative values for emissions reductions indicate that 2030 emissions are higher than in 2010. Figures are averages across models. The numbers in parenthesis show the 25th to 75th percentile range across scenarios. The number of underlying scenarios is the same as in Figure 6.9. Source: WG III AR5 Scenario Database (Annex II.10), idealized implementation and default technology scenarios.

		OECD	**ASIA**	**LAM**	**MAF**	**REF**
Peak year of emissions	430-530 ppm eq	2020 (2020/2020)	2030 (2030/2040)	2025 (2020/2030)	2030 (2020/2040)	2025 (2020/2030)
Peak year of emissions	530-650 ppm eq	2025 (2020/2025)	2040 (2040/2040)	2030 (2030/2040)	2040 (2030/2050)	2025 (2020/2030)
2030 Emission reductions w.r.t. 2010	430-530 ppm eq	32% (23/40 %)	-1% (-15/14 %)	35% (16-59 %)	8% (-7/18 %)	32% (18/40 %)
2030 Emission reductions w.r.t. 2010	530-650 ppm eq	14% (6/21 %)	-34% (-43/-26 %)	9% (-17/41 %)	-22% (-41/-12 %)	8% (-5/16 %)

6.3.2.4 Projected CO_2 emissions from land use and land use change

Net CO2 emissions from land-use change (LUC) result from an interplay between the use of land to produce food and other non-energy products, to produce bioenergy, and to store carbon in land. Land-management practices can also influence CO2 emissions (see Section 6.3.5). Currently about 10-20% of global CO_2 emissions originate from land use and land-use change. In general, most scenarios show declining CO_2 emissions from land-use changes as a result of declining deforestation rates, both with and without mitigation (see also Section 6.3.1.4). In fact, many scenarios project a net uptake of CO_2 as a result of reforestation after 2050 (Figure 6.9).

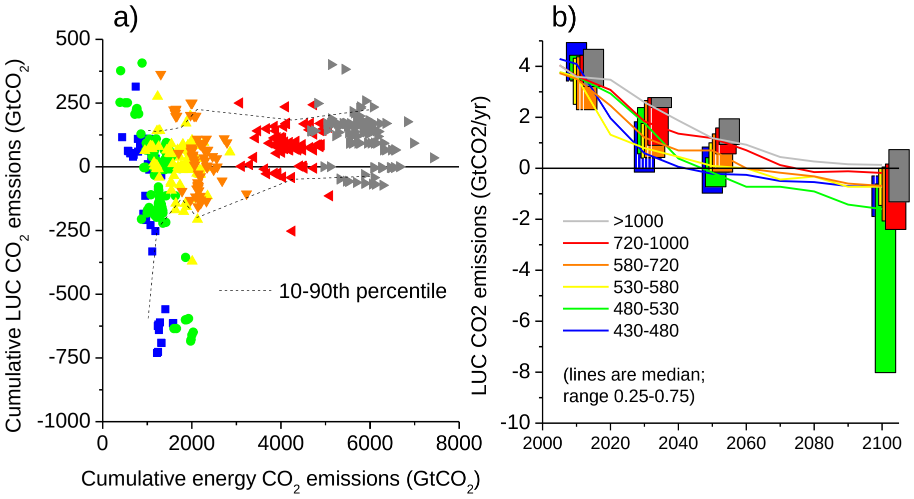


Figure 6.10. Land use emissions in mitigation scenarios. Panel a shows cumulative emission 2010-2100 for energy/industry and land use. Panel b shows CO2 emission from land use as function of time (the 25-75th percentile in bars and median value by lines). Source: WG III AR5 Scenario Database (Annex II.10).

Scenarios provide a wide range of outcomes for the contribution of CO2 emissions from LUC (see Section 11.9 for a sample from a model inter-comparison study). However, one difficulty in interpreting this range is that many scenarios were developed from models that do not explicitly look at strategies to reduce LUC CO_2 emissions. Nonetheless, the spread in LUC emissions still reflects the implications of land-related mitigation activities – bioenergy and afforestation – in both models that explicitly represent land use and those that do not (see Section 6.3.5 for a detailed discussion). Some studies emphasize a potential increase in LUC emissions due to bioenergy production displacing forests (van Vuuren et al., 2007; Searchinger et al., 2008; Wise et al., 2009b; Melillo et al., 2009; Reilly et al., 2012). Others show a decrease in LUC emissions as a result of decreased deforestation, forest protection, or net afforestation enacted as a mitigation measure (e.g. Kindermann et al., 2008; Wise et al., 2009b; Popp et al., 2011b; Riahi et al., 2011; Reilly et al., 2012). Wise et al. (2009b) show a range of results from a single model, first focusing mitigation policy on the energy sector, thereby emphasizing the bioenergy production effect, and then focusing policy more broadly to also encourage afforestation and slow deforestation. Reilly et al. (2012) conduct a similar analysis, but with more policy design alternatives. However, policies to induce large-scale land-related mitigation will be challenging and actual implementation will affect costs and net benefits (Lubowski and Rose, 2013) (see Section6.3.5 , Section, and Chapter 11).

6.3.2.5 Projected Emissions of other radiatively important substances

Beyond CO_2, the scenario literature has focused most heavily on the mitigation opportunities for the gases covered by the Kyoto protocol, including the two most important non-CO2 gases, CH4 and N2O. Attention is also increasingly being paid to the climate consequences of other emissions such as aerosols and ozone precursors (e.g. Shindell et al., 2012; Rose et al., 2014b). Although several models have produced projections of aerosol forcing and have incorporated these emissions into the constraint on total forcing, most of them do not have specific mitigation measures for these emissions.

For non-CO2 Kyoto gases, the relative depth and timing of emissions reductions are influenced by two primary factors: (1) the abatement potential and costs for the various substances and (2) the strategies for making trade-offs between different greenhouse forcers. With respect to abatement potential, studies indicate that in the short run, there are many low-cost options to reduce non-CO_2

gases relative to opportunities to reduce CO_2 emissions. Partially as a result, studies indicate that short-term reduction strategies may rely more heavily in the near-term on non-CO_2 gases than in the long-run (Weyant et al., 2006; Lucas et al., 2007),). In the longer run, emission reductions, particularly for CH4 and N2O, are expected to be constrained by several hard to mitigate sources such as livestock and emissions associated with fertilizers. This results ultimately in lower reduction rates than for CO_2, for stringent mitigation categories despite slower growth in baseline projections (see Figure 6.11 and also discussed by Lucas et al., (2007)). For scenarios resulting in 430-480 CO2-e forcing in 2100, CH_4 reductions in 2100 are about 50% compared to 2005. For N_2O, the most stringent scenarios result in emission levels just below today's level. For halogenated gases, emission growth is significantly reduced for the lower concentration categories, but variation among models is large, ranging from a 90% reduction to a 100% increase compared to 2005.

Strategies for making tradeoffs across the gases must account for differences in both radiative effectiveness and atmospheric lifetime and the associated impacts on near-term and long-term climate change. They must also consider relationships between gases in terms of common sources and non-climate impacts such as air pollution control. Models handle these trade-offs differently, but there are essentially two classes of approaches. Most models rely on exogenous metrics (discussed further below) and trade off abatement among gases based on metric-weighted prices. Other models make the trade-off on the basis of economic optimization and the physical characterization of the gases within the model with respect to a specified goal such as total forcing (e.g. Manne and Richels, 2001). Differences both within these categories and among them lead to very different results, especially with respect to the timing of mitigation for short-lived substances. Several studies have looked into the role of these substances in mitigation (Shine et al., 2007; Berntsen et al., 2010; UNEP and WMO, 2011; Myhre et al., 2011; McCollum et al., 2013c; Rose et al., 2014a). Studies can be found that provide argument for early emission reduction as well as a more delayed response of short-lived forcers. Arguments for early reductions emphasize the near-term benefits for climate and air pollution associated with ozone and particulate matter. An argument for a delayed response is that, in the context of long-term climate goals, reducing short-lived forcers now has only a very limited long-term effect (Smith and Mizrahi, 2013).

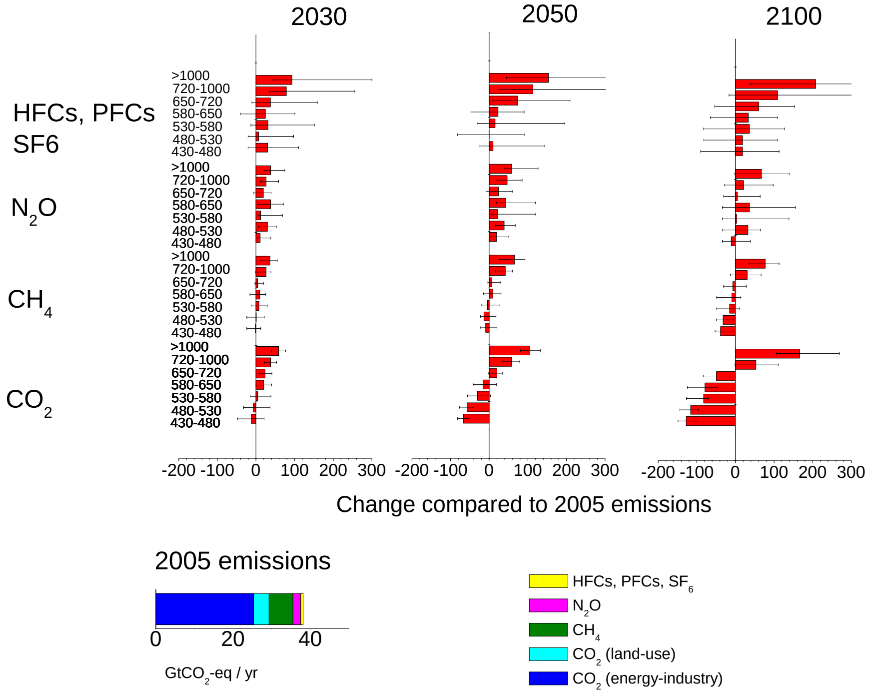


Figure 6.11. Emissions reductions in greenhouse gases in 2030, 2050 and 2100. Upper bars indicate changes compared to 2005 for different gases. The bars indicate median across the scenarios, while range represents the 10-90th percentile of scenarios. Source: WG III AR5 Scenario Database (Annex II.10).

Model analysis has also looked into the impact of using different substitution metrics (See Section 3.9.6 for a theoretical discussion the implication of various substitution metrics and Section 8.7 of the Working Group 1 report for the physical aspects of substitution metrics). 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. Several papers have explored the use of metrics other than 100-year GWPs, including updated Global Warming Potential (GWP) values and Global Temperature Potential (GTP) values (Smith et al., 2012; Reisinger et al., 2012; Azar and Johansson, 2012; van den Berg et al., 2014). Quantitative studies show that the choice of metrics is critical for the timing of CH4 emission reductions among the Kyoto gases, but that it rarely has a strong impact on overall, global costs. The use of dynamic GTP values (as alternative to GWPs) has been shown to postpone emissions reductions of short-lived gases. Using different estimates for 100-year GWP from the various previous IPCC Assessment Reports has no major impact on transition pathways.

6.3.2.6 The link between concentrations, radiative forcing, and temperature

The assessment in this Chapter focuses on scenarios that result in alternative CO2-e concentrations by the end of the century. However, temperature goals are also an important consideration in policy discussions. This raises the question of how the scenarios assessed in this chapter relate to possible temperature outcomes. One complication for assessing this relationship is that scenarios can follow different concentration pathways to the same end-of-century goal (as discussed in6.3.2.2), and this will lead to different temperature responses. A second complication is that several uncertainties confound the relationship between emissions and temperature responses, including uncertainties about carbon cycle, the climate sensitivity and the transient climate response (see WG1 Box 12.2). This means that the temperature outcomes of different concentration pathways assessed here (See Section 6.3.2.1) are best expressed in terms of a range of probable temperature outcomes (see Chapter 2 and Section 6.2.3 for a discussion of evaluating scenarios under uncertainty). The definition of the temperature goals themselves forms a third complication. Temperature goals might be defined in terms of the long-term equilibrium associated with a given concentration, in terms of the temperature in a specific year (e.g., 2100), or based on never exceeding a particular level. Finally, the reference year, often referred to as “pre-industrial”, is ambiguous given both the lack of real measurements and the use of different reference periods. Given all of these complications, a range of emission pathways can be seen as consistent with a particular temperature goal (see also Figure 6.12, 6.13 and 6.14).

Because of the uncertain character of temperature outcomes, probabilistic temperature information has been created for the scenarios in the AR5 database that have reported information on at least CO_2, CH_4, N_2O and sulphur aerosol emissions. Several papers have introduced methods for probabilistic statements on temperature increase for emission scenarios. (Knutti et al, 2008, (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). For this assessment, the method described by Rogelj et al. (2012) and Schaeffer et al. (2013) is used, which employs the MAGICC model based on the probability distribution of input parameters from Meinshausen, (2009)(see Meinshausen et al., 2011c; Rogelj et al., 2012; Schaeffer et al., 2013). MAGICC was run 600 times for each scenario. Probabilistic temperature statements are based on the resulting distributions (see also the Methods and Metrics Annex; and the underlying papers cited). Because the distribution of these runs is based on only a single probability distribution, resulting probabilistic statements should be regarded as indicative.

An important consideration in the evaluation of this method is the consistency between the distributions of key parameters used here and the outcome of the WG1 research regarding these same parameters. Carbon-cycle parameters in the MAGICC model used in this chapter are based on earth-system C4MIP model results from AR4, and a PDF for climate sensitivity is assumed that corresponds to the assessment of IPCC AR4 (Rogelj et al., 2012) (Meehl et al., 2007b, Box 10.2;). The MAGICC output based on this approach has been shown to be consistent with the output of the

CMIP5 earth-system models (see also WG1 12.4.1.2 and 12.4.8). The MAGICC model captures the temperature outcomes of the CMIP5 models reasonably well, with median estimates close to the middle of the CMIP5 uncertainty ranges (see panel a and b inFigure 6.12). For lower-emission scenarios, the MAGICC uncertainty range is more narrow, mainly due to the larger range of methodologies representing non-CO2 forcings in the CMIP5 models, as well as the fact that MAGICC does not reflect all of the structural uncertainty represented by the range of CMIP5 models (see panels a and b in Figure 6.12 and WG1 Figure 12.8 and Section 12.4.1.2). Uncertainty ranges are largest for emissions-driven runs (only available for RCP8.5), since uncertainties in carbon-cycle feedbacks play a larger role (see also WG 12.4.8.1). The relationship between the cumulative CO2 emissions and the transient temperature increase from MAGICC is well aligned with the CMIP5 model results for the RCP pathways (Figure 6.12 panel c and WG1 12.5.4.2, Figure 12.46, TFE.8 Figure 1). WG1 has estimated that a cumulative CO$_2$ emissions budget of around 1,000 GtCO2 from 2010 onward is associated with a likely (>66%) chance of maintaining temperature change to less than 2^{o}C. For the database of scenarios assessed here, the majority of scenarios with a likely (>66%) chance of staying below 2^{o}C are associated with cumulative emissions over the century of 630-1180 GtCO2 (Table 6.3). The two budgets are not fully comparable, however, since the WG1 budget is defined until the time of peak warming while the budgets here cover a fixed time period.

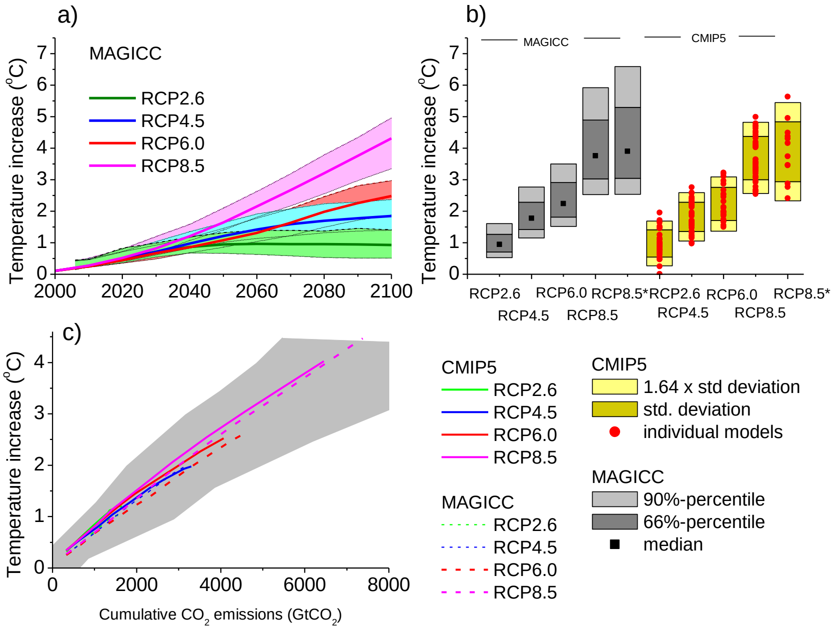


Figure 6.12. Comparison of CMIP5 results (as presented in Working Group 1) and MAGICC output for global temperature increase. Note that temperature increase is presented relative to the 1986-2005 average in this figure (see also Figure 6.13). Panel a shows concentration driven runs for the RCP scenarios from MAGICC (lines) and one-standard deviation ranges from CMIP5 models. Panel b compares 2081-2100 period projections from MAGICC with CMIP5 for scenarios driven by prescribed RCP concentrations (four left-hand bars of both model categories) and the RCP8.5 run with prescribed emissions (fifth bar; indicated by a star). Panel c shows temperature increases for the concentration-driven runs of a subset of CMIP5 models against cumulative CO2 emissions back-calculated by these models from the prescribed CO2-concentration pathways (full lines) and temperature increase projected by the MAGICC model against cumulative CO2 emissions (dotted lines) (Based on WG1 Figure SPM.10). Cumulative emissions are calculated from 2000 onwards.

Based on the results of the MAGICC analysis, temperature outcomes are similar across all scenarios in the next few decades due in part to physical inertia in the climate system (Figure 6.13, Panel a). In the second half of the century, however, temperatures diverge. Scenarios leading to 2100 concentrations over 1000 ppm CO2-e lead to a temperature increase of 3 to 6°C (66th percentile of the distribution of temperature outcomes), while scenarios with 2100 concentrations between 430 and 480 ppm CO2-e lead to a temperature increase of about 1.3 to 2.2 °C (66th percentile of the distribution of temperature outcomes) (Figure 6.13, Panels a and b). Cumulative CO_2 emissions from 2011 through 2100 for all scenarios in the database correlate well to the 2100 temperature level – see also WG1 Section 12.5.4 (Figure 6.13, Panel c). However, there is some variation due to differences in emissions of other forcing agents, in particular CH_4 and sulphur, along with the timing of emissions reduction and the associated extent of overshoot. In general, both the 2100 temperatures and the relationship between the cumulative emissions and 2100 temperature change are roughly consistent with the correlation for the RCPs in WGI (Figure 6.13, Panels c). Scenarios that overshoot the 2100 concentration goal by more than 0.4 W/m^2 result in higher levels of temperature increase mid-century and prolonged periods of relatively rapid rates of change in comparison to those without overshoot or with less overshoot (Figure 6.13, Panel d). By 2100, however, the different scenarios converge.

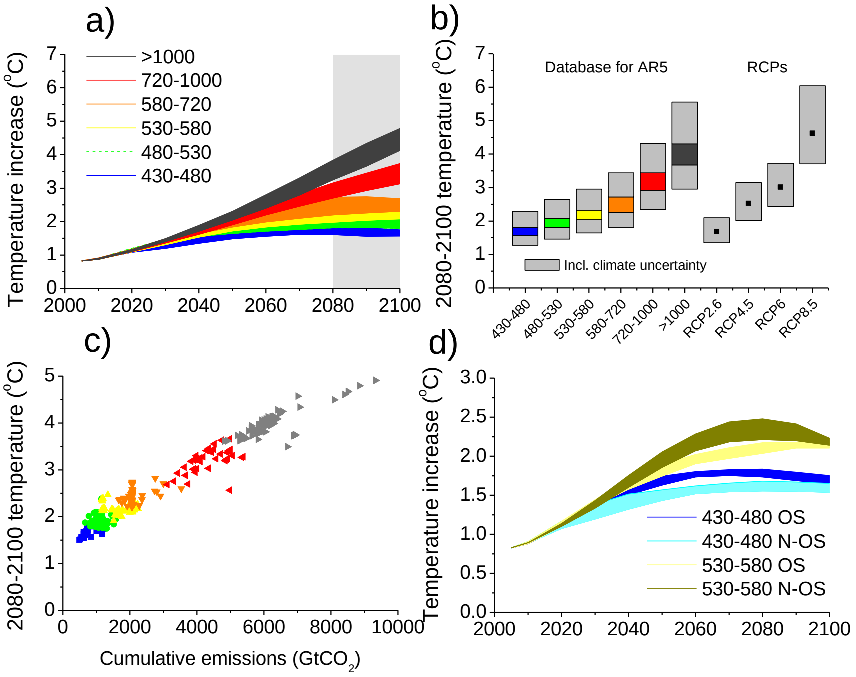


Figure 6.13. Changes in global temperature for the scenario categories above 1850-1875 reference level as calculated by MAGICC. (Warming in the 1985-2005 period in MAGICC is equal to about 0.6 deg C compared to the reference level). Panel a shows temperature increase relative reference as calculated by MAGICC (10-90th percentile for median MAGICC outcomes). Panel b shows 2081-2100 temperature levels for the scenario categories and RCPs for the MAGICC outcomes. The bars for the scenarios used in this assessment include both the 10-90th percentile range for median MAGICC outcomes (colored portion of the bars) and the 16-84th percentile range of the full distribution of MAGICC outcomes from these scenarios, which also captures the earth-system uncertainty. The bars for the RCPs are based on the 16-84th of MAGICC outcomes based on the RCP emissions scenarios, capturing only the earth-system uncertainty. Panel c shows relationship between cumulative CO2 emissions in the 2000-2100 period and median 2081-2100 temperature levels calculated by MAGICC. Panel d indicates the median temperature development of overshoot (>0.4 W/m2) and non-overshoot scenarios for the first two scenario categories (25-75th percentile of scenario outcomes). Source: WG III AR5 Scenario Database (Annex II.10).

Defining temperature goals in terms of the chance of exceeding a particular temperature this century accounts for both the 2100 concentration and the pathway to get to this concentration (Figure 6.14). For example, overshoot scenarios of greater than 0.4 W/m2 have a higher probability of exceeding 2°C prior to 2100 than in 2100 (Figure 6.14, panel a). In general, the results suggest that the peak concentration during the 21st century is a fundamental determinant of the probability of remaining below a particular temperature goal (Figure 6.14, panel c). The CO_2-e concentration in 2100, on the other hand, is a proxy for the probability of exceeding end-of-the-century temperature goals (panel d). Only scenarios leading to 2100 concentrations of 430-480 ppm and a small number of scenarios leading to 2100 concentrations of 480-530 ppm have a likely (>66%) chance of maintaining temperature change below 2°C throughout the century. Scenarios that reach 2100 concentrations between 530 ppm and 580 ppm CO2eq while exceeding this range during the course of the century are *unlikely* (<33%) to limit transient temperature change to below 2°C over the course of the century.

Other temperature levels in addition to 2°C are relevant for mitigation strategy. Scenarios leading to concentrations between 430 and 480 ppm CO2-e are less likely than not (<50%) to remain below 1.5°C throughout the 21st century, and many are unlikely (<33%) to reach this goal. However, as noted in Section 6.3.2.1 , there are scenarios in the literature that reach levels below 430 ppm CO2-e by 2100, but these were not submitted to the database used for this assessment. Using the same methods for assessing temperature implications of scenarios as used in this assessment, the associated studies found that 2100 temperature changes for these scenarios are likely (>66%) to lie below 1.5 C, after peaking earlier in the century (e.g. Luderer et al, 2013, Rogelj et al, 2013a,b). In contrast, all scenarios submitted to this assessment that lead to CO2-e concentration below 580 ppm CO2-e by 2100 provide are more likely than not (>50%) to remain below 2.5°C during the 21st century, and many are likely (>66%). (Section 6.9 discusses how the use of geoengineering techniques can change the relationships between greenhouse gas emissions and radiative forcing.)

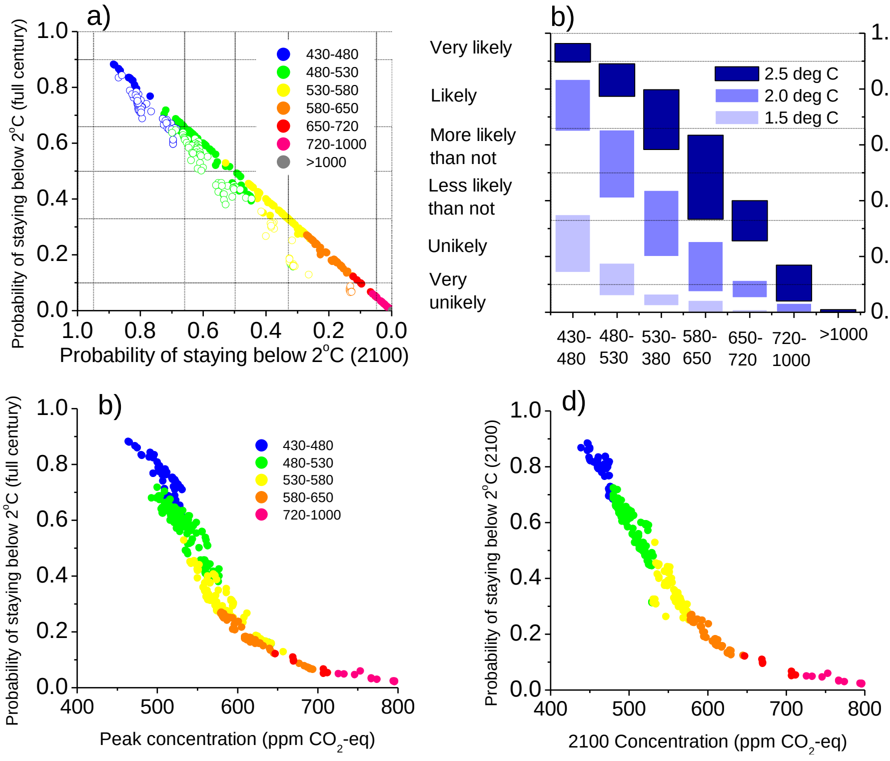


Figure 6.14. The probability of staying below temperature levels for the different scenario categories as assessed by the MAGICC model (representing the statistics of 600 different climate scenarios). Panel a: 2 Probability in 2100 of being below 2°C versus probability of staying below 2°C throughout the 21st century. Open dots indicate overshoot scenarios (>0.4 W/m2). Panel b: probability of staying below 1.5, 2.0 and 2.5°C (10-90th percentile) during 21st century. Panel c: Relationship between peak concentration and the probability of exceeding 2°C during the 21st century. Panel d: Relationship between 2100 concentration and the probability of exceeding 2°C in 2100. Source: Scenario database for AR5.

6.3.3 Treatment of impacts and adaptation in transformation pathways

The importance of considering impacts and adaptation responses when assessing the optimal level of mitigation in a cost-benefit framework has been well studied in highly-aggregated models (see Box6.1. on cost-benefit analysis). However the role impacts and adaptation in scenarios from large-scale integrated models has seen far less treatment. Mitigation, impacts and adaptation are interlinked in several important ways and should, ideally, be considered jointly in the context of achieving concentration goals. A few studies consider mitigation, impacts, and adaptation simultaneously in their construction of scenarios (see Nelson and et al.; Reilly et al., 2007a; Isaac and van Vuuren, 2009; Chum et al., 2011; Calvin et al., 2013; Zhou et al., 2013; Dowling, 2013). In the vast majority of cases, however, the scenarios discussed in this chapter do not consider these linkages, and this is considered a major gap in the transformation pathways literature. (For a summary of integrated models that capture impacts and adaptation see, e.g., Füssel (2010) and Fisher-Vanden et al. (2012). (For a comprehensive discussion of climate impacts, adaptation, and vulnerability, see IPCC WGII AR5). Major efforts are now underway to incorporate impacts and adaptation into large-scale integrated models, but these efforts must overcome a range of challenges, including incorporating the sectoral and regional character of impact and adaptation into integrated models, which have higher spatial aggregation, and a desperate lack of data and empirical evidence on impacts and adaptation required for model inputs.

Omitting climate impacts and adaptation responses from scenarios is likely to lead to biased results for three main reasons. First, climate impacts could influence the effectiveness of emissions mitigation options. For instance, electricity production could be affected by changes in cooling water availability (Schaeffer et al., 2012) or air temperature, changes in precipitation will alter hydroelectric power, or climate change could impact biofuel crop productivities (Chum et al., 2011). 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, either increasing or decreasing the emissions reductions required to reach GHG concentration goals. 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, a warmer climate will lead to reductions in heating demand, which would lower emissions. Also, impacts could potentially lead to lower economic growth and thus 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 (Isaac and van Vuuren, 2009; Zhou et al., 2013). Climate change will also change the ability of the terrestrial biosphere to store carbon. Again, there is a limited number of studies that account for this adaptive response to climate change (Bosello et al., 2010b; Eboli et al., 2010; Anthoff et al., 2011) or optimal mitigation levels when adaptation responses are included (Patt et al., 2009). Finally, mitigation strategies will need to compete with adaptation strategies for scarce investment and R&D resources, assuming these occur contemporaneously. A number of studies account for competition for investment and R&D resources. In cost-benefit several modeling studies (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, such as investment and R&D (Hope, 2006). No existing study, however, examines how this crowding out will affect an economy’s ability to invest in mitigation options to reach concentration goals.

6.3.4 Energy sector in transformation pathways

The fundamental transformation required in the energy system to meet long-term concentration goals is a phase-out in the use of freely-emitting fossil fuels, the timing of which depends on the concentration goal (Fischedick et al., 2011). Reference scenarios indicate that scarcity of fossil fuels alone will not be sufficient to limit CO2-e concentrations to levels such as 450, 550, or 650 ppm by 2100 (Bauer, Mouratiadou, et al.; Verbruggen and Al Marchohi, 2010; Keywan Riahi et al., 2012; McCollum, Bauer, et al., 2013; Calvin et al., 2014, Section 7.4.1). Mitigation scenarios indicate that meeting long-term goals will most significantly reduce coal use, followed by unconventional oil and gas use, with conventional oil and gas affected the least (Bauer, Bosetti, et al.; Bauer, Mouratiadou, et al.; David McCollum et al., 2014) (Figure 6.15). This will lead to strong re-allocation effects on international energy markets (Section 6.3.6.6).

The reduction in freely-emitting fossil fuels is not necessarily equal to the reduction in fossil fuels more generally, however, because fossil resources can be used in combination with CCS to serve as a low-carbon energy source (Bauer et al.; McFarland et al., 2009; McCollum et al., 2013a; van der Zwaan et al., 2014) (see also Sections 7.5.5 and 7.11.2). This means that the total use of fossil fuels can exceed the use of freely-emitting fossil fuels.

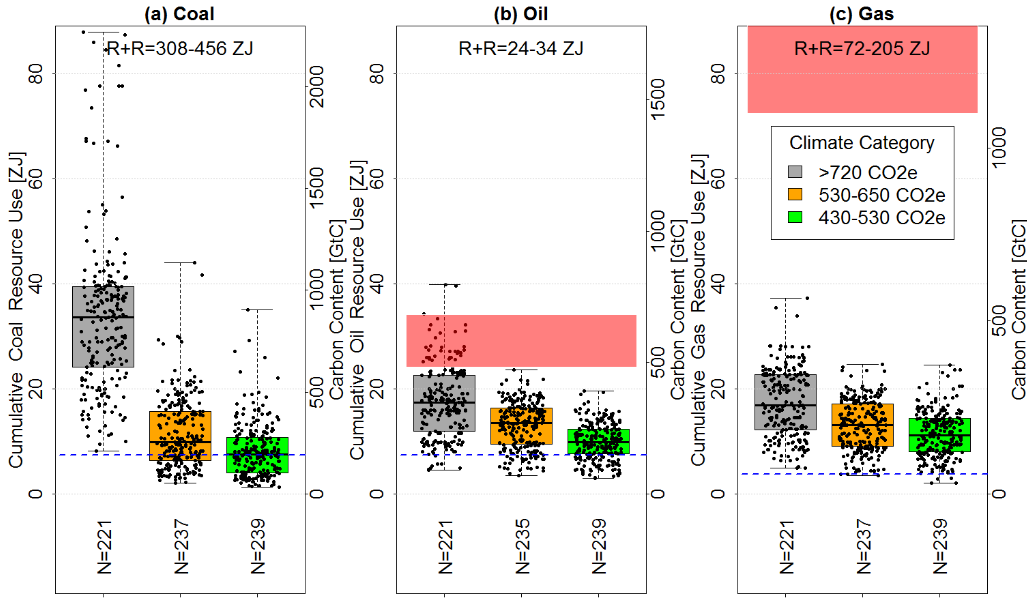


Figure 6.15. Cumulative global coal (a), oil (b) and gas (c) use in baseline and mitigation scenarios compared to reserves and resources. Reserves and resources ("R+R") are shown in red and historical cumulative use until 2010 is shown as dashed blue line. The thick black line corresponds to the median, the coloured box to the inter-quartile range (25th to 75th percentile) and the whiskers to the total range across all reviewed scenarios. Dots correspond to individual scenarios, of which the number in each sample is indicated at the bottom of each panel. Note that the horizontal distribution of dots does not have a meaning, but avoids overlapping dots. Source: WG III AR5 Scenario Database (Annex II.10). Includes only scenarios based on idealized policy implementation. Reserve, resource and historical cumulative use from Table 7.1 in Section 7.4.1.

To accommodate this reduction in freely-emitting fossil fuels, transformations of the energy system rely on a combination of three high-level strategies: (1) decarbonisation of energy supply, (2) an associated switch to low-carbon energy carriers such as decarbonized electricity, hydrogen, or biofuels in the end-use sectors, and (3) reductions in energy demand. The first two of these can be illustrated in terms of changes in the carbon intensity of energy. The last can be illustrated in terms of energy intensity of GDP, energy per capita, or other indexed measures of energy demand.

The integrated modeling 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 concentration goals

(Figure 6.16). The fundamental reason for this is that the ultimate potential for end use reduction is limited; some energy will always be required to provide energy services. Bringing energy system CO2 emissions down toward zero, as is ultimately required for meeting any concentration goal, 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.

At the same time, integrated modelling studies also sketch out a dynamic in which energy intensity reductions equal or outweigh decarbonisation of energy supply in the near-term when the supply system is still heavily reliant on largely carbon intensive fossil fuels, and then the trend is reversed over time (Figure 6.17, cf. Fisher et al. (2007a, fig. 3.21)). At the most general level, this results directly from assumptions about the flexibility to achieve end use demand reductions relative to decarbonization of supply in integrated models (Kriegler et al., 2013b), about which there is a great deal of uncertainty (see Section6.8). More specifically, one reason for this dynamic 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 (cf. Section 7.11.3), there is an increasing incentive to increase its use relative to sources associated with higher emissions, such as natural gas. 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. Indeed, much of the energy reduction takes place in baseline scenarios. 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.

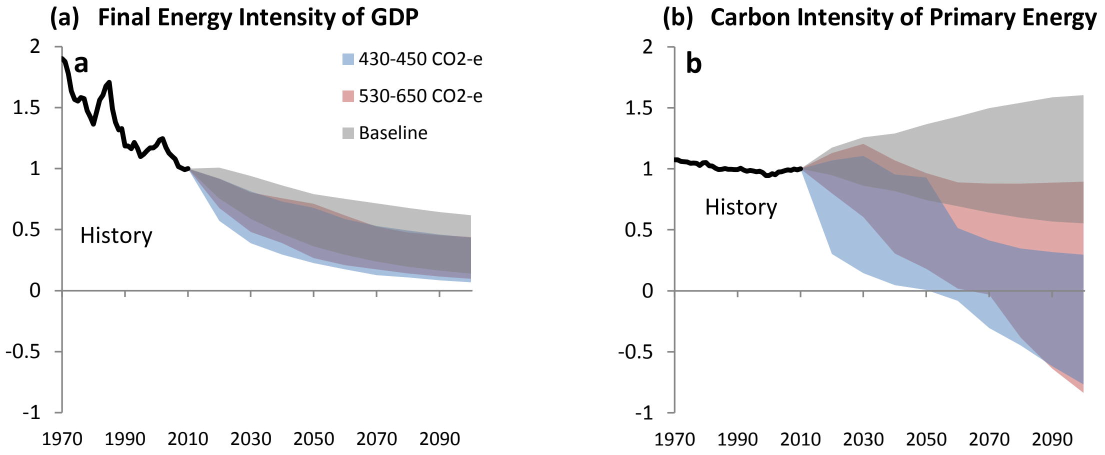


Figure 6.16. Final energy intensity of GDP (a) and carbon intensity of primary energy (b) in transformation pathways and baseline scenarios, normalized to 1 in 2010. GDP is aggregated using base-year market exchange rates. Sources: Heston et al (2012), World Bank (2013), BP (2013), JRC/PBL (2012), IEA (2012a), IPCC AR5 Scenario Database.

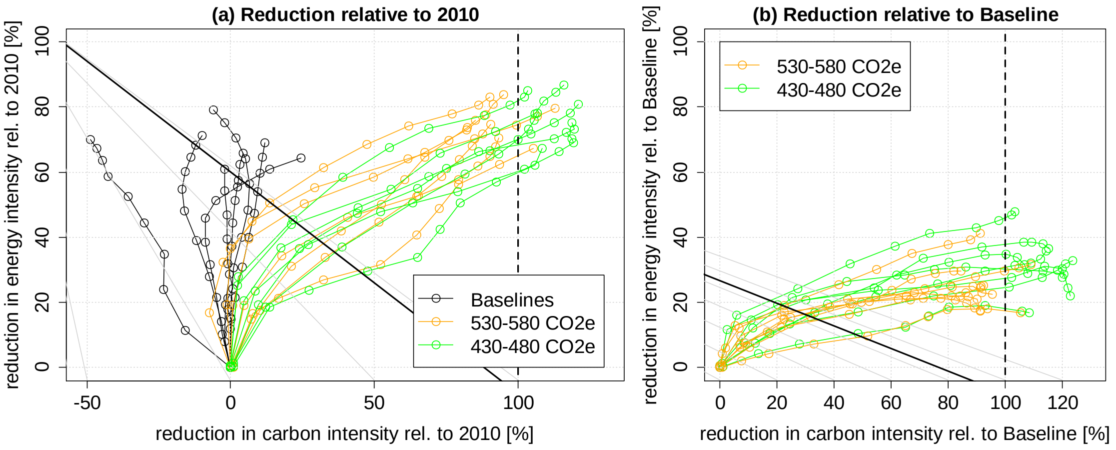


Figure 6.17. Development of carbon intensity vs. final energy intensity reduction (a) relative to 2010 in selected baseline, and mitigation scenarios reaching 550 and 450 ppm CO2-e concentrations in 2100 and (b) relative to baseline in the same 550 and 450 ppm CO2-e scenarios. Consecutive dots represent 10-year time steps starting in 2010 at the origin and going out to 2100. Source: WG III AR5 Scenario Database (Annex II.10). Includes only 2100 scenarios with idealized policy implementation for which a baseline, a 550 ppm and a 450 ppm CO2-e scenario are available from the same set.

The decarbonization of the energy supply will require a significant scale-up of low-carbon energy supplies which may impose significant challenges (cf. Section 7.11.2). The deployment levels of low-carbon energy technologies are substantially higher than today in the vast majority of scenarios, even under baseline conditions, and particularly for the most stringent concentration categories. Scenarios based on an idealized implementation approach in which mitigation begins immediately across the world and with a full portfolio of supply options indicate a scale up of anywhere from a modest increase to upwards of three times today's low carbon energy by 2030 in order to bring concentrations to roughly 450 ppm CO2-e by 2100. 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 6.18, Section 7.11.4). The degree of scale up depends critically on the degree of overshoot, which allows emissions reductions to be pushed into the future.

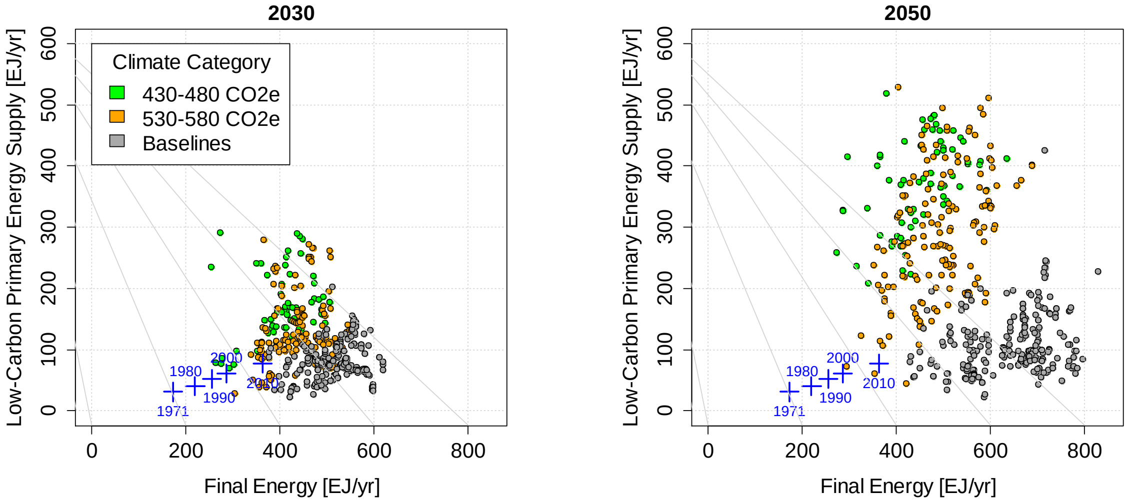


Figure 6.18. Global low-carbon primary energy supply (direct equivalent) vs. total final energy use in scenarios by 2030 and 2050 for idealized implementation scenarios. Low-carbon primary energy includes fossil energy with CCS, nuclear energy, bioenergy and non-biomass renewable energy. Source: WG III AR5 Scenario Database (Annex II.10). Includes baseline and idealized policy implementation scenarios. Historical data from IEA (2012a).

The degree of low-carbon energy scale-up also depends crucially on the degree that final energy use is altered along a transformation pathway. All other things being equal, higher low carbon energy technology deployment tends to go along with higher final energy use and vice versa (Figure 6.18, Figure 7.11). Final energy demand reductions will occur both in response to higher energy prices brought about by mitigation as well as by approaches to mitigation focused explicitly on reducing energy demand. Hence the relative importance of energy supply and demand technologies varies across scenarios (Riahi et al., 2012a).

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 economic and 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 7.9.4). 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 ppm CO_2-e when particularly important technologies are removed from the portfolio. This topic is discussed in more detail in Section 6.3.6.3 .

Delays in climate change mitigation both globally and at regional levels simply alter the timing of the deployment of low-carbon energy sources and demand reductions. As noted in Sections 6.3.2 and Chapter 6: 6.4 , less mitigation over the coming decades will require greater emissions reductions in the decades that follow to meet a particular long-term climate goal. The nature of technology transitions follows the emissions dynamic directly. Delays in mitigation in the near-term will lower the rate of energy system transformation over the coming decades but will call for a more rapid transformation in the decades that follow. Delays lead to higher utilization of fossil fuels, and coal in particular, in the short run, which can be prolonged after the adoption of stringent mitigation action due to carbon lock-ins. In order to compensate for the prolonged use of fossil fuels over the next decades, fossil fuel use - particularly oil and gas - would need to be reduced much more strongly in the long run. One study found that this leads to a reduction in overall fossil energy use over the century compared to a scenario of immediate mitigation (Bauer et al., 2013a). Another study (Riahi et al., 2014) found that if 2030 emissions are kept to below 50 GtCO2-e, then low-carbon energy deployment is tripled between 2030 and 2050 in most scenarios reaching concentrations of roughly 450 ppm CO2-e by 2100. In contrast, if emissions in 2030 are greater than 55 GtCO2-e in 2030, then low-carbon energy deployment increases by five-fold in most scenarios meeting this same long-term concentration goal (see Section 7.11.4 and Figure 7.15 in specific).

Beyond these high-level characteristics of the energy system transformation lie a range of more detailed characteristics and tradeoffs. Important issues include the options for producing low-carbon energy and the changes in fuels used in end uses, and the increase in electricity use in particular, both with and without mitigation. These issues are covered in detail in Section 6.8 and Chapter 7 through 12.

6.3.5 Land and bioenergy in transformation pathways

Scenarios suggest a substantial cost-effective, and possibly essential, mitigation role for land in transformation (Section 6.3.2.4 and Section 11.9), with baseline land emissions and sequestration an important uncertainty (Section 6.3.1.3). Changes in land use and management will result from a confluence of factors, only some of which are due to mitigation. The key forces associated with mitigation are (1) the demand for bioenergy, (2) the demand to store carbon in land by reducing deforestation, encouraging afforestation, and altering soil management practices, and (3) reductions in non-CO2 GHG emissions by changing management practices. Other forces include demand for food and other products, such as forest products, land for growing urban environments, and protecting lands for environmental, aesthetic and economic purposes.. Currently, only a subset of models explicitly model land-use change in scenarios. The development of fully integrated land use models is an important area of model development.

Scenarios from integrated models suggest the possibility of very different landscapes relative to today, even in the absence of mitigation. Projected global baseline land use changes by 2050 typically exhibit increases in non-energy cropland and decreases in “other” land, such as abandoned land, other arable land, and non-arable land (Figure 6.19). On the other hand, projected baseline pasture and forest land exhibit both increases and decreases. The projected increases in non-energy cropland and decreases in forest area through 2050 are typically projected to outpace historical changes from the previous 40-years (+165 and -105 million hectares of crop and forest area changes respectively from 1961-2005 (Food and Agriculture Organization of the United Nations (FAO), 2012)).Energy cropland is typically projected to increase as well, but there is less agreement among scenarios. Overall, baseline projections portray large differences across models in the amount and composition of the land converted by agricultural land expansion. These baseline differences are important in that they represent differences in the opportunity costs of land use and management changes for mitigation. (See chapter 11.9 for regional baseline, and mitigation, land use projections for a few models and scenarios.)

Mitigation generally induces greater land cover conversion than in baseline scenarios, but for a given level of mitigation, there is large variation in the projections (Figure 6.19). Projections also suggest additional land conversion with tighter concentration goals, but declining additional conversion with increased mitigation stringency. This is consistent with the declining role of land-related mitigation with the stringency of the mitigation goal (Rose et al., 2012). However, additional land conversion with more stringent goals could be substantial if there are only bioenergy incentives.

A common, but not universal, characteristic of transformation scenarios is an expansion of energy cropland to support the production of modern bioenergy. There is also a clear trade-off in the scenarios between energy crop land cover and other cover types. Most scenarios project reduced non-energy cropland expansion, relative to baseline expansion, with some projections losing cropland relative to today. On the other hand, there are projected pasture changes of every kind. Forest changes depend on the incentives and constraints considered in each scenario. Some of the variations in projected land-use change are attributable to specific assumptions, such as fixed pasture acreage, prioritized food provision, land availability constraints for energy crops, and the inclusion or exclusion of afforestation options (e.g., Popp et al., 2013). Others are more subtle outcomes of combinations of modelling assumption and structure, such as demands for food and energy, land productivity & heterogeneity, yield potential, land production options, and land conversion costs.

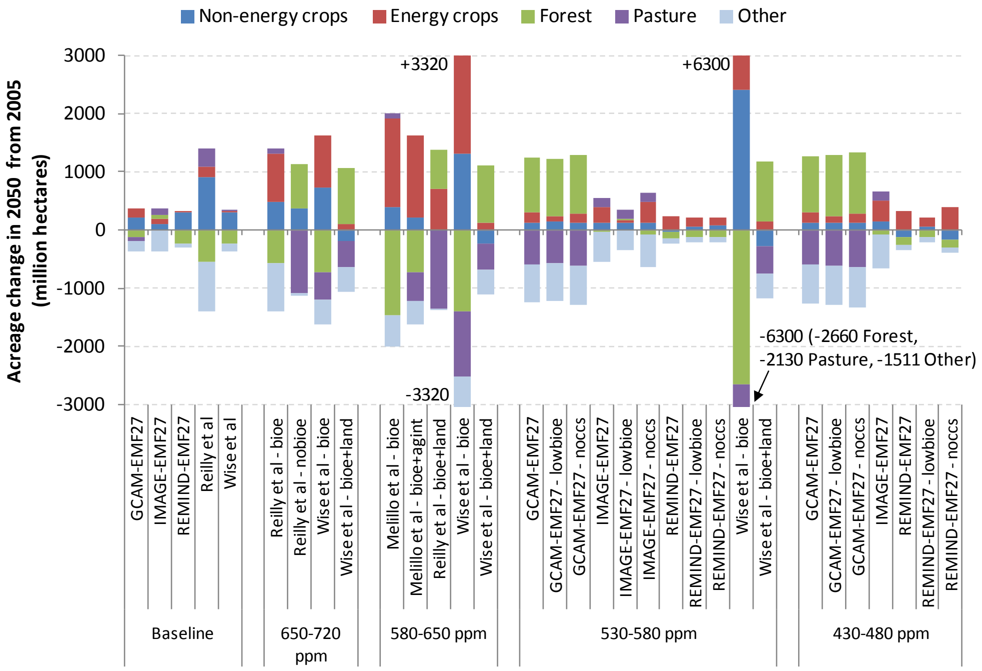


Figure 6.19. Global land cover change by 2050 from 2005 for a sample of baseline and mitigation scenarios with different technology assumptions. Sources: EMF-27 Study (Kriegler et al., 2014c), Reilly et al. (2012), Melillo et al. (2009), Wise et al. (2009b). Notes: default (see Section 6.3.1) fossil fuel, industry, and land mitigation technology incentives assumed except as indicated – "bioe" = only land-based mitigation incentive is, "nobioe" = land incentives but not for modern bioenergy, "bioe+land" = modern bioenergy and land carbon stocks incentives, "bioe+agint" = modern bioenergy incentive and agricultural intensification response allowed, "lowbio" = global modern bioenergy constrained to 100 EJ/year, "noccs" = CCS unavailable for fossil or bioenergy use. Other land cover includes abandoned land, other arable land, and non-arable land.

Which mitigation activities are available or incentivized has important implications for land conversion (Figure 6.19). Bioenergy incentives alone can produce energy crop expansion, with increased forest and other land conversion (Wise et al., 2009b; Reilly et al., 2012). In general, forest land contraction results when increased demand for energy crops is not balanced by policies that incentivize or protect the storage of carbon in terrestrial systems. However, the degree of this forest conversion will depend on a range of factors, including the potential for agricultural intensification and underlying modeling approaches. For example, Melillo et al. (2009) find twice as much forest land conversion by 2050 when they ignore agricultural intensification responses. Forest land expansion is projected when forests are protected, there are constraints on bioenergy deployment levels, or there are combined incentives for bioenergy and terrestrial carbon stocks (e.g., Wise et al., 2009a; Reilly et al., 2012, and GCAM-EMF27 in Figure 6.19). Differences in forest land expansion result largely from differences in approaches to incorporating land carbon in the mitigation regime. For example, In Figure 6.19, GCAM-EMF27 (all variants), Wise et al. (low bioe+land) and Reilly et al. (low bioe and bioe+land) include an explicit price incentive to store carbon in land, which serves to encourage afforestation and reduce deforestation of existing forests, and discourage energy cropland expansion. In contrast, other scenarios consider only avoided deforestation (REMIND-EMF27), or land conversion constraints (IMAGE-EMF27). Both 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 (2011a) (not shown) impose conservation policies that protect forest regardless of cost. The explicit pricing of land carbon incentives can lead to large land use carbon sinks in scenarios, and an afforestation incentive or constraint on bioenergy use can result in less land conversion from bioenergy, but not necessarily less land conversion as afforestation may increase.

An important issue with respect to bioenergy, and therefore to land transformation, is the availability and use of BECCS. As discussed in Section 6.3.2 , BECCS could be valuable for reaching lower concentration levels, in part by facilitating concentration overshoot. The availability of CCS could therefore also have land use implications. Constraints on the use of CCS would prohibit BECCS deployment. However, CCS (for BECCS as well as fossil energy with CCS) may not increase land conversion through 2050 relative to scenarios without BECCS. Instead, the presence of BECCS could decrease near-term energy crop expansion as some models project delayed mitigation with BECCS (Rose et al., 2014a, 6.3.2.2). In addition to biomass feedstock requirements, BECCS land considerations include bioenergy CCS facility land, as well as optimal siting relative to feedstock, geologic storage, and infrastructure.

As noted above, land transformation is tightly linked to the role of bioenergy in mitigation. To understand bioenergy's role in transformation pathways, it is important to understand bioenergy's role within the energy system. The review by Chum et al. (2011) review estimated technical potential for bioenergy of 300 and 500 EJ/year in 2020 and 2050 respectively, and deployment of 100 to 300 EJ of biomass for energy globally in 2050, while Rose et al. (2012) found bioenergy contributing up to 15% of cumulative primary energy over the century under climate policies. Rose et al. (2014a) analyze more recent results from fifteen models (Figure 6.20). They find that modelled bioenergy structures vary substantially across models, with differences in feedstock assumptions, sustainability constraints, and conversion technologies. Nonetheless, the scenarios project increasing deployment of, and dependence on, bioenergy with tighter climate change goals, both in a given year as well as earlier in time. 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 is projected to be up to 35% and 75% respectively by 2050. However, there is no single vision about where biomass is cost-effectively deployed within the energy system (electricity, liquid fuels, hydrogen, and/or heat), due in large part to uncertainties about relative technology options and costs over time. (See Chapter 7 for more detail on bioenergy's role in energy supply.) As noted above, the availability of CCS, and therefore BECCS, has important implications for bioenergy deployment. In scenarios that do include BECCS technologies, BECCS is deployed in greater quantities and earlier in time the more stringent the goal, potentially representing 100% of bioenergy in 2050 (Figure 6.20).

Models universally project that the majority of biomass supply for bioenergy and bioenergy consumption will occur in developing and transitional economies. For instance, the study by (Rose et al., 2014a) found that 50-90% of global bioenergy primary energy is projected from non-OECD countries in 2050, with the share increasing beyond 2050. Developing and transitional regions are also projected to be the home of the majority of agricultural and forestry mitigation.

A number of integrated models have explicitly modeled land-use with full emissions accounting, including indirect land-use change and agricultural intensification. These models have found that it is cost-effective to trade-off lower land carbon stocks from land-use change and increased N_2O emissions from agricultural intensification for the long-run climate change management benefits of bioenergy (Popp et al., 2013; Rose et al., 2014a).

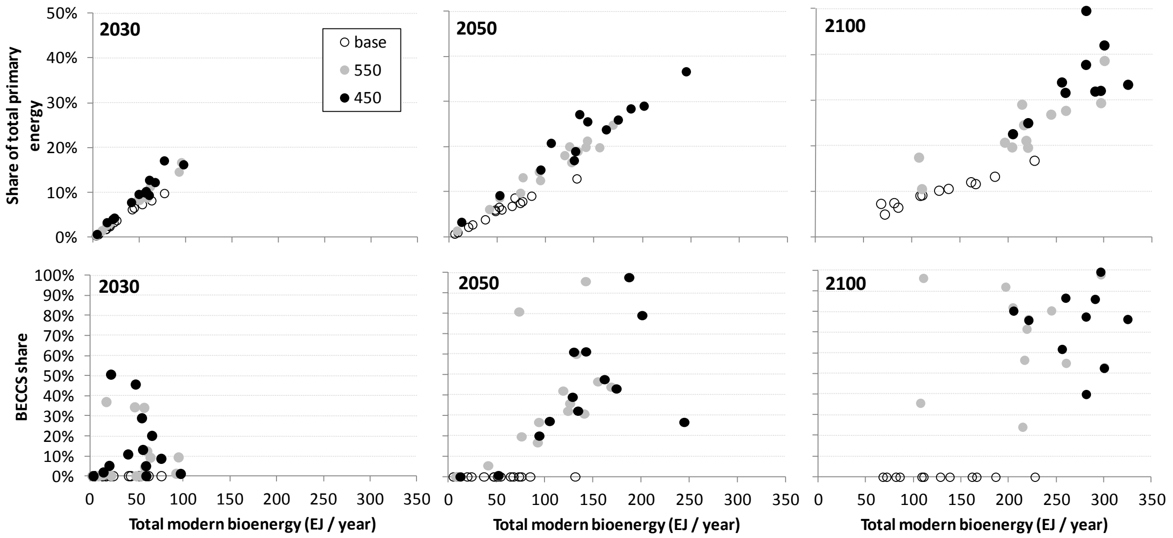


Figure 6.20. Annual global modern biomass primary energy (top) and BECCS share of modern bioenergy (bottom) in baseline, 550 and 450 CO2-e ppm scenarios in 2030, 2050, and 2100. Source: Rose et al. (2014a). Notes: All scenarios shown assume idealized implementation. Results for 15 models shown (3 models project to only 2050). Also, some models do not include BECCS technologies and some no more than biopower options.

Overall, the integrated modeling literature suggests opportunities for large-scale global deployment of bioenergy and terrestrial carbon gains. However, these transformations, associated with mitigation, will be 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. Among other things, bioenergy deployment is complicated by a variety of social concerns, such as land conversion and food security (See Section 6.6 and the Chapter 11 Bioenergy Annex). Coordination between land mitigation policies, regions, and activities over time will affect forestry, agricultural, and bioenergy mitigation costs and net GHG effectiveness. When land options and bioenergy are included in transformation scenarios, it is typically under the assumption of a highly-idealized implementation, with immediate, global, and comprehensive availability of land related mitigation options. In these cases, models are assuming a global terrestrial carbon stock incentive or global forest protection policy, global incentives for bioenergy feedstocks and global agriculture mitigation policies. They also assume no uncertainty, risk, or transactions costs. (For a discussion of these issues, see Lubowski and Rose, 2013). The literature has begun exploring more realistic policy contexts and found that there is likely less available mitigation potential in the near-term than previously estimated, and possibly unavoidable emissions leakage associated with getting programs in place, and with voluntary mitigation supply mechanisms (Section 11.9, Section 6.8) Additional exploration into the need for and viability of large-scale land-based mitigation is an important area for future research.

6.3.6 The aggregate economic implications of transformation pathways

6.3.6.1 Overview of the aggregate economic implications of mitigation

Emissions mitigation will require a range of changes, including behavioural changes and the use of alternative technologies. These changes will affect economic output and the consumption of goods and services. The primary source of information on these costs over multi-decade or century-long time horizons are integrated models such as those reviewed in this chapter.

Mitigation will affect economic conditions through several avenues, only some of which are included in estimates from integrated models. To a first-order, mitigation involves reductions in the consumption of energy services, and perhaps agricultural products, and the use of more expensive technologies. This first-order effect is the predominant feature and focus of the integrated modeling estimates discussed in this chapter and will lead to aggregate economic losses. However, mitigation policies may interact with pre-existing distortions in labour, capital, energy and land markets, and market failures in markets for technology adoption and innovation, among other things. These interactions might increase or decrease economic impacts (Sections 3.6.3 and 6.3.6.5).

Estimates of the potential aggregate economic effects from mitigation are generally expressed as deviations from a counterfactual baseline scenario without mitigation policies; that is, the difference in economic conditions relative to what would have happened without mitigation. The estimates, and those discussed in this section, generally do not include the benefits from reducing climate change, nor do they consider the interactions between mitigation, adaptation, and impacts (Section 6.3.3). In addition, the estimates do not take into account important co-benefits and adverse side-effects from mitigation, such as impacts on land use and health benefits from reduced air pollution (Sections 11.13.6 and 6.6).

A wide range of methodological issues attend the estimation of aggregate economic costs in integrated models, one of which is the metric itself. (For more discussion on these issues in estimating aggregate economic costs, see Annex II.3.2.on mitigation costs metrics and Chapter 3.) A change in welfare due to changes in household consumption is commonly measured in terms of equivalent and compensating variation, but other, more indirect, cost measures such as GDP losses, consumption losses, and area under the marginal abatement cost function are more widely used. For consistency, results in this section are presented preferentially in terms of cost measures commonly reported by the models: consumption losses and GDP losses for general-equilibrium models, and area under the marginal abatement cost function or reduction of consumer and producer surplus (in the following summarized with the term abatement cost) for partial-equilibrium models. These cost metrics differ in terms of whether or not general equilibrium effects in the full economy have been taken into account and whether or not the direct impact on households or the intermediate impact on economic output is measured. They are therefore treated separately in this chapter.

Emissions prices (carbon prices) are also assessed in this chapter. However, they are not a proxy for aggregate economic costs for two primary reasons. First, emissions prices measure marginal cost; that is, the cost of an additional unit of emissions reduction. In contrast, total economic costs represent the costs of all mitigation that has taken place. Second, emissions prices can interact with other policies and measures, such as regulatory policies or subsidies directed at low carbon technologies, and will therefore indicate a lower marginal cost than is actually warranted if mitigation is achieved partly by these other measures.

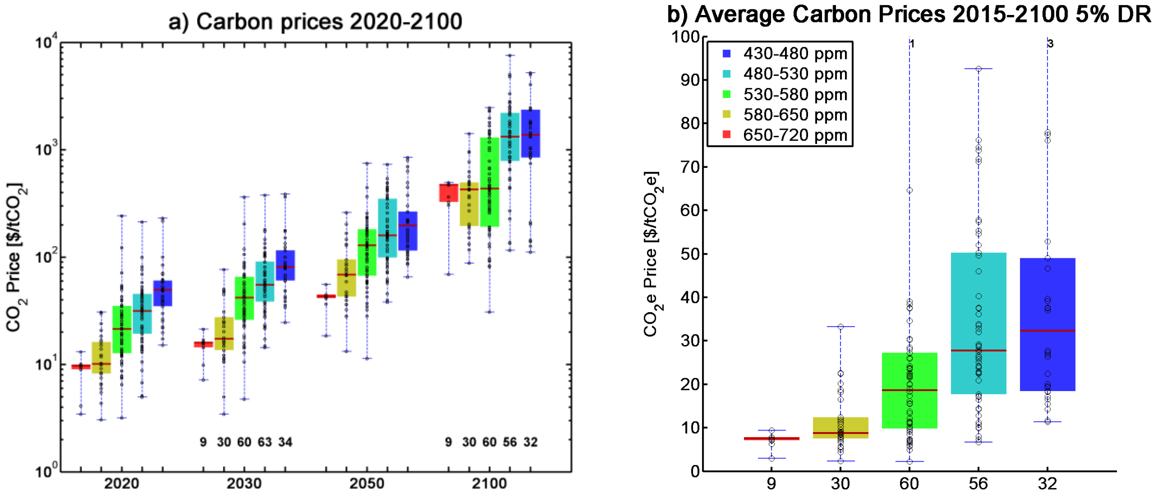
Different methods can be used to sum costs over time. For this purpose, in the absence of specific information from individual models about the discount rate used in studies, the estimates of net present value costs in this chapter are aggregated ex-post using a discount rate of 5%. This is roughly representative of the average interest rate that underlies the discounting approach in most models (Kriegler et al., 2014c). Other rates could have been used to conduct this ex-post aggregation. Since mitigation costs tend to rise over time, lower (higher) rates would lead to higher (lower) aggregate costs than what are provided here. However, it is important to note that constructing NPV metrics based on other rates is not the same as actually evaluating scenarios under alternative discounting assumptions and will not accurately reflect aggregate costs under such assumptions.

Estimates of aggregate economic effects from integrated models vary substantially. This arises because of differences in assumptions about driving forces such as population and economic growth and the policy environment in the baseline, as well as differences in the structures and scopes of the models (Section 6.2). In addition, aggregate economic costs are influenced by the future cost, performance, and availability of mitigation technologies (Section 6.3.6.3), the nature of international participation in mitigation (Section 6.3.6.4), and the policy instruments used to reduce emissions and the interaction between these instruments and pre-existing distortions and market failures (Section 6.3.6.5).

6.3.6.2 Global aggregate costs of mitigation in idealized implementation scenarios

A valuable benchmark for exploring aggregate economic mitigation costs are estimates based on the assumption of a stylized implementation approach in which a ubiquitous price on carbon and other greenhouse gases is applied across the globe in every sector of every country and that rises over time in a way that minimizes the discounted sum of costs over time. These "idealized implementation" scenarios are included in most studies as a benchmark against which to compare results based on less-idealized circumstances. One reason that these idealized scenarios have been used as a benchmark is that the implementation approach provides the lowest costs under idealized implementation conditions of efficient global markets in which there are no pre-existing distortions or interactions with other, non-climate market failures. For this reason, they are often referred to as "cost-effective" scenarios. However, the presence of pre-existing market distortions, non-climate market failures, or complementary policies means that the cost of the idealized approach could be lower or higher than in an idealized implementation environment, and that the idealized approach may not be the least cost strategy (see Section 6.3.6.5). Most of the idealized implementation scenarios assessed here consider these additional factors only to a limited degree or not at all, but the extent to which a non-idealized implementation environment is accounted for varies between them.

A robust result across studies is that aggregate global costs of mitigation tend to increase over time and with stringency of the concentration goal (Figure 6.21). For idealized implementation scenarios reaching levels of 430-480 ppm CO_2e by 2100 in the WG III AR5 Scenario Database (Annex II.10), the central 70% of global consumption loss estimates (10 out of 14) range between 1% to 4% in 2030, 2% to 6% in 2050, and 2% to 12% in 2100 relative to consumption in the baseline (Figure 6.21c). For context, consumption is assumed to grow by roughly a factor of two to four-and-one-half by 2050, and four-fold to over ten-fold over the century in the baseline scenarios in the scenario database (values are based on global projections in market exchange rates).



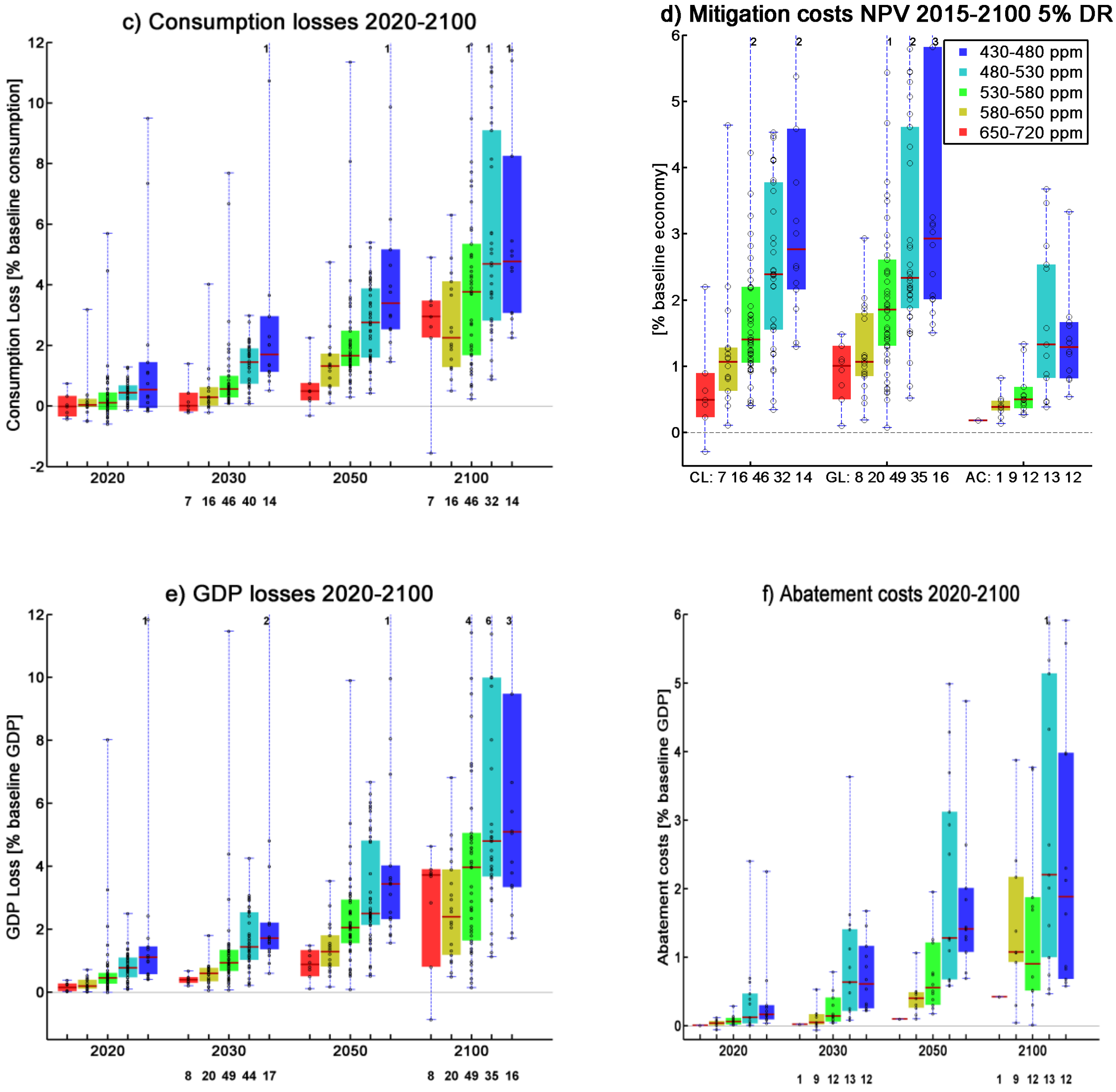
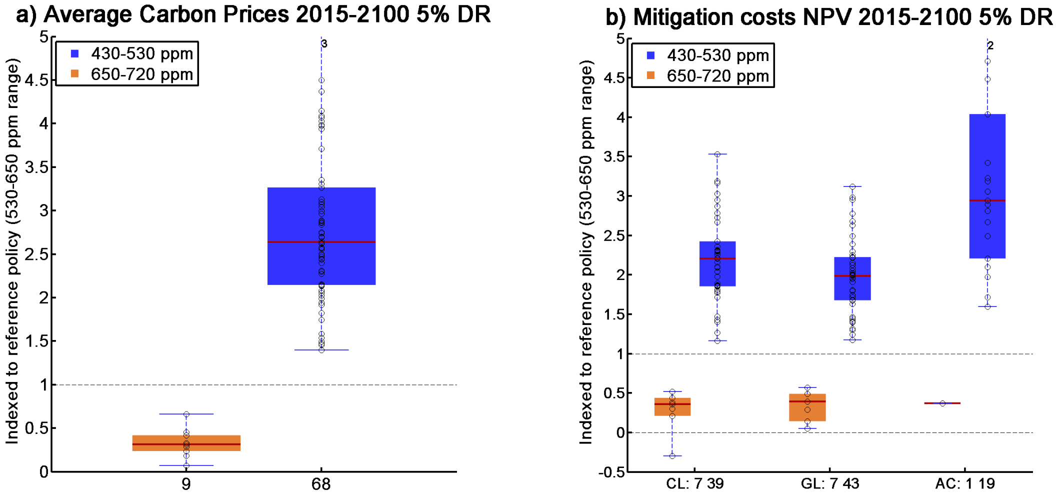


Figure 6.21. Global mitigation costs of idealized implementation scenarios. Panels show the development of (a) carbon prices, (c) consumption losses (CL), (e) GDP losses (GL) and (f) abatement costs (AC) over time, and (b) the average carbon price (2015-2100) and (d) the net present value mitigation costs (CL, GL, and AC; 2015-2100) discounted at 5%. Costs are expressed as a fraction of economic output – or in the case of consumption losses – consumption in the baseline. Box plots show full range (whiskers), interquartile range (box extending to the data points at or below (above) the 25th (75th) percentile) and median (red line) of scenario samples. Sample size is indicated at the bottom of the panels. The number of scenarios outside the figure range is noted at the top. One model shows net present value consumption losses of 13%/9% and GDP losses of 15%/11% for 430-480/530-580 ppm CO2-e (see text). Source: WG III AR5 Scenario Database (Annex II.10).The scenario selection includes all idealized implementation scenarios that reported costs or carbon prices to 2050 or 2100 (only the latter are included in aggregate cost and price plots) after removal of similar scenarios (in terms of reaching similar goals with similar overshoots and assumptions about baseline emissions) from the same model.

An important caveat to these results is that they do not account for a potential model bias due to the fact that higher-cost models may have not been able to produce low concentration scenarios and have therefore not reported results for these scenarios (see discussion of model failures in Section 6.2, and Tavoni and Tol, 2010). They also do not capture uncertainty in model parameter assumptions (Webster et al., 2012). Since scenario samples for different concentration levels do not come from precisely the same models it is informative to look at the cost changes between different concentration levels as projected by individual models within a given study (Figure 6.22). This can partly remove model bias, although the bias from a lack of models that could not produce low concentration scenarios remains. The large majority of studies in the scenario database for AR5 report a factor 1.5 to 3 higher global consumption and GDP losses, and 2 to 4 time higher abatement costs, for scenarios reaching 430-530 ppm CO_2-e by 2100 compared to the 530-650 ppm CO2-e range.


a) Average Carbon Prices 2015-2100 5% DR

b) Mitigation costs NPV 2015-2100 5% DR

Figure 6.22. Carbon price (left panel) and global mitigation cost changes (right panel) for idealized implementation scenarios relative to a reference concentration category (530-650 ppm in 2100). Results for NPV costs are shown by consumption losses (CL), GDP losses (GL) and abatement costs (AC). Results are based on pairs of idealized implementation scenarios, one in the 530-650 ppm range and one in a neighbouring concentration range, from a single model and study. Cost changes were calculated on the basis of net present value economic costs (discounted at 5% per year) and carbon price changes on the basis of average discounted values for the period 2015-2100. See figure caption 6.21 for further explanation on the presentation of results. Source: WG III AR5 Scenario Database (Annex II.10).

Aggregate economic costs vary substantially, even in idealized scenarios. The variation of cost estimates for individual climate categories can be attributed, among other things, to differences in assumptions about driving forces such as population and GDP and differences in model structure and scope (see Section 6.2 for a discussion of model differences). Diagnostic studies have indicated that the assumed availability and flexibility of low carbon technologies to substitute fossil energy is a key factor influencing the level of carbon prices for a given level of emissions reductions (Kriegler et al., 2013b). The extent to which carbon prices translate into mitigation costs through higher energy prices is another factor that differs between models. Both the variation of carbon prices and the variation of the economic impact of higher prices are major determinants of the observed range of aggregate economic costs for a given amount of emissions reductions. Assumptions about the implementation environment can be another important driver of costs. For example, the highest consumption and GDP losses in the scenario sample are from a model with an emphasis on market imperfections, infrastructure lock-ins and myopia (Waisman et al., 2012).

It is possible to control for several key sources of variation by relating mitigation costs to cumulative emissions reductions from baseline emissions (Figure 6.23). As expected, carbon prices and mitigation costs increase with the amount of mitigation. Since different models have different capabilities for deep emissions reductions, the inter-model spread in carbon price and cost estimates increases as well. In other words, scenarios indicate greater consensus regarding the nature of mitigation costs at higher concentration levels than those at lower levels. This increase in variation reflects the challenge associated with modelling energy and other human systems that are dramatically different than those of today.

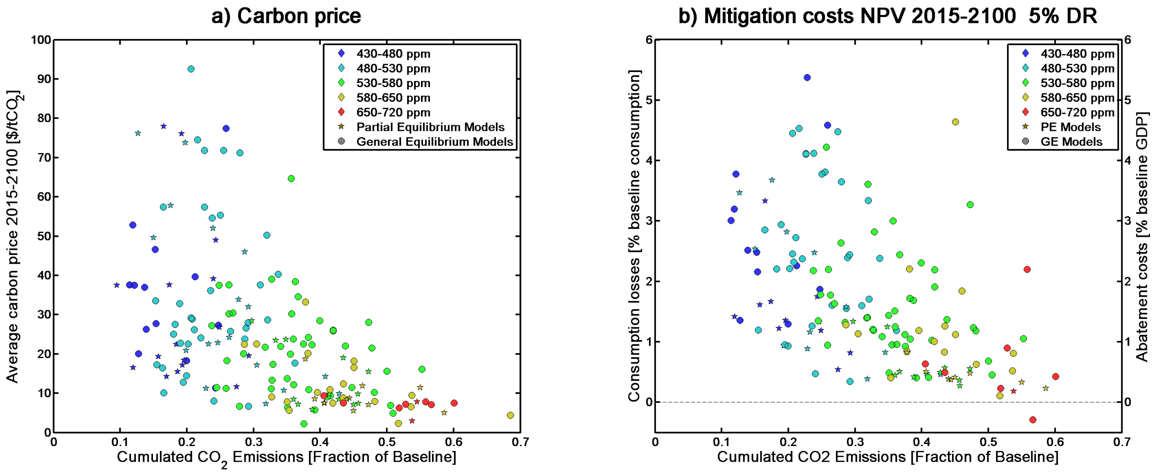


Figure 6.23. Average carbon prices (a) and global mitigation costs (b) as a function of residual cumulative CO2 emissions reduction from fossil fuel combustion and industry expressed as fraction of cumulative baseline emissions over the period 2010-2100. Emissions reductions relative to baseline can be deduced by subtracting the fraction of residual cumulative emissions from unity. Mitigation costs are reported in NPV consumption losses for general equilibrium (GE) models or abatement costs for partial equilibrium (PE) models. See description of Figure 6.21 for the selection of scenarios. Source: WG III AR5 Scenario Database (Annex II.10).

6.3.6.3 The implications of technology portfolios for aggregate global economic costs

Because technology will underpin the transition to a low-carbon economy, the availability, cost, and performance of technologies will exert an influence on economic costs. Several multi-model studies and a wide range of individual model studies have explored this space (see Section 6.1.2.2 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 and therefore do not exhibit a strong cost increase if these options are restricted. These models may instead have difficulties in achieving tighter concentration goals regardless of the restriction (Krey et al., 2014). In addition, assumptions about cost and performance can vary across models, even within a single, multi-model study. Moreover, many limited technology scenarios are characterized by frequent model infeasibilities, as shown by the fraction of models able to meet a particular goal with different technology combinations for EMF 27 at the bottom of Figure 6.24. (see Section 6.2.4 regarding interpretation of model infeasibility).

Despite these limitations the literature broadly confirms that mitigation costs are heavily influenced by the availability, cost, and performance of mitigation technologies. In addition, these studies indicate that the influence of technology on costs generally increases with increasing stringency of the concentration goal (Figure 6.24). The effect on mitigation costs varies by technology, however, the ranges reported by the different models tend to strongly overlap (Figure 6.24, Krey et al. (2014)), reflecting the general variation of mitigation costs across models (Section 6.3.6.2, Fisher et al. (2007a). In general, models have been able to produce scenarios leading to roughly 550 ppm CO2-e by 2100, even under limited technology assumptions. However, many models could not produce scenarios leading to roughly 450 ppm CO2-e by 2100 with limited technology portfolios, particularly when assumptions preclude or limit the use of BECCS (Azar et al., 2006a; van Vliet et al., 2009; Krey et al., 2014; Kriegler et al., 2014c).

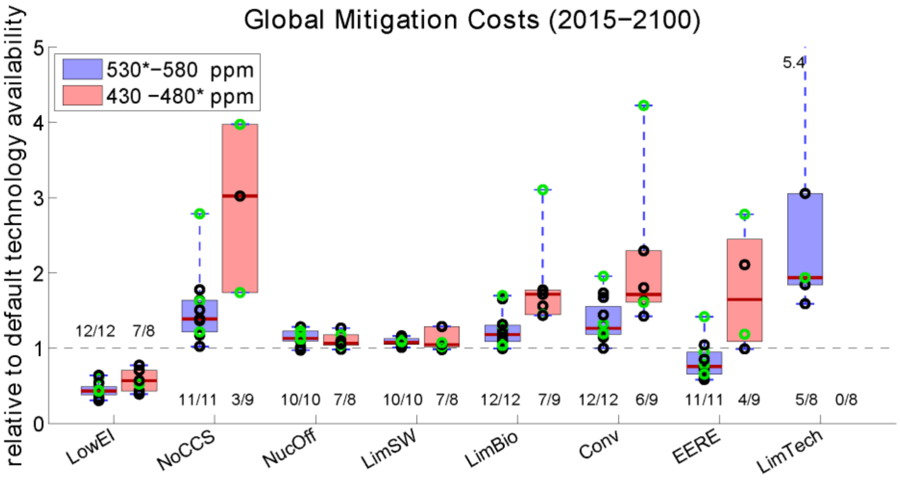


Figure 6.24. Relative mitigation cost increase in case of technology portfolio variations compared to a scenario with default (see Section 6.3.1) technology assumptions under a 450 ppm (red) and a 550 ppm (blue) CO2-e 2100 goals from the EMF27 study. Net present value of mitigation costs, discounted at 5%, for the period 2015-2100 is shown. The thick red 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 scenarios. Dots correspond to individual scenarios with partial equilibrium models being shown in green and general equilibrium models in black. The numbers at the bottom indicate the number of models that attempted the reduced technology portfolio scenarios and how many in each sample were feasible. Scenario names on x-axis indicate the technology variation relative to the default assumptions: Low EI = higher energy intensity improvement; NoCCS = CCS excluded; NucOff = nuclear energy phase out; LimSW = 20% limit on solar and wind electricity generation; LimBio = maximum of 100 EJ/yr bioenergy supply; Conv = conventional energy future, combining pessimistic assumptions for bioenergy and solar and wind (LimSW + LimBio); EERE = energy efficiency and renewable energy future, combining low energy intensity (LowEI) with non-availability of CCS and nuclear phase-out (NoCCS + NucOff); LimTech = limited technology future with all supply side options constrained and energy intensity developing in line with historical records in the baseline. Source: EMF27 study, adapted from (Kriegler et al., 2014c)

As noted above, the lack of availability of CCS is most frequently associated with the most significant cost increase (Kriegler et al., 2014c)(Edenhofer et al., 2010; Tavoni et al., 2012; Krey et al., 2014; Riahi et al., 2014), particularly for concentration goals approaching 450 ppm CO2-e, which are characterized by often substantial overshoot. One fundamental reason for this is that the combination of biomass with CCS can serve as a CDR technology in the form of BECCS (Azar et al., 2006a; van Vliet et al., 2009; Krey and Riahi, 2009; Van Vuuren et al., 2013; Edmonds et al., 2013; Kriegler et al., 2013a) (see Sections 6.3.2 and 6.9). In addition to the ability to produce negative emissions when coupled with bioenergy, CCS is a versatile technology which can be combined with electricity, synthetic fuel and hydrogen production from several feedstocks and in energy-intensive industries such as cement and steel. CCS can also act as bridge technology that is compatible with existing fossil-fuel dominated supply structures (see Sections 7.5.5, 7.9 and 6.9 for a discussion of challenges and risks of CCS and CDR). Bioenergy shares some of these characteristics with CCS. It is also an essential ingredient for BECCS, and it can be applied in various sectors of the energy system, including for the provision of liquid low-carbon fuels for transportation (see Chapter 11, Bioenergy Annex for a discussion of related challenges and risks). In contrast, those options that are largely confined to the electricity sector (e.g., wind, solar and nuclear energy) and heat generation tend to show a lower value, both because they cannot be used to generate negative emissions and because there are a number of low-carbon electricity supply options available that can generally substitute each other (Krey et al., 2014).

Scenarios also suggest that energy end use technologies and measures have an important influence on mitigation costs. For example, in the EMF27 and AMPERE multi-model studies, reductions in the final energy demand of 20-30% by 2050 and 35-45% by 2100 led to reductions in the cumulative discounted aggregate mitigation costs on the order of 50% (Kriegler et al., 2014c)(Krey et al., 2014; Riahi et al., 2014). An important caveat to these results is that the costs of achieving these reductions were not considered nor were the policy or technology drivers that led to them. Energy end use measures are important not just for reducing energy consumption, but also for facilitating the use of low-carbon fuels. For example, a number of studies (Kyle and Kim, 2011; Riahi et al., 2012b; Pietzcker et al., 2013; McCollum et al., 2014a) 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). An increasing ability to electrify the end-use sectors and transport in particular, in turn, tends to reduce the importance of CCS and bioenergy technologies for achieving lower concentration goals such as 450 ppm CO2-e.

6.3.6.4 Economic implications of non-idealized international mitigation policy implementation

Research has consistently demonstrated that delaying or limiting near-term global mitigation as well as reducing the extent of international participation in mitigation can significantly affect aggregate economic costs of mitigation. One way in which aggregate mitigation costs are increased is by delaying or limiting near-term mitigation relative to what would be warranted in the hypothetical idealized case that a long term goal was adopted and a least cost approach to reach the global mitigation goal was implemented immediately. This represents one manifestation of not undertaking mitigation “when” it is least expensive (Keppo and Rao, 2007; Bosetti et al., 2009b; Krey and Riahi, 2009; Jakob et al., 2012; Luderer et al., 2013a; Luderer G et al., 2013; Rogelj et al., 2013b; Kriegler et al., 2014b; Riahi et al., 2014). In scenarios in which near-term mitigation is limited, the increase in mitigation costs is significantly and positively related to the gap in short term mitigation with respect to the idealized scenarios (Figure 6.25). Costs are lower in the near-term, but increase more rapidly in the transition period following the delayed action, and are higher in the longer term. Future mitigation costs are higher because limited near-term action not only requires deeper reductions in the long run to compensate for higher emissions in the short term, but also produces a larger lock-in in carbon infrastructure, increasing the challenge of these accelerated emissions reduction rates. The effects of delay on mitigation costs increase with the stringency of the mitigation goal. Studies suggest that important transitional economic metrics other than aggregate costs – for example, reduced growth rates in economic output and consumption, escalating energy prices, and increasing carbon rents – may be more affected by delayed mitigation than aggregate costs (Luderer et al., 2013a; Luderer G et al., 2013; Kriegler et al., 2014b).

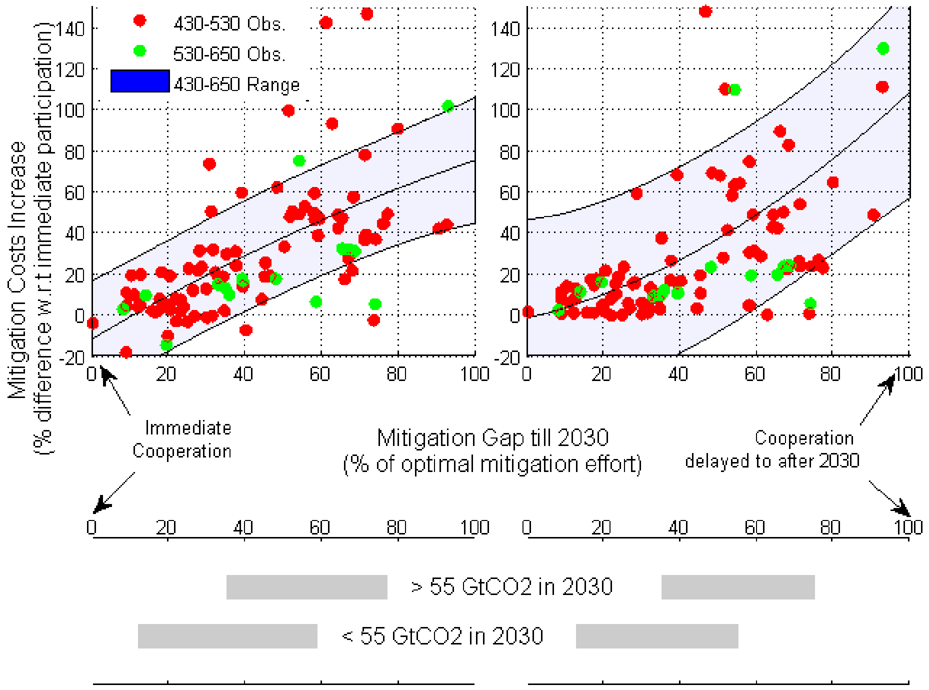


Figure 6.25. Mitigation costs increase as a function of reduced near term mitigation effort, both expressed as relative change to immediate mitigation (idealized implementation) scenarios (mitigation gap). Cost increase is shown both in the medium term (2030-2050, left panel) and in the long term (2050-2100, right panel), calculated on undiscounted costs. The mitigation gap is calculated from cumulative CO2 mitigation to 2030. Red and green dots show scenarios belonging to 430-530 and 530-650 ppm-e scenarios. The shaded area indicates the range for the whole scenario set (2 standard deviations). The bars in the lower panel indicate the mitigation gap range where 75% of scenarios with 2030 emissions respectively above and below 55 GtCO2 are found. Source: WG III AR5 Scenario Database (Annex II.10), differences between delayed participation to 2020 and 2030 and immediate participation categories.

Studies have consistently found that delays through 2030 have substantially more profound aggregate economic implications than delays through 2020, both in terms of higher transitional impacts due to more rapidly increasing mitigation costs at the time of adopting the long term strategy and higher long term costs (Luderer et al., 2013a; Rogelj et al., 2013a; Kriegler et al., 2014b). This is directly related to prolonged limited mitigation action in the short run leading to both larger carbon lock-ins and higher short term emissions that need to be compensated by deeper emissions cuts in the long run (Sections 6.3.2 and 6.4). Moreover, delayed action further increases the dependence on the full availability of mitigation options, especially on CDR technologies such as BECCS (Luderer G et al., 2013; Rogelj et al., 2013b; Riahi et al., 2014). (see Section 6.3.6.3).

Fragmented action or delayed participation by particular countries – that is, not undertaking mitigation “where” it is least expensive – has also been broadly shown to increase global mitigation costs (Blanford, et al., 2013, Kriegler et al, 2014, Edmonds et al., 2008; K. Calvin, Patel, et al., 2009; Tol, 2009; van Vliet et al., 2009; Richels et al., 2009; Bosetti, Carraro, and Tavoni, 2009b; Clarke et al., 2009b). Fragmented action will influence aggregate global economic costs not only because of misallocation of mitigation across countries, but also through emissions leakage and trade related spillover effects (Babiker, 2005; Böhringer et al., 2012, p. 29; Bosetti and De Cian, 2013; Arroyo-Curras et al, 2014). The range and strength of these adverse effects and risks depends on the type of policy intervention and the stringency of the mitigation effort. Border carbon adjustments have been found to reduce economic impacts of exposed industries, but not to yield significant global cost savings (Böhringer et al., 2012, p. 29). Some studies have indicated that the increased costs from fragmented action could be counterbalanced by increased incentives to carry out innovation, though only to a limited extent (Di Maria and Werf, 2007; Golombek and Hoel, 2008; Gerlagh et al., 2009; De Cian and Tavoni, 2012b; De Cian et al., 2013).

Multi model studies have indeed found that the smaller the proportion of total global emissions included in a climate regime due to fragmented action, the higher the costs and the more challenging it becomes to meet any long-term goal. For example, only 2 (5) of 10 participating models could produce a 450 ppm CO2-e overshoot (550 ppm CO2-e not to exceed) scenarios under the regional fragmentation assumptions in the EMF 22 scenarios. In these scenario, the. Annex I countries began mitigation immediately, followed by major emerging economies in 2030, and the rest of the world in 2050 (see Table 6.1, Clarke et al., 2009b) (see Section 6.2 for a discussion of model infeasibility). Discounted global aggregate mitigation costs over the century increased by 50% to more than double.

In general, when some countries act earlier than others, the increased costs of fragmented action fall on early actors. However, aggregate economic costs can also increase for late entrants, even taking into account their lower near-term mitigation (Clarke et al., 2009a; Jakob et al., 2012). Late entrants benefit in early periods from lower mitigation; however, to meet long-term goals, they must then reduce emissions more quickly once they begin to take action, in just the same way that global emissions must undergo a more rapid transition if they are delayed in total. The increased costs of this rapid and deep mitigation can be larger than the reduced costs from limited near-term mitigation (Figure 6.26). The degree to which the late entrants' mitigation costs increase with fragmented 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 emissions reductions. Indeed, in the face of a future mitigation commitment it is optimal to anticipate emissions reductions, reducing the adjustment costs of confronting mitigation policy with a more carbon intensive capital stock (Bosetti et al., 2009a; Richels et al., 2009). In addition, countries may incur costs from international mitigation policy even if they do not participate, for example, from a loss of fossil fuel revenues (Blanford et al., 2014).

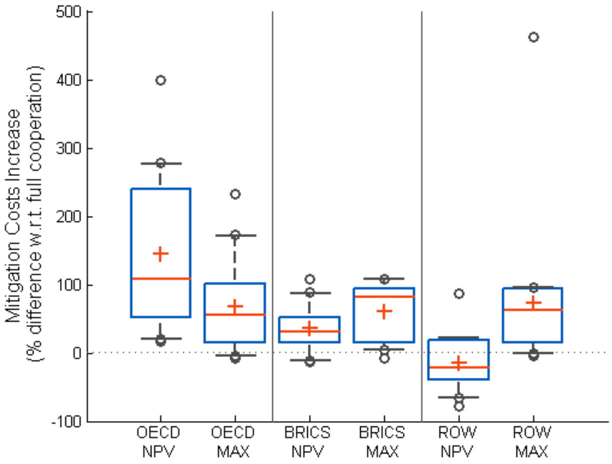


Figure 6.26. Impact of fragmented cooperation on the relative mitigation costs of 3 representative regions (OECD, BRICS and Rest Of the World) from the EMF 22 Study. In this study, OECD joins immediately, BRIC (Brasil, Russia, India and China) in 2030, and Rest of the World (ROW) in 2050 – See Table 6.1. The vertical axis shows the increase in mitigation costs between partial and full participation scenarios. Thus, values above 0 indicate that fragmented cooperation increases costs. Mitigation costs are calculated relative to baseline over 2015-2100 both in NPV at 5% discount rate (left bars) and as maximum losses over the century (right bars). Box plots indicate mean, median, 25-75th percentiles. Whiskers extend to outliers, shown with dots. Source: EMF22 data base.

6.3.6.5 The interactions between policy tools and their implementation, pre-existing taxes, market failures, and other distortions

The aggregate economic costs reported in section 6.3.6.2 have assumed an idealized policy implementation and in many cases an idealized implementation environment with perfectly functioning economic markets devoid of market failures, institutional constraints, and pre-existing tax distortions. Many models represent some of these distortions, but most models represent only a small portion of possible distortions and market failures. The reality that assumptions of idealized implementation and idealized implementation environment will not be met in practice means that real-world aggregate mitigation costs could be very different from those reported here.

Under the assumption of a perfect implementation environment, economic analysis has long demonstrated that the way to minimize the aggregate economic costs of mitigation is to undertake mitigation where and when it is least expensive (Montgomery, 1972). This implies that policies be flexible and comprehensive with a ubiquitous price on greenhouse gas emissions, as might be achieved by a cap-and-trade policy or carbon tax (Goulder and Parry, 2008). The literature presented thus far in this section has assumed such an approach. Even scenarios with fragmented or limited near-term emissions reductions have typically assumed efficient, full-economy carbon prices for all countries undertaking mitigation. However, real-world approaches may very well deviate from this approach. For example, some policies may only address particular sectors, such as power generation; other policies may regulate the behaviour of particular sectors through command and control measures, for example through renewable portfolio standards for power generation or fuel economy standards for transport.

In an idealized implementation environment, the literature shows that approaches that exclude sectors or regulate reductions by sector will lead to higher aggregate mitigation costs, particularly for goals requiring large emissions reductions where coverage and flexibility are most important (Paltsev et al., 2008). A wide range of recent studies have corroborated this general result, including the large scale multi-model comparison studies such as EMF 22 (Böhringer et al., 2009), EMF 24 (Fawcett et al., 2013), and EMF 28 (Knopf et al., 2013) along with a wide range of individual papers. As an example, a survey of results (OECD, 2009) indicates that exempting energy-intensive industries increases mitigation costs for achieving concentrations of 550 ppm by 50% in 2050, and that excluding non-CO2 GHG emissions increases the mitigation costs by 75% in 2050. EMF 22 (Böhringer et al., 2009) find that differential prices for the EU Emission Trading Scheme (ETS) and non-ETS emissions in the EU and the inclusion of a renewable portfolio standard could double the mitigation costs for the EU goals for 2020. Wise et al. (2009b) found that the failure to include land use change emissions in mitigation policy could double global carbon prices in a 450 ppm CO_2 scenario. At the same time, it is important to recognize that mitigation may not be the only objective of these sectoral approaches and regulatory policies. They may also be designed to address other policy priorities such as energy security and local environmental concerns.

In addition, climate policies will interact with pre-existing policy structures as well as with other market failures beyond the market failure posed by climate change – that is, a non-idealized implementation environments – and these interactions can either increase or decrease policy costs. A number of authors have argued that costs could be much lower or even negative compared to those produced by studies assuming idealized policy and implementation environments (Bosquet, 2000; Bye et al., 2002; Waisman et al., 2012). The results of these studies rest on one or several assumptions: that mitigation policy be used not only to address the climate externality, but also to achieve other policy priorities such as sustainable development; the use of mitigation policy instruments for the correction of the implementation environment including removal of market failures and pre-existing distortions; and/or on optimistic views of climate-related innovation and technology development, adoption, and penetration.

Because technology is so critical to the economic costs of mitigation, the economic costs and efficacy of climate policies more generally will necessarily be influenced by market failures in markets for technology adoption and those for development and R&D (Jaffe, 2012). There are numerous market failures, such as research and adoption spillvers, limited foresight, limited information, and imperfect capital markets, which can cause underinvestment in mitigation technologies as discussed in Section 15.6 in more detail (Thollander et al., 2010; Allcott, 2011, 2013; Kalkuhl et al., 2012, among many others). This literature indicates aggregate mitigation costs could be lower if these market failures could be removed through complementary policies (Jaffe et al., 2005; Thollander et al., 2010). Additionally, literature that focuses in particular on failures in markets for investments in technology and R&D has found large reductions in aggregate mitigation costs as a result of correcting these failures, for example, through the recycling of revenue from climate policies or otherwise using public funds (Bosquet, 2000; Edenhofer et al., 2010; Waisman et al., 2012). The literature has also shown the value of related complementary policies to enhance labor flexibility (Guivarch et al., 2011) or impact the mobility of demand, such as transportation infrastructures or urban and fiscal policies lowering real estate prices and urban sprawl (Waisman et al., 2012).

Interactions with pre-existing policies and associated distortions will also influence economic costs. The EU ETS offers an example where an efficient policy tool (cap-and-trade system) that is applied on partial sectors (partial coverage) and interacts with pre-existing distortions (high energy taxes) and other energy policies (renewable energy requirements) is affected by over-allocation of permits and slower than expected economic growth (Ellerman and Buchner, 2008; Ellerman, 2010; Batlle et al., 2012). 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. In contrast, literature has also looked into the use of carbon revenues to reduce pre-existing taxes (generally known as the “double dividends” literature). This literature indicates that total mitigation costs can be reduced through such recycling of revenues (Goulder, 1995; Bovenberg and Goulder, 1996). Nonetheless, a number of authors have also cautioned against the straight generalization of such results indicating that the interplay between carbon policies and pre-existing taxes can differ markedly across countries showing empirical cases where a “double dividend” does not exist as discussed in Section 3.6.3.3 (Fullerton and Metcalf, 1997; Babiker et al., 2003; Metcalf et al., 2004).

6.3.6.6 Regional mitigation costs and effort-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; Lüken et al., 2011; Luderer et al., 2012b; Aboumahboub et al., 2014; Blanford et al., 2014; Tavoni et al., 2014). The regional variation in costs will be influenced by the nature of international participation in mitigation, regional mitigation potentials, and transfer payments across regions. In the idealized setting of a universal carbon price leading to reductions where they would be least expensive, and in the absence of transfer payments, the total aggregate economic costs of mitigation would vary substantially across countries and regions. In results collected from modeling studies under these circumstances, aggregate costs in the OECD, measured as a percentage change from baseline conditions, are typically lower than the global average, those in Latin America are typically around the global average, and those in other regions are higher than the global average (Clarke et al., 2009b; Tavoni et al., 2014).

The variation in these regional costs can be attributed to several factors (Tavoni et al., 2014). First, costs are driven by relative abatement with respect to BAU, which is expected to be somewhat higher in developing countries (see Section 6.3.2 for more discussion). Second, 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 et al., 2012b). Third, 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 originate from unfavourable terms of trade effects of the mitigation policy (OECD, 2008; Massetti and Tavoni, 2011; Luderer et al., 2012a; Aboumahboub et al., 2014; Blanford et al., 2014), while some regions could experience increased bio-energy exports (Persson et al., 2006; Wise et al., 2009a; Leimbach et al., 2010). A final consideration is that the total costs (as opposed to costs relative to baseline conditions) and associated mitigation investments are also heavily influenced by baseline emissions, which are projected to be larger in the developing regions than the developed regions (see Section 6.3.1).

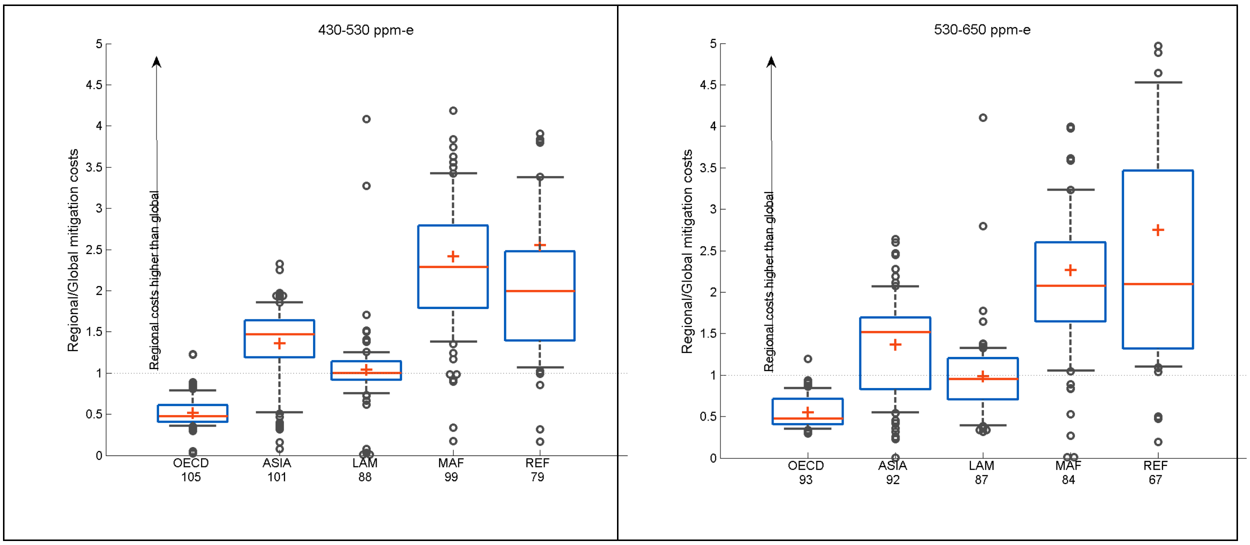


Figure 6.27. Ratio between regional and global relative mitigation costs for idealized implementation scenarios in the WG III AR5 Scenario Database (Annex II.10). Values above (below) 1 indicate that the region has relative mitigation costs higher (lower) than global ones. Relative costs are computed as the cumulative costs of mitigation over the period 2020-2100, discounted at at 5% d.r., divided by cumulative discounted economic output over that period. Costs are displayed for scenarios reaching 430-530 CO2-e in 2100 (left panel) and 530-650 CO2-e in 2100(right panel). Scenarios assume no carbon trading across regions. Box plots indicate mean, median, 25-75th percentiles. Whiskers extend to outliers, shown with dots. The numbers below the regions names indicate the number of scenarios in each box plot. Source: Scenario database for AR5, idealized implementation and default (see Section 6.3.1) technology scenarios.

A crucial consideration in the analysis of the aggregate economic costs of mitigation is that the mitigation costs borne in a region can be separated from who pays those costs. Under the assumption of efficient markets, effort-sharing schemes have the potential to yield a more equitable cost distribution between countries (Ekholm et al., 2010b; Tavoni et al., 2014). Effort-sharing approaches will not meaningfully change the globally efficient level of regional abatement, but can substantially influence the degree to which mitigation costs or investments might be borne within a given country or financed by other countries (e.g. Edenhofer et al., 2010). A useful benchmark for consideration of effort-sharing principles is the analysis of a framework based on the creation of endowments of emission allowances and the ability to freely exchange them in an international carbon market. Within this framework, many studies have analysed different effort-sharing allocations according to equity principles and other indicators (see Section 3.3, Section 4.6.2) (den Elzen and Höhne, 2008; Den Elzen and Höhne, 2010; Höhne et al., 2013).

Comparing emission allocation schemes from these proposals is 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-e (see Höhne et al., 2013). The range of results for a selected year and concentration goal 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. To allow comparison of substantially different proposals, Höhne et al. (2013) developed a categorisation into seven categories based on three equity principles (see Chapter 4): responsibility, capability, and equality (Table 6.5). The first three categories represent these equity principles alone. The following three categories represent combinations of these principles. “Equal cumulative per capita emissions" combines equality (per capita) with responsibility (cumulative accounting for historical emissions); "responsibility, capability and need" includes approaches that put high emphasis on historical responsibility and at the same time on capability plus the need for sustainable development; "staged approaches" includes those that already constitute a compromise over several principles. Finally, the last category, "equal marginal abatement costs" (implemented in the models as uniform carbon tax with no compensatory transfers), represents the initial allocation to that which would emerge from a global price on carbon. This is used as a reference against which to compare the implications of other regimes.

Table 6.5. Categories of effort-sharing proposals. Source: Höhne et al. (2013)

Categories	**Responsibility**	**Capability**	**Equality**	**Description**	**References**
Responsibility	X			The concept to use historical emissions to derive emission goals was first directly proposed by Brazil in the run-up of the Kyoto negotiations (UNFCCC, 1997), without allocations. Allowances based only on this principle were quantified by only a few studies.	Berk and den Elzen (2001)*, Den Elzen et al. (2005); Den Elzen and Lucas (2005)
Capability		X		Frequently used for allocation relating reduction goals or reduction costs to GDP or human development index (HDI). This includes also approaches that are focussed exclusively on basic needs.	Den Elzen and Lucas (2005); Knopf et al. (2011); Jacoby et al. (2009); Miketa and Schrattenholzer (2006); Kriegler et al. (2014b) and Tavoni et al. (2014) **
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);	Berk and den Elzen (2001)*, Kriegler et al. (2014b) and Tavoni et al. (2014)**, 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. (2010b); 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. (2009a, 2010)
Responsibility, capability and need	X	X		Recent studies used responsibility and capability explicitly as a basis, e.g. Greenhouse Development Rights (Baer et al., 2008); or "Responsibility, Capability and Sustainable Development"(Winkler et al., 2011)	Baer et al. (2008); Baer (2013); Höhne and Moltmann (2008, 2009); Winkler et al. (2011)
Equal cumulative per capita emissions	X		X	Several studies allocate equal cumulative per capita emission rights based on a global carbon budget (Pan, 2005, 2008). Studies diverge on how they assign the resulting budget for a country to individual years.	Bode (2004); Nabel et al. (2011); Jayaraman et al. (2011); Schellnhuber et al. (2009);
Staged approaches	X	X	X	A suite of studies propose or analyse approaches, where countries take differentiated commitments in various stages. Also approaches based on allocation for sectors such as the Triptych approach (Phylipsen et al., 1998) or sectoral approaches are included here. Categorisation to a stage and the respective commitments are determined by indicators using all four equity principles. Finally, studies using equal percentage reduction goals, also called grandfathering, are also placed in this category.	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); Hof et al.(2010a); Höhne and Moltmann (2008, 2009); Höhne et al.(2005, 2006); Knopf et al. (2011); Vaillancourt and Waaub (2004); Peterson and Klepper (2007); Böhringer and Welsch (2006); Knopf et al.(2011) Berk and den Elzen (2001)
Equal Marginal Abatement Costs (for reference)				Modelling studies often use the allocations that would emerge from a global carbon price as a reference case for comparing other allocations.	Peterson and Klepper (2007), Van Vuuren et al. (2009a), Kriegler et al. (2014b) and Tavoni et al. (2014) **

*: Not included in *the quantitative results, because either too old or pending clarifications of the data.

**: This is a model comparison study of seven integrated models as part of the LIMITS research project: PBL, IIASA, FEEM, ECN, PIK*, PNNL*, NIES*. Each of these models represents one data point. Some of these model studies are more extensively described in a particular model study (Kober and al., 2014).

The range of allowances can be substantial even within specific categories of effort sharing, depending on the way the principle is implemented (Figure 6.28). For some effort sharing categories, the ranges are smaller because only a few studies were found. Despite the ranges within a category, distributional impacts differ significantly with underlying criteria for effort sharing.

The concentration goal is significant for the resulting emissions allowances (Figure 6.29**)**. Indeed, for many regions, the concentration goal is of equal or larger importance for emission allowances than the effort-sharing approach. For concentration levels between 430 and 480 in 2100, the allowances in 2030 under all effort sharing approaches in OECD1990 are approximately half of 2010 emissions with a large range, roughly two-thirds in the Economies in Transition (EIT), roughly at the 2010 emissions level or slightly below in Asia, slightly above the 2010 level in the Middle East and Africa, and well below the 2010 level in Latin America. For these same concentration levels, allowances in OECD1990 and EITs are a fraction of today's emissions in 2050, and allowances for Asia and Latin America are approximately half of 2010 emission levels in 2050. For higher stabilization scenarios most studies show a significant decline in allowances below current levels for OECD1990 and EITs by 2050. Most studies show a decline in allowances below current levels for the Latin America region, mostly increasing above current levels for the Africa and Middle East region and an inconsistent picture for ASIA.

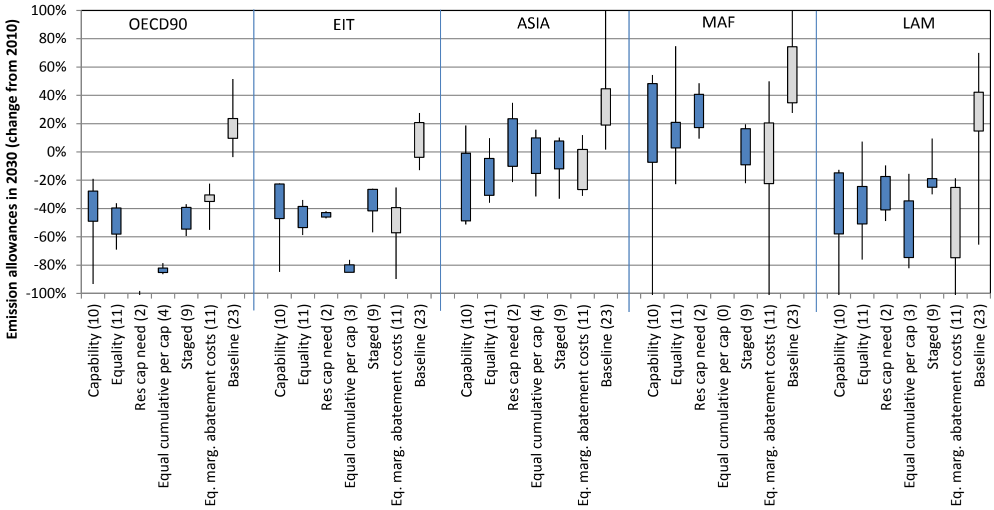


Figure 6.28. Emission allowances in 2030 relative to 2010 emissions by effort-sharing category for scenarios reaching 430-480 ppm CO2-e in 2100 (minimum, 20th percentile, 80th percentile, maximum value). Number of data points in brackets. GHG emissions (all gases and sectors) in GtCO2-e in 1990 and 2010 were OECD1990 13.4, 14.2, Economies in Transition (EIT) 8.4, 5.6, ASIA 10.7, 19.9, Middle East and North Africa (MAF) 3.0, 6.2, Latin America and Caribbean (LAM) 3.3, 3.8. Emissions allowances are shown compared to 2010 levels, but this does not imply a preference for a specific base-year. For the OECD the category "Responsibility, capability, need" the emission allowances in 2030 is -106% to -128% (20th to 80th percentile) below 2010 level (therefore not shown here). The studies with the Equal per capita cumulative emissions approaches do not have the regional representation MAF. "Equal marginal abatement cost" refers to an allocation based on the imposition of a global carbon price. Source: Adapted from Höhne et al.(2013). Studies were placed in this category based on the level that the studies themselves indicate. The pathways of the studies were compared with the characteristics of the categories, but were not recalculated.

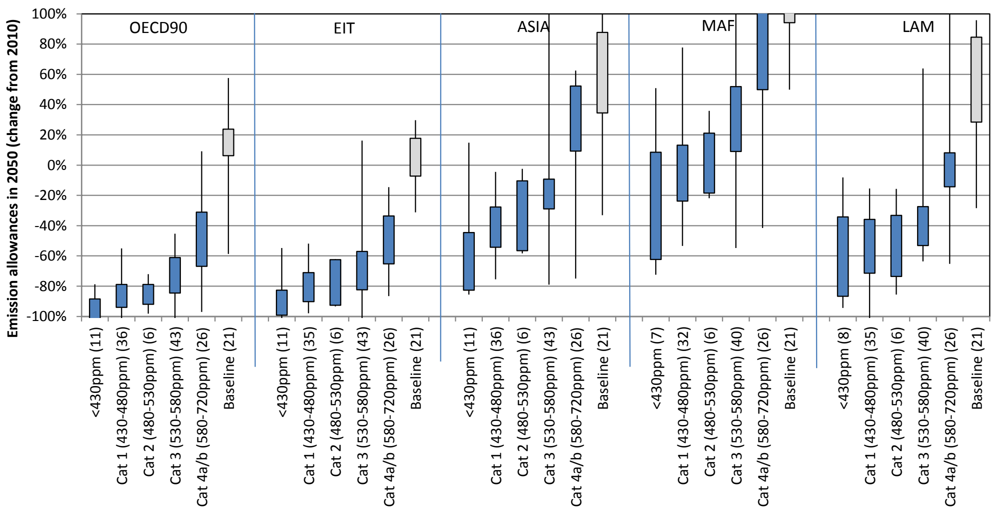


Figure 6.29. Emission allowances for various concentration levels in 2050 relative to 2010 emissions (minimum, 20th percentile, 80th percentile, maximum). Includes all effort-sharing regimes except “equal marginal abatement costs”. Number of data points in brackets. Source: Adapted from Höhne et al. (2013). Studies were placed in the categories based on the level that the studies themselves indicate. The pathways of the studies were compared with the characteristics of the categories, but were not recalculated. Includes all effort-sharing approaches considered.

The creation of endowments of emissions allowances would generate payment transfers across regions in a global carbon market. These transfer payments would depend on the regional abatement opportunities, the distribution of allowances, and the concentration goal. To the extent that regional mitigation levels represents the cost-effective mitigation strategy across regions, the size of these allocations relative to domestic emissions provide an indication of the degree to which allowances would be transferred to or from any region. If allocations are higher than the “equal marginal abatement cost” allocation in a particular country, then the country could possibly improve its financial position by reducing emissions and selling the remaining allowances. If allocations are lower than the “equal marginal abatement cost” allocation, the country could possibly purchase allowances and therefore provide transfers.

Multi-model studies indicate that the size of the carbon market transfers would be significant in relation to the total global aggregate economic costs of mitigation, of the order of hundred billions of U.S. dollars per year before mid-century (Clarke et al., 2009b; Luderer et al., 2012b; Tavoni et al., 2014). Transfers through emissions allowances are also particularly high if the carbon price is high, because the transfers are based on the quantity of the allowances traded and the price of those allowances. Higher prices are associated with more ambitious mitigation. For some regions, financial flows could be on the same order of magnitude as the investment requirements for emissions reductions (McCollum and al, 2013). Financial transfers are particularly high for some regions for the categories “Equal per capita cumulative emissions” and “Responsibility, capability and need” in general and for “Staged approaches” in some of studies.

The transfers associated with different effort-sharing schemes have a direct impact on the regional distribution of mitigation policy costs (Luderer et al., 2012b). These costs are sensitive both to local abatement costs and to size and direction of transfers, both of which are related to the effort-sharing scheme as well as the carbon price and the associated climate goal (Russ and Criqui, 2007; den Elzen et al., 2008; Edenhofer et al., 2010; Ekholm et al., 2010b; Luderer et al., 2012b). Given the large uncertainty about future transfers and carbon prices, the regional distribution of costs under different sharing schemes varies widely (Luderer et al., 2012b; Tavoni et al., 2014). For example, emerging economies like China could incur in relatively high expenditures (den Elzen et al., 2012; Johansson et al., 2012), but this would change when cumulative past emissions are also accounted for (Jiahua, 2008; Ding et al., 2009; He et al., 2009). Moreover, the uneven regional distribution of relative mitigation costs observed in Figure 6.27 in the case without transfers is not significantly alleviated when emissions rights are equalized per capita by 2050 and the concentration goal is stringent, as shown in Figure 6.30.

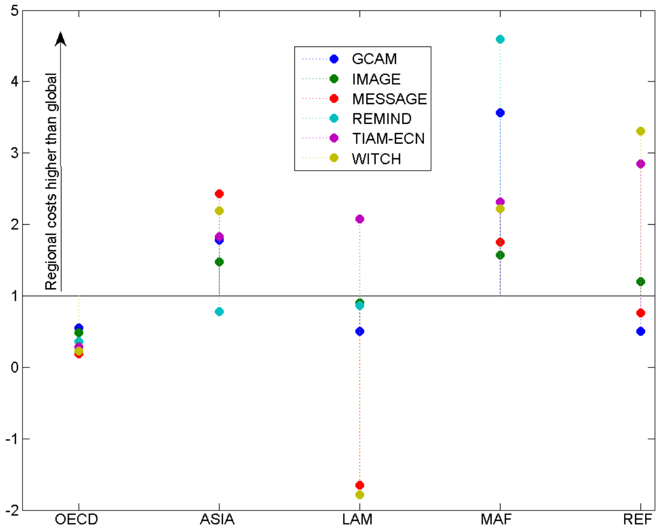


Figure 6.30. Ratio between regional and global relative mitigation costs for a 450 ppm-eq goal for a per capita effort-sharing scheme from the LIMITS multi-model study. Values above (below) 1 indicate that the region has relative mitigation costs higher (lower) than global ones. Values below 0 are possible for regions who are large net sellers of carbon allowances. Mitigation costs are computed relative to the baseline, over 2020-2100 in NPV at 5% d.r. Emission allocations are based on linear convergence from 2020 levels to equal per capita by 2050, with per capita equalization thereafter. Regions are allowed to trade emission rights after 2020 without any constraint. Source: WG III AR5 Scenario Database (Annex II.10), LIMITS per capita scenarios.

Optimal transfers can also be devised as a way to provide 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).

The impacts of mitigation policies on global fossil fuel trade depend on the type of fuel, time horizon and stringency of mitigation efforts. Recent model inter-comparison studies focusing on low-concentration goals (430-530 CO_2-e in 2100) have found an unambiguous decrease in coal trade over the first half of the century (Cherp et al., 2013; Jewell et al., 2013b). In contrast, studies indicate that natural gas trade could potentially increase over the coming decades as gas serves as a transition fuel and substitutes for coal (Cherp et al., 2013). Studies present a less clear picture regarding the future of oil trade in for concentration goals in this range. In general, however, studies find oil trade to be less sensitive to mitigation policy than coal and gas trade through 2030, and perhaps even to 2050 (Bauer et al., 2013a; b; Cherp et al., 2013; Jewell et al., 2013b; McCollum et al., 2013b).

These changes in trade patterns will have important implications for the future trade revenues of fossil exporting countries. There is high agreement among integrated models that revenues from coal trade are likely to fall for major exporters (Lüken et al., 2011; Bauer et al., 2013a; b). For oil and gas, on the other hand, the effect of stringent climate policies on export revenues is a bit less clear, with results varying across models. Notwithstanding these differences, the general conclusion of recent inter-comparison exercises is that there is likely to be a decrease in oil and gas revenues for exporting countries over the first half of the century (IEA, 2009; Haurie and Vielle, 2010; Bauer et al., 2013a; b; McCollum et al., 2013b; Tavoni et al., 2014). It is important to note, however, that several recent studies have shown a potential gain in revenues from conventional oil resources as a result of climate policies (Persson et al., 2007; Johansson et al., 2009; Nemet and Brandt, 2012). Because exporters of these resources can benefit from the cheaper extraction costs and less carbon-intensive nature of conventional oil (relative to unconventional oil deposits and coal- or gas-derived liquids), mitigation efforts could potentially have a positive impact on export revenues. These dynamics depend critically on future commodity prices. No global studies have, as yet, systematically explored the impact of stringent climate policies on unconventional gas trade and export revenues, particularly those where methane leakage from extraction activities could be an issue.

Box 6.2. LDCs in integrated models

There are significant data and information deficits pertaining to LDCs and limits to the modeling of the specific features and characteristics of LDCs. For this reason, the integrated modeling literature provides relatively little information on the specific implications of transformation pathways for LDCs. Based on the limited available literature, LDCs contribute little to future GHG emissions until 2050 even though they are projected to grow faster than global emissions. Post 2050 emissions trends for LDCs depend on highly uncertain projections of their long term economic growth prospects. One study in the available integrated modeling literature suggests that LDC's contribution to global emissions increases by about 50% between 2000 and 2100 (Calvin et al., 2009c).The mitigation challenges for LDCs are particularly significant 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. Trade-offs can include, among other things, a prolonged use of traditional bioenergy and a reduction in final energy use. Potential synergies include accelerated electrification (Calvin and al., 2014).

The literature on the transformation pathways has also indicated the need for large deployment of low-carbon technologies. These projections pose critical challenges and uncertainties for LDCs when taking into account issues related to deployment, institutions and program design, and non-climate socioeconomic implications. In particular, many scenarios rely on technologies with potentially large land footprints, such as bioenergy and afforestation or reforestation, to achieve mitigation goals. The scenarios surveyed in the chapter universally project the majority of bioenergy primary energy will occur in developing economies (60-75% in non-OECD in 2050). These abatement patterns imply significant challenges for developing countries in general, and LDCs in particular, where large land-use abatement potentials lie.

The literature related to effort-sharing and distributional implications of mitigation in LDCs is relatively scarce. The literature suggests that there are trade-offs between food security and mitigation (e.g. Reilly et al., 2012) with negative impacts for poor, developing countries due to the high share of their incomes spent on food. Mitigation might increase the rural-urban gap and deteriorate the living standards of large sections of the population in developing countries (e.g. Liang and Wei, 2012). In contrast, policy and measures aligned to development and climate objectives can deliver substantial co-benefits and help avoid climate risks in developing countries (Shukla et al., 2009). Modelling studies that use the "low carbon society" framework arrive at a similar conclusion about co-benefits in DCs and LDCs (Kainuma et al., 2012a; Shrestha and Shakya, 2012). Spillover effects from trade-related mitigation policies may pose certain risks for LDCs such as induced factor mobility, unemployment, and international transport related impacts on food and tourism sectors (Nurse, 2009; ICTSD, 2010; Pentelow and Scott, 2011). Downscaling of integrated modeling to the level of LDCs is a key area for future research.

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 mitigation goal 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, transformation pathways to long-term climate goals are 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 choices available to future decision makers. Some decisions may maintain a range of future options, while others may constrain the future set of options for meeting long-term climate goals.

6.4.2 Near-term emissions and long-term transformation pathways

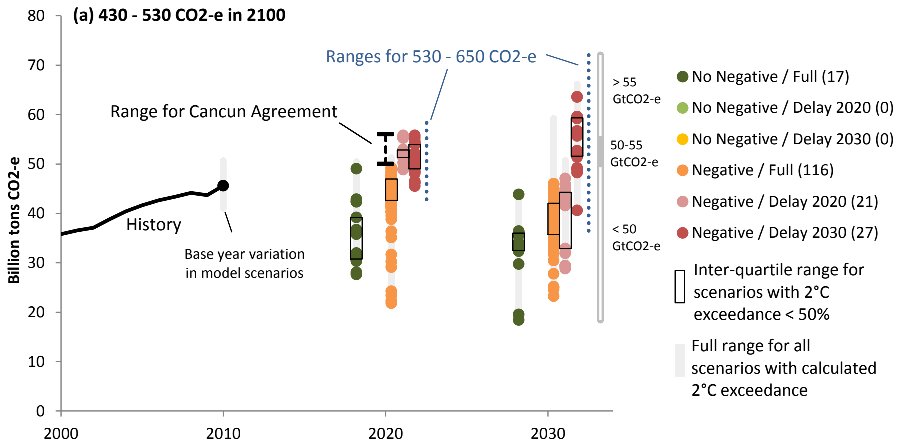
A key outcome of current decision-making will be the level of near-term global emissions. Scenarios can provide important insights into the implications of the near-term (i.e. 2020-2030) emissions level for long-term climate outcomes. As discussed in Section 6.1.2 , a number of multi-model studies have been designed specifically for this purpose, exploring delays in global mitigation, in which near-term emissions are held fixed to particular levels, and fragmented action, in which only a subset of regions initially respond to a long-term goal (see Table 6.1). These scenarios are typically designed as counterpoint to idealized implementation scenarios in which timing of reductions is unconstrained and full participation is assumed from the outset. This distinction is essential for characterizing the relationship between the path emissions follow through 2030 and the possible climate outcomes through the end of the century. Among idealized implementation scenarios with long-term forcing in the range of 430-530 CO2-e, emissions in 2020 fall almost exclusively below the Cancun range, as in Rogelj et al (2013a) (Figure 6.31a). However, several scenarios with delayed mitigation imposed through either through global delays or delayed participation have 2020 emissions in the Cancun range and in some cases 2030 emissions even higher than this range while still remaining consistent with the long-term goal (the cost implications of delay are discussed in Section 6.3.6.4).

A second distinction that can play a critical role is the extent to which CDR options are available and deployed. In scenarios designed with a forcing goal applied only at the end of the century, particularly lower goals in the range of 430-530 CO2-e by the end of the century, idealized implementation scenarios often choose to temporarily overshoot the 2100 goal (Section 6.3.2). As noted in Section 6.3.2 , CDR options, typically represented in integrated models by BECCS but also afforestation in some cases, facilitate more rapid declines in emissions, amplifying this overshoot pattern (Krey et al., 2014). A large number of scenarios reaching CO2-e concentrations below 530 ppm CO2-e by 2100 deploy CDR technologies at large enough scales that net global emissions become negative in the second half of the century. The availability of CDR options, as well as the representation of intertemporal flexibility, varies significantly across models and studies. The spread in reliance on CDR options across scenarios reveals a strong impact on the timing of emissions pathways. In scenarios reaching the long-term forcing range of 430-530 CO2-e in which global net CO2 emissions remain positive through the century, near-term emissions are generally lower than if the scenario deploys CDR technologies to a large enough scale to lead to net negative total global CO2 emissions later in the century (Figure 6.31 a). More generally, the scenarios indicate that a reliance on large-scale CDR, whether or not emissions become net negative, leads to higher near-term emissions in the near-term (van Vuuren and Riahi, 2011).

The interaction between delayed mitigation and CDR options is also important. Very few scenarios are available to demonstrate emissions pathways consistent with long term forcing of 430-530 CO2-

e in which mitigation effort is delayed in some form and global carbon emissions do not become net negative. Whether these circumstances are not represented 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 (see discussion of model infeasibility in Section 6.3.2). However, there are instances where the combination of delay and limited options for CDR has been explored and has resulted in model infeasibilities (Luderer G et al., 2013; Rogelj et al., 2013b; Riahi et al., 2014), , which supports the notion that this combination presents important challenges. For example, in the AMPERE study, seven out of nine models could not produce a scenario with global delay through 2030 and a restriction on CCS technology that was consistent with a long-term 450 CO2-e goal (one of the remaining two had net negative global emissions through other channels and the other did not run past 2050). Several individual modelling team studies have also explored this space, and have found situations in which they could not reach solutions for more ambitious goals and delayed action or constrained technology, including O'Neill et al. (2010), Edmonds et al. (2008) and Edmonds et al. (2013). Studies have found that delayed reductions through 2020 do not have as substantial an effect on the cost and challenge more broadly of meeting 2100 goals such as 450 ppm CO2-e as delayed reductions through 2030 (Luderer G et al., 2013; Rogelj et al., 2013b; Luderer et al., 2013b; Kriegler et al., 2014b)

The implications of delayed mitigation, CDR options, and overshoot for possible temperature outcomes are also significant. Numerous studies have attempted to place the possible outcome of the Cancun Agreements in the context of longer-term climate goals (Höhne et al., 2012; UNEP, 2012). Due to the factors discussed above, but also variation in assumptions about baseline growth, mitigation costs, trade-offs between sectors such as energy and land-use, and the evolution of non-gas forcing agents, models have found that a wide range of near-term emissions could be consistent with a given long-term outcome. Among scenarios with long-term forcing between 430 and 530 CO2-e, focusing on those scenarios in the AR5 database for which temperature implications were calculated (see Section 6.3.2), near-term global emissions range from 22 to 56 GtCO2-e in 2020 and from 18 to 66 GtCO2-e in 2030 (Figure 6.31a). However, not all pathways in this range are consistent with at least a 50% chance of remaining below 2° C, in particular those that rely on net negative global emissions. Pathways reaching the same long-term forcing level with higher emissions in 2030 tend to have more overshoot; when forcing stays higher for longer, the likelihood of reaching a temperature threshold increases. Very few scenarios in the 430-530 ppm CO2-e range have a 50% chance of remaining below 1.5° C, and none with delay or limited deployment of CDR technologies; most have a probability between 0 and 25%. A few studies have explored scenarios that lead to concentrations below 430 ppm CO2-e in 2100 (e.g. Luderer et al, 2013, Rogelj et al, 2013a,b), some of which have a likely (>66%) chance of returning to 1.5°C by the end of the century after peaking at higher levels; these scenarios are characterized by immediate emissions reductions followed by very low mid-century emissions and extensive deployment of CDR technologies. For scenarios with long-term forcing in the range of 530-650 CO2-e, nearly all have a greater than a 50% chance of exceeding 2°C by 2100, but many have a probability of less than 50% of exceeding 2.5°C (Figure 6.31 b). Because of the higher long-term forcing range, some growth in emissions can occur, and the preferred least-cost range is similar to the delayed range and largely consistent with the Cancun range in 2020.



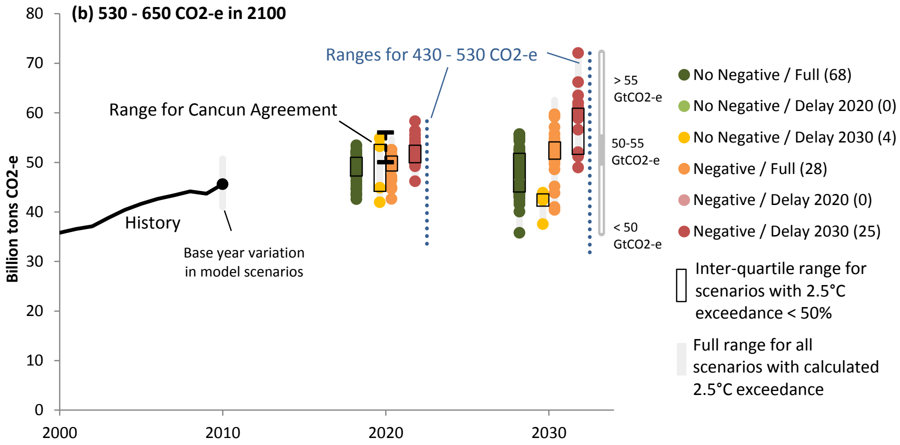
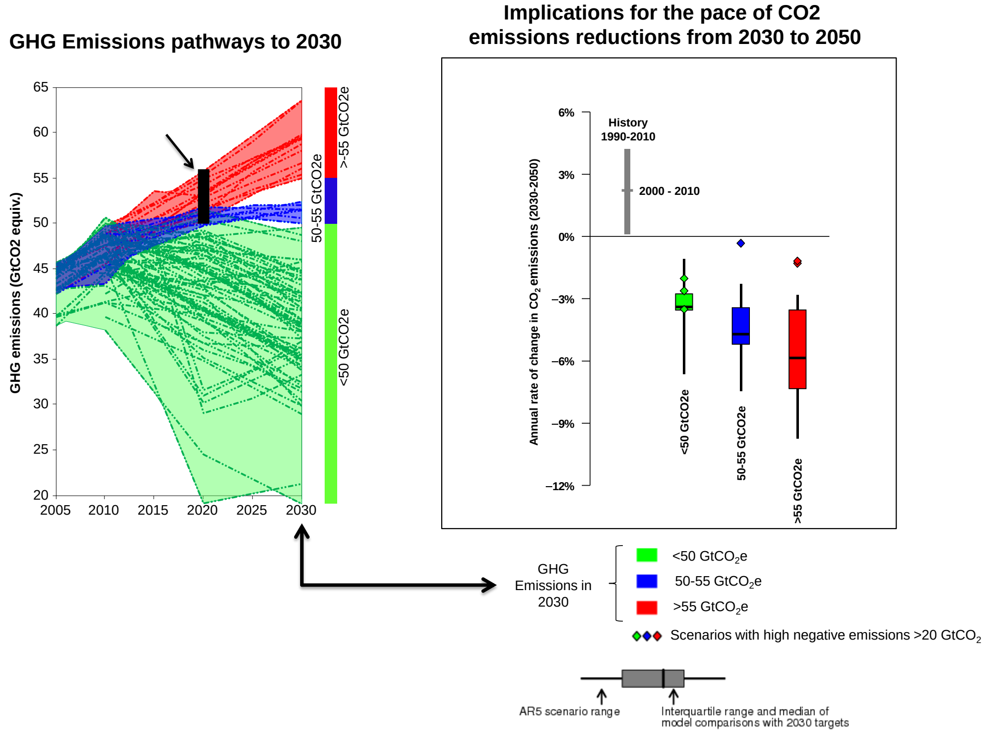


Figure 6.31. Near-Term Global Emissions from Scenarios With Climate Forcing in the range of 430-530 CO2-e (a) and 530-650 CO2-e (b) in 2100. Includes only scenarios for which temperature exceedance probabilities were calculated (see Section 6.3.2). Individual model results are indicated with a data point when 2°C exceedance probability is below 50% for Panel (a) or when 2.5°C exceedance probability is below 50% for Panel (b). Colours refer to scenario classification in terms of whether net CO2 emissions become negative before 2100 and the timing of international participation (full vs. delay). Number of reported individual results is shown in legend. Cancun range is based on analysis of alternative interpretations of national pledges (see Chapter 13 for details). Source: WG III AR5 Scenario Database (Annex II.10). Note: Only four reported scenarios were produced based on delayed mitigation without net negative emissions while still lying below 530 ppm CO2-e by 2100. They do not appear in panel a because the model had insufficient coverage of non-gas species to enable a temperature calculation (see Section 6.3.2). Delay in these scenarios extended only to 2020, and their emissions fell in the same range as the "No Negative/Full" category. Note: Delayed scenarios include both delayed global mitigation and fragmented action scenarios.

Whether due to delayed mitigation or widespread use of CDR options or some combination of the two, higher levels of emissions in the near-term imply an emissions pathway shifted in time, resulting in steeper reductions later to remain consistent with a given long term forcing goal. As discussed in 6.3.2 , emissions in 2030 have been used a rough indicator for understanding the relationship between near-term and long-term mitigation. Higher emissions in 2030 require more rapid decreases in emissions from 2030 through 2050, both to make up for the larger cumulative emissions up through 2030 and because emissions must be reduced from a higher 2030 level (Figure 6.32). Emissions decline rates for any scenario that meets 2100 concentration goals such as 450 or 550 ppm CO2-e must at some point push beyond historical experience, because emissions have in general followed growth, with past instances of decline associated only with large-scale disruptions such as the collapse of the Soviet Union or special cases of policy intervention such as France and Sweden (see Chapter 5). Less mitigation over the coming decades will only exacerbate the required departure from the past to meet long-term goals – pathways with emissions above 55 GtCO2-e in

2030 indicate decline rates between 2030 and 2050 of around 6% for scenarios in the range of 430-530 CO2-e in 2100 (Figure 6.32).


GHG Emissions pathways to 2030

Implications for the pace of CO2 emissions reductions from 2030 to 2050

Figure 6.32. The implications of different 2030 GHG emissions levels for the pace of CO2 emissions reductions to 2050 in low mitigation scenarios reaching 430-530 ppm CO2-e concentrations by 2100. Left-hand panel shows the development of GHG emissions to 2030. Right-hand panel denotes the corresponding annual CO2 emissions reduction rates for the period 2030-2050. The scenarios are grouped according to different emissions levels by 2030 (colored in red, blue and green). The right-hand panel compares the median and interquartile range across scenarios from recent intermodeling comparisons with explicit 2030 interim goals with the range of scenarios in the WG III AR5 Scenario Database (Annex II.10). Annual rates of historical emissions change (sustained over a period of 20 years) are shown in grey. Sources: intermodeling comparisons with explicit interim goals (AMPERE: Riahi et al, 2013; LIMITS: Kriegler et al 2013, ROSE: Luderer et al 2013) and the WG III AR5 Scenario Database (Annex II.10). Note: Only scenarios with default technology assumptions are shown. Scenarios with non-optimal timing of mitigation due to exogenous carbon price trajectories are excluded.

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 concentration goals, whether these goals are met in the long-run depends to a greater extent on the potential for deep GHG emissions reductions several decades from now. Thus efforts to begin the transformation to lower concentrations 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 goals. The way in which countries begin low-carbon technology deployment and the implementation of climate change mitigation policies may well turn out to be quite different from the approach that proves best in the long run. The benefit of beginning to create and improve technologies as well as to develop appropriate institutional capacity today is that these present-day activities create opportunities to make early and mid-course corrections.

The likelihood of a unified global policy for a deep GHG emissions reduction 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 generally understood to deliver emissions reductions at the lowest economic cost (see Section 6.3.6.5 for a discussion of issues that influence the efficiency of implementation approaches). 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 to facilitate flexible mitigation strategies, as well as political structures to manage the large capital flows associated with carbon pricing (see e.g. Kober and al., 2014), could provide substantial benefits over the coming decades when mitigation efforts reach their full proportions.

R&D investments to bring down the costs of low-emitting technology options, combined with 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 (see e.g. Sagar and van der Zwaan, 2006). R&D investments are important 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 for generating 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. Mitigation policy is essential for spurring R&D and learning-by-doing, because it creates commitments to future GHG 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 GHG 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 climate change 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 (see, for example, Bosetti et al., 2009c; Richels et al., 2009).

6.5 Integrating technological and societal change

Technological change occurs as innovations create new possibilities for processes and products, and market demand shifts over time in response to changes in preferences, purchasing power, and other societal factors. Societal changes can be viewed as both a requirement for and a result of global climate change mitigation. Because the use of improved and new technologies is an inherent element of society's transformation required for climate change mitigation, technological and societal changes necessarily interact. Their analysis therefore needs to be integrated.

6.5.1 Technological change

The development and deployment of technology is central to long-term mitigation, since established fossil-fuel-based energy supply will need to be replaced by new low-carbon energy techniques. The importance of technological change raises key questions about whether current technology is sufficient for deep GHG emissions reductions, the best ways 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. Essential questions also surround the appropriate timing of investments in technological change relative to other efforts to reduce GHG emissions.

A primary question regarding technological change is whether current technology is sufficient for the deep emissions reductions ultimately needed for to stabilize greenhouse gas concentrations. Arguments have been made on both sides of this debate (see Hoffert et al., (2002), and Pacala and Socolow, (2004), for complementary perspectives on this question). The integrated modelling literature provides limited information regarding the sufficiency of current technology, because virtually all transformation scenarios assume that technology will improve significantly over time, especially for technologies with a large potential for advancement (see Riahi et al., 2013, and van der Zwaan et al., 2013, for two recent cross-model comparison examples). There is generally more agreement about the rate of incremental cost and performance improvements for mature technologies than for emerging technologies upon which transformation pathways may depend (see McCollum et al., 2013, for a cross-model study on the investment dimension of this matter). Nonetheless, the literature makes clear that improvements in technology and the availability of advanced technologies can dramatically alter the costs of climate change mitigation (see also Section 6.3.6.3). The current scientific literature also emphasizes that the development and deployment of CDR technologies (see Section 6.9), are a further requirement for particular transformation pathways, for example those leading to 450 ppm CO2-e by 2100 yet assuming substantial near-term delays in mitigation.

Various steps can be observed in the life of a technology, from invention through innovation, demonstration, commercialization, diffusion and maturation (see e.g. Grübler et al., 1999). Both investments in R&D and the accumulation of experience through learning-by-doing play important roles in the mechanisms behind technological change. These forces are complemented by economies-of-scale. All these drivers of technological change are complementary yet and inter-linked (Clarke and Weyant, 2002; Goulder and Mathai, 2000; Sagar and van der Zwaan, 2006; Stoneman, 2013).

Although technological change has received extensive attention and analysis in the context of transformation pathways (for recent examples, see SRREN, 2011; GEA, 2012), a clear systematic understanding of the subject matter is still not available. For this reason, most of the scenarios developed since the 1970s for energy and climate change analysis make exogenous assumptions about the rate of technological change. Only since the late 1990s has the effect of induced innovation been considered in a subset of integrated models used for the development of these scenarios (such as in Messner, 1997; Goulder and Schneider, 1999; van der Zwaan et al., 2002; Carraro et al., 2003). This restricted treatment is due to limitations in the ability to represent the complexity of technological change, and also results from the incomplete empirical evidence on the magnitude of the effects of technological change (Popp, 2006b). More recently, empirical data on technological change have been incorporated in some models for the integrated of climate change (see e.g. Fisher-Vanden, 2008), which advances the endogenous representation of technological progress. Unsettled issues remain, however, including the proper accounting for opportunity costs of climate-related knowledge generation, the treatment of knowledge spill-overs and appropriability, and the empirical basis for parameterizing technological relationships (Gillingham et al., 2008).

The relation between mitigation and innovation, and the presence of market failures associated with both, raises the question of the proper combination of innovation and mitigation policy for reducing GHG emissions over the long-term. The modelling literature broadly indicates that relying solely on innovation policies would not be sufficient to stabilize greenhouse gas concentrations (see e.g. Bosetti et al., 2011; Kalkuhl et al., 2013), as evidenced by the fact that although most reference scenarios assume substantial technological change, none of them lead to emissions reductions on the level of those needed to bring CO2-e concentrations to levels such as 650 ppm CO2-e or below by 2100 (see Section 6.3.2). 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 contributing to emission reductions. The positive effect of climate policies on technological change, however, does not necessarily obviate the need for specific policies aimed at incentivizing R&D investments. Market failures associated with innovation provide the strongest rationale for subsidizing R&D (see Section 15.6).

The joint use of R&D subsidies and climate policies has been shown to possibly generate further advantages, with some studies indicating benefits of the order of 10-30% overall climate control cost reductions (D. Popp, 2006; V. Bosetti et al., 2011). 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 CO2 in the short term because of rebound effects from stimulating innovation (Otto and Reilly, 2008) (See Section 6.3.6.5 for further discussion of combining policy instruments to reduce aggregate mitigation costs). In the absence of explicit efforts to address innovation market failures, carbon taxes might be increased or differentiated across regions to indirectly address the under-provision of R&D (Golombek and Hoel, 2008; Hart, 2008; Greaker and Pade, 2009; Heal and Tarui, 2010; De Cian and Tavoni, 2012a).

Although there is no definitive conclusion on the subject matter, several studies suggest that the benefits of increased technological change for climate change mitigation may be sufficiently high to justify upfront investments and policy support in innovation and diffusion of energy efficiency and low carbon mitigation options (see e.g. Dowlatabadi, 1998; Newell et al., 1999; Nordhaus, 2002; Buonanno et al., 2003; Gerlagh and van der Zwaan, 2003). For example, it has been suggested that the current rates of investments are relatively low and that an average increase several times from current clean energy R&D expenditures may be closer towards optimality to stabilize greenhouse gas concentrations (Popp, 2006a; Nemet and Kammen, 2007; Bosetti et al., 2009a; IEA, 2010a; Marangoni and M. Tavoni, 2013). Bridging a possible “R&D gap” is particularly important and challenging, given that public energy R&D investments in OECD countries have generally been decreasing as a share of total research budgets over the past 30 years (from 11% down to 4%, according to recent IEA R&D statistics). On the other hand, in the private sector the rate of innovation (if measured by clean energy patents) seems to have accelerated over the past ten years.

Table 6.6. Preliminary findings on energy efficiency and clean energy R&D investments, as suggested in the literature to date, as needed to attain concentration goals. For reference, current public R&D expenditures are approximately 10 USD Billions/yr.

Study	**Foreseen total clean energy R&D investments**	**Notes**
Nemet and Kammen (2007)based on Davis and Owens (2003)	17-27 USD Billions/yr	For the period 2005-2015
IEA (2010a)	50-100 USD Billion/yr	To achieve the ‘Blue Map’ scenario in 2050. Roughly half of the investments are reserved for advanced vehicle R&D.
Bosetti et al. (2009a)	70-90 USD Billions/yr	Average to 2050 for a range of climate concentration goals. A large share is reserved for low-carbon fuel R&D.

An unequivocal call for energy innovation policy can be questioned, however, when all inventive activities – hence including those stimulating progress for ‘’dirty’’- technology– are accounted for. It might also not be straightforward to determine the overall effect of mitigation policy on technological innovation, since clean energy R&D may crowd out other inventive activity and result in lower overall welfare (Goulder and Schneider, 1999). The degree of substitutability between different inputs of production has been shown to drive the outcome of scenarios from integrated models (Otto et al., 2008; Acemoglu et al., 2009; Carraro et al., 2010). Innovation is found to play an important role for attempts to hedge against future uncertainties such as related to climate change impacts, technological performance and policy implementation (Loschel, 2002; Bohringer and Löschel, 2006; Baker and Shittu, 2008; Bosetti and Tavoni, 2009).

6.5.2 Integrating societal change

Individual behavior, social preferences, historical legacies, and institutional structures can influence the use of technologies and mitigation more generally. Technological transitions necessarily encompass more than simply improving and deploying technology. Because they co-evolve with technologies, social determinants of individual and collective behaviours can be either causes or consequences of transformation pathways. Moreover, governance and policies can influence these factors and thereby affect transformation pathways. This more complex framing of transformation pathways implies the need for a broader perspective on mitigation that explicitly considers the obstacles to deployment and mitigation more generally.

Research on these societal change elements are analytically diverse and often country-specific, which complicates comparative modelling exercises of the type reviewed in this chapter. The difficulty in representing these processes in models has meant that societal change research has often been divorced from the literature on transformation pathways. However, significant bodies of literature show how societal changes can affect the costs and acceptability of mitigation, and the interactions of climate policies and other dimensions of public policies beyond the energy sector.

Non-optimal or real world institutional conditions can influence how technological pathways evolve even under an economy-wide price on carbon. Because of the heterogeneity of the carbon impact of different sectors, the impact of a carbon price differs widely across sectors (Smale et al., 2006; Houser et al., 2009; Fischer and Fox, 2011; Monjon and Quirion, 2011) Demailly & al 2008). Even in less energy intensive sectors, pre-existing characteristics in the national economy—such as inflexible labor markets—can complicate the deployment of technologies (Guivarch et al., 2011). A further obstacle is the uneven impacts of a carbon price on household purchasing power, particularly for lower income brackets (Combet et al., 2010; Grainger and Kolstad, 2010).

Policy uncertainty can have implications for low-carbon technology investment. High levels of uncertainty force risk-averse firms not to adopt technologies by merit order in terms of net present value (Kahneman and Tversky, 1979; Pindyck, 1982; Majd and Pindyck, 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. Bosetti et al. (2011) show that investment uncertainty increases the costs and reduces the pace of transformation pathways. Perceived policy risks can not only dampen investment but can also encourage perverse outcomes such as non-additionality in the CDM (Hultman et al., 2012b). This raises the potential for linking mitigation policies, energy sector regulatory reforms, and financial policies to increase the risk-adverse returns of mitigation investments (Hourcade and Shukla, 2013).

Changes in institutional structures will be required to facilitate the technological change envisaged in the scenarios reviewed in this chapter. Historically, political and institutional pre-conditions, changing decision routines, and organisational skills help explain why countries with similar dependence on oil imports adopted very different energy responses to oil shocks (Hourcade and Kostopoulou, 1994; Hultman et al., 2012a). Similar issues arise in a low-carbon transition. New policies and institutional structures might be developed to manage infrastructures such as those associated with large quantities of intermittent resources on the electric grid, CO_2 transport and storage, dispersed generation or storage of electricity, or nuclear waste and materials.

Although modelling exercises have been able to assess the possible changes in the energy supply portfolio and the pressures to deploy energy efficiency technologies, such changes are difficult in practice to separate from the evolution of preference and lifestyles. The literature on energy efficiency investments highlights the frequent incongruity between perceived economic benefits for energy efficiency and actual consumer behaviour which seems often to ignore profitable investments. Such behaviour has been shown to stem from perceived unreliability, unfounded expectations for maintenance, information failures, property rights, split incentives, and differentiation across income.

Finally, social factors influence the changes in the way energy systems couple with other large-scale systems of production such as the built environment, transportation, and agriculture. The way that energy is used and consumed in urban areas (such as in transportation, heating and air-conditioning) is often driven by the structure and form of the urban infrastructure (Leck, 2006). Recent modelling exercises demonstrated the trade-off between commuting costs and housing costs and their impact on the urban sprawl and the mobility needs (Gusdorf and Hallegatte, 2007; Gusdorf et al., 2008). In many cases, the price of real estate is as powerful a driver of mobility demand as the price of transportation fuel, and therefore affects the price of carbon needed for meeting a given climate objective (Waisman et al., 2012; Lampin et al., 2013). The transport contribution to carbon can be affected by, for example, just-in-time processes and geographical splits of the productive chains (Crassous and Hourcade, 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) and Chapter 4). Yet, climate change is but one of many challenges facing society in the twenty-first century. Others include, for instance, providing access to clean, reliable and affordable energy services to the world's poorest; maintaining stable and plentiful employment opportunities; 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. A complex web of interactions and feedback effects links these various policy objectives, all of which are important for sustainable development (see section 4.8 and table 4.1).

Implementation of mitigation policies and measures therefore may be adequately described within a multi-objective framework and may be aligned with other objectives in order to maximize synergies and minimize trade-offs. Because the relative importance of individual objectives differs among diverse stakeholders and may change over time, transparency on the multiple effects that accrue to different actors at different points of time is important for decision making (see Sections 2.4, 3.6.3, 3.7.1 and 4.8).

Although 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 less attention. To the extent these mitigation side-effects are positive, they can be deemed "co-benefits"; if adverse, they imply "risks" with respect to the other non-climate objectives (see Annex I for definitions). Despite their importance for mitigation strategies, side-effects are often not monetized or even quantified in analyses of climate change (see e.g. Levine et al., 2007).

6.6.1 Co-benefits and adverse side-effects of mitigation measures: Synthesis of sectoral information and linkages to transformation pathways

One source of information on side-effects emerges from literature exploring the nature of individual technological or sectoral mitigation measures. These studies are covered in Chapters 7-12. Based on those assessments, Table 6.7 provides an aggregated but qualitative overview of the potential co-benefits and adverse side-effects that could be realized if certain types of mitigation measures are enacted in different sectors: side-effects resulting from energy supply-side transformations; via technological and behavioural changes in the transport, buildings, and industry end-use sectors; and through modified agriculture, forestry, and land use practices. These co-benefits and adverse side-effects can be classified by the nature of their sustainable development implications: economic, social, or environmental (see sections 4.2 and 4.8 for a discussion of the three pillars of sustainable development). Other types of impacts are also possible and are highlighted in the table where relevant.

Whether or not any of these side-effects actually materialize, and to what extent, will be highly case- and site-specific, as they 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 (Barker et al., 2007) . Such detailed considerations are not reflected in Table

6.7, which is meant to give an aggregated sense of the potential co-benefits and adverse side-effects throughout the world when mitigation policies are in place. Details are discussed in 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 6.7 also provides *quantitative* information for each sector regarding the mid-century contribution of the respective (group of) mitigation measures to reach stringent mitigation goals (see section 6.8 , 7.11 and 11.9 for the underlying data).

The compilation of sectoral findings in Table 6.7 suggests that the number of co-benefits clearly outweigh that of adverse side-effects in the case of demand-side mitigation measures (transport, buildings, and industry), whereas the evidence suggests this is not the case for all supply-side measures. Although no single category of mitigation measures is completely devoid of risk, Table 6.7 highlights that certain co-benefits are valid across all sectors. For instance, by contributing to a phase-out of conventional fossil fuels, nearly all mitigation options have major health and environmental benefits for society, owing to significant reductions in both outdoor and indoor air pollution, and lead to improved energy security at the national level for most countries. In addition to the many sector-specific co-benefits and adverse side-effects, sectoral employment and productivity gains, technological spill-overs, more equitable energy/mobility access, and increased quality of life (such as thermal comfort and improved working conditions) offer examples of co-benefits that are possible across all demand sectors. While energy demand reductions additionally mitigate risks associated with energy supply technologies (see also Rogelj et al., 2013b), the upstream effects of fuel switching are more complex and depend to a large extent on local circumstances (see Section 7.11).

Moreover, while nearly all mitigation measures for reducing (fuel) carbon and energy intensity have higher up-front investment requirements than conventional technologies, their often lower operating costs, and sometimes even life-cycle costs, can contribute to reduced energy service prices for consumers, depending on local and national institutional settings (see Section 7.9.1). If, on the other hand, energy prices rise as a consequence, so do the political challenges of implementation, such as those associated with the provision of universal energy access and associated economic, social, environmental, and health risks for the poorest members of society (Markandya et al., 2009; Sathaye et al., 2011; Rao, 2013). Well-designed policies are thus important to avoid perverse incentives of climate policies, including increasing traditional biomass use for heating and cooking (see Bollen et al., 2009a and Section 9.7.1).

In addition to furthering the achievement of various global goals for sustainability, namely those of the major environmental conventions (e.g., the United Nations' Convention to Combat Desertification (UNCCD, 2004), Convention on Biological Diversity (CBD, 1992), 'Sustainable Energy for All' initiative, and the Millennium Development Goals (MDG)), mitigation can potentially yield positive side-effects in the impacts, adaptation, and vulnerability (IAV) dimensions (see Section 11.7 Haines et al., 2009; Rogelj et al., 2013b). 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).

Table 6.7. Potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main sectoral mitigation measures; arrows pointing up/down denote a positive/negative effect on the respective objective/concern; a question mark (**?**) denotes an uncertain net effect. Co-benefits and adverse side-effects depend on local circumstances as well as on the implementation practice, pace and scale (see Tables 7.3, 8.4, 9.7, 10.5, 11.9, 11.12). Column two provides the contribution of different sectoral mitigation strategies to stringent mitigation scenarios reaching atmospheric CO_2eq concentrations of 430-530 ppm in 2100. The interquartile ranges of the scenario results for the year 2050 show that there is flexibility in the choice of mitigation strategies within and across sectors consistent with low concentration goals (see Sections 6.4 and 6.8). Scenario results for energy supply and end-use sectors are based on the AR5 Scenario Database (see Section 6.2.2). For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. The uncertainty qualifiers in brackets denote the level of evidence and agreement on the respective effects. Abbreviations for evidence: l=limited, m=medium, r=robust; for agreement: l=low, m=medium, h=high.

Sectoral mitigation measures	**Integrated model results for stringent mitigation scenarios**			**Effect on additional objectives/concerns**			
				Economic	**Social**	**Environmental**	**Other**
Energy Supply	**Deployment[1]**		**Rate of change %/yr**	*For possible upstream effects of biomass supply for bioenergy, see AFOLU.*			
	2010	***2050***					
Nuclear replacing coal power	10 EJ/yr	(4-22) *17-47*	(-2-2) *1-4*	↑ Energy security (reduced exposure to fuel price volatility) (**m/m**) ↑ Local employment impact (but uncertain net effect) (**l/m**) ↑ Legacy cost of waste and abandoned reactors (**m/h**)	Health impact via ↓ Air pollution and coal mining accidents (**m/h**) ↑ Nuclear accidents and waste treatment, uranium mining and milling (**m/l**) ↑ Safety and waste concerns (**r/h**)	Ecosystem impact via ↓ Air pollution (**m/h**) and coal mining (**l/h**) ↑ Nuclear accidents (**m/m**)	Proliferation risk (**m/m**)
RE (Wind, PV, CSP, hydro, geothermal, bioenergy) replacing coal	62 EJ/yr	(66-125) *194-282*	(0.2-2) *3-4*	↑ Energy security (resource sufficiency, diversity in the near/medium term) (**r/m**) ↑ Local employment impact (but uncertain net effect) (**m/m**) ↑ Irrigation, flood control, navigation, water supply (reservoir hydro, regulated rivers)(**m/h**) ↑ Extra measures to match demand (for PV, wind and some CSP) (**r/h**)	Health impact via ↓ Air pollution (except bioenergy) (**r/h**) ↓ Coal mining accidents (**m/h**) ↑ Contribution to (off-grid) energy access (**m/l**) **?** Project-specific public acceptance concerns (e.g., visibility of wind) (**l/m**) ↑ Threat of displacement (large hydro) (**m/h**)	Ecosystem impact via ↓ Air pollution (except bioenergy) (**m/h**) ↓ Coal mining (**l/h**) ↑ Habitat impact (for some hydro) (**m/m**) ↑ Landscape and wildlife impact (for wind) **m/m**) ↓ Water use (for wind and PV) (**m/m**) ↑ Water use (for bioenergy, CSP, geothermal, and reservoir hydro) (**m/h**)	Higher material use of critical metals for PV and direct drive wind turbines (**r/m**)
Fossil CCS replacing coal	0 Gt CO_2/yr stored	(0) *4-12*	(0) *NA*	↑↑Preservation vs lock-in of human and physical capital in the fossil industry (**m/m**)	Health impact via ↑ Risk of CO_2 leakage (**m/m**) ↑ Upstream supply-chain activities (**m/h**) ↑ Safety concerns (CO_2 storage and transport) (**m/h**)	↑ Ecosystem impact via upstream supply-chain activities (**m/m**) ↑ Water use (**m/h**)	Long-term monitoring of CO_2 storage (**m/h**)
BECCS replacing coal	0 Gt CO_2/yr	(0) *0-6*	*NA*	*See fossil CCS where applicable. For possible upstream effect of biomass supply, see AFOLU.*			
Methane leakage prevention, capture or treatment	NA	NA	NA	↑ Energy security (potential to use gas in some cases) (**l/h**)	↑ Health impact via reduced air pollution (**m/m**) ↑ Occupational safety at coal mines (**m/m**)	↓ Ecosystem impact via reduced air pollution (**l/m**)	

1) Deployment levels for baseline scenarios (in parentheses) and stringent mitigation scenarios leading to 430-530 ppm CO_2-e in 2100 (in italics). Ranges correspond to the 25-75 interquartile across the scenario ensemble of the AR5 Scenario Database (for mitigation scenarios, only assuming idealized policy implementation: P1)

Transport	Scenario results	*For possible upstream effects of low-carbon electricity, see Energy Supply. For possible upstream effects of biomass supply, see AFOLU.*			
Reduction of fuel carbon intensity: e.g. electricity, H_2, CNG, biofuels and other measures	*Interquartile ranges for the whole sector in 2050 with 430-530 ppm CO_2eq concentrations in 2100 (see Figures 6.37 & 6.38):* 1) Final energy low-carbon fuel shares 27 - 41 % 2) Final energy reduction relative to baseline 20 - 45 %	↑ Energy security (diversification, reduced oil dependence and exposure to oil price volatility) **(m/m)** ↑ Technological spillovers (e.g. battery technologies for consumer electronics) **(l/l)**	Health impact via urban air pollution by ? CNG, biofuels: net effect unclear **(m/l)** ↓ Electricity, H_2: reducing most pollutants **(r/h)** ↑ Diesel: potentially increasing pollution **(l/m)** ↓ Noise (electrification and fuel cell LDVs) **(l/m)** ↓ Road safety (silent electric LDVs at low speed) **(l/l)**	Ecosystem impact of electricity and hydrogen via ↓ Urban air pollution **(m/m)** ↑ Material use (unsustainable resource mining) **(l/l)** Ecosystem impact of biofuels: *see AFOLU*	
Reduction of energy intensity		↑ Energy security (reduced oil dependence and exposure to oil price volatility) **(m/m)**	↓ Health impact via reduced urban air pollution **(r/h)** ↑ Road safety (via increased crash-worthiness) **(m/m)**	↓ Ecosystem and biodiversity impact via reduced urban air pollution **(m/h)**	
Compact urban form + improved transport infrastructure Modal shift		↑ Energy security (reduced oil dependence and exposure to oil price volatility) **(m/m)** ↑ Productivity (reduced urban congestion and travel times, affordable and accessible transport) **(m/h)** ? Employment opportunities in the public transport sector vs car manufacturing **(l/m)**	Health impact for non-motorized modes via ↓ Increased activity **(r/h)** ↑ Potentially higher exposure to air pollution **(r/h)** ↑ Noise (modal shift and travel reduction) **(r/h)** ↑ Equitable mobility access to employment opportunities, particularly in DCs **(r/h)** ↑ Road safety (via modal shift and/or infrastructure for pedestrians and cyclists) **(r/h)**	Ecosystem impact via reduced ↓ Urban air pollution **(r/h)** ↓ Land-use competition **(m/m)**	
Journey reduction and avoidance		↑ Energy security (reduced oil dependence and exposure to oil price volatility) **(r/h)** ↑ Productivity (reduced urban congestion, travel times, walking) **(r/h)**	↓ Health impact (non-motorized transport modes) **(r/h)**	Ecosystem impact via ↓ Urban air pollution **(r/h)** ↑ New/shorter shipping routes **(r/h)** ↓ Land-use competition (transport infrastructure) **(r/h)**	
Buildings	Scenario results	*For possible upstream effects of fuel switching and RES, see Energy Supply.*			
Fuel switching, RES incorporation, green roofs, and other measures reducing emissions intensity	*Interquartile ranges for the whole sector in 2050 with 430-530 ppm CO_2eq concentrations in 2100 (see Figures 6.37 & 6.38):* 1) Final energy low-carbon fuel shares 51 - 60 % 2) Final energy reduction relative to baseline 14 – 35 %	↑ Energy security **(m/h)** ↑ Employment impact **(m/m)** ↑ Lower need for energy subsidies **(l/l)** ↑ Asset values of buildings **(l/m)**	Fuel poverty (residential) via ↓ Energy demand **(m/h)** ↑ Energy cost **(l/m)** ↓ Energy access (for higher energy cost) **(l/m)** ↑ Productive time for women/children (replaced traditional cookstoves) **(m/h)**	Health impact in residential buildings via ↓ Outdoor air pollution **(r/h)** ↓ Indoor air pollution (in DCs) **(r/h)** ↓ Fuel poverty **(r/h)** ↓ Ecosystem impact (less outdoor air pollution) **(r/h)** ↑ Urban biodiversity (green roofs) **(m/m)**	Reduced Urban Heat Island Effect (UHI) **(l/m)**
Retrofits of existing buildings (e.g. cool roof, passive solar, etc.) Exemplary new buildings Efficient equipment		↑ Energy security **(m/h)** ↑ Employment impact **(m/m)** ↑ Productivity (commercial buildings) **(m/h)** ↑ Lower need for energy subsidies **(l/l)** ↑ Asset values of buildings **(l/m)** ↑ Disaster resilience **(l/m)**	↓ Fuel poverty (retrofits, efficient equipment) **(m/h)** ↓ Energy access (higher cost for housing due to the investments needed) **(l/m)** ↑ Quality of life (thermal comfort in retrofits and exemplary new buildings) **(m/h)** ↑ Productive time for women and children (replaced traditional cookstoves) **(m/h)**	Health impact via ↓ Outdoor air pollution **(r/h)** ↓ Indoor air pollution (efficient cookstoves) **(r/h)** ↓ Indoor environmental conditions **(m/h)** ↓ Fuel poverty **(r/h)** ↓ Insufficient ventilation **(m/m)** ↓ Ecosystem impact (less outdoor air pollution) **(r/h)** ↓ Water consumption and sewage production **(l/l)**	Reduced UHI (retrofits and new exemplary buildings) **(l/m)**
Behavioral changes reducing energy demand		↑ Energy security **(m/h)** ↑ Lower need for energy subsidies **(l/l)**		↓ Health impact via less outdoor air pollution **(r/h)** & improved indoor environmental conditions **(m/h)** ↓ Ecosystem impact (less outdoor air pollution) **(r/h)**	

Industry	Scenario results	*For possible upstream effects of low-carbon energy supply (incl CCS), see Energy Supply and of biomass supply, see AFOLU.*			
CO_2/non-CO_2 emission intensity reduction	*Interquartile ranges for the whole sector in 2050 with 430-530 ppm CO_2eq concentrations in 2100 (see Figures 6.37 & 6.38):* 1) Final energy low-carbon fuel shares: 44 - 57 % 2) Final energy reduction relative to baseline: 22 – 38 %	↑ Competitiveness and productivity (**m/h**)	↓ Health impact via reduced local air pollution and better work conditions (PFC from aluminium) (**m/m**)	↓ Ecosystem impact via reduced local air pollution and reduced water pollution (**m/m**) ↑ Water conservation (**l/m**)	
Energy efficiency improvements via new processes/technologies		↑ Energy security (lower energy intensity)(**m/m**) ↑ Employment impact (**l/l**) ↑ Competitiveness and productivity (**m/h**) ↑ Technological spillovers in DCs (due to supply chain linkages) (**l/l**)	↓ Health impact via reduced local pollution (**l/m**) ↑ New business opportunities (**m/m**) ↑ Water availability and quality (**l/l**) ↑ Safety, working conditions and job satisfaction (**m/m**)	Ecosystem impact via ↓ Fossil fuel extraction (**l/l**) ↓ Local pollution and waste (**m/m**)	
Material efficiency of goods, recycling		↓ National sales tax revenue (medium term)(**l/l**) ↑ Employment impact (waste recycling) (**l/l**) ↑ Competitiveness in manufacturing (**l/l**) ↑ New infrastructure for industrial clusters (**l/l**)	↓ Health impacts and safety concerns (**l/m**) ↑ New business opportunities (**m/m**) ↓ Local conflicts (reduced resource extraction) (**l/m**)	↓ Ecosystem impact via reduced local air and water pollution and waste material disposal (**m/m**) ↓ Use of raw/virgin materials and natural resources implying reduced unsustainable resource mining (**l/l**)	
Product demand reductions		↓ National sales tax revenue (medium term)(**l/l**)	↓ Local conflicts (reduced inequity in consumption)(**l/l**) ↑ New diverse lifestyle concept (**l/l**)	↓ Post-consumption waste (**l/l**)	
AFOLU	Scenario results	*Note: co-benefits and adverse side-effects depend on the development context and the scale of the intervention (size).*			
Supply side: forestry, land-based agriculture, livestock, integrated systems and bioenergy (**marked by** *) **Demand side:** reduced losses in the food supply chain, changes in human diets, changes in wood demand and demand from forestry products	Ranges for cumulative land-related emissions reductions relative to baseline for CH_4, CO_2, and N_2O in idealized implementation scenarios with 450 CO_2eq ppm concentrations in 2100 (see Table 11.10): CH_4: 2 – 18 % CO_2: - 104 – 423 % N_2O: 8 – 17 %	* Employment impact via ↑ entrepreneurship development (**m/h**) ↓ use of less labor-intensive (**m/m**) technologies in agriculture ↑ * Diversification of income sources and access to markets (**r/h**) ↑ * Additional income to (sustainable) landscape management (**m/h**) ↑ * Income concentration (**m/m**) ↑ * Energy security (resource sufficiency) (**m/h**) ↑ Innovative financing mechanisms for sustainable resource management (**m/h**) ↑ Technology innovation and transfer (**m/m**)	↑ * Food-crops production through integrated (**r/m**) systems and sustainable agriculture intensification ↓ * Food production (locally) due to large-scale monocultures of non-food crops (**r/l**) ↑ Cultural habitats and recreational areas via (**m/m**) (sustainable) forest management and conservation ↑ *Human health and animal welfare e.g. through less pesticides, reduced burning practices and practices like agroforestry & silvo-pastoral systems (**m/h**) ↓ *Human health when using burning practices (in agriculture or bioenergy) (**m/m**) * Gender, intra- and inter-generational equity via ↑ participation and fair benefit sharing (**r/h**) ↑ concentration of benefits (**m/m**)	Provision of ecosystem services via ↑ ecosystem conservation and sustainable management as well as sustainable agriculture (**r/h**) ↓ * large scale monocultures (**r/h**) ↑ * Land use competition (**r/m**) ↑ Soil quality (**r/h**) ↓ Erosion (**r/h**) ↑ Ecosystem resilience (**m/h**) ↑ Albedo and evaporation (**r/h**)	<u>*Institutional aspects:*</u> ↑↓ * Tenure and use rights at the local level (for indigenous people and local communities) especially when implementing activities in natural forests (**r/h**) ↑↓ Access to participative mechanisms for land management decisions (**r/h**) ↑ Enforcement of existing policies for sustainable resource management (**r/h**)
Human Settlements and Infrastructure		*For co-benefits and adverse side effects of compact urban form and improved transport infrastructure, see also Transport.*			
Compact development and infrastructure		↑ Innovation and efficient resource use (**r/h**) ↑↑Higher rents and property values(**m/m**)	↑ Health from physical activity: *see Transport*	↑ Preservation of open space (**m/m**)	
Increased accessibility		↑ Commute savings (**r/h**)	↑ Health from increased physical activity: *see Transport* ↑ Social interaction & mental health (**m/m**)	↑ Air quality and reduced ecosystem and health impacts (**m/h**)	
Mixed land use		↑ Commute savings (**r/h**) ↑↑Higher rents and property values (**m/m**)	↑ Health from increased physical activity (**r/h**) ↑ Social interaction and mental health (**l/m**)	↑ Air quality and reduced ecosystem and health impacts (**m/h**)	

6.6.2 Transformation pathways studies with links to other policy objectives

As indicated above, the overall nature and extent of the co-benefits and risks arising from global transformation pathways depends importantly on which mitigation options are implemented and how. The full systems-level welfare impacts for multi-objective decision-making are therefore best viewed from an integrated perspective that permits the full accounting of the impacts of each of the objectives on social welfare (see Section 3.5.3) (Bell et al., 2008; Sathaye et al., 2011; Rao et al., 2013). Taking such a perspective poses a significant challenge, since the costs of mitigation need to be weighed against the multiple benefits and adverse side-effects for the other objectives. To complicate matters further, these other objectives are traditionally measured in different units (e.g., health benefits of reduced air pollution in terms of deaths avoided). In addition, combining the different objectives into a single overall welfare formulation implies subjective choices about the ranking or relative importance of policy priorities. Such a ranking is highly dependent on the policy context (see Sections 2.4 and 3.6.3).

Since AR4, a number of scenario studies have been conducted to shed light on the global implications of transformation pathways for other objectives. Earlier scenario literature primarily focused on the health and ecosystem benefits of mitigation via reduced air pollution; some evidence of co-benefits for employment and energy security was also presented in AR4. More recent studies have broadened their focus to include energy security, energy access, biodiversity preservation, water and land use requirements (see the bioenergy appendix for a review of scenario studies focusing on water and land use and implications for food security). Many of these newer analyses use globally consistent methods, meaning they employ long-term, multi-region frameworks that couple models of both bio-geophysical and human processes, thereby permitting the consideration of targeted policies for the additional objectives in their own right. While the majority of these studies focus on two-way interactions (e.g., the effect of 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 (Section 6.6.2.7). Important to note in this context is that many of the non-technical measures listed in Table 6.7 (e.g., behavioral changes) are not fully taken into account by models, though the state-of-the-art continues to improve.

6.6.2.1 Air pollution and health

Greenhouse gases and air pollutant emissions typically derive from the same sources, such as power plants, factories, and cars. Hence mitigation strategies that reduce the use of fossil fuels typically result in major cuts in emissions of black carbon (BC), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and mercury, among other harmful species. Together with tropospheric ozone and its precursors (mainly deriving from AFOLU and fossil fuel production/transport processes), these pollutants separately or jointly cause a variety of detrimental health and ecosystem effects at various scales (see 7.9.2). The magnitude of these effects varies across pollutants and atmospheric concentrations (as well as the concentrations of pollutants created via further chemical reactions) and is due to different degrees of population exposure, whether indoor or outdoor or in urban or rural settings (see Barker et al., 2007; Bollen et al., 2009b; Markandya et al., 2009; Smith et al., 2009; Sathaye et al., 2011; GEA, 2012). The term “fine particular matter ($PM_{2.5}$)” is frequently used to refer to a variety of air pollutants that are extremely small in diameter and therefore cause some of the most serious health effects.

The literature assessed in AR4 focused on air pollution reductions in individual countries and regions, pointing to large methodological differences in, for example, the type of pollutants analysed, sectoral focus, and the treatment of existing air pollution policy regimes. As confirmed by recent literature (Friel et al., 2009; Wilkinson et al., 2009; Woodcock et al., 2009; Markandya et al., 2009; Haines et al., 2009; Smith et al., 2009; Nemet et al., 2010), AR4 showed that the monetized air quality co-benefits from mitigation are of a similar order of magnitude as the mitigation costs themselves (see sections 3.6.3 and 5.7.1). For instance, taking into account new findings on the relationship between chronic mortality and exposure to PM and ozone as well as the effect of slowing climate change on air quality, West et al., (2013) calculate global average monetized co-benefits of avoided mortality of US$50-380/tCO$_2$. They find that the values for East Asia far exceed the marginal mitigation costs in 2030. (See Section 5.7 for a broader review of this issue, as well as a discussion of the importance of baseline conditions for these results.) Furthermore, it has been noted that reductions in certain air pollutants can potentially increase radiative warming (see Sections 1.2.5, 5.2 and WGI Chapter 7). This is an important adverse side-effect, and one that is not discussed here due to the lack of scenario studies addressing the associated trade-off between health and climate benefits.

The available evidence indicates that transformation pathways leading to 430-530 ppm CO2-e in 2100 will have major co-benefits in terms of reduced air pollution (Figure 6.33). Recent integrated modelling studies agree strongly with earlier findings by van Vuuren et al. (2006) and Bollen et al. (2009a) in this regard. For example, Rose et al. (2014b) find that national air pollution policies may no longer be binding constraints on pollutant emissions depending on the stringency of climate policies. In China, for instance, mitigation efforts consistent with a global goal of 3.7 W/m^2 (2.8 W/m^2) in 2100 result in SO$_2$ emissions 15 to 55% (25–75%) below reference levels by 2030 and 40 to 80 % (55–80%) by 2050. (Chaturvedi and Shukla, 2013) find similar results for India. Globally, Rafaj et al. (2012) calculate that stringent mitigation efforts 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. Riahi et al. (2012b) find that 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 indoor/household air pollution), the near-term air pollution co-benefits of mitigation could be even greater: 50% for SO$_2$, 35% for NO$_x$, and 30% for PM$_{2.5}$ by 2030. Amann et al. (2011) and Rao et al. (2013) find significant reductions in air quality control costs due to mitigation policies (see Section 6.6.2.7).

Riahi et al. (2012b) further estimate that stringent mitigation efforts can help to reduce globally-aggregated disability-adjusted life years (DALYs) by more than 10 million by 2030, a decrease of one-third compared to a reference scenario. The vast majority of these co-benefits would accrue in urban households of the developing world. Similarly, West et al. (2013) find that global mitigation (RCP4.5) can avoid 0.5±0.2, 1.3±0.5 and 2.2±0.8 million premature deaths in 2030, 2050 and 2100, relative to a reference case that foresees decreasing PM and O$_3$ concentrations. Regarding mercury, Rafaj et al. (2012) show that under a global mitigation regime, atmospheric releases from anthropogenic sources can be reduced by 45% in 2050, relative to a reference case without climate measures.

Several studies published since AR4 have analysed the potential climate impacts of methane mitigation and local air pollutant emissions control (West et al., 2006, 2007; Shine et al., 2007; Reilly et al., 2007b; Ramanathan and Carmichael, 2008; Jerrett et al., 2009; Anenberg et al., 2012). For instance, Shindell et al. (2012) identify fourteen different methane and BC mitigation measures that, in addition to slowing the growth in global temperatures in the medium term (~0.5 °C lower by 2050, central estimate), lead to important near-term (2030) co-benefits for health (avoiding 0.7 to 4.7 million premature deaths from outdoor air pollution globally) and food security (increasing annual crop yields globally by 30 to 135 million metric tons due to ozone reductions; see the bioenergy appendix for a further discussion of the relationship between mitigation and food security). Smith et al. (2013) also acknowledge the important co-benefits of reducing certain short-lived climate forcers (SLCF) but at the same time conclude that (1) the near-to-medium term climate impacts of these measures are likely to be relatively modest (0.16 °C lower by 2050, central estimate; 0.04–0.35 °C considering the various uncertainties), and (2) the additional climate benefit of targeted SLCF measures after 2050 is comparatively low.

6.6.2.2 Energy security

A number of analyses have studied the relationship between mitigation and energy security. The assessment here focuses on energy security concerns that relate to (1) the sufficiency of resources to meet national energy demand at competitive and stable prices, and (2) the resilience of energy supply (see section 7.9.1 for a broader discussion). A number of indicators have been developed to quantitatively express these concerns (Kruyt et al., 2009; Jewell, 2011; Jewell et al., 2013a). The most common indicators of sufficiency of energy supply are energy imports (see SRREN Figure 9.6) and the adequacy of the domestic resource base (Gupta, 2008; Kruyt et al., 2009; Le Coq and Paltseva, 2009; IEA, 2011; Jewell, 2011; Jewell et al., 2013b). Resilience of energy systems is commonly measured by the diversity of energy sources and carriers (Stirling, 1994, 2010; Grubb et al., 2006; Bazilian and Roques, 2009; Skea, 2010) and the energy intensity of GDP (Gupta, 2008; Kruyt et al., 2009; Jewell, 2011; Cherp et al., 2012).

Recent studies show that climate mitigation policies would likely increase national energy sufficiency and resilience (Figure 6.33). Mitigation policies lead to major reductions in the import dependency of many countries, thus making national and regional energy systems less vulnerable to price volatility and supply disruptions (Criqui and Mima, 2012; Shukla and Dhar, 2011; Jewell et al., 2013b). One multi-model study finds that in stringent mitigation scenarios global energy trade would be 10-70% lower by 2050 and 40-74% by 2100 than in the reference case (Jewell et al., 2013b). Most of the decrease in regional import dependence would appear after 2030 since mitigation decreases the use of domestic coal in the short term, which counteracts the increase in domestic renewables (Akimoto et al., 2012; Jewell et al., 2013b). At the same time mitigation leads to much lower extraction rates for fossil resources (Kruyt et al., 2009; Jewell et al., 2013b; McCollum et al., 2013a). The International Energy Agency, for example, finds that rapid deployment of energy efficiency technologies could reduce oil consumption by as much as 13 million barrels a day (IEA 2012). Mitigation actions could thus alleviate future energy price volatility, given that perceptions of resource scarcity are a key driver of rapid price swings. This would mean that domestic fossil resources could act as a “buffer of indigenous resources” (Turton and Barreto, 2006). Improved energy security of importers, however, could adversely impact the ‘demand security’ of exporters (Luft, 2013); on the other hand, there are studies which indicate that oil exporters could benefit under climate policies (Persson et al., 2007; Johansson et al., 2009; Tavoni et al., 2014). (See Section 6.3.6.6 regarding the impacts that these trade shifts would have on major energy exporters.)

Studies also indicate that mitigation would likely increase the resilience of energy systems (Figure 6.33). The diversity of energy sources used in the transport and electricity sectors would rise relative to today and to a baseline scenario in which fossils remain dominant (Grubb et al., 2006; Riahi et al., 2012b; Cherp et al., 2013; Jewell et al., 2013b). Additionally, energy trade would be much less affected by fluctuations in GDP growth and by uncertainties in fossil resource endowments and energy demand growth (Cherp et al., 2013; Jewell et al., 2013b). These developments (mitigation and energy efficiency improvements) would make energy systems more resilient to various types of shocks and stresses and would help insulate economies from price volatility and supply disruptions (see Chapters 8-10).

6.6.2.3 Energy access

According to the literature, providing universal energy access (see section 7.9.1 for a broader discussion) would likely result in negligible impacts on GHG emissions globally (PBL, 2012; Riahi et al., 2012b). Rogelj et al (2013c) find that the UN’s energy access goals for 2030 are fully consistent with stringent mitigation measures while other scenario analyses indicate that deployment of RE in LDCs can help to promote access to clean, reliable and affordable energy services (Kaundinya et al., 2009; Reddy et al., 2009). In addition, a number of recent integrated modelling studies ensure, by design, that developing country household final energy consumption levels are compatible with minimal poverty thresholds (Ekholm et al., 2010a; van Ruijven et al., 2011; Daioglou et al., 2012; Narula et al., 2012; Krey et al., 2012). An important message from these studies is that the provision of energy access in developing countries should not be confused with broader economic growth. The latter could have a pronounced GHG effect, particularly in today’s emerging economies (see section 6.3.1.3).

The primary risk from mitigation is that an increase in energy prices for the world’s poor could potentially impair the transition to universal energy access by making energy less affordable (see sections 6.6.1 and 7.9.1). A related concern is that increased energy prices could also delay structural changes and the build-up of physical infrastructure (Goldemberg et al., 1985; Steckel et al., 2013) Jakob and Steckel, 2013). Isolating these effects has proven to be difficult in the integrated modeling context because these models typically aggregate consumption losses from climate policies (see section 6.3.6).

6.6.2.4 Employment

The potential consequences of climate policies on employment are addressed in the scientific literature in different ways. One strand of literature analyzes the employment impacts associated with the deployment of specific low-carbon technologies, such as renewables or building retrofits (see 7.9.1 and 9.7.2.1). This literature often finds a significant potential for *gross* job creation, either directly or indirectly; however, a number of issues are left unresolved regarding the methodologies used in computing those impacts on one hand and the gap between this potential and *net* employment impacts in a particular sector on the other hand (see Wei et al. (2010)). The net effect is typically addressed in general equilibrium literature. Although many integrated models used to develop long-term scenarios are general equilibrium models, they usually assume full employment and are therefore not well suited to addressing gross versus net employment-related questions.

According to the literature, employment benefits from mitigation depends on the direction and strength of income/output and substitution impacts of mitigation. These impacts are governed by two interrelated sets of factors related to mitigation technologies and general equilibrium effects. One set involves the characteristics of mitigation technologies, including: (1) their costs per job created, which determines the crowding out of jobs in other sectors when capital is constrained (Frondel et al., 2010); (2) the portion of the low-carbon technologies that is imported, which determines domestic job creation and the net positive impact on the trade balance; and (3) the availability of skills in the labor force, as well as its capacity to adapt (Babiker and Eckaus, 2007; Fankhauser et al., 2008; Guivarch et al., 2011), which determines the pace of job creation and the real cost of low-carbon technology deployment in terms of increased wages due to skilled labor scarcities.

A second set of factors encompasses all the general equilibrium effects, some of which are triggered by the above parameters and others by the net income effects of higher carbon prices (see 3.6.3) Recycling the revenues from carbon pricing and subsequently lowering labor taxes changes the relative prices of labor and energy (and to a lesser extent the costs of production inputs), which in turn leads to a redirection of technology choices and innovation towards more labor-intensive techniques. In addition, by contributing to higher energy costs, climate policies change the relative prices of energy- and non-energy intensive goods and services, thereby causing households to consume more of the latter. These mechanisms operate differently in developed, emerging and developing economies, particularly with respect to the various forms of informal labor. Some of mechanisms operate over the medium (more labor-intensive techniques) and long term (structural change) (Fankhauser et al., 2008). Others, however, operate over the short term and might therefore be influenced by near-term mitigation policies.

6.6.2.5 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 integrated modelling 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 (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.

The primary biodiversity-related side-effects from mitigation involve the potentially large role of reforestation and afforestation efforts and of bioenergy production. These elements of mitigation strategy could either impose risks or lead to co-benefits, depending on where and how they are implemented (see Table 6.7). The integrated modelling literature does not at this time provide an explicit enough treatment of these issues to effectively capture the range of transformation pathways. One study (PBL, 2012) suggests that it is possible to stabilize average global biodiversity at the 2020/2030 level (MSA = 65%) by 2050 even if land use mitigation measures are deployed. Such an achievement represents more than a halving of all biodiversity loss projected to occur by mid-century in the reference case and is interpreted to be in accordance with the Aichi Biodiversity Targets (CBD, 2010). Of critical importance in this regard are favourable institutional and policy mechanisms for reforestation/afforestation and bioenergy that complement mitigation actions (as described in Section 11.13)

6.6.2.6 Water use

The last decades have seen the world's freshwater resources come under increasing pressure. Almost three billion people live in water-scarce regions (Molden, 2007), some two billion in areas of severe water stress in which demand accounts for more than 40% of total availability (PBL, 2012). Water withdrawals for energy and industrial processes (currently 20% globally) and municipal applications (10%) are projected to grow considerably over the next decades, jointly surpassing irrigation (70%) as the primary water user by 2050 (Alcamo and Henrichs, 2002; Shiklomanov and Rodda, 2003; Molden, 2007; Fischer et al., 2007; Shen et al., 2008; Bruinsma, 2011). This growth is projected to be greatest in areas already under high stress, such as South Asia.

Renewable energy technologies such as solar PV and wind power will reduce freshwater withdrawals for thermal cooling relative to fossil alternatives. On the other hand, CCS and some forms of renewable energy, especially bioenergy, could demand a significant amount of water (see Table 6.7 and section 7.9.2). For bioenergy in particular, the overall effect will depend importantly on which feedstocks are grown, where, and if they require irrigation (see 11.13.7). Similarly, reforestation and afforestation efforts, as well as attempts to avoid deforestation, will impact both water use and water quality. The net effects could be either positive (Townsend et al., 2012) or negative (Jackson et al., 2005), depending on the local situation (see section 11.7).

When accounting for the system dynamics and relative economics between alternative mitigation options (both in space and time), recent integrated modelling scenarios generally indicate that stringent mitigation actions, combined with heightened water-use efficiency measures, could lead to significant reductions in global water demand over the next several decades. PBL (2012), for instance, calculates a 25% reduction in total demand by 2050, translating to an 8% decline in the number of people living in severely water-stressed regions worldwide. Other studies by Hanasaki et al. (2013) and Hejazi et al.(2013) find the co-benefits from mitigation to be of roughly the same magnitude: reductions of 1.0–3.9% and 1.2–5.5%, respectively, in 2050. Hejazi et al. (2013) note, however, that water scarcity could be exacerbated if mitigation leads to more intensive production of bioenergy crops. In contrast, Akimoto et al. (2012) find that stringent mitigation increases water-stressed populations globally (+3% in 2050) as a result of decreases in annual water availability in places like South Asia.

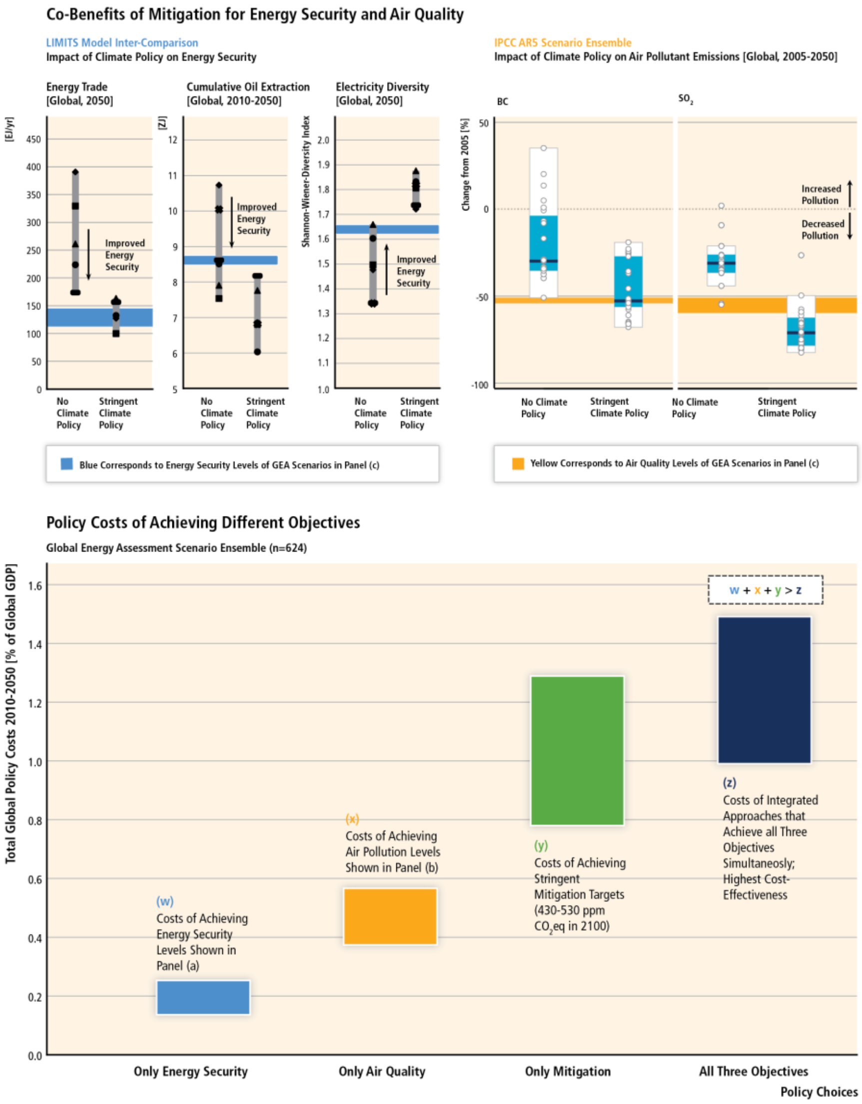


Figure 6.33. Co-benefits of mitigation for energy security and air quality in scenarios with stringent climate policies (concentration 430-530 ppm CO2-e in 2100). Upper panels show co-benefits for different energy security indicators and air pollutant emissions. Lower panel shows related global policy costs of achieving the energy security, air quality and mitigation objectives, either alone (w, x, y) or simultaneously (z). Integrated approaches that achieve these objectives simultaneously show the highest cost-effectiveness due to synergies (w+x+y>z). Policy costs are given as the increase in total energy system costs relative to a no-policy baseline; hence, they only capture the mitigation component and do not include the monetized benefits of, for example, reduced health impacts or climate damages. In this sense costs are indicative and do not represent full uncertainty ranges. Sources: LIMITS model inter-comparison (Jewell et al., 2013b; Tavoni et al., 2014), IPCC AR5 database (includes only scenarios based on idealized policy implementation and full technology availability), Global Energy Assessment scenarios (Riahi et al., 2012b; McCollum et al., 2013c).

6.6.2.7 Integrated studies of multiple objectives

Integrated scenario research is just beginning to assess multiple sustainable development objectives in parallel. This emerging literature generally finds that mitigation goals can be achieved more cost-effectively if the objectives are integrated and pursued simultaneously rather than in isolation. Recent examples of such studies include Bollen et al. (2010) and the Global Energy Assessment (GEA) (McCollum et al., 2011, 2013c; Riahi et al., 2012b). These two analyses are unique from other integrated studies (e.g., PBL (2012), IEA, (2011); Akimoto et al.,(2012); Howell et al., (2013), (Shukla et al., 2008; See e.g. Skea and Nishioka, 2008; Strachan et al., 2008; Shukla and Dhar, 2011)) in that they attempt to quantify key interactions in economic terms on a global scale, employing varying methodologies to assess the interactions between climate change, air pollution, and energy security policies. Bollen et al. employs a cost-benefit social welfare optimization approach while the GEA study employs a cost-effectiveness approach (see section 3.7.2.1). Despite these differences the two studies provide similar insights. Both suggest that near-term synergies that can be realized through decarbonisation and energy efficiency and that mitigation policy may be seen as a strategic entry point for reaping energy security and air quality co-benefits. The GEA study in particular finds major cost savings from mitigation policy in terms of reduced expenditures for imported fossil fuels and end-of-pipe air pollution control equipment (see bottom panel of Figure 6.33). The magnitude of these co-benefits depends importantly on the future stringency of energy security and air pollution policies in the absence of mitigation policy. If these are more aggressive than currently planned, then the co-benefits would be smaller.

Another class of sustainable development scenarios are the Low-Carbon Society (LCS) assessments (Kainuma et al., 2012b), which collectively indicate that explicit inclusion of mitigation co-benefits in the cost calculation results in a lower carbon price in the LCS scenarios than in a scenario which only considers mitigation costs (Shukla et al., 2008). A key message from these studies is that co-benefits are neither automatic nor assured, but result from conscious and carefully coordinated policies and implementation strategies, such as life-style changes, green manufacturing processes, and investments into energy-efficient devices, recycling measures and other targeted actions (Shukla and Chaturvedi, 2012).

Finally, studies suggest that co-benefits could influence the incentives for global climate agreements discussed in Section 13.3 (Pittel and Rübbelke, 2008; Bollen et al., 2009b; Wagner, 2012). At the present time, however, international policy regimes for mitigation and its important co-benefits remain separate (Holloway et al., 2003; Swart et al., 2004; Nemet et al., 2010; Rao et al., 2013). Dubash et al. (2013) propose a methodology for operationalising co-benefits in mitigation policy formulation, thus helping to bring the varied policy objectives closer together (see Section 15.2).

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.

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 policy priorities, such as clean air, energy security, or energy access. These linkages may be positive (co-benefits) or negative (risks). These relationships are discussed in Section 6.6 . Another set of risks is associated with the possibility that particular mitigation measures might be taken off the table because of perceived negative side effects and that stabilization will prove more challenging that what might have been expected (Strachan and Usher, 2012). These issues are discussed in Section 6.3 as well as elsewhere in the chapter, including Section 6.9 for CDR options. Another risk is that the economic 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 . 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 can be seen as creating or limiting options to manage risk rather than leading to particular goals. This topic is discussed in Sections 6.3 and 0through the exploration of the consequences of different levels of near-term mitigation. This issue is particularly important in the context of scenarios that lead to concentration goals such as 450 ppm CO_2-e by 2100. The vast majority of these scenarios temporarily overshoot the long-term goal and then descend to it by the end of the century through increasing emissions reductions. When near-term mitigation is not sufficiently strong, future mitigation must rely heavily on CDR technologies such as BECCS, putting greater pressure on future decision-makers and highlighting any uncertainties and risks surrounding these technologies. While these scenarios are possible in a physical sense, they come with a very large risk that future decision makers will not take on the ambitious action that would ultimately be required. Indeed, studies have shown that delayed and fragmented mitigation can lead to a relaxation of long term goals if countries that delay their participation in a global mitigation strategy are not willing or unable to pick up the higher costs of compensating higher short term emissions (Blanford et al., 2014; Kriegler et al., 2014a).

6.8 Integrating sector analyses and transformation scenarios

6.8.1 The sectoral composition of GHG emissions along transformation pathways

Options for reducing GHG emissions exist across a wide spectrum of human activities. The majority of these options fall into three broad areas: energy supply, energy end use, and agriculture, forestry, and other land use (AFOLU). The primary focus of energy supply options is to provide energy from low- or zero-carbon energy sources; that is, to decarbonize energy supply. Options in energy end use sectors focus either on reducing the use of energy and/or on using energy carriers produced from low-carbon sources, including electricity generated from low-carbon sources. Direct options in agriculture, forestry, and land use involve storing carbon in terrestrial systems (for example, through afforestation). This sector is also the source of bioenergy. Options to reduce non-CO2 emissions exist across all these sectors, but most notably in agriculture, energy supply, and industry.

These sectors and the associated options are heavily interlinked. For example, energy demand reductions may be evident not only as direct emissions reductions in the end use sectors but also as emissions reductions from the production of energy carriers such as electricity ("indirect emissions", see Annex A.II.4). Replacing fossil fuels in energy supply or end-use sectors by bioenergy reduces emissions in these sectors, but may increase land-use emissions in turn (cf. Chapter 11, Bioenergy Appendix). In addition, at the most general level, sectoral mitigation actions are linked by the fact that reducing emissions through a mitigation activity in one sector reduces the required reductions from mitigation activities in other sectors in order to meet a long-term CO2-equivalent concentration goal.

The precise set of mitigation actions taken in any sector will depend on a wide range of factors, including their relative economics, policy structures, and linkages to other objectives (cf. Section 6.6) and interactions among measures across sectors. Both integrated models, such as those assessed in this chapter, and sectorally-focused research, such as that assessed in Chapters 7 through 12, offer insights into the options for mitigation across sectors. The remainder of this section first assesses the potential for mitigation within the sectors based on integrated studies and then in each of the emitting sectors based on the combined assessments from sectoral and integrated studies. An important question is how closely the results from integrated modelling studies are consistent with sectorally-focused literature or how they complement each other.

6.8.2 Mitigation from a cross-sectoral perspective: insights from integrated models

Integrated models are a key source of research on the tradeoffs and synergies in mitigation across sectors. In scenarios from these models, energy sector emissions are the dominant source of GHG emissions in baseline scenarios, and these emissions continue to grow over time relative to land-use change CO2 emissions and non-CO2 GHG emissions (Section 6.3.1 and Figure 6.34). Within the energy sector, direct emissions from energy supply, and electricity generation in particular, are larger than the emissions from any single end-use sector (Figure 6.34). Direct emissions, however, do not provide a full representation of the importance of different activities causing the emissions, because the consumption of energy carriers such as electricity by the end use sectors, leads to indirect emissions from the production of those energy carriers (consumption-based approach). An alternative perspective is to allocate these indirect energy supply emissions to the end use sectors that use these supplies (see, for example, in Figure 6.34). At present indirect emissions from electricity use are larger than direct emissions in buildings and constitute an important share of industrial emissions while they are small in transport compared to direct CO2 emissions.

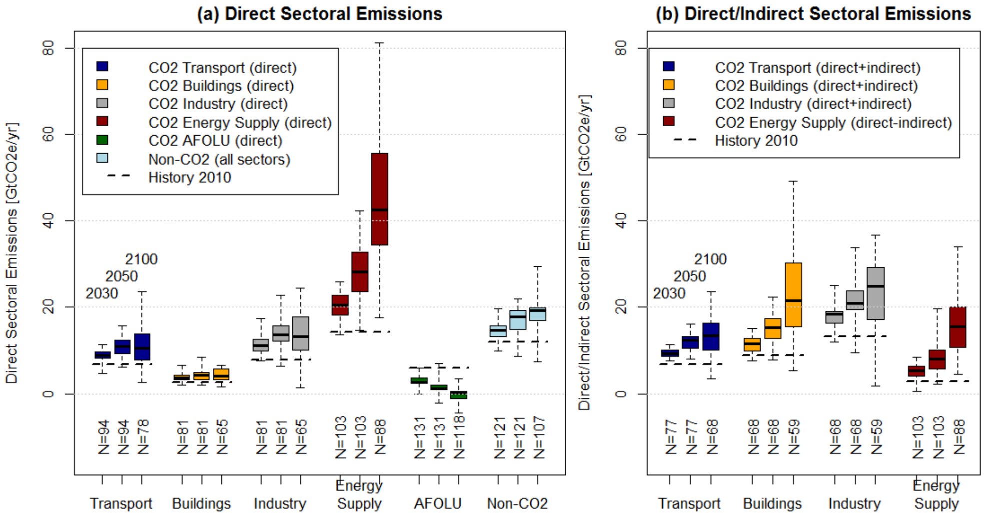


Figure 6.34 Direct (a) and direct and indirect emissions (b) of CO2 and non-CO2 GHGs across sectors in baseline scenarios. Note that in the case of indirect emissions only electricity emissions are allocated from energy supply to end-use sectors. The thick black lines corresponds to the median, the coloured boxes to the inter-quartile range (25th to 75th percentile) and the whiskers to the total range across scenarios. The numbers at the bottom of the graphs refer to the number of scenarios included in the ranges which differs across sectors and time due to different sectoral resolution and time horizon of models. Source: WG III AR5 Scenario Database (Annex II.10). Includes only baseline scenarios. Historical data from (IEA, 2012a; 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 (see Sections 7.11.3 and Figure 6.35.). For example, in 450 ppm CO2-e scenarios, the electricity sector is largely decarbonized by 2050, whereas deep reductions in direct emissions in the end use sectors largely arise beyond mid-century. More so than any other energy supply technology, the availability of BECCS and its role as a primary CDR technology (Section 6.3.2 and 6.9) has a substantial effect on this dynamic, allowing for energy supply sectors to serve as a net negative emissions source by mid-century and allowing for more gradual emissions reductions in other sectors. In contrast, sectoral studies show available pathways to deep reductions in emissions (both direct and indirect) already by mid-century (see, e.g. Chapter 9).

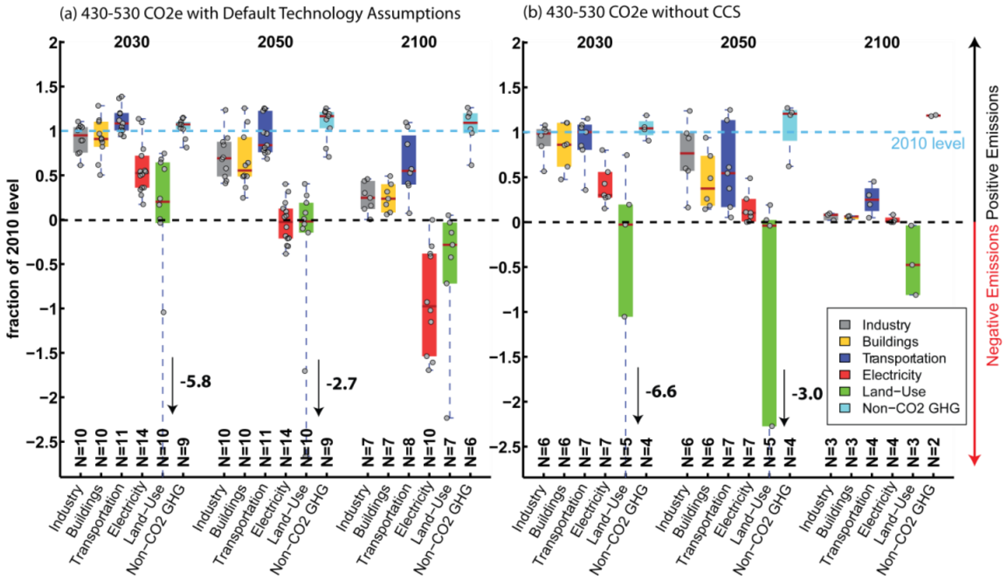


Figure 6.35. Direct emissions by sector normalized to 2010 levels (light blue dished line) in 430-530 ppm CO2-e scenarios with default technology assumptions (a) and in 430-530 ppm CO2-e scenarios without CCS (b). Note that values below the dashed black zero line indicate negative sectoral emissions. The thick red lines corresponds to the median, the coloured boxes to the inter-quartile range (25th to 75th percentile) and the whiskers to the total range across scenarios. Gray dots refer to emissions of individual models to give a sense of the spread within the ranges shown. The numbers at the bottom of the graphs refer to the number of scenarios included in the range which differs across sectors and time due to different sectoral resolution and time horizon of models. Source: EMF27 study, adapted from (Krey et al., 2014).

Within the end-use sectors, deep emissions reductions in transport are generally the last to emerge in integrated modelling studies because of the assumption that options to switch to low-carbon energy carriers in transport are more limited than in buildings and industry and also because of the expected high growth for mobility and freight transport (Section 8.9.1). In the majority of baseline scenarios from integrated models, net land use CO2 emissions largely disappear by mid-century, with some models projecting a net sink after 2050 (Section 6.3.1.4). There is a wide uncertainty in the role of afforestation and reforestation in mitigation, however. In some mitigation scenarios the land use sector can become a significant carbon sink (Section 6.3.2.4).

6.8.3 Decarbonizing energy supply

Virtually all integrated modeling studies indicate that decarbonization of electricity is critical for mitigation, but there is no general consensus regarding the precise low-carbon technologies that might support this decarbonisation (Fischedick et al., 2011; Clarke et al., 2012) (Section 7.11.3). These studies have presented a wide range of combinations of renewable energy sources (Krey and Clarke, 2011; Luderer et al., 2014), nuclear power (Bauer et al., 2012; Rogner and Riahi, 2013), and CCS-based technologies (Bauer et al.; McFarland et al., 2009; McCollum et al., 2013a; van der Zwaan et al., 2014) as both viable and cost-effective (cf. Section 7.11). The breadth of different, potentially cost-effective strategies raises the possibility not only that future costs and performances of competing electricity technologies are uncertain today, but also that regional circumstances, including both energy resources and links to other regional objectives (e.g. national security, local air pollution, energy security, see Section 6.6), might be as important decision-making factors as economic costs (Krey et al., 2014)). The one exception to this flexibility in energy supply surrounds the use of BECCS. CDR technologies such as BECCS are fundamental to many scenarios that achieve low CO2-e concentrations, particularly those based on substantial overshoot as might occur if near-term mitigation is delayed (Sections 6.3.2 and 6.4). In contrast to the electricity sector, decarbonisation of the non-electric energy supply sector (e.g., liquid fuels supply) is progressing typically at much lower pace (Section 7.11.3, Figures 7.14 and 7.15) and therefore constitutes a bottleneck in the transformation process.

6.8.4 Energy demand reductions and fuel switching in end use sectors

The two major groups of option in energy end use sectors focus either on reducing the use of energy and/or on using energy carriers produced from low-carbon sources. Three important issues are therefore the potential for fuel switching, the potential for reductions of energy use per unit of output/service, and the relationship and timing between the two. In general, as discussed in Section 6.3.4, integrated studies indicate that energy intensity (per unit of GDP) reductions outweigh decarbonisation of energy supply in the near-term when the energy supply system is still heavily reliant on largely carbon intensive fossil fuels (Figure 6.16). Over time, the mitigation dynamic switches to one focused on carbon intensity reductions (cf. AR4, Fisher et al. (2007b Section 3.3.5.2)). From the perspective of end-use sectors, decarbonization of energy involves both the decarbonization of existing sources, for example, by producing electricity from low-carbon sources or using liquid fuels made from bioenergy, and an increase in the use of lower-carbon fuels, for example, through an increase in the use of electricity (Edmonds et al., 2006; Kyle et al., 2009; Sugiyama, 2012; Williams et al., 2012; Krey et al., 2014; Yamamoto et al., 2014). 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) as well as electricity typically showing a slower cost increase over time compared to other energy carriers (Edmonds et al., 2006; Krey et al., 2014).

The comparison between integrated and sectoral studies is difficult with regards to the timing and tradeoffs between fuel switching and energy reduction, 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, asking how much energy use for a particular activity can be reduced with state-of-the-art technology. One reason for this focus on energy reduction is that sectoral research is more commonly focused on near-term actions based on available mitigation technologies, and, in the near-term, major fuel sources such as liquid fuels and electricity may have high carbon intensities. This means that energy reductions will have substantial near-term mitigation effects. In the longer-term, however, these fuel sources will be largely decarbonized along low-concentration 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 utilizing energy sources and the associated co-benefits and risks, see Section 6.6).

This evolution can be clearly seen through a comparison of direct and indirect emissions in end use sectors in integrated modelling scenarios (Figure 6.35). In 2010, the largest emissions from the buildings sector are the indirect emissions from electricity. This trend continues in baseline scenarios (Figure 6.35). However, in deep emission reduction scenarios, indirect emissions from electricity are largely eliminated by 2050, and in many scenarios, the electricity sector even becomes a sink for CO2 through the use of BECCS (Figure 6.35a). 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 by taking advantage of a largely decarbonized electricity sector. The industrial sector lies between the buildings and transport sectors. Of importance, the observed trends can be very regional in character. For example, the value of electrification will be higher in countries or regions that already have low-carbon electricity portfolios.

The primary distinction between sectoral studies and integrated modelling studies with regard to end use options for fuel switching and end-use reductions is that integrated models typically represent end use options at a more aggregated scale than sectoral studies. In addition, however, there is an important difference in the way that the two types of studies attempt to ascertain opportunities (cf. Section 8.9). Long-term transformation scenarios from integrated models achieve reductions from baseline emissions based almost exclusively on the imposition of a carbon price and generally assume functioning markets and may not fully represent existing barriers, in particular in end use sectors. In contrast, sectoral studies explore options for energy demand reduction based on engineering and/or local details and do so based on cost-effectiveness calculations regarding a typically much richer portfolio of tailored options. They also recognise that there are many boundaries to consumer rationality and thus not all options that are cost-effective happen automatically in a baseline, but are mobilised by mitigation policies. It is also challenging to compare the potential for energy reductions across sectoral and integrated studies, because of difficulties 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. It is important to note that the emphasis on economic instruments like carbon pricing in integrated studies leads to a negative correlation between energy demand reduction and the option of switching to low-carbon energy carriers at modest cost. Therefore, integrated studies that foresee a significant potential for switching to, for example electricity, in an end-use sector at modest costs, usually show a lower need for reducing energy demand in this sector and the other way around. It should also be noted that there is thus not always a clear cut distinction between sectoral and integrated studies. Some sectoral studies, in particular those that provide estimates for both energy savings and fuel switching, are in fact integrated studies with considerable sectoral detail such as the IEA World Energy Outlook (IEA, 2010b, 2012b) or the Energy Technology Perspectives report (IEA, 2008, 2010c) (see Annex II.10).

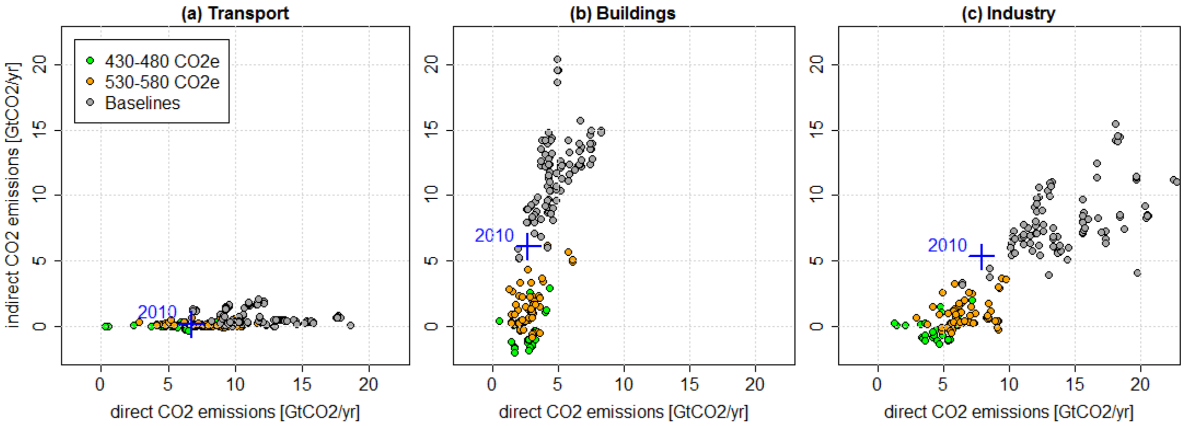


Figure 6.36. Direct CO2 emissions vs. indirect CO2 emissions from electricity in the transport (a), buildings (b), and industry (c) sectors in 2050. The colour coding is based on categories of 2100 CO2-e concentrations as defined in Section 6.3.2.1. Source: WG III AR5 Scenario Database (Annex II.10). Includes only scenarios based on idealized policy implementation that provide emissions at the sectoral level. Historical data from (IEA, 2012a; JRC/PBL, 2012).

In general, in the transport sector, the opportunities for energy use reductions and fuel switching are broadly consistent between integrated and sectoral studies (Figure 6.37 and Figure 6.38, Section 8.9). However, the underlying mechanisms utilized in these studies may be different. Comprehensive transport sector studies tend to include technical efficiency measures, switching to low carbon fuels, behavioural changes that affect both the modal split and the amount of transport services demanded, and a broader set of infrastructural characteristics such as compact cities. In integrated studies these factors are not always addressed explicitly, and the focus is usually on technical efficiency measures, fuel switching and service demand reduction. Regarding fuel choice, the majority of integrated studies indicate a continued reliance on liquid and gaseous fuels, supported by an increase in the use of bioenergy up to 2050. Many integrated studies 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. Hydrogen has also been identified by numerous studies as a potential long-term solution should storage, production and distribution challenges be overcome (Section 8.9.1). While electricity and hydrogen achieve substantial shares in some scenarios, many integrated modelling scenarios show no dominant transport fuel source in 2100. This prevails in scenarios leading to 430-530 ppm

CO2-e concentration levels in 2100 with the median values for the share of electricity and hydrogen in 2100 being 22% and 25% of final energy, respectively (Section 8.9.1, Figure 8.9.4).

Detailed building sector studies indicate energy savings potential by 2050 on the upper end of what integrated studies show (Section 9.8.2, Figure 9.19), and both sectoral and integrated studies show modest opportunities for fuel switching due to the already high level of electricity consumption in the buildings sector, particularly in developed countries (Figure 6.37 and Figure 6.38). Building sector studies have focused largely on identifying options for saving energy whereas fuel switching as a means for reducing emissions is not considered in detail by most studies. In general, both sectoral and integrated studies indicate that electricity will supply a dominant share of building energy demand over the long term, especially if heating demand decreases due to a combination of efficiency gains, better architecture and climate change. Best case new buildings can reach 90% lower space heating and cooling energy use compared to the existing stock (Section 9.3.3) while for existing buildings deep retrofits can achieve heating and cooling energy savings in the range of 50-90% (Section 9.3.4).

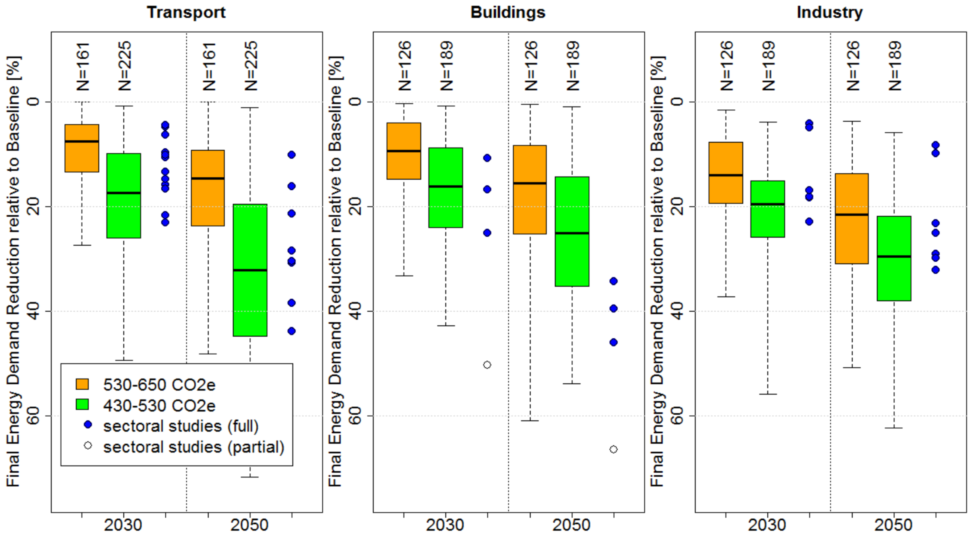


Figure 6.37. Sectoral final energy reduction relative to baseline in the end-use sectors, transport (a), buildings (b), and industry (c) by 2030 and 2050 in transformation scenarios from two different concentration categories (see Section 6.3.2) compared to sectoral studies assessed in Chapters 8-10. 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. Filled circles correspond to sectoral studies with full sectoral coverage while empty circles correspond to studies with only partial sectoral coverage (e.g., heating and cooling only for buildings). Source: WG III AR5 Scenario Database (Annex II.10). Includes only scenarios based on idealized policy implementation. Sectoral studies as provided by Chapters 8, 9 and 10, see Annex II.10.

Detailed industry sector studies tend to be more conservative regarding savings in industrial final energy compared to baseline, but on the other hand foresee a greater potential for switching to low-carbon fuels, including electricity, heat, hydrogen and bioenergy than integrated studies (Figure 6.37 and Figure 6.38). Sectoral studies, which are often based on micro unit level analyses, indicate that the broad application of best available technologies for energy reduction could lead to about 25% of energy savings in the sector with immediate deployment and similar contributions could be achieved with new innovations and deployment across a large number of production processes (Section 10.4). Integrated models in general (with exceptions, see Section 10.10.1) treat the industry sector in a more aggregated fashion and mostly do not provide detailed sub-sectoral material flows, options for reducing material demand, and price-induced inter-input substitution possibilities explicitly (Section 10.10.1). Similar to the transportation sector, there is no single perceived near or long-term configuration for industrial energy (cf. Sections 10.4 and 10.7). Multiple pathways may be pursued or chosen depending on process selection and technology development. For the industry sector to achieve near zero emission with carbonaceous energy carriers will need carbon capture and storage facilities though market penetration of this technology is still highly uncertain and only limited examples are in place so far. Some integrated studies indicate a move toward electricity whereas others indicate a continued reliance on liquid or solid fuels, largely supported through bioenergy (Section 10.10.1, Figure 10.14). Due to the heterogeneous character of the industry sector a coherent comparison between sectoral and integrated studies remains difficult.

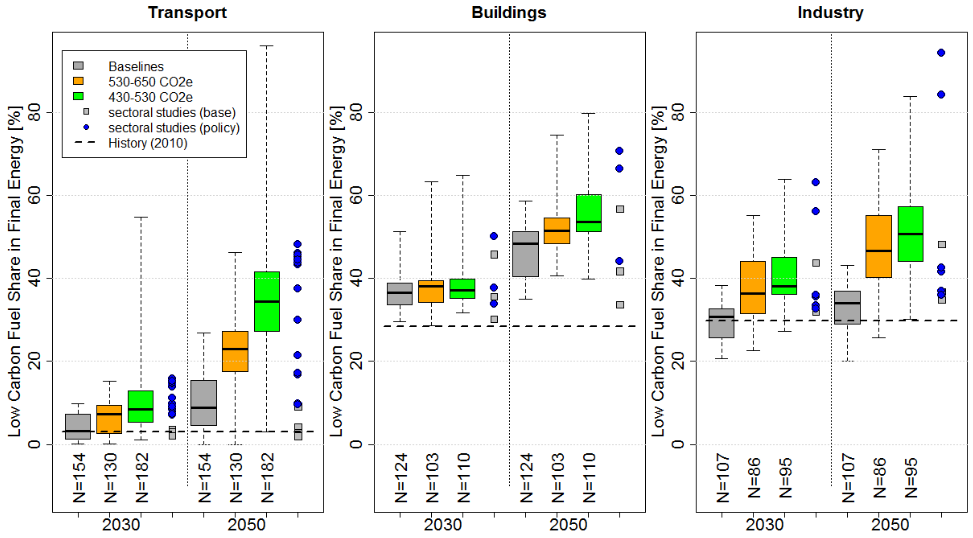


Figure 6.38. Development of final energy low-carbon fuel shares in the end-use sectors transport (a), buildings (b), and industry (c) by 2030 and 2050 in transformation scenarios from three different concentration categories (see Section 6.3.2) compared to sectoral studies assessed in Chapters 8-10. Low-carbon fuels include electricity, hydrogen and liquid biofuels in transport, electricity in buildings and electricity, heat, hydrogen and bioenergy in industry. 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. Filled symbols correspond to sectoral studies with full sectoral coverage. Source: WG III AR5 Scenario Database (Annex II.10). Includes only scenarios based on idealized policy implementation. Sectoral studies as provided by Chapters 8, 9 and 10, see Annex II.10. Historical data from (IEA, 2012c; d).

6.8.5 Options for bioenergy production, reducing land use change emissions and creating land use GHG sinks

As noted in Section 6.3.5, land use has four primary roles in mitigation: bioenergy production, storage of carbon in terrestrial systems, mitigation of non-CO_2 GHGs, and biogeophysical factors such as albedo. Integrated modelling studies are the primary means by which the tradeoffs and synergies between these different roles, in particular the first two, might unfold over the rest of the century. The integrated modelling studies sketch out a wide range of ways in which these forces might affect the land surface, from widespread afforestation under comprehensive climate policies to widespread deforestation if carbon storage is not included in the mitigation policy (Sections 6.3.5 and 11.9).

Sectoral studies complement integrated modelling studies by exploring the ability of policy and social structures to support broad changes in land use practices over time (Section 11.6). In general, sectoral studies point to the challenges associated with making large-scale changes to the land surface in the name of mitigation, such as challenges associated with institutions, livelihoods, social and economic concerns, and technology and infrastructure. These challenges raise questions about transformation pathways (Section 11.6). For example, although increasing the land area covered by natural forests could enhance biodiversity and a range of other ecosystem services, afforestation occurring through large scale plantations could negatively impact biodiversity, water and other ecosystem services (Sections 11.7 and 11.13.6). Similarly, the use of large land areas for afforestation or dedicated feedstocks for bioenergy could increase food prices, and compromise food security, if land normally used for food production is converted to bioenergy or forests (Section 11.4). The degree of these effects is uncertain and depends on a variety of sector-specific details regarding intensification of land use, changes in dietary habits, global market interactions, and biophysical characteristics and dynamics. The implications of transformation pathways 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 (Section 11.6), and the role of large scale intensive agriculture which has often not been implemented sustainably (e.g., large areas of monoculture food or energy crops or intensive livestock production, potentially damaging ecosystem services). Furthermore, sector studies are beginning to elucidate implementation issues, such as the implications of staggered and/or partial regional adoption of land mitigation policies, as well as institutional design. For example, realizing large-scale bioenergy without compromising the terrestrial carbon stock might require strong institutional conditions, such as an implemented and enforced global price on land carbon. Finally, sector studies will continue to provide revised and new characterizations of mitigation technologies that can be evaluated in a portfolio context (Section 11.9).

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

Some scientists have argued that it might be useful to consider, in addition to mitigation and adaptation measures, various intentional interventions into the climate system as part of a broader climate policy strategy (Keith, 2000; Crutzen, 2006). Such technologies have often been grouped under the blanket term “geoengineering” or, alternatively, “climate engineering”(Keith, 2000; Vaughan and Lenton, 2011). Calls for research into these technologies have increased in recent years (Caldeira and Keith, 2010; Science and Technology Committee, 2010), and several assessments have been conducted (Royal Society, 2009; Edenhofer et al., 2011; Ginzky et al., 2011). Two categories of geoengineering are generally distinguished. Removal of greenhouse gases, in particular carbon dioxide (termed “carbon dioxide removal”, or CDR), would reduce atmospheric greenhouse gas concentrations. The boundary between some mitigation and some CDR methods is not always clear (Boucher, et al., 2011; Boucher et al., 2013b) “Solar radiation management” (SRM) technologies aim to increase the reflection of sunlight to cool the planet and do not fall within the usual definitions of mitigation and adaptation. Within each of these categories, there is a wide range of techniques that are addressed in more detail in sections 6.5 and 7.7 of the WG 1 report.

Many geoengineering technologies are presently only hypothetical. Whether or not they could actually contribute to the avoidance of future climate change impacts is not clear (Blackstock et al., 2009; Royal Society, 2009). Beyond open questions regarding environmental effects and technological feasibility, questions have been raised about the socio-political dimensions of geoengineering and its potential implications for climate politics (Barrett, 2008; Royal Society, 2009; Rickels et al., 2011). In the general discussion, geoengineering has been framed in a number of ways (Nerlich and Jaspal, 2012; Macnaghten and Szerszynski, 2013; Luokkanen et al., 2013; Scholte et al., 2013), for instance, as a last resort in case of a climate emergency (Blackstock et al., 2009; McCusker et al., 2012), or as a way to buy time for implementing conventional mitigation (Wigley, 2006; Institution of Mechanical Engineers, 2009; MacCracken, 2009). Most assessments agree that geoengineering technologies should not be treated as a replacement for conventional mitigation and adaptation due to high costs, potential risks or pervasive uncertainties involved (Royal Society, 2009; Rickels et al., 2011). The potential role of geoengineering as a viable component of climate policy is yet to be determined, and it has been argued that geoengineering could become a distraction from urgent mitigation and adaptation measures (Lin, 2013; Preston, 2013).

6.9.1 Carbon dioxide removal

6.9.1.1 Proposed CDR Methods and Characteristics

Proposed CDR methods involve removing CO_2 from the atmosphere and storing the carbon in land, ocean or geological reservoirs. These methods vary greatly in their estimated costs, risks to humans and the environment, potential scalability, and notably in the depth of research about their potential and risks. Some techniques that fall within the definition of CDR are also regarded as mitigation measures such as afforestation and bio-energy with carbon capture and storage (BECCS) (see Glossary). The term 'negative emissions technologies' can be used as an alternative to CDR (McGlashan et al., 2012; McLaren, 2012; Tavoni and Socolow, 2013).

The WGI report (Section 6.5.1) provides an extensive but not exhaustive list of CDR techniques (Table 6.14 of WGI). Here only techniques that feature more prominently in the literature are covered. This includes (1) increased land carbon sequestration by reforestation and afforestation, soil carbon management or biochar (see Chapter 11 of WGIII); (2) increased ocean carbon sequestration by ocean fertilisation; (3) increased weathering through the application of ground silicates to soils or the ocean; and (4) chemical or biological capture with geological storage by biomass energy carbon capture and storage (BECCS) or direct air capture (DAC). CDR techniques can be categorized in alternative ways. For example, they can be categorized (1) as industrial technologies versus ecosystem manipulation; (2) by the pathway for carbon capture (e.g. McLaren, 2012; Caldeira et al., 2013); (3) by the fate of the stored carbon (Stephens and Keith, 2008); and (4) by the scale of implementation (Boucher et al. 2013). Removal of other greenhouse gases, e.g., CH_4 and N_2O, have also been proposed (Boucher and Folberth, 2010; de_Richter and Caillol, 2011; Stolaroff et al., 2012).

All CDR techniques have a similar slow impact on rates of warming as mitigation measures (van Vuuren and Stehfest, 2013) (see section 6.5.1 of WGI). An atmospheric 'rebound effect' (see WGI glossary) dictates that CDR requires roughly twice as much CO_2 removed from the atmosphere for any given net reduction in atmospheric CO_2 concentration, as CO_2 will be added from the natural carbon sinks (Lenton and Vaughan, 2009; Matthews, 2010). Permanence of the storage reservoir is a key consideration for CDR efficacy. Permanent (larger than tens of thousands of years) could be geological reservoirs while non-permanent reservoirs include oceans and land (the latter could, among others, be affected by the magnitude of future climate change) (see section 6.5.1 of WGI). Storage capacity estimates suggest geological reservoirs could store several thousand GtC; the oceans a few thousand GtC in the long term and the land may have the potential to store the equivalent to historical land use loss of 180 ± 80GtC (also see table 6.15 of WG1)(Metz et al., 2005; House et al., 2006; Orr, 2009; Matthews, 2010).

Ocean fertilisation field experiments show no consensus on the efficiency of iron fertilisation (Boyd et al., 2007; Smetacek et al., 2012). Modelling studies estimate between 15 ppm and less than 100 ppm drawdown of CO_2 from the atmosphere over 100 years (Zeebe and Archer, 2005; Cao and Caldeira, 2010) while simulations of mechanical upwelling suggest 0.9 Gt/yr (Oschlies et al., 2010). The latter technique has not been field tested. There are a number of possible risks including downstream decrease in productivity, expanded regions of low oxygen concentration and increased N_2O emissions (See WGI Section 6.5.3.2) (low confidence). Given the uncertainties surrounding effectiveness and impacts, this CDR technique is at a research phase with no active commercial ventures. Furthermore current international governance states that marine geoengineering including ocean fertilisation is to be regulated under amendments to the London Convention/London Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, only allowing legitimate scientific research (Güssow et al., 2010; IMO, 2013).

Enhanced weathering on land using silicate minerals mined, crushed, transported and spread on soils has been estimated to have a potential capacity, in an idealised study, of 1 GtC/yr (Köhler et al., 2010). Ocean based weathering CDR methods include use of carbonate or silicate minerals processed or added directly to the ocean (see section 6.5.2.3 in WGI). All of these measures involve a notable energy demand through mining, crushing and transporting bulk materials. Preliminary hypothetical cost estimates are in the order of 23-66 $/tCO$_2$ (Rau and Caldeira, 1999; Rau et al., 2007) for land and 51-64 $/tCO$_2$ for ocean methods (McLaren, 2012). The confidence level on the carbon cycle impacts of enhanced weathering is low (section 6.5.3.3 in WGI).

The use of carbon capture and storage technologies (Metz et al., 2005) with biomass energy also creates a carbon sink (Azar et al., 2006; Gough and Upham, 2011). BECCS is included in the RCP2.6 (van Vuuren et al., 2007, 2011c) and a wide range of scenarios reaching similar and higher concentration goals. From a technical perspective, BECCS is very similar to a combination of other techniques that are part of the mitigation portfolio: the production of bio-energy and CCS for fossil fuels. Estimates of the global technical potential for BECCS vary greatly ranging from 3 to more than 10 Gt CO$_2$/yr (Koornneef et al., 2012; McLaren, 2012; van Vuuren et al., 2013), while initial cost estimates also vary greatly from around 60 to 250 $/tCO$_2$ (McGlashan et al., 2012; McLaren, 2012). Important limiting factors for BECCS include land availability, a sustainable supply of biomass and storage capacity (Gough and Upham, 2011; McLaren, 2012). There is also a potential issue of competition for biomass under bioenergy dependent mitigation pathways.

Direct air capture (DAC) uses a sorbent to capture CO$_2$ from the atmosphere and the long term storage of the captured CO$_2$ in geological reservoirs (GAO, 2011; McGlashan et al., 2012; McLaren, 2012). There are a number of proposed capture methods including adsorption of CO$_2$ using amines in a solid form and the use of wet scrubbing systems based on calcium or sodium cycling. Current research efforts focus on capture methodologies (Keith et al., 2006; Baciocchi et al., 2006; Lackner, 2009; Eisenberger et al., 2009; Socolow et al., 2011) with storage technologies assumed to be the same as CCS (Metz et al, 2005). A US GAO (2011) technology assessment concluded that all DAC methods were currently immature. A review of initial hypothetical cost estimates, summarizes 40-300 $/tCO$_2$ for supported amines and 165-600 $/tCO$_2$ for sodium or calcium scrubbers (McLaren, 2012) reflecting an ongoing debate across very limited literature. Carbon captured through CCS, BECCS and DAC are all intended to use the same storage reservoirs (in particular deep geologic reservoirs), potentially limiting their combined use under a transition pathway.

6.9.1.2 Role of CDR in the context of transformation pathways

Two of the CDR techniques listed above, BECCS and afforestation, are already evaluated in the current integrated models. For concentration goals on the order of 430 to 530 ppm CO2-e by 2100, BECCS forms an essential component of the response strategy for climate change in the majority of scenarios in the literature, particularly in the context of concentration overshoot. As discussed in Section 6.2.2, BECCS offers additional mitigation potential, but also an option to delay some of the drastic mitigation action that would need to happen in order to reach low greenhouse gas concentration goals by the second half of the century. In scenarios aiming at such low concentration levels, BECCS is usually competitive with conventional mitigation technologies, but only after these have been deployed at very large scale (cf. Azar et al., 2010b; Tavoni and Socolow, 2013). At same time, BECCS applications do not feature in less ambitious mitigation pathways (van Vuuren et al., 2011a). Key implications of the use of BECCS in transition pathways is that emission reduction decisions are directly related to expected availability and deployment of BECCS in the second half of the century and that scenarios might temporarily overshoot temperature or concentration goals.

The vast majority of scenarios in the literature show CO$_2$ emissions of land-use change become negative in the second half of the century – even in the absence of mitigation policy (see Section 6.3.2). This is a consequence of demographic trends and assumptions on land-use policy. Addition afforestation as part of mitigation policy is included in a smaller set of models. In these models, afforestation measures increase for lower concentration categories, potentially leading to net uptake of carbon of around 10 GtCO$_2$/yr.

There are broader discussions in the literature regarding the technological challenges and potential risks of large-scale BECCS deployment. The potential role of BECCS will be influenced by the sustainable supply of large-scale biomass feedstock and feasibility of capture, transport and long-term underground storage of CO_2 as well as the perceptions of these issues. BECCS faces large challenges in financing and currently no such plants have been built and tested at scale. IAM studies have therefore explored the sensitivities regarding the availability of BECCS in the technology portfolio by limiting bioenergy supply or CCS storage (Section 6.3.6.3).

Only few papers have assessed the role of DAC in mitigation scenarios (Keith et al., 2006; Pielke Jr, 2009; Nemet and Brandt, 2012; Chen and Tavoni, 2013). These studies generally show that the contribution of DAC hinges critically on the stringency of the concentration goal, the costs relative to other mitigation technologies, time discounting and assumptions about scalability. In these models the influence of DAC on the mitigation pathways is similar to that of BECCS (assuming similar costs). That is, it leads to a delay in short-term emission reduction in favour of further reductions in the second half of the century. Other techniques are even less mature and currently not evaluated in integrated models.

There are some constraints to the use of CDR techniques as emphasized in the scenario analysis. First of all, the potential for BECCS, afforestation and DAC are constrained on the basis of available land and/or safe geologic storage potential for CO_2. Both the potential for sustainable bio-energy use (including competition with other demands e.g. food, fibre and fuel production) and the potential to store >100 GtC of CO_2 per decade for many decades are very uncertain (see previous section) and raise important societal concerns. Finally, the large scale availability of CDR, by shifting the mitigation burden in time, could also exacerbate inter-generational impacts.

6.9.2 Solar radiation management

6.9.2.1 Proposed SRM Methods and Characteristics

SRM geoengineering technologies aim to lower the Earth's temperature by increasing the planetary albedo by reflecting a fraction of the incoming sunlight back to space. This would reduce the amount of sunlight that is absorbed by the Earth's surface, and thus counter some of the greenhouse gas induced global warming. A number of methods have been proposed that could enhance planetary albedo:

- Mirrors (or sunshades) placed in a stable orbit between the Earth and Sun would directly reduce the insolation the Earth receives (Early, 1989; Angel, 2006). Studies suggest that such a technology is unlikely to be feasible within the next century (Angel, 2006).
- Stratospheric aerosol injection would attempt to replicate the global cooling that large volcanic eruptions produce (Budyko and Miller, 1974; Crutzen, 2006; Rasch et al., 2008). This might be achieved by lofting sulphate aerosols (or other aerosol species) or their precursors to the stratosphere to create a high-altitude reflective layer that would need to be continually replenished. Section 7.7.2.1 of WG1 assessed that there is medium confidence that up to 4 Wm^{-2} of forcing could be achieved with this approach.
- Cloud brightening could be achieved by increasing the albedo of certain marine clouds through the injection of cloud condensation nuclei, most likely sea-salt, replicating the effect that is seen when ship-tracks of brighter clouds form behind polluting ships (Latham, 1990; Latham et al., 2008, 2012). Section 7.7.2.2 of WG1 assessed that too little was known about marine cloud brightening to provide a definitive statement on its potential efficacy but noted that it might be sufficient to counter the radiative forcing that would result from a doubling of CO_2 levels.
- Various methods have been proposed which could increase the albedo of the planetary surface, for example in urban, crop and desert regions (President's Science Advisory Committee. Environmental Pollution Panel, 1965; Gaskill, 2004; Hamwey, 2007; Ridgwell et al., 2009). These methods would likely only be possible on a much smaller scale than those listed above. Section 7.7.2.3 of WG 1 discusses these approaches.

This list is non-exhaustive and new proposals for SRM methods may be put forward in the future. Another method which is discussed alongside SRM methods aims to increase outgoing thermal radiation, instead of enhancing the planetary albedo, through the modification of cirrus clouds (Mitchell and Finnegan, 2009) (see section 7.7.2.4 of WG1).

As SRM geoengineering techniques only target the solar radiation budget of the Earth, the effects of CO_2 and other GHGs on the Earth System would remain, for example, greater absorption and re-emission of thermal radiation by the atmosphere (section 7.7 of WG 1), an enhanced CO_2 physiological effect on plants (section 6.5.4 of WG1), and increased ocean acidification (Matthews et al., 2009). Although SRM geoengineering could potentially reduce the global mean surface air temperature, no SRM technique could fully return the climate to a pre-industrial or low-CO_2-like state. One reason for this is that global mean temperature and global mean hydrological intensity cannot be simultaneously returned to a pre-industrial state (Govindasamy and Caldeira, 2000; Robock et al., 2008; Schmidt et al., 2012; Kravitz et al., 2013; MacMartin et al., 2013; Tilmes et al., 2013). Section 7.7.3 of WG1 details the current state of knowledge on the potential climate consequences of SRM geoengineering. In brief, simulation studies suggest that some SRM geoengineering techniques applied to a high-CO_2 climate could create climate conditions more like those of a low-CO_2 climate (Moreno-Cruz et al., 2011; MacMartin et al., 2013), but the annual mean, seasonality, and interannual variability of climate would be modified compared to the pre-industrial climate across the (Govindasamy and Caldeira, 2000; Lunt et al., 2008; Robock et al., 2008; Ban-Weiss and Caldeira, 2010; Moreno-Cruz et al., 2011; Schmidt et al., 2012; Kravitz et al., 2013; MacMartin et al., 2013) [SRM geoengineering that could reduce global mean temperatures would reduce thermosteric sea-level rise and would likely also reduce glacier and ice-sheet contributions to sea-level rise . (Irvine et al., 2009, 2012; Moore et al., 2010).

Model simulations suggest that SRM would result in substantially altered global hydrological conditions, with uncertain consequences for specific regional responses such as precipitation and evaporation in monsoon regions (Bala et al., 2008; Schmidt et al., 2012; Kravitz et al., 2013; Tilmes et al., 2013) . In addition to the imperfect cancellation of GHG-induced changes in the climate by SRM, CO_2 directly affects the opening of plant stomata, and thus the rate of transpiration of plants and in turn the recycling of water over continents, soil moisture and surface hydrology (Bala et al., 2007; Betts et al., 2007; Boucher et al., 2009; Spracklen et al., 2012).

Due to these broadly altered conditions which would result from an implementation of geoengineering, and based on experience from studies of the detection and attribution of climate change, it may take many decades of observations to be certain whether SRM is responsible for a particular regional trend in climate (Stone et al., 2009; MacMynowski et al., 2011). These detection and attribution problems also imply that field testing to identify some of the climate consequences of SRM geoengineering would require deployment at a sizeable fraction of full deployment for a period of many years or even decades (Robock et al., 2010; MacMynowski et al., 2011).

It is important to note that in addition to affecting the planet’s climate, many SRM methods could have serious non-climatic side-effects. Any stratospheric aerosol injection would affect stratospheric chemistry and has the potential to affect stratospheric ozone levels. Tilmes et al. (2009) found that sulphate aerosol geoengineering could delay the recovery of the ozone hole by decades (section 7.7.2.1 of WG1). Stratospheric aerosol geoengineering would scatter light, modifying the optical properties of the atmosphere. This would increase the diffuse to direct light ratio which would make the sky appear hazier (Kravitz et al., 2012), reduce the efficacy of concentrated solar power facilities (Murphy, 2009) and potentially increase the productivity of some plant species, and preferentially those below the canopy layer, with unknown long-term ecosystem consequences (Mercado et al., 2009). The installations and infrastructure of SRM geoengineering techniques may also have some negative effects that may be particularly acute for techniques that are spatially extensive, such as desert albedo geoengineering. SRM would have very little effect on ocean acidification and the other direct effects of elevated CO_2 concentrations which are likely to pose significant risks (see section 6.5.4 of WG1).

6.9.2.2 The Relation of SRM to Climate Policy and Transformation Pathways

A key determinant of the potential role, if any, of SRM in climate policy is that some methods might act relatively quickly. For example, stratospheric aerosol injection could be deployable within months to years, if and when the technology is available, and the climate response to the resulting changes in radiative forcing could occur on a timescale of a decade or less (e.g. Keith, 2000; Matthews and Caldeira, 2007; Royal Society, 2009; Swart and Marinova, 2010; Goes et al., 2011). Mitigating greenhouse gas emissions would affect global mean temperatures only on a multi-decadal to centennial time-scale because of the inertia in the carbon cycle (Van Vuuren and Stehfest, 2013). Hence, it has been argued that SRM technologies could potentially complement mitigation activities, for example by limiting global radiative forcing while mitigation activities are being implemented, or by providing a back-up strategy for a hypothetical future situation where short-term reductions in radiative forcing may be desirable (Royal Society, 2009; Rickels et al., 2011). However, the relatively fast and strong climate response expected from some SRM techniques would also impose risks. The termination of SRM geoengineering forcing either by policy choice or through some form of failure would result in a rapid rise of global mean temperature and associated changes in climate, the magnitude of which would depend on the degree of forcing that was being exerted and the rate at which it was withdrawn (Wigley, 2006; Matthews and Caldeira, 2007; Goes et al., 2011; Irvine et al., 2012; Jones et al., 2013). It has been suggested that this risk could be minimized if SRM geoengineering was used moderately and combined with strong CDR geoengineering and mitigation efforts (Ross and Matthews, 2009; Smith and Rasch, 2012). The potential of SRM to significantly impact the climate on short timescales, at potentially low cost, and the uncertainties and risks involved in this raise important socio-political questions in addition to natural scientific and technological considerations in the section above.

The economic analysis of the potential role of SRM as a climate change policy is an area of active research and has, thus far, produced mixed and preliminary results (cf. Klepper and Rickels, 2012). Estimates of the direct costs of deploying various proposed SRM methods differ significantly. A few studies have indicated that direct costs for some SRM methods might be considerably lower than the costs of conventional mitigation, but all estimates are subject to large uncertainties because of questions regarding efficacy and technical feasibility (Coppock, 1992; Barrett, 2008; Blackstock et al., 2009; Robock et al., 2009; Pierce et al., 2010; Klepper and Rickels, 2012; McClellan et al., 2012).

However, SRM techniques would carry uncertain risks, do not directly address some impacts of anthropogenic greenhouse gas emissions, and raise a range of ethical questions (see WGIII 3.3.8) (Royal Society, 2009; Goes et al., 2011; Moreno-Cruz and Keith, 2012; Tuana et al., 2012). While costs for the implementation of a particular SRM method might potentially be low, a comprehensive assessment would need to consider all intended and unintended effects on ecosystems and societies and the corresponding uncertainties (Rickels et al., 2011; Goes et al., 2011; Klepper and Rickels, 2012). Because most proposed SRM methods would require constant replenishment and an increase in their implementation intensity if emissions of greenhouse gases continue, the result of any assessment of climate policy costs is strongly dependent on assumptions about the applicable discount rate, the dynamics of deployment, the implementation of mitigation, and the likelihood of risks and side-effects of SRM (cf. Bickel and Agrawal, 2011; Goes et al., 2011). While it has been suggested that SRM technologies may “buy time” for emission reductions (Rickels et al., 2011), they cannot substitute for emission reductions in the long term because they do not address concentrations of greenhouse gases and would only partially and imperfectly compensate for their impacts.

The acceptability of SRM as a climate policy in national and international socio-political domains is uncertain. While international commitment is required for effective mitigation, a concern about SRM is that direct costs might be low enough to allow countries to unilaterally alter the global climate (Bodansky, 1996; Schelling, 1996; Barrett, 2008). Barrett (2008) and Urpelainen (2012) therefore argue that SRM technologies introduce structurally obverse problems to the “free-rider” issue in climate mitigation. Some studies suggest that deployment of SRM hinges on interstate cooperation, due to the complexity of the climate system and the unpredictability of outcomes if states do not coordinate their actions (Horton, 2011). In this case, the political feasibility of an SRM intervention would depend on the ability of state-level actors to come to some form of agreement.

The potential for interstate cooperation and conflict will likely depend on the institutional context in which SRM is being discussed, as well as on the relative importance given to climate change issues at the national and international levels. Whether a broad international agreement is possible is a highly contested subject (see WGIII 13.4.4) (EDF; The Royal Society; TWAS, 2012). Several researchers suggest that a UN-based institutional arrangement for decision-making on SRM would be most effective (Barrett, 2008; Virgoe, 2009; Zürn and Schäfer, 2013). So far there are no legally binding international norms that explicitly address SRM, although certain general rules and principles of international law are applicable (see WGII chapt.13 p.37). States parties to the UN Convention on Biological Diversity have adopted a non-binding decision on geoengineering which establishes criteria that could provide guidance for further development of international regulation and governance (CBD Decision IX/16 C (ocean fertilization) and Decision X/33(8)(w); see also LC/LP Resolutions LC-LP.1(2008) and LC-LP.2(2010), preamble).

Commentators have identified the governance of SRM technologies as a significant political and ethical challenge, especially in ensuring legitimate decision-making, monitoring and control (Victor, 2008; Virgoe, 2009; Bodansky, 2012). Even if SRM would largely reduce the global temperature rise due to anthropogenic climate change, as current modelling studies indicate, it would also imply a spatial and temporal redistribution of risks. SRM thus introduces important questions of intra- and intergenerational justice, both distributive and procedural (cf. Wigley, 2006; Matthews and Caldeira, 2007; Goes et al., 2011; Irvine et al., 2012; Tuana et al., 2012; Bellamy et al., 2012; Preston, 2013). Furthermore, since the technologies would not remove the need for emission reductions, in order to effectively ameliorate climate change over a longer term SRM regulation would need to be based on a viable relation between mitigation and SRM activities, and consider the respective and combined risks of increased greenhouse gas concentrations and SRM interventions. The concern that the prospect of a viable SRM technology may reduce efforts to mitigate and adapt has featured prominently in discussions to date (Royal Society, 2009; Gardiner, 2011; Preston, 2013).

Whether SRM field research or even deployment would be socially and politically acceptable is also dependent on the wider discursive context in which the topic is being discussed. Bellamy et al. (2013) show that the success of mitigation policies is likely to have an influence on stakeholder acceptability of SRM. While current evidence is limited to few studies in a very narrow range of cultural contexts, in a first review of early studies on perceptions of geoengineering Corner et al. (2012) find that participants of different studies tend to prefer CDR over SRM and mitigation over geoengineering. Considerations that influence opinions are, amongst others, the perceived "naturalness" of a technology, its reversibility, and the capacity for responsible and transparent governance (Corner et al., 2012). Furthermore, the way that the topic is framed in the media and by experts plays an important role in influencing opinions on SRM research or deployment (Luokkanen et al., 2013; Scholte et al., 2013). The direction that future discussions may take is impossible to predict, since deepened and highly differentiated information is rapidly becoming available (Corner et al., 2012; Macnaghten and Szerszynski, 2013).

6.9.3 Summary

Whether proposed CDR or SRM geoengineering techniques can play a useful role in transformation pathways is uncertain as the efficacy and risks of many techniques are poorly understood at present. CDR techniques aim to reduce CO_2 (or potentially other GHG) concentrations. A broad definition of CDR would cover afforestation and biomass energy with carbon capture and storage (BECCS), which are sometimes classified as mitigation techniques, but also proposals which are very distinct in terms of technical maturity, scientific understanding and risks from mitigation such as ocean iron fertilization. The former are often included in current integrated models and scenarios and are, in fact, in terms of their impact on the climate directly comparable with techniques that are considered to be conventional mitigation, notably fossil CCS and bio-energy use. Both BECCS and afforestation may play a key role in reaching low greenhouse gas concentrations, but at a large scale have substantial land-use demands which may conflict with other mitigation strategies and societal needs such as food production. Whether other CDR techniques would be able to supplement mitigation at any significant scale in the future depends upon efficacy, cost, and risks of these techniques, which at present are highly uncertain. The properties of potential carbon storage reservoirs are also critically important, as limits to reservoir capacity and longevity will constrain the quantity and permanence of CO_2 storage. Furthermore, some CDR techniques, such as ocean iron fertilization may pose transboundary risks. The impacts of CDR would be relatively slow: climate effects would unfold over the course of decades.

In contrast to CDR, SRM would aim to cool the climate by shielding sunlight. These techniques would not reduce elevated GHG concentrations, and thus not affect other consequences of high GHG concentrations, such as ocean acidification. Some SRM proposals could potentially cause a large cooling within years, much quicker than mitigation or CDR, and a few studies suggest that costs might be considerably lower than CDR for some SRM techniques. It has thus been suggested that SRM could be used to quickly reduce global temperatures or to limit temperature rise while mitigation activities are being implemented. However, in order to avoid warming, SRM would need to be maintained as long as GHG concentrations remain elevated. Modelling studies show that SRM may be able to reduce global average temperatures but would not perfectly reverse all climatic changes that occur due to elevated GHG concentrations, especially at local to regional scales. For example, SRM is expected to weaken the global hydrological cycle with consequences for regional precipitation patterns and surface hydrology, and is expected to change the seasonality and variability of climate. As the potential climate impacts of any SRM intervention are uncertain and evidence is very limited, it is too early to conclude how effective SRM would be in reducing climate risks. SRM approaches may also carry significant non-climatic side-effects. For example, sulphate aerosol injection would modify stratospheric chemistry, potentially reducing ozone levels, and would change the appearance of the sky. The risks of SRM interventions and large-scale experiments, alongside any potential benefits, raise a number of ethical and political questions which would require public engagement and international cooperation to address adequately.

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: development of a broader set of socioeconomic and technological storylines to support the development of future scenarios; scenarios pursuing a wider set of climate goals including those related to temperature change; more mitigation scenarios that include impacts from, and adaptations to, a changing climate, including energy and land use systems critical for mitigation; expanded treatment of the benefits and risks of CDR and SRM options; expanded treatment of co-benefits and risks of mitigation pathways; improvements in the treatment and understanding of mitigation options and responses in end use sectors in transformation pathways; and more sophisticated treatments of land use and land used based mitigation options in mitigation 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.

6.11 Frequently Asked Questions

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?

Many commonly discussed concentration goals, including the goal of reaching 450 ppm CO2-e by the end of the century, are both physically and technologically possible. However, meeting long-term climate goals will require large-scale transformations in human societies, from the way that we produce and consume energy to how we use the land surface, that are inconsistent with both long-term and short-term trends. For example, to achieve a 450 ppm CO2-e concentration by 2100, supplies of low-carbon energy – energy from nuclear power, solar power, wind power, hydroelectric power, bioenergy, and fossil resources with carbon capture and storage – might need to increase five-fold or more over the next forty years. The possibility of meeting any concentration goal therefore depends not just on the available technologies and current emissions and concentrations, but also on the capacity of human societies to bear the associated economic implications, accept the associated rapid and large-scale deployment of technologies, develop the necessary institutions to manage the transformation, and reconcile the transformation with other policy priorities such as sustainable development. Improvements in the costs and performance of mitigation technologies will ease the burden of this transformation. In contrast, if the world's countries cannot take on sufficiently ambitious mitigation over the next 20 years or obstacles impede the deployment of important mitigation technologies at large scale, goals such as 450 ppm CO2-e by 2100 may no longer be possible.

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

Limiting CO2-e concentrations will require a portfolio of options, because no single option is sufficient to reduce CO2-e concentrations and eventually eliminate net CO2 emissions. Options include a range of energy supply technologies such as nuclear power, solar energy, wind power and hydroelectric power, as well as bioenergy and fossil resources with carbon capture and storage. A range of end-use technologies will be needed to reduce energy consumption, and therefore the need for low-carbon energy, and to allow the use of low-carbon fuels in transportation, buildings, and industry. 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. Many of these options must be deployed to some degree to stabilize CO2-e concentrations. A portfolio approach can be tailored to local circumstances in order to take into account other priorities such as those associated with sustainable development. At the same time, if emissions reductions are too modest over the coming two decades, it may no longer be possible to reach a goal of 450 ppm CO2-e by the end of the century without large-scale deployment of carbon dioxide removal (CDR) technologies. Thus, while no individual technology is sufficient, CDR technologies could become necessary in such a scenario.

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

Aggregate economic mitigation costs metrics are an important criterion for evaluating transformation pathways and can indicate the level of difficulty associated with particular pathways. However, the broader socio-economic implications of mitigation go beyond measures of aggregate economic costs, as transformation pathways involve a range of tradeoffs that link to other policy priorities. Global mitigation cost estimates vary widely due to methodological differences along with differences in assumptions about future emissions drivers, technologies, and policy conditions. Most scenario studies collected for this assessment that are based on the idealized assumptions that all countries of the world begin mitigation immediately, there is a single global carbon price applied to well-functioning markets, and key technologies are available, find that meeting a 430-480 ppm CO2-e goal by century’s end would entail a reduction in the amount global consumers spend of 1% to 4% in 2030, 2% to 6% in 2050, and 2% to 12% in 2100 relative to what would happen without mitigation. To put these losses in context, studies assume that consumption spending might grow from four- to over ten-fold over the century without mitigation. Less ambitious goals are associated with lower costs this century. Substantially higher and lower estimates have been obtained by studies that consider interactions with pre-existing distortions, non-climate market failures, and complementary policies. Studies explicitly exploring the implications of less-idealized policy approaches and limited technology performance or availability have consistently produced higher cost estimates. Delaying mitigation would reduce near-term costs; however studies indicate that subsequent costs will rise much more rapidly to higher levels.

References

Aboumahboub T., et al, E. Kriegler, M. Leimbach, Bauer, Pehl, and L. Baumstark (2014). On the regional distribution of climate mitigation costs: the impact of delayed cooperative action. *Accepted for publication in Climate Change Economics* **In press.**

Acemoglu D., P. Aghion, L. Bursztyn, and D. Hemous (2009). *The environment and directed technical change*. National Bureau of Economic Research.

Agarwal A., and S. Narain (1991). *Global warming in an unequal world: A case of environmental colonialism*. Centre for Science and Environment (CSE), New Delhi, India.

Akimoto K., F. Sano, A. Hayashi, T. Homma, J. Oda, K. Wada, M. Nagashima, K. Tokushige, and T. Tomoda (2012). Consistent assessments of pathways toward sustainable development and climate stabilization. *Natural Resources Forum* **36**, 231–244. (DOI: 10.1111/j.1477-8947.2012.01460.x). Available at: http://dx.doi.org/10.1111/j.1477-8947.2012.01460.x.

Alcamo J., and T. Henrichs (2002). Critical regions: A model-based estimation of world water resources sensitive to global changes. *Aquatic Sciences* **64**, 352–362. (DOI: 10.1007/PL00012591). Available at: http://dx.doi.org/10.1007/PL00012591.

Allcott H. (2011). Consumers’ Perceptions and Misperceptions of Energy Costs. *American Economic Review* **101**, 98–104. (DOI: 10.1257/aer.101.3.98). Available at: http://www.aeaweb.org/articles.php?doi=10.1257/aer.101.3.98.

Allcott H. (2013). The Welfare Effects of Misperceived Product Costs: Data and Calibrations from the Automobile Market. *American Economic Journal: Economic Policy* **5**, 30–66. (DOI: 10.1257/pol.5.3.30). Available at: http://www.aeaweb.org/articles.php?doi=10.1257/pol.5.3.30.

Allen M., D.J. Frame, C. Huntingford, C.D. Jones, J.A. Lowe, M. Meinshausen, and N. Meinshausen (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458**, 1163–1166. Available at: http://adsabs.harvard.edu/abs/2009Natur.458.1163A.

Anenberg S.C., J. Schwartz, D. Shindell, M. Amann, G. Faluvegi, Z. Klimont, G. Janssens-Maenhout, L. Pozzoli, R. Van Dingenen, and E. Vignati (2012). Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls. *Environmental health perspectives* **120**, 831.

Angel R. (2006). Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proceedings of the National Academy of Sciences of the United States of America* **103**, 17184–17189. (DOI: 10.1073/pnas.0608163103). Available at: ://WOS:000242249400024.

Anthoff D., S. Rose, R. Tol, and S. Waldhoff (2011). Regional and sectoral estimates of the social cost of carbon: An application of FUND. *Economics Discussion Paper*.

Arroyo-Curras et al (2014). Carbon Leakage in a Fragmented Climate Regime: The Dynamic Response of Global Energy Markets. *Tech For. & Soc. Change, accepted.*

Azar C., and D.J.A. Johansson (2012). On the relationship between metrics to compare greenhouse gases – the case of IGTP, GWP and SGTP. *Earth Syst. Dynam.* **3**, 139–147. (DOI: 10.5194/esd-3-139-2012). Available at: http://www.earth-syst-dynam.net/3/139/2012/.

Azar C., D.J.A. Johansson, and N. Mattsson (2013). Meeting global temperature targets—the role of bioenergy with carbon capture and storage. *Environmental Research Letters* **8**, 034004. Available at: http://stacks.iop.org/1748-9326/8/i=3/a=034004.

Azar C., K. Lindgren, E. Larson, and K. Mollersten (2006a). Carbon capture and storage from fossil fuels and biomass - Costs and potential role in stabilizing the atmosphere. *CLIMATIC CHANGE* **74**, 47–79. (DOI: 10.1007/s10584-005-3484-7).

Azar C., K. Lindgren, E. Larson, and K. Möllersten (2006b). Carbon Capture and Storage From Fossil Fuels and Biomass – Costs and Potential Role in Stabilizing the Atmosphere. *Climatic Change* **74**, 47–79. (DOI: 10.1007/s10584-005-3484-7). Available at: http://dx.doi.org/10.1007/s10584-005-3484-7.

Azar C., K. Lindgren, M. Obersteiner, K. Riahi, D. Vuuren, K.M.G.J. Elzen, K. Möllersten, and E.D. Larson (2010a). The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change* **100**, 195–202. (DOI: 10.1007/s10584-010-9832-7). Available at: http://www.springerlink.com/content/w10q4881225g6697/.

Azar C., K. Lindgren, M. Obersteiner, K. Riahi, D.P. van Vuuren, M.G.J. den Elzen, K. Möllersten, and E.D. Larson (2010b). The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change* **100**, 195–202. (DOI: 10.1007/s10584-010-9832-7). Available at: http://www.springerlink.com/content/w10q4881225g6697/.

Babiker M.H. (2005). Climate change policy, market structure, and carbon leakage. *Journal of international Economics* **65**, 421–445. Available at: http://www.sciencedirect.com/science/article/pii/S0022199604000467.

Babiker M.H., and R.S. Eckaus (2007). Unemployment effects of climate policy. *Environmental Science & Policy* **10**, 600–609. (DOI: 10.1016/j.envsci.2007.05.002). Available at: http://www.sciencedirect.com/science/article/pii/S1462901107000664.

Babiker M.H., G.E. Metcalf, and J. Reilly (2003). Tax distortions and global climate policy. *Journal of Environmental Economics and Management* **46**, 269–287. (DOI: 10.1016/S0095-0696(02)00039-6). Available at: http://www.sciencedirect.com/science/article/pii/S0095069602000396.

Baciocchi R., G. Storti, and M. Mazzotti (2006). Process design and energy requirements for the capture of carbon dioxide from air. *Chemical Engineering and Processing: Process Intensification* **45**, 1047–1058. (DOI: 10.1016/j.cep.2006.03.015). Available at: http://www.sciencedirect.com/science/article/pii/S0255270106000791.

Baer P. (2013). The greenhouse development rights framework for global burden sharing: reflection on principles and prospects. *Wiley Interdisciplinary Reviews: Climate Change* **4**, 61–71. (DOI: 10.1002/wcc.201). Available at: http://dx.doi.org/10.1002/wcc.201.

Baer P., T. Athanasiou, S. Kartha, and E. Kemp-Benedict (2008). *The Greenhouse Development Rights Framework: The Right to Development in a Climate Constrained World*. Heinrich Böll Foundation, Christian Aid, EcoEquity, and the Stockholm Environment Institute, Berlin and Albany, CA.

Baker E., and E. Shittu (2008). Uncertainty and endogenous technical change in climate policy models. *Energy Economics* **30**, 2817–2828.

Bala G., K. Caldeira, M. Wickett, T. Phillips, D. Lobell, C. Delire, and A. Mirin (2007). Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences* **104**, 6550–6555.

Bala G., P.B. Duffy, and K.E. Taylor (2008). Impact of geoengineering schemes on the global hydrological cycle. *Proceedings of the National Academy of Sciences* **105**, 7664–7669. (DOI: 10.1073/pnas.0711648105). Available at: http://www.pnas.org/content/105/22/7664.abstract.

Barker T., I. Bashmakov, A. Alharthi, M. Amann, L. Cifuentes, J. Drexhage, M. Duan, O. Edenhofer, B. Flannery, M. Grubb, M. Hoogwijk, F.I. Ibitoye, C.J. Jepma, W.A. Pizer, and K. Yamaji (2007). Mitigation from a cross-sectoral perspective. In: *Climate Change 2007 - Mitigation*. Cambridge University Press, Cambridge.

Barrett S. (2008). The incredible economics of geoengineering. *Environmental and Resource Economics* **39**, 45–54. Available at: http://www.springerlink.com/index/a91294x25w065vk3.pdf.

Batlle C., I.J. Pérez-Arriaga, and P. Zambrano-Barragán (2012). Regulatory design for RES-E support mechanisms: Learning curves, market structure, and burden-sharing. *Modeling Transport (Energy) Demand and Policies* **41**, 212–220. (DOI: 10.1016/j.enpol.2011.10.039). Available at: http://www.sciencedirect.com/science/article/pii/S0301421511008238.

Bauer N., V. Bosetti, M. Hamdi-Cherif, A. Kitous, D. McCollum, A. Mejean, S. Rao, H. Turton, L. Paroussos, S. Ashina, K. Calvin, K. Wada, and D. van Vuuren CO2 emission mitigation and fossil fuel markets: Dynamic and international aspects of climate policies. *Technological Forecasting and Social Change* **Accepted**.

Bauer N., V. Bosetti, M. Hamdi-Cherif, A. Kitous, D. McCollum, A. Méjean, S. Rao, H. Turton, L. Paroussos, S. Ashina, K. Calvin, K. Wada, and D. van Vuuren (2013a). CO2 emission mitigation and fossil fuel markets: Dynamic and international aspects of climate policies. *Technological Forecasting and Social Change* **In press**. (DOI: 10.1016/j.techfore.2013.09.009). Available at: http://www.sciencedirect.com/science/article/pii/S0040162513002382.

Bauer N., R.J. Brecha, and G. Luderer (2012). Economics of nuclear power and climate change mitigation policies. *Proceedings of the National Academy of Sciences*. (DOI: 10.1073/pnas.1201264109). Available at: http://www.pnas.org/content/early/2012/09/27/1201264109.abstract.

Bauer N., I. Mouratiadou, G. Luderer, L. Baumstark, R.J. Brecha, O. Edenhofer, and E. Kriegler (2013b). Global fossil energy markets and climate change mitigation – an analysis w ith ReMIND. *Climatic Change* **121**. (DOI: 10.1007/s10584-013-0901-6). Available at: http://link.springer.com/article/10.1007/s10584-013-0901-6.

Bazilian M., and F. Roques (2009). *Analytical Methods for Energy Diversity and Security: Portfolio Optimization in the Energy Sector: A Tribute to the work of Dr. Shimon Awerbuch*. Access Online via Elsevier, (ISBN: 0080915310).

Bell M., D. Davis, L. Cifuentes, A. Krupnick, R. Morgenstern, and G. Thurston (2008). Ancillary human health benefits of improved air quality resulting from climate change mitigation. *Environmental Health* **7**, 41. Available at: http://www.ehjournal.net/content/7/1/41.

Bellamy R., J. Chilvers, N.E. Vaughan, and T.M. Lenton (2012). A review of climate geoengineering appraisals. *Wiley Interdisciplinary Reviews-Climate Change* **3**, 597–615. (DOI: 10.1002/wcc.197). Available at: ://WOS:000309911100007.

Bellamy R., J. Chilvers, N.E. Vaughan, and T.M. Lenton (2013). "Opening up" geoengineering appraisal: Multi-Criteria Mapping of options for tackling climate change. *Global Environmental Change*. (DOI: 10.1016/j.gloenvcha.2013.07.011).

Van den Berg M., A. Hof, J. Van Vliet, and D. Van Vuuren (2014). Impact of the Choice of Emission Metrics on Greenhouse Gas Abatement and Costs.

Berk M.M., and M.G.J. den Elzen (2001). Options for differentiation of future commitments in climate policy: how to realise timely participation to meet stringent climate goals? *Climate Policy* **1**, 465–480. (DOI: 10.3763/cpol.2001.0148). Available at: http://www.tandfonline.com/doi/abs/10.3763/cpol.2001.0148.

Berntsen T., K. Tanaka, and J. Fuglestvedt (2010). Does black carbon abatement hamper CO2 abatement? *Climatic Change* **103**, 627–633. (DOI: 10.1007/s10584-010-9941-3). Available at: http://dx.doi.org/10.1007/s10584-010-9941-3.

Betts R.A., O. Boucher, M. Collins, P.M. Cox, P.D. Falloon, N. Gedney, D.L. Hemming, C. Huntingford, C.D. Jones, D.M.H. Sexton, and M.J. Webb (2007). Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature* **448**, 1037–U5. (DOI: 10.1038/nature06045). Available at: ://WOS:000249097600035.

Bickel J.E., and S. Agrawal (2011). Reexamining the economics of aerosol geoengineering. *Climatic Change*, 1–14.

Blackstock J.J., D.S. Battisti, K. Caldeira, D.M. Eardley, J.I. Katz, D. Keith, A.A.N. Patrinos, D. Schrag, R.H. Socolow, and S.E. Koonin (2009). *Climate Engineering Responses to Climate Emergencies*. Novim. Available at: http://tinyurl.com/m4w3ca.

Blanford G., E. Kriegler, and M. Tavoni (2014). Harmonization vs. Fragmentation: Overview of Climate Policy Scenarios in EMF27. *Accepted for publication in Climatic Change*. (DOI: DOI: 10.1007/s10584-013-0951-9).

Blanford G.J., S.K. Rose, and M. Tavoni (2012). Baseline projections of energy and emissions in Asia. *The Asia Modeling Exercise: Exploring the Role of Asia in Mitigating Climate Change* **34**, S284–S292. (DOI: 10.1016/j.eneco.2012.08.006). Available at: http://www.sciencedirect.com/science/article/pii/S0140988312001764.

Bodansky D. (1996). May we engineer the climate? *Climatic Change* **33**, 309–321. (DOI: 10.1007/bf00142579). Available at: ://WOS:A1996VB19700005.

Bodansky D. (2012). The who, what, and wherefore of geoengineering governance. *Climatic Change*, 1–13.

Bode S. (2004). Equal emissions per capita over time – a proposal to combine responsibility and equity of rights for post-2012 GHG emission entitlement allocation. *European Environment* **14**, 300–316. (DOI: 10.1002/eet.359). Available at: http://dx.doi.org/10.1002/eet.359.

Boden T.A., G. Marland, and R.J. Andres (2013). *Global, Regional, and National Fossil-Fuel CO2 Emissions*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn. Available at: http://cdiac.ornl.gov/trends/emis/overview_2010.html.

Böhringer C., E.J. Balistreri, and T.F. Rutherford (2012). The role of border carbon adjustment in unilateral climate policy: Overview of an Energy Modeling Forum study (EMF 29). *Energy Economics* **34, Supplement 2**, S97–S110. (DOI: 10.1016/j.eneco.2012.10.003). Available at: http://www.sciencedirect.com/science/article/pii/S0140988312002460.

Bohringer C., and A. Löschel (2006). Promoting Renewable Energy in Europe: A Hybrid Computable General Equilibrium Approach. *The Energy Journal* **Hybrid Modeling**, 135–150. Available at: http://econpapers.repec.org/article/aenjournl/2006se_5fjaccard-a07.htm.

Böhringer C., T.F. Rutherford, and R.S.J. Tol (2009). THE EU 20/20/2020 targets: An overview of the EMF22 assessment. *Energy Economics* **31**, S268–S273. (DOI: 16/j.eneco.2009.10.010). Available at: http://www.sciencedirect.com/science/article/pii/S0140988309001935.

Böhringer C., and H. Welsch (2006). Burden sharing in a greenhouse: egalitarianism and sovereignty reconciled. *Applied Economics* **38**, 981–996. (DOI: 10.1080/00036840500399453). Available at: http://dx.doi.org/10.1080/00036840500399453.

Bollen J., B. Guay, S. Jamet, and J. Corfee-Morlot (2009a). *Co-Benefits of Climate Change Mitigation Policies*. OECD Publishing. Available at: /content/workingpaper/224388684356.

Bollen J., S. Hers, and B. van der Zwaan (2010). An integrated assessment of climate change, air pollution, and energy security policy. *Energy Policy* **38**, 4021–4030. (DOI: 10.1016/j.enpol.2010.03.026).

Bollen J., B. van der Zwaan, C. Brink, and H. Eerens (2009b). Local air pollution and global climate change: A combined cost-benefit analysis. *Resource and Energy Economics* **31**, 161–181. (DOI: 10.1016/j.reseneeco.2009.03.001). Available at: http://www.sciencedirect.com/science/article/pii/S092876550900013X.

Bosello F., C. Carraro, and E. De Cian (2010b). Climate Policy and the Optimal Balance between Mitigation, Adaptation and Unavoided Damage. *Climate Change Economics* **1**, 71–92.

Bosello F., C. Carraro, and E. De Cian (2010a). An Analysis of Adaptation as a Response to Climate Change. In: *Smart Solutions to Climate Change*. B. Lomborg, (ed.), Cambridge University Press, Cambridge.

Bosello F., R. Roson, and R. Tol (2007). Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise. *Environmental and Resource Economics* **37**, 549–571.

Bosetti V., C. Carraro, R. Duval, and M. Tavoni (2011). What should we expect from innovation? A model-based assessment of the environmental and mitigation cost implications of climate-related R&D. *Energy Economics* **33**, 1313–1320. (DOI: 10.1016/j.eneco.2011.02.010). Available at: http://www.sciencedirect.com/science/article/pii/S0140988311000466.

Bosetti V., C. Carraro, E. Massetti, A. Sgobbi, and M. Tavoni (2009a). Optimal energy investment and R&D strategies to stabilize atmospheric greenhouse gas concentrations. *Resource and Energy Economics* **31**, 123–137. (DOI: 10.1016/j.reseneeco.2009.01.001). Available at: http://www.sciencedirect.com/science/article/pii/S0928765509000025.

Bosetti V., C. Carraro, A. Sgobbi, and M. Tavoni (2009b). Delayed action and uncertain stabilisation targets. How much will the delay cost? *Climatic Change* **96**, 299–312. (DOI: 10.1007/s10584-009-9630-2). Available at: http://www.springerlink.com/content/1677543587156355/.

Bosetti V., C. Carraro, and M. Tavoni (2009c). A Chinese commitment to commit: can it break the negotiation stall? *Climatic change* **97**, 297–303.

Bosetti V., C. Carraro, and M. Tavoni (2009d). Climate change mitigation strategies in fast-growing countries: The benefits of early action. *Energy Economics* **31, Supplement 2**, S144–S151. (DOI: doi:

10.1016/j.eneco.2009.06.011). Available at: http://www.sciencedirect.com/science/article/pii/S0140988309001091.

Bosetti V., and E. De Cian (2013). A Good Opening: The Key to Make the Most of Unilateral Climate Action. *Environmental and Resource Economics*. (DOI: 10.1007/s10640-013-9643-1). Available at: http://link.springer.com/10.1007/s10640-013-9643-1.

Bosetti V., and J. Frankel (2012). Politically Feasible Emissions Targets to Attain 460 ppm CO2 Concentrations. *Review of Environmental Economics and Policy* **6**, 86–109. (DOI: 10.1093/reep/rer022). Available at: http://reep.oxfordjournals.org/content/6/1/86.abstract.

Bosetti V., and M. Tavoni (2009). Uncertain R&D, backstop technology and GHGs stabilization. *Energy Economics* **31**, S18–S26.

Bosquet B. (2000). Environmental tax reform: does it work? A survey of the empirical evidence. *Ecological Economics* **34**, 19–32. (DOI: 10.1016/S0921-8009(00)00173-7). Available at: http://www.sciencedirect.com/science/article/pii/S0921800900001737.

Boucher O., and G.A. Folberth (2010). New Directions: Atmospheric methane removal as a way to mitigate climate change? *Atmospheric Environment* **44**, 3343–3345. (DOI: 10.1016/j.atmosenv.2010.04.032). Available at: http://www.sciencedirect.com/science/article/pii/S1352231010003262.

Boucher O., P. Forster, N. Gruber, M. Ha-Duong, M. Lawrence, T. Lenton, and A. Maas (2013a). Rethinking climate engineering categorization in the context of climate change mitigation and adaptation. *WIREs Climate Change* **In press**. (DOI: doi:10.1002/wcc.261.).

Boucher O., P.M. Forster, N. Gruber, M. Ha-Duong, M.G. Lawrence, T.M. Lenton, A. Maas, and N.E. Vaughan (2013b). Rethinking climate engineering categorization in the context of climate change mitigation and adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, n/a–n/a. (DOI: 10.1002/wcc.261). Available at: http://dx.doi.org/10.1002/wcc.261.

Boucher O., A. Jones, and R.A. Betts (2009). Climate response to the physiological impact of carbon dioxide on plants in the Met Office Unified Model HadCM3. *Climate Dynamics* **32**, 237–249. (DOI: 10.1007/s00382-008-0459-6). Available at: ://WOS:000262086300006.

Boucher, O., Gruber, N., and Blackstock (2011). Summary of the Synthesis Session. IPCC Expert Meeting Report on Geoengineering. In: *IPCC Expert Meeting Report on Geoengineering.*LIma, Peru.

Bovenberg A., and L. Goulder (1996). Optimal environmental taxation in the presence of other taxes: General equilibrium analyses. *American Economic Review* **86**, 985–1006.

Bows A., and K. Anderson (2008). Contraction and convergence: an assessment of the CCOptions model. *Climatic Change* **91**, 275–290. (DOI: 10.1007/s10584-008-9468-z). Available at: http://dx.doi.org/10.1007/s10584-008-9468-z.

Boyd P.W., T. Jickells, C.S. Law, S. Blain, E.A. Boyle, K.O. Buesseler, K.H. Coale, J.J. Cullen, H.J.W. de Baar, M. Follows, M. Harvey, C. Lancelot, M. Levasseur, N.P.J. Owens, R. Pollard, R.B. Rivkin, J. Sarmiento, V. Schoemann, V. Smetacek, S. Takeda, A. Tsuda, S. Turner, and A.J. Watson (2007). Mesoscale Iron Enrichment Experiments 1993-2005: Synthesis and Future Directions. *Science* **315**, 612 –617. Available at: http://www.sciencemag.org/content/315/5812/612.abstract.

BP (2013). *BP Statistical Review of World Energy*. BP, London. Available at: http://www.bp.com/en/global/corporate/about-bp/statistical-review-of-world-energy-2013.html.

Bradford D.F. (1999). On the uses of benefit-cost reasoning in choosing policy toward global climate change. In: *Discounting and intergenerational equity*. J.P. Weyant, P. Portney, (eds.), RFF Press, Washington DC, USA pp.37–44, (ISBN: 0915707896).

Bréchet T., F. Gerard, and H. Tulkens (2011). Efficiency vs. stability in climate coalitions: a conceptual and computational appraisal. *Energy Journal* **32**, 49. Available at: http://www.ulouvain.be/cps/ucl/doc/core/documents/E2M2_123.pdf.

De Bruin K.C., R.B. Dellink, and R.S.J. Tol (2009). AD-DICE: an implementation of adaptation in the DICE model. *Climatic Change* **95**, 63–81. (DOI: 10.1007/s10584-008-9535-5). Available at: http://www.springerlink.com/index/10.1007/s10584-008-9535-5.

Bruinsma J. (2011). The resources outlook: by how much do land, water and crop yields need to increase by 2050? In: *Looking ahead in world food and agriculture: Perspectives to 2050.* P. Conforti, (ed.), Food and Agriculture Organization of the United Nations., Rome, Italy.

Budyko M.I., and D.H. Miller (1974). *Climate and life*. Academic press New York.

Buonanno P., C. Carraro, and M. Galeotti (2003). Endogenous induced technical change and the costs of Kyoto. *Resource and Energy Economics* **25**, 11–34. Available at: http://ideas.repec.org/a/eee/resene/v25y2003i1p11-34.html.

Bye B., S. Kverndokk, and K. Rosendahl (2002). Mitigation costs, distributional effects, and ancillary benefits of carbon policies in the Nordic countries, the U.K., and Ireland. *Mitigation and Adaptation Strategies for Global Change* **7**, 339–366. (DOI: 10.1023/A:1024741018194). Available at: http://dx.doi.org/10.1023/A%3A1024741018194.

Caldeira K., G. Bala, and L. Cao (2013). The Science of Geoengineering. *Annual Review of Earth and Planetary Sciences* **41**, 231–256. (DOI: 10.1146/annurev-earth-042711-105548). Available at: http://dx.doi.org/10.1146/annurev-earth-042711-105548.

Calvin K., and al. (2014). The effect of African growth on future global energy, emissions, and regional development. *Accepted for publication in Climatic Change*. (DOI: DOI: 10.1007/s10584-013-0964-4).

Calvin K., J. Edmonds, B. Bond-Lamberty, L. Clarke, S.H. Kim, P. Kyle, S.J. Smith, A. Thomson, and M. Wise (2009a). 2.6: Limiting climate change to 450 ppm CO2 equivalent in the 21st century. *Energy Economics* **31**, S107–S120. Available at: http://www.sciencedirect.com/science/article/B6V7G-4WHFD6P-1/2/f1cf35774f38ef95e30797310db37533.

Calvin K., P. Patel, A. Fawcett, L. Clarke, K. Fisher-Vanden, J. Edmonds, S.H. Kim, R. Sands, and M. Wise (2009b). The distribution and magnitude of emissions mitigation costs in climate stabilization under less than perfect international cooperation: SGM results. *Energy Economics* **31**, S187–S197. (DOI: 16/j.eneco.2009.06.014). Available at: http://www.sciencedirect.com/science/article/pii/S014098830900111X.

Calvin K., P. Patel, A. Fawcett, L. Clarke, K. Fisher-Vanden, J. Edmonds, S.H. Kim, R. Sands, and M. Wise (2009c). The distribution and magnitude of emissions mitigation costs in climate stabilization under less than perfect international cooperation: SGM results. *Energy Economics* **31, Supplement 2**, S187–S197. (DOI: 10.1016/j.eneco.2009.06.014). Available at: http://www.sciencedirect.com/science/article/pii/S014098830900111X.

Calvin K., M. Wise, L. Clarke, J. Edmonds, P. Kyle, P. Luckow, and A. Thomson (2013). Implications of simultaneously mitigating and adapting to climate change: initial experiments using GCAM. *Climatic Change* **117**, 545–560. (DOI: 10.1007/s10584-012-0650-y). Available at: http://dx.doi.org/10.1007/s10584-012-0650-y.

Calvin K., M. Wise, P. Luckow, P. Kyle, L. Clarke, and J. Edmonds (2014). Implications of uncertain future fossil energy resources on bioenergy use and terrestrial carbon emissions. *Climatic Change* **Forthcoming**.

Cao L., and K. Caldeira (2010). Can ocean iron fertilization mitigate ocean acidification? *Climatic Change* **99**, 303–311. (DOI: 10.1007/s10584-010-9799-4). Available at: http://dx.doi.org/10.1007/s10584-010-9799-4.

Carraro C., E. De Cian, L. Nicita, E. Massetti, and E. Verdolini (2010). Environmental policy and technical change: A survey. *International Review of Environmental and Resource Economics* **4**, 163–219. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-77958611711&partnerID=40&md5=0596bb1762ab82596c68d8245efeca7e.

Carraro C., R. Gerlagh, and B. van der Zwaan (2003). Endogenous technical change in environmental macroeconomics. *Resource and Energy Economics* **25**, 1–10. Available at: http://ideas.repec.org/a/eee/resene/v25y2003i1p1-10.html.

CBD (1992). *Convention on Biological Diversity (CBD)*. Available at: http://www.cbd.int/convention/.

CBD (2010). *COP 10 Decision X/2: Strategic Plan for Biodiversity 2011–2020*. Secretariat of the Convention on Biological Diversity, Aichi.

Chakravarty S., A. Chikkatur, H. de Coninck, S. Pacala, R. Socolow, and M. Tavoni (2009). Sharing global CO2 emission reductions among one billion high emitters. *Proceedings of the National Academy of Sciences* **106**, 11884–11888. (DOI: 10.1073/pnas.0905232106). Available at: http://www.pnas.org/content/106/29/11884.abstract.

Chaturvedi V., and P. Shukla (2013). Role of energy efficiency in climate change mitigation policy for India: assessment of co-benefits and opportunities within an integrated assessment modeling framework. *Climatic Change*, 1–13. (DOI: 10.1007/s10584-013-0898-x). Available at: http://dx.doi.org/10.1007/s10584-013-0898-x.

Chaturvedi V., S. Waldhoff, L. Clarke, and S. Fujimori (2012). What are the starting points? Evaluating base-year assumptions in the Asian Modeling Exercise. *The Asia Modeling Exercise: Exploring the Role of Asia in Mitigating Climate Change* **34, Supplement 3**, S261–S271. (DOI: 10.1016/j.eneco.2012.05.004).

Chen C., and M. Tavoni (2013). Direct Air Capture of CO2 and Climate Stabilization: A Model Based Assessment. *submitted to Climatic Change*.

Chen,W, Yin,X, and Zhang, H. (2013). Towards low carbon development in China: a comparison of national and global models. *CLIMATIC CHANGE*.

Cherp A., A. Adenikinju, A. Goldthau, F. Hernandez, L. Hughes, J. Jansen, J. Jewell, M. Olshanskaya, R. Soares de Oliveira, B. Sovacool, and S. Vakulenko (2012). Chapter 5 - Energy and Security. In: *Global Energy Assessment - Toward a Sustainable Future*.Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria pp.325–384, (ISBN: 9781 10700 5198 hardback 9780 52118 2935 paperback). Available at: www.globalenergyassessment.org.

Cherp A., J. Jewell, V. Vinichenko, N. Bauer, and E. Cian (2013). Global energy security under different climate policies, GDP growth rates and fossil resource availabilities. *Climatic Change* **In press**. (DOI: 10.1007/s10584-013-0950-x). Available at: http://dx.doi.org/10.1007/s10584-013-0950-x.

Chum H., A. Faaij, J. Moreira, G. Berndes, P. Dharnija, H. Dong, and B. Gabrielle (2011). Bioenergy. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

De Cian E., and al. (2014). The influence of economic growth, population and fossil fuel scarcity on energy investments. *Accepted for publication in Climatic Change* **In press.**

De Cian E., Carrara, S., and Tavoni, M (2013). Innovation benefits from nuclear phase-out: can they compensate the costs? *Accepted for publication in Climatic Change*. (DOI: doi 10.1007/s10584-013-0870-9).

De Cian E., and M. Tavoni (2012a). Do technology externalities justify restrictions on emission permit trading? *Resource and Energy Economics*. Available at: http://www.sciencedirect.com/science/article/pii/S0928765512000425.

De Cian E., and M. Tavoni (2012b). Do technology externalities justify restrictions on emission permit trading? *Resource and Energy Economics* **34**, 624–646. (DOI: 10.1016/j.reseneeco.2012.05.009). Available at: http://www.sciencedirect.com/science/article/pii/S0928765512000425.

Clarke L., J. Edmonds, V. Krey, R. Richels, S.K. Rose, and M. Tavoni (2009a). International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics* **31**, S64–S81. Available at: http://www.sciencedirect.com/science/article/B6V7G-4XHVH34-2/2/67f06e207a515adba42f7455a99f648e.

Clarke L., J. Edmonds, V. Krey, R. Richels, S.K. Rose, and M. Tavoni (2009b). International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics* **31, Supplement 2**, S64–S81. (DOI: doi: 10.1016/j.eneco.2009.10.013). Available at: http://www.sciencedirect.com/science/article/pii/S0140988309001960.

Clarke L., V. Krey, J. Weyant, and V. Chaturvedi (2012). Regional energy system variation in global models: Results from the Asian Modeling Exercise scenarios. *Energy Economics* **34**, S293–S305. (DOI: 10.1016/j.eneco.2012.07.018). Available at: http://www.sciencedirect.com/science/article/pii/S0140988312001624.

Combet E., F. Ghersi, J.C. Hourcade, and D. Thery (2010). Carbon Tax and Equity, the importance of Policy Design. In: *Critical Issues in Environmental Taxation*. Oxford University Press, Oxford pp.277–295, .

Coppock R. (1992). Policy implications of greenhouse warming. *AIP Conference Proceedings* **247**, 222–236. (DOI: 10.1063/1.41930). Available at: http://link.aip.org/link/?APC/247/222/1.

Le Coq C., and E. Paltseva (2009). Measuring the security of external energy supply in the European Union. *Energy Policy* **37**, 4474–4481. (DOI: 10.1016/j.enpol.2009.05.069). Available at: http://www.sciencedirect.com/science/article/pii/S0301421509004091.

Corner A., N. Pidgeon, and K. Parkhill (2012). Perceptions of geoengineering: public attitudes, stakeholder perspectives, and the challenge of “upstream” engagement. *Wiley Interdisciplinary Reviews-Climate Change* **3**, 451–466. (DOI: 10.1002/wcc.176). Available at: ://WOS:000307725300005.

Crassous R., and J.-C. Hourcade (2006). Endogenous Structural Change and Climate Targets Modeling Experiments with Imaclim-R. *The Energy Journal* **0**, 259–276. Available at: http://ideas.repec.org/a/aen/journl/2006se-a13.html.

Criqui P., A. Kitous, M.M. Berk, M.G.J. Den Elzen, B. Eickhout, P. Lucas, D.P. van Vuuren, N. Kouvaritakis, and D. Vanregemorter (2003). *Greenhouse gas reduction pathways in the UNFCCC Process up to 2025-Technical Report*. European Commission, DG Environment, Brussels, Belgium.

Criqui P., and S. Mima (2012). European climate—energy security nexus: A model based scenario analysis. *Modeling Transport (Energy) Demand and Policies* **41**, 827–842. (DOI: 10.1016/j.enpol.2011.11.061). Available at: http://www.sciencedirect.com/science/article/pii/S0301421511009591.

Crutzen P. (2006). Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma? *Climatic Change* **77**, 211–220. (DOI: 10.1007/s10584-006-9101-y). Available at: http://dx.doi.org/10.1007/s10584-006-9101-y.

Daioglou V., B.J. van Ruijven, and D.P. van Vuuren (2012). Model projections for household energy use in developing countries. *7th Biennial International Workshop “Advances in Energy Studies”* **37**, 601–615. (DOI: 10.1016/j.energy.2011.10.044). Available at: http://www.sciencedirect.com/science/article/pii/S0360544211007110.

Darwin R., and R. Tol (2001). Estimates of the Economic Effects of Sea Level Rise. *Environmental and Resource Economics* **19**, 113–129.

de_Richter R., and S. Caillol (2011). Fighting global warming: The potential of photocatalysis against CO2, CH4, N2O, CFCs, tropospheric O3, BC and other major contributors to climate change. *Journal of Photochemistry and Photobiology C: Photochemistry Reviews* **12**, 1–19. (DOI: 10.1016/j.jphotochemrev.2011.05.002). Available at: http://www.sciencedirect.com/science/article/pii/S1389556711000281.

Ding Z.L., X.N. Duan, Q.S. Ge, and Z.Q. Zhang (2009). Control of atmospheric CO 2 concentrations by 2050: A calculation on the emission rights of different countries. *Science in China Series D: Earth Sciences* **52**, 1447–1469. Available at: http://www.springerlink.com/index/jr264276077q161j.pdf.

Dowlatabadi H. (1998). Sensitivity of climate change mitigation estimates to assumptions about technical change. *Energy Economics* **20**, 473–493. (DOI: 10.1016/S0140-9883(98)00009-7). Available at: http://www.sciencedirect.com/science/article/pii/S0140988398000097.

Dowling P. (2013). The impact of climate change on the European energy system. *Energy Policy* **60**, 406–417. (DOI: 10.1016/j.enpol.2013.05.093). Available at: http://www.sciencedirect.com/science/article/pii/S0301421513004485.

Dubash N.K., D. Raghunandan, G. Sant, and A. Sreenivas (2013). Indian Climate Change Policy. *Economic & Political Weekly* **48**, 47.

Early J.T. (1989). Space-based solar shield to offset greenhouse effect. *Journal of the British Interplanetary Society* **42**, 567–569.

Eboli F., R. Parrado, and R. Roson (2010). Climate-change feedback on economic growth: explorations with a dynamic general equilibrium model. *Environment and Development Economics* **15**, 515–533. (DOI: 10.1017/S1355770X10000252).

Edenhofer O., B. Knopf, T. Barker, L. Baumstark, E. Bellevrat, B. Chateau, P. Criqui, M. Isaac, A. Kitous, S. Kypreos, M. Leimbach, K. Lessmann, B. Magne, Å. Scrieciu, H. Turton, and D. Van Vuuren (2010). The economics of low stabilization: Model comparison of mitigation strategies and costs. *Energy Journal* **31**, 11–48. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-77749319301&partnerID=40&md5=8553abeac6ecffe853fbc430f7b17972.

Edenhofer O., R. Pichs-Madruga, Y. Sokon, Christopher Field,, V. Barros,, T.F. Stocker, and et al. (2011). *IPCC Expert Meeting on Geoengineering: Meeting Report*. Intergovernmental Panel on Climate Change, Lima, Peru. Available at: http://www.ipcc.ch/pdf/supporting-material/EM_GeoE_Meeting_Report_final.pdf.

EDF; The Royal Society; TWAS (2012). Solar radiation management. The governance of research. Available at: http://www.srmgi.org/files/2012/01/DES2391_SRMGI-report_web_11112.pdf.

Edmonds J., L. Clarke, J. Lurz, and M. Wise (2008). Stabilizing CO2 concentrations with incomplete international cooperation. *Climate Policy* **8**, 355–376.

Edmonds J., P. Luckow, K. Calvin, M. Wise, J. Dooley, P. Kyle, S. Kim, P. Patel, and L. Clarke (2013). Can radiative forcing be limited to 2.6 Wm−2 without negative emissions from bioenergy AND CO2 capture and storage? *Climatic Change*, 1–15. (DOI: 10.1007/s10584-012-0678-z). Available at: http://dx.doi.org/10.1007/s10584-012-0678-z.

Edmonds J.A., T. Wilson, M.A. Wise, and J.P. Weyant (2006). Electrification of the Economy and CO2 Emissions Mitigation. *Environmental Economics and Policy Studies* **7**, 175–203.

Eisenberger P., R. Cohen, G. Chichilnisky, N. Eisenberger, R. Chance, and C. Jones (2009). Global Warming and Carbon-Negative Technology: Prospects for a Lower-Cost Route to a Lower-Risk Atmosphere. *Energy & Environment* **20**, 973–984. (DOI: 10.1260/095830509789625374). Available at: http://dx.doi.org/10.1260/095830509789625374.

Ekholm T., V. Krey, S. Pachauri, and K. Riahi (2010a). Determinants of household energy consumption in India. *The socio-economic transition towards a hydrogen economy - findings from European research, with regular papers* **38**, 5696–5707. (DOI: 10.1016/j.enpol.2010.05.017). Available at: http://www.sciencedirect.com/science/article/pii/S0301421510003885.

Ekholm T., S. Soimakallio, S. Moltmann, N. Höhne, S. Syri, and I. Savolainen (2010b). Effort sharing in ambitious, global climate change mitigation scenarios. *Energy Policy* **38**, 1797–1810. (DOI: 16/j.enpol.2009.11.055).

Ellerman A.D. (2010). *Pricing carbon: the European Union emissions trading scheme*. Cambridge University Press, (ISBN: 0521196477).

Ellerman A.D., and B. Buchner (2008). Over-Allocation or Abatement? A Preliminary Analysis of the EU ETS Based on the 2005–06 Emissions Data. *Environmental and Resource Economics* **41**, 267–287. (DOI: 10.1007/s10640-008-9191-2). Available at: http://dx.doi.org/10.1007/s10640-008-9191-2.

Den Elzen M.G.J., A.M. Beltran, A.F. Hof, B. van Ruijven, and J. van Vliet (2012). Reduction targets and abatement costs of developing countries resulting from global and developed countries' reduction targets by 2050. *Mitigation and Adaptation Strategies for Global Change*, 1–22. Available at: http://www.springerlink.com/index/a51gwx7337mt25t8.pdf.

Den Elzen M., and N. Höhne (2008). Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets. *Climatic Change* **91**, 249–274. (DOI: 10.1007/s10584-008-9484-z). Available at: http://dx.doi.org/10.1007/s10584-008-9484-z.

Den Elzen M., and N. Höhne (2010). Sharing the reduction effort to limit global warming to 2°C. *Climate Policy* **10**, 247–260. (DOI: 10.3763/cpol.2009.0678). Available at: http://www.tandfonline.com/doi/abs/10.3763/cpol.2009.0678.

Den Elzen M.G.J., N. Höhne, B. Brouns, H. Winkler, and H.E. Ott (2007). Differentiation of countries' future commitments in a post-2012 climate regime: An assessment of the "South–North Dialogue" Proposal. *Environmental Science & Policy* **10**, 185–203. (DOI: 10.1016/j.envsci.2006.10.009). Available at: http://www.sciencedirect.com/science/article/pii/S1462901106001341.

Den Elzen M., and P. Lucas (2005). The FAIR model: A tool to analyse environmental and costs implications of regimes of future commitments. *Environmental Modeling & Assessment* **10**, 115–134. (DOI: 10.1007/s10666-005-4647-z). Available at: http://dx.doi.org/10.1007/s10666-005-4647-z.

Den Elzen M., P. Lucas, and D. van Vuuren (2005). Abatement costs of post-Kyoto climate regimes. *Energy Policy* **33**, 2138–2151. (DOI: 10.1016/j.enpol.2004.04.012). Available at: http://www.sciencedirect.com/science/article/pii/S0301421504001211.

Den Elzen M.G.J., P.L. Lucas, and D.P. Vuuren (2008). Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO 2-equivalent concentrations. *Climatic change* **90**, 243–268. Available at: http://www.springerlink.com/index/q14328j1822q4723.pdf.

Den Elzen M., and M. Meinshausen (2006). Meeting the EU 2°C climate target: global and regional emission implications. *Climate Policy* **6**, 545–564. (DOI: 10.1080/14693062.2006.9685620). Available at: http://www.tandfonline.com/doi/abs/10.1080/14693062.2006.9685620.

Den Elzen M.G.J., and D. van Vuuren (2007). Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs. *Proceedings of the National Academy of Sciences* **104**, 17931 –17936. (DOI: 10.1073/pnas.0701598104). Available at: http://www.pnas.org/content/104/46/17931.abstract.

Eom J., J.A. Edmonds, V. Krey, N. Johnson, T. Longden, G. Luderer, K. Riahi, and D. van Vuuren The Impact of Near-term Climate Policy Choices on Technology and Emissions Transition Pathways. *Technological Forecasting and Social Change* **Accepted**.

Fankhauser S., F. Sehlleier, and N. Stern (2008). Climate change, innovation and jobs. *Climate Policy* **8**, 421–429. (DOI: 10.3763/cpol.2008.0513). Available at: http://www.tandfonline.com/doi/abs/10.3763/cpol.2008.0513.

Fawcett A., L. Clarke, S. Rausch, and J. Weyant (2013). Policy Overview of the EMF24 Study. *Energy Journal*.

Finon D., and E. Romano (2009). Electricity market integration: Redistribution effect versus resource reallocation. *Energy Policy* **37**, 2977–2985. (DOI: 10.1016/j.enpol.2009.03.045). Available at: http://www.sciencedirect.com/science/article/pii/S0301421509001906.

Finus M., E. Van Ierland, and R. Dellink (2003). Stability of climate coalitions in a cartel formation game. Available at: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=447461.

Fischedick M., R. Schaeffer, A. Adedoyin, M. Akai, T. Bruckner, L. Clarke, V. Krey, I. Savolainen, S. Teske, D. Urge-Vorsatz, R. Wright, and G. Luderer (2011). Chapter 10: Mitigation potential and costs. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press, Cambridge.

Fischer C., and A.K. Fox (2011). The Role of Trade and Competitiveness Measures in US Climate Policy. *American Economic Review* **101**, 258–62. (DOI: 10.1257/aer.101.3.258). Available at: http://www.aeaweb.org/articles.php?doi=10.1257/aer.101.3.258.

Fischer G., F.N. Tubiello, H. van Velthuizen, and D.A. Wiberg (2007). Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. *Greenhouse Gases - Integrated Assessment* **74**, 1083–1107. (DOI: 10.1016/j.techfore.2006.05.021).

Fisher B.S., N. Nakicenovic, K. Alfsen, J. Corfee Morlot, F. de la Chesnaye, J.-C. Hourcade, K. Jiang, M. Kainuma, E. La Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S.K. Rose, D. van Vuuren, and R. Warren (2007a). Issues related to mitigation in the long term context. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

Fisher B.S., N. Nakicenovic, K. Alfsen, J. Corfee Morlot, F. de la Chesnaye, J.-C. Hourcade, K. Jiang, M. Kainuma, E. La Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S. Rose, D. van Vuuren, and R. Warren (2007b). Issues related to mitigation in the long term context. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

Fisher-Vanden K. (2008). Introduction to the special issue on technological change and the environment. *Energy Economics* **30**, 2731–2733. (DOI: 10.1016/j.eneco.2008.08.001). Available at: http://www.sciencedirect.com/science/article/pii/S0140988308001102.

Fisher-Vanden K., I. Sue Wing, E. Lanzi, and D. Popp (2011). Modeling Climate Change Impacts and Adaptation: Recent Approaches. Pennsylvania State University, 31 pp.

Fisher-Vanden K., I. Sue Wing, E. Lanzi, and D. Popp (2012). Modeling climate change feedbacks and adaptation responses: recent approaches and shortcomings. *Climatic Change*, 1–15. (DOI: 10.1007/s10584-012-0644-9). Available at: http://dx.doi.org/10.1007/s10584-012-0644-9.

Food and Agriculture Organization of the United Nations (FAO) (2012). FAOSTAT database. Available at: http://faostat.fao.org/.

Friel S., A.D. Dangour, T. Garnett, K. Lock, Z. Chalabi, I. Roberts, A. Butler, C.D. Butler, J. Waage, A.J. McMichael, and A. Haines (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture. *The Lancet* **374**, 2016–2025. (DOI: 10.1016/S0140-6736(09)61753-0). Available at: http://www.sciencedirect.com/science/article/pii/S0140673609617530.

Frondel M., N. Ritter, C.M. Schmidt, and C. Vance (2010). Economic impacts from the promotion of renewable energy technologies: The German experience. *Energy Policy* **38**, 4048–4056. (DOI: 10.1016/j.enpol.2010.03.029). Available at: http://www.sciencedirect.com/science/article/pii/S0301421510001928.

Fullerton D., and G.E. Metcalf (1997). Environmental Taxes and the Double-Dividend Hypothesis: Did You Really Expect Something for Nothing. *Chi.-Kent L. Rev.* **73**, 221.

Füssel H. (2010). Modeling impacts and adaptation in global IAMs. *Wiley Interdisciplinary Reviews: Climate Change* **1**, 288–303. (DOI: 10.1002/wcc.40). Available at: http://onlinelibrary.wiley.com/doi/10.1002/wcc.40/abstract.

G8 (2009). Responsible Leadership for a Sustainable Future. L'Aquila Summit.

GAO (2011). *Technology Assessment: Climate Engineering: Technical Status, Future Directions, and Potential Responses*. United States Government Accountability Office (GAO), USA. Available at: http://www.gao.gov/assets/330/322208.pdf.

Gardiner S.M. (2011). Some Early Ethics of Geoengineering the Climate: A Commentary on the Values of the Royal Society Report. *Environmental Values* **20**, 163–188. (DOI: 10.3197/096327111x12997574391689). Available at: ://WOS:000291279900004.

Gaskill A. (2004). Summary of Meeting with US DOE to discuss Geoengineering options to prevent abrupt and long-term climate change. Available at: http://www.see.ed.ac.uk/~shs/Climate%20change/Geo-politics/Gaskill%20DOE.pdf.

GEA (2012). *Global Energy Assessment – Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK and New York, NY, USA, and the International Institute for Applied Systems Analysis, Laxenburg, Austria [ISBN 9781107005198 (hardback); ISBN 9780521182935 (paperback)], (ISBN: [ISBN 9781107005198 (hardback); ISBN 9780521182935 (paperback)]).

Gerlagh R., S. Kverndokk, and K.E. Rosendahl (2009). Optimal timing of climate change policy: Interaction between carbon taxes and innovation externalities. *Environmental and resource Economics* **43**, 369–390.

Gerlagh R., and B. van der Zwaan (2003). Gross world product and consumption in a global warming model with endogenous technological change. *Resource and Energy Economics* **25**, 35–57. Available at: http://ideas.repec.org/a/eee/resene/v25y2003i1p35-57.html.

Gillingham K., R.. Newell, and W.A. Pizer (2008). Modeling endogenous technological change for climate policy analysis. *Energy Economics* **30**, 2734–2753.

Ginzky H., F. Harmann, K. Kartschall, W. Leujak, K. Lipsius, C. Mäder, S. Schwermer, and G. Straube (2011). *Geoengineering. Effective Climate Protection or Megalomania*. German Federal Environment Agency, Germany.

Goes M., N. Tuana, and K. Keller (2011). The economics (or lack thereof) of aerosol geoengineering. *Climatic Change* **109**, 719–744. (DOI: 10.1007/s10584-010-9961-z). Available at: http://dx.doi.org/10.1007/s10584-010-9961-z.

Goldemberg J., T.B. Johansson, A.K.N. Reddy, and R.H. Williams (1985). Basic needs and much more with one kilowatt per capita (energy). *Ambio* **14**, 190–200. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-0022170501&partnerID=40&md5=08df48b968bb18d199133d1bcc3e0c3a.

Golombek R., and M. Hoel (2008). Endogenous technology and tradable emission quotas. *Resource and Energy Economics* **30**, 197–208.

Gough C., and P. Upham (2011). Biomass energy with carbon capture and storage (BECCS or Bio-CCS). *Greenhouse Gases: Science and Technology* **1**, 324–334. (DOI: 10.1002/ghg.34). Available at: http://dx.doi.org/10.1002/ghg.34.

Goulder L.H. (1995). Environmental taxation and the double dividend: A reader's guide. *International Tax and Public Finance* **2**, 157–183. (DOI: 10.1007/BF00877495). Available at: http://dx.doi.org/10.1007/BF00877495.

Goulder L.H., and K. Mathai (2000). Optimal CO2 Abatement in the Presence of Induced Technological Change. *Journal of Environmental Economics and Management* **39**, 1–38. Available at: http://ideas.repec.org/a/eee/jeeman/v39y2000i1p1-38.html.

Goulder L.H., and I.W.H. Parry (2008). Instrument Choice in Environmental Policy. *Review of Environmental Economics and Policy* **2**, 152–174. Available at: http://ideas.repec.org/a/oup/renvpo/v2y2008i2p152-174.html.

Goulder L.H., and S.H. Schneider (1999). Induced technological change and the attractiveness of CO2 abatement policies. *Resource and Energy Economics* **21**, 211–253. Available at: http://ideas.repec.org/a/eee/resene/v21y1999i3-4p211-253.html.

Govindasamy B., and K. Caldeira (2000). Geoengineering Earth's radiation balance to mitigate CO2-induced climate change. *Geophysical Research Letters* **27**, 2141–2144. (DOI: 10.1029/1999gl006086). Available at: ://WOS:000088335500032 http://www.agu.org/journals/gl/v027/i014/1999GL006086/1999GL006086.pdf.

Grainger C.A., and C.D. Kolstad (2010). Who Pays a Price on Carbon? *Environmental and Resource Economics* **46**, 359–376.

Greaker M., and L.L. Pade (2009). Optimal carbon dioxide abatement and technological change: should emission taxes start high in order to spur R&D? *Climatic change* **96**, 335–355.

Grubb M., L. Butler, and P. Twomey (2006). Diversity and security in UK electricity generation: The influence of low-carbon objectives. *Energy Policy* **34**, 4050–4062. (DOI: 10.1016/j.enpol.2005.09.004). Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421505002442.

Grübler A., N. Nakicenovic, and D.G. Victor (1999). Dynamics of energy technologies and global change. *Energy Policy* **27**, 247–280. Available at: http://ideas.repec.org/a/eee/enepol/v27y1999i5p247-280.html.

Guivarch C., R. Crassous, O. Sassi, and S. Hallegatte (2011). The costs of climate policies in a second-best world with labour market imperfections. *Climate Policy* **11**, 768–788. (DOI: 10.3763/cpol.2009.0012). Available at: http://dx.doi.org/10.3763/cpol.2009.0012.

Gupta E. (2008). Oil vulnerability index of oil-importing countries. *Energy Policy* **36**, 1195–1211. (DOI: 10.1016/j.enpol.2007.11.011). Available at: http://www.sciencedirect.com/science/article/pii/S0301421507005022.

Gusdorf F., and S. Hallegatte (2007). Compact or spread-out cities: Urban planning, taxation, and the vulnerability to transportation shocks. *Energy Policy* **35**, 4826–4838. (DOI: 10.1016/j.enpol.2007.04.017). Available at: http://www.sciencedirect.com/science/article/pii/S030142150700167X.

Gusdorf F., S. Hallegatte, and A. Lahellec (2008). Time and space matter: How urban transitions create inequality. *Local evidence on vulnerabilities and adaptations to global environmental change* **18**, 708–719. (DOI: 10.1016/j.gloenvcha.2008.06.005). Available at: http://www.sciencedirect.com/science/article/pii/S0959378008000502.

Güssow K., A. Proelss, A. Oschlies, K. Rehdanz, and W. Rickels (2010). Ocean iron fertilization: Why further research is needed. *Marine Policy* **34**, 911–918. (DOI: 10.1016/j.marpol.2010.01.015). Available at: http://www.sciencedirect.com/science/article/pii/S0308597X10000163.

Hadjilambrinos C. (2000). Understanding technology choice in electricity industries: a comparative study of France and Denmark. *Energy Policy* **28**, 1111–1126.

Haines A., A.J. McMichael, K.R. Smith, I. Roberts, J. Woodcock, A. Markandya, B.G. Armstrong, D. Campbell-Lendrum, A.D. Dangour, M. Davies, N. Bruce, C. Tonne, M. Barrett, and P. Wilkinson (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. *The Lancet* **374**, 2104–2114. (DOI: 10.1016/S0140-6736(09)61759-1).

Hallegatte S., M. Ghil, P. Dumas, and J.-C. Hourcade (2008). Business cycles, bifurcations and chaos in a neo-classical model with investment dynamics. *Journal of Economic Behavior & Organization* **67**, 57–77.

Hamwey R. (2007). Active Amplification of the Terrestrial Albedo to Mitigate Climate Change: An Exploratory Study. *Mitigation and Adaptation Strategies for Global Change* **12**, 419–439. (DOI: 10.1007/s11027-005-9024-3). Available at: http://dx.doi.org/10.1007/s11027-005-9024-3.

Hanasaki N., S. Fujimori, T. Yamamoto, S. Yoshikawa, Y. Masaki, Y. Hijioka, M. Kainuma, Y. Kanamori, T. Masui, K. Takahashi, and S. Kanae A global water scarcity assessment under Shared Socio-economic Pathways: Part 2 Water availability and scarcity.

Hanasaki N., S. Fujimori, T. Yamamoto, S. Yoshikawa, Y. Masaki, Y. Hijioka, M. Kainuma, Y. Kanamori, T. Masui, K. Takahashi, and S. Kanae (2013). A global water scarcity assessment under Shared Socio-economic Pathways: Part 2 Water availability and scarcity. *Hydrology and Earth System Sciences* **17**, 2393–2413. (DOI: 10.5194/hess-17-2393-2013). Available at: http://www.hydrol-earth-syst-sci.net/17/2393/2013/.

Hart R. (2008). The timing of taxes on CO2 emissions when technological change is endogenous. *Journal of Environmental Economics and Management* **55**, 194–212.

Haurie A., and M. Vielle (2010). A Metamodel of the Oil Game under Climate Treaties. *INFOR: Information Systems and Operational Research* **48**, 215–228. (DOI: 10.3138/infor.48.4.215). Available at: http://dx.doi.org/10.3138/infor.48.4.215.

He J., W. Chen, F. Teng, and B. Liu (2009). Long-term climate change mitigation target and carbon permit allocation. *Adv. Clim. Change Res* **5**, S78–S85.

Heal G., and N. Tarui (2010). Investment and emission control under technology and pollution externalities. *Resource and Energy Economics* **32**, 1–14.

Hejazi M.I., J. Edmonds, L. Clarke, P. Kyle, E. Davies, V. Chaturvedi, J. Eom, M. Wise, P. Patel, and K. Calvin (2013). Integrated assessment of global water scarcity over the 21st century; Part 2: Climate change mitigation policies. *Hydrology and Earth System Sciences Discussions* **10**, 3383–3425. (DOI: 10.5194/hessd-10-3383-2013). Available at: http://www.hydrol-earth-syst-sci-discuss.net/10/3383/2013/.

Heston A., R. Summers, and B. Aten (2012). Penn World Table Version 7.1. Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania.

Hof A.F., M.G.J. Den Elzen, and D.P. Van Vuuren (2009). Environmental effectiveness and economic consequences of fragmented versus universal regimes: what can we learn from model studies? *International Environmental Agreements: Politics, Law and Economics* **9**, 39–62. Available at: http://www.springerlink.com/index/du1682182j417227.pdf.

Hof A., M.J. Elzen, and D. Vuuren (2010a). Including adaptation costs and climate change damages in evaluating post-2012 burden-sharing regimes. *Mitigation and Adaptation Strategies for Global Change* **15**, 19–40. (DOI: 10.1007/s11027-009-9201-x). Available at: http://dx.doi.org/10.1007/s11027-009-9201-x.

Hof A.F., D.P. van Vuuren, and M.G.J. den Elzen (2010b). A quantitative minimax regret approach to climate change: Does discounting still matter? *Ecological Economics* **70**, 43–51. (DOI: 16/j.ecolecon.2010.03.023). Available at: http://www.sciencedirect.com/science/article/pii/S0921800910001199.

Hoffert M.I., K. Caldeira, G. Benford, D.R. Criswell, C. Green, H. Herzog, A.K. Jain, H.S. Kheshgi, K.S. Lackner, J.S. Lewis, H.D. Lightfoot, W. Manheimer, J.C. Mankins, M.E. Mauel, L.J. Perkins, M.E. Schlesinger, T. Volk, and T.M.L. Wigley (2002). Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet. *Science* **298**, 981–987. (DOI: 10.1126/science.1072357). Available at: http://www.sciencemag.org/content/298/5595/981.abstract.

Höhne N., M.G.J. Den Elzen, and D. Escalante (2013). Regional greenhouse gas mitigation targets based on equity principles – a comparison of studies. *Climate Policy* **In press**. (DOI: 10.1080/14693062.2014.849452).

Höhne N., M. den Elzen, and M. Weiss (2006). Common but differentiated convergence (CDC): a new conceptual approach to long-term climate policy. *Climate Policy* **6**, 181–199. (DOI: 10.1080/14693062.2006.9685594). Available at: http://www.tandfonline.com/doi/abs/10.1080/14693062.2006.9685594.

Höhne N., J. Kejun, J. Rogelj, L. Segafredo, R.S. da Motta, P.R. Shukla, J.V. Fenhann, J.I. Hansen, A. Olhoff, and M.B. Pedersen (2012). *The Emissions Gap Report 2012: A UNEP Sythesis Report*. United Nations Environment Programme, Nairobi, Kenya, (ISBN: 978-92-807-3303-7).

Höhne N., and S. Moltmann (2008). *Distribution of emission allowances under the greenhouse development rights and other effort sharing approaches*. Heinrich-Böll-Stiftung, Germany.

Höhne N., and S. Moltmann (2009). *Sharing the effort under a global carbon budget*. ECOFYS Gmbh, Cologne, Germany.

Höhne N., D. Phylipsen, S. Ullrich, and K. Blok (2005). *Options for the second commitment period of the Kyoto Protocol*. Umweltbundesamt / German Federal Environmental Agency, Berlin, Germany.

Holloway T., A. Fiore, and M.G. Hastings (2003). Intercontinental Transport of Air Pollution: Will Emerging Science Lead to a New Hemispheric Treaty? *Environmental Science & Technology* **37**, 4535–4542. (DOI: 10.1021/es034031g). Available at: http://dx.doi.org/10.1021/es034031g.

Hope C. (2006). The Marginal Impact of CO2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern. *The Integrated Assessment Journal* **6**, 19–56.

Hope C. (2008). Optimal carbon emissions and the social cost of carbon over time under uncertainty. *Integrated Assessment; Vol 8, No 1 (2008)*. Available at: http://journals.sfu.ca/int_assess/index.php/iaj/article/view/273.

Horton J.B. (2011). Geoengineering and the Myth of Unilateralism : Pressures and Prospects for International Cooperation. *Stanford Journal of Law, Science & Policy* **6**, 56–69.

Houghton R.A. (2008). Carbon Flux to the Atmosphere from Land-Use Changes 1850-2005. In: *TRENDS: A Compendium of Data on Global Change.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn, USA.

Houghton R.A., J.I. House, J. Pongratz, G.R. van der Werf, R.S. DeFries, M.C. Hansen, C. Le Quéré, and N. Ramankutty (2012). Carbon emissions from land use and land-cover change. *Biogeosciences* **9**, 5125–5142. (DOI: 10.5194/bg-9-5125-2012). Available at: http://www.biogeosciences.net/9/5125/2012/.

Hourcade J.-C., and M. Kostopoulou (1994). Quelles politiques face aux chocs énergétiques. France, Italie, Japon, RFA: quatre modes de résorption des déséquilibres. *Futuribles* **189**, 7–27.

Hourcade J.-C., and P. Shukla (2013). Triggering the low-carbon transition in the aftermath of the global financial crisis. *Climate Policy* **13**, 22–35. (DOI: 10.1080/14693062.2012.751687). Available at: http://dx.doi.org/10.1080/14693062.2012.751687.

House K.Z., D.P. Schrag, C.F. Harvey, and K.S. Lackner (2006). Permanent carbon dioxide storage in deep-sea sediments. *Proceedings of the National Academy of Sciences* **103**, 12291–12295. Available at: http://www.pnas.org/content/103/33/12291.abstract.

Houser T., R. Bradley, B. Childs, J. Werksman, and R. Heilmayr (2009). *Leveling the Carbon Playing Field: International Competition and US Climate Policy Design*. Peterson Institute for International Economics, World Resource Institute.

Howells M., S. Hermann, M. Welsch, M. Bazilian, R. Segerstrom, T. Alfstad, D. Gielen, H. Rogner, G. Fischer, H. van Velthuizen, D. Wiberg, C. Young, R.A. Roehrl, A. Mueller, P. Steduto, and I. Ramma (2013). Integrated analysis of climate change, land-use, energy and water strategies. *Nature Clim. Change* **3**, 621–626. Available at: http://dx.doi.org/10.1038/nclimate1789.

Hultman N.E., E.L. Malone, P. Runci, G. Carlock, and K.L. Anderson (2012a). Factors in low-carbon energy transformations: Comparing nuclear and bioenergy in Brazil, Sweden, and the United States. *Strategic Choices for Renewable Energy Investment* **40**, 131–146. (DOI: 10.1016/j.enpol.2011.08.064). Available at: http://www.sciencedirect.com/science/article/pii/S0301421511006823.

Hultman N.E., S. Pulver, L. Guimarães, R. Deshmukh, and J. Kane (2012b). Carbon market risks and rewards: Firm perceptions of CDM investment decisions in Brazil and India. *Energy Policy* **40**, 90–102. (DOI: 10.1016/j.enpol.2010.06.063). Available at: http://www.sciencedirect.com/science/article/pii/S0301421510005331.

ICTSD (2010). *International Transport, Climate Change and Trade – What are the options for regulating emissions from aviation and shipping and what will be their impact on trade?* International Centre for Trade and Sustainable Development.

IEA (2008). *Energy technology perspectives 2008 : scenarios & strategies to 2050*. International Energy Agency, Paris, (ISBN: 9789264041424).

IEA (2009). *World Energy Outlook 2009*. OECD/IEA, Paris.

IEA (2010a). *Global gaps in clean energy RD&D: updates and recommendations for international collaboration*. International Energy Agency. Available at: http://www.iea.org/publications/freepublications/publication/global_gaps.pdf.

IEA (2010b). *World Energy Outlook 2010*. OECD/IEA, Paris, (ISBN: 978-92-64-08624-1).

IEA (2010c). *Energy technology perspectives 2010 - Scenarios and strategies to 2050*. IEA; OECD, Paris, France :, (ISBN: 9789264085978).

IEA (2011). *World Energy Outlook 2011 Special Report: Energy for All*. IEA/OECD, Paris, France. Available at: http://www.iea.org/publications/freepublications/publication/weo2011_energy_for_all.pdf.

IEA (2012a). *CO2 Emissions from Fuel Combustion. Beyond 2020 Online Database. 2012 Edition.* International Energy Agency, Paris. Available at: http://data.iea.org.

IEA (2012b). *World Energy Outlook 2012*. OECD/IEA, Paris, (ISBN: 978-92-64-18084-0).

IEA (2012c). *Energy Balances of Non-OECD Countries*. International Energy Agency, Paris, (ISBN: 978-92-64-08414-8).

IEA (2012d). *Energy Balances of OECD Countries*. International Energy Agency, Paris, (ISBN: 978-92-64-17382-8).

IMO (2013). Report of the thirty-fifth consultative meeting and the eighth meeting of contracting parties. International Maritime Organization.

Institution of Mechanical Engineers (2009). Geoengineering. **Environment Policy Statement 09/02.**

Irvine P.J., D.J. Lunt, E.J. Stone, and A. Ridgwell (2009). The fate of the Greenland Ice Sheet in a geoengineered, high CO2 world. *Environmental Research Letters* **4**. (DOI: 10.1088/1748-9326/4/4/045109). Available at: ://WOS:000272900500054.

Irvine P.J., R.L. Sriver, and K. Keller (2012). Tension between reducing sea-level rise and global warming through solar-radiation management. *Nature Clim. Change* **2**, 97–100. (DOI: 10.1038/nclimate1351). Available at: http://dx.doi.org/10.1038/nclimate1351.

Isaac M., and D.P. van Vuuren (2009). Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy* **37**, 507–521. (DOI: 10.1016/j.enpol.2008.09.051). Available at: http://www.sciencedirect.com/science/article/pii/S0301421508005168.

Jackson R.B., E.G. Jobbágy, R. Avissar, S.B. Roy, D.J. Barrett, C.W. Cook, K.A. Farley, D.C. le Maitre, B.A. McCarl, and B.C. Murray (2005). Trading Water for Carbon with Biological Carbon Sequestration. *Science* **310**, 1944–1947. (DOI: 10.1126/science.1119282). Available at: http://www.sciencemag.org/content/310/5756/1944.abstract.

Jacoby H.D., M.H. Babiker, S. Paltsev, and J.M. Reilly (2009). Sharing the Burden of GHG Reductions. In: *Post-Kyoto International Climate Policy: Implementing Architectures for Agreement*. J.E. Aldy, R.N. Stavins, (eds.), Cambridge University Press, (ISBN: 0521138000). Available at: http://belfercenter.ksg.harvard.edu/publication/18613/sharing_the_burden_of_ghg_reductions.html.

Jaffe A.B. (2012). TECHNOLOGY POLICY AND CLIMATE CHANGE. *Climate Change Economics* **03**, 1250025. (DOI: 10.1142/S201000781250025X). Available at: http://www.worldscientific.com/doi/abs/10.1142/S201000781250025X.

Jaffe A.B., R.G. Newell, and R.N. Stavins (2005). A tale of two market failures: Technology and environmental policy. *Technological Change and the Environment Technological Change* **54**, 164–174. (DOI: 10.1016/j.ecolecon.2004.12.027). Available at: http://www.sciencedirect.com/science/article/pii/S0921800905000303.

Jakob M., G. Luderer, J. Steckel, M. Tavoni, and S. Monjon (2012). Time to act now? Assessing the costs of delaying climate measures and benefits of early action. *Climatic Change*, 1–21. Available at: http://www.springerlink.com/index/113470145513L749.pdf.

Jayaraman T., T. Kanitkar, and T. Dsouza (2011). Equitable access to sustainable development: An Indian approach. In: *Equitable access to sustainable development: Contribution to the body of scientific knowledge: A paper by experts from BASIC countries*. BASIC expert group, Beijing, Brasilia, Cape Town and Mumbai.

Jensen M.C. (1986). Agency costs of free cash flow, corporate finance, and takeovers. *The American Economic Review* **76**, 323–329.

Jerrett M., R.T. Burnett, C.A. Pope, K. Ito, G. Thurston, D. Krewski, Y. Shi, E. Calle, and M. Thun (2009). Long-Term Ozone Exposure and Mortality. *New England Journal of Medicine* **360**, 1085–1095. (DOI: 10.1056/NEJMoa0803894). Available at: http://dx.doi.org/10.1056/NEJMoa0803894.

Jewell J. (2011). *The IEA Model of Short-Term Energy Security (MOSES): Primary Energy Sources and Secondary Fuels*. OECD Publishing, Paris, France.

Jewell J., A. Cherp, and K. Riahi (2013a). Energy security under de-carbonization energy scenarios. *Energy Policy* **In press**. (DOI: dx.doi.org/10.1016/j.enpol.2013.10.051i).

Jewell J., A. Cherp, V. Vinichenko, N. Bauer, T. Kober, D. McCollum, D. Van Vuuren, and B. van der Zwaan (2013b). Energy security of China, India, the E.U. and the U.S. under long-term scenarios: Results from six IAMs. *Accepted for publication in Climate Change Economics* **In press**.

Jiahua P. (2008). Carbon Budget for Basic Needs Satisfaction: implications for international equity and sustainability [J]. *World Economics and Politics* **1**, 003. Available at: http://en.cnki.com.cn/Article_en/CJFDTOTAL-SJJZ200801003.htm.

Johansson D.J., C. Azar, K. Lindgren, and T.A. Persson (2009). OPEC strategies and oil rent in a climate conscious world. *Energy Journal* **30**, 23–50.

Johansson D.J.A., P.L. Lucas, M. Weitzel, E.O. Ahlgren, A.B. Bazaz, W. Chen, M.G.J. den Elzen, J. Ghosh, M. Grahn, and Q.M. Liang (2012). Multi-model analyses of the economic and energy implications for China and India in a post-Kyoto climate regime. *submitted to Energy Policy*. Available at: http://www.econstor.eu/handle/10419/67337.

Jones A., J.M. Haywood, K. Alterskjær, O. Boucher, J.N.S. Cole, C.L. Curry, P.J. Irvine, D. Ji, B. Kravitz, J. Egill Kristjánsson, J.C. Moore, U. Niemeier, A. Robock, H. Schmidt, B. Singh, S. Tilmes, S. Watanabe, and J.-H. Yoon (2013). The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres* **118**, 9743–9752. (DOI: 10.1002/jgrd.50762). Available at: http://dx.doi.org/10.1002/jgrd.50762.

JRC/PBL (2012). *Emission Database for Global Atmospheric Research (EDGAR) - release version 4.2 FT2010*. European Commission, Joint Research Centre (JRC)/PBL Netherlands Environmental Assessment Agency. Available at: http://edgar.jrc.ec.europa.eu.

Kahneman D., and A. Tversky (1979). Prospect theory: An analysis of decision under risk. *Econometrica: Journal of the Econometric Society*, 263–291.

Kainuma M., P.R. Shukla, and K. Jiang (2012a). Framing and modeling of a low carbon society: An overview. *Energy Economics* **34, Supplement 3**, S316–S324. (DOI: 10.1016/j.eneco.2012.07.015). Available at: http://www.sciencedirect.com/science/article/pii/S014098831200151X.

Kainuma M., P.R. Shukla, and K. Jiang (2012b). Framing and Modelling of a Low Carbon Society: An Overview. *Energy Economics* **In press**.

Kalkuhl M., O. Edenhofer, and K. Lessmann (2012). Learning or Lock-In: Optimal Technology Policies to Support Mitigation. *SSRN eLibrary* **34**, 1–23. Available at: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1824232.

Kalkuhl M., O. Edenhofer, and K. Lessmann (2013). Renewable energy subsidies: Second-best policy or fatal aberration for mitigation? *Resource and Energy Economics* **35**, 217–234. (DOI: 10.1016/j.reseneeco.2013.01.002). Available at: http://www.sciencedirect.com/science/article/pii/S0928765513000043.

Kaundinya D.P., P. Balachandra, and N.H. Ravindranath (2009). Grid-connected versus stand-alone energy systems for decentralized power—A review of literature. *Renewable and Sustainable Energy Reviews* **13**, 2041–2050. (DOI: 10.1016/j.rser.2009.02.002).

Keith D.W. (2000). Geoengineering the Climate: History and Prospect. *Annu. Rev. Energy. Environ.* **25**, 245–284. (DOI: 10.1146/annurev.energy.25.1.245). Available at: http://dx.doi.org/10.1146/annurev.energy.25.1.245.

Keith D.W., M. Ha-Duong, and J.K. Stolaroff (2006). Climate strategy with CO 2 capture from the air. *Climatic Change* **74**, 17–45. Available at: http://www.springerlink.com/index/Y81415636R82065G.pdf.

Keller K., D. McInerney, and D. Bradford (2008). Carbon dioxide sequestration: how much and when? *Climatic Change* **88**, 267–291. (DOI: 10.1007/s10584-008-9417-x). Available at: http://dx.doi.org/10.1007/s10584-008-9417-x.

Keppo I., and S. Rao (2007). International climate regimes: Effects of delayed participation. *Technological Forecasting and Social Change* **74**, 962–979. Available at: http://www.sciencedirect.com/science/article/B6V71-4KXDR29-1/1/2e6ef11afdf377e999fcd606740dca00.

Kim S., C. MacCracken, and J. Edmonds (2000). Solar Energy Technologies And Stabilizing Atmospheric CO2 Concentrations. *Progress in Photovoltaics* **8**, 3–15.

Kindermann G., M. Obersteiner, B. Sohngen, J. Sathaye, K. Andrasko, E. Rametsteiner, B. Schlamadinger, S. Wunder, and R. Beach (2008). Global cost estimates of reducing carbon emissions through avoided deforestation. *Proceedings of the National Academy of Sciences* **105**, 10302–10307. (DOI: 10.1073/pnas.0710616105). Available at: http://www.pnas.org/content/105/30/10302.abstract.

Klepper G., and W. Rickels (2012). The Real Economics of Climate Engineering. *Economics Research International* **2012**. Available at: http://www.hindawi.com/journals/econ/aip/316564/.

Knopf B., Y.-H.H. Chen, E. De Cian, H. Förster, A. Kanudia, I. Karkatsouli, I. Keppo, T. Koljonen, K. Schumacher, and D. Van Vuuren (2013). Beyond 2020 - Strategies and costs for transforming the European energy system. Overview paper of the EMF28 model comparison of the EU Energy Roadmap,. *Climate Change Economics* **4**. (DOI: 10.1142/S2010007813500140).

Knopf B., O. Edenhofer, T. Barker, N. Bauer, L. Baumstark, B. Chateau, P. Criqui, A. Held, M. Isaac, M. Jakob, E. Jochem, A. Kitous, S. Kypreos, M. Leimbach, B. Magne, S. Mima, W. Schade, S. Scrieciu, H. Turton, and D. van Vuuren (2009). The economics of low stabilisation: implications for technological change and policy. In: *Making climate change work for us*. Cambridge University Press, Cambridge.

Knopf B., G. Luderer, and O. Edenhofer (2011). Exploring the feasibility of low stabilization targets. *Wiley Interdisciplinary Reviews: Climate Change* **2**, 617–626. (DOI: 10.1002/wcc.124). Available at: http://onlinelibrary.wiley.com/doi/10.1002/wcc.124/abstract.

Kober, and al. (2014). Regional Burden Sharing Regimes for reaching a global long-term 2 C Climate Change Control Target. *Accepted for publication in Climate Change Economics* **In press.**

Köhler P., J. Hartmann, and D.A. Wolf-Gladrow (2010). Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proceedings of the National Academy of Sciences* **107**, 20228–20233.

Koornneef J., P. van Breevoort, C. Hamelinck, C. Hendriks, M. Hoogwijk, K. Koop, M. Koper, T. Dixon, and A. Camps (2012). Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. *International Journal of Greenhouse Gas Control* **11**, 117–132. (DOI: 10.1016/j.ijggc.2012.07.027). Available at: http://www.sciencedirect.com/science/article/pii/S1750583612001843.

Kravitz B., K. Caldeira, O. Boucher, A. Robock, P.J. Rasch, K. Alterskjær, D.B. Karam, J.N. Cole, C.L. Curry, and J.M. Haywood (2013). Climate model response from the geoengineering model intercomparison project (geomip). *Journal of Geophysical Research: Atmospheres* **118**, 8320–8332.

Kravitz B., D.G. MacMartin, and K. Caldeira (2012). Geoengineering: Whiter skies? *Geophysical Research Letters* **39**. (DOI: 10.1029/2012gl051652). Available at: ://WOS:000304772800004 http://www.agu.org/journals/gl/gl1211/2012GL051652/2012GL051652.pdf.

Krey V., and L. Clarke (2011). Role of renewable energy in climate mitigation: A synthesis of recent scenarios. *Climate Policy* **11**, 1131–1158.

Krey V., G. Luderer, L. Clarke, and E. Kriegler (2014). Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. *Accepted for publication in Climatic Change*. (DOI: DOI 10.1007/s10584-013-0947-5).

Krey V., B.C. O'Neill, B. van Ruijven, V. Chaturvedi, V. Daioglou, J. Eom, L. Jiang, Y. Nagai, S. Pachauri, and X. Ren (2012). Urban and rural energy use and carbon dioxide emissions in Asia. *The Asia Modeling Exercise: Exploring the Role of Asia in Mitigating Climate Change* **34, Supplement 3**, S272–S283. (DOI: 10.1016/j.eneco.2012.04.013). Available at: http://www.sciencedirect.com/science/article/pii/S0140988312000904.

Krey V., and K. Riahi (2009). Implications of delayed participation and technology failure for the feasibility, costs, and likelihood of staying below temperature targets—Greenhouse gas mitigation scenarios for the 21st century. *Energy Economics* **31, Supplement 2**, S94–S106. (DOI: doi: 10.1016/j.eneco.2009.07.001). Available at: http://www.sciencedirect.com/science/article/pii/S0140988309001170.

Kriegler E., O. Edenhofer, L. Reuster, G. Luderer, and D. Klein (2013a). Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change* **118**, 45–57. (DOI: 10.1007/s10584-012-0681-4). Available at: http://dx.doi.org/10.1007/s10584-012-0681-4.

Kriegler E., N. Petermann, V. Krey, J. Schwanitz, G. Luderer, S. Ashina, V. Bosetti, A. Kitous, A. Méjean, L. Paroussos, F. Sano, H. Turton, C. Wilson, and D. van Vuuren (2013b). Diagnostic indicators for integrated assessment models of climate policies. *Accepted for publication in Technological forecasting and social change*.

Kriegler E., K. Riahi, N. Bauer, V.J. Schanitz, N. Petermann, V. Bosetti, A. Marcucci, S. Otto, L. Paroussos, and et al. (2014a). Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Accepted for publication in Technological Forecasting and Social Change*.

Kriegler E., M. Tavoni, T. Aboumahboub, G. Luderer, K. Calvin, G. DeMaere, V. Krey, K. Riahi, H. Rosler, M. Schaeffer, and D.P. Van Vuuren (2014b). Can we still meet 2°C with a climate agreement in force by 2020? The LIMITS study on implications of Durban Action Platform scenarios. *Accepted for publication in Climate Change Economics*.

Kriegler E., J. Weyant, G. Blanford, L. Clarke, J. Edmonds, A. Fawcett, V. Krey, G. Luderer, K. Riahi, R. Richels, S. Rose, M. Tavoni, and D. van Vuuren (2014c). The Role of Technology for Climate Stabilization: Overview of the EMF 27 Study on Energy System Transition Pathways Under Alternative Climate Policy Regimes. *Accepted for publication in Climatic Change* **In press**.

Kruyt B., D.P. van Vuuren, H.J.M. de Vries, and H. Groenenberg (2009). Indicators for energy security. *Energy Policy* **37**, 2166–2181. (DOI: 10.1016/j.enpol.2009.02.006).

Kuntsi-Reunanen E., and J. Luukkanen (2006). Greenhouse gas emission reductions in the post-Kyoto period: Emission intensity changes required under the “contraction and convergence” approach. *Natural Resources Forum* **30**, 272–279. (DOI: 10.1111/j.1477-8947.2006.00119.x). Available at: http://dx.doi.org/10.1111/j.1477-8947.2006.00119.x.

Kyle P., L. Clarke, G. Pugh, M. Wise, K. Calvin, J. Edmonds, and S. Kim (2009). The value of advanced technology in meeting 2050 greenhouse gas emissions targets in the United States. *Energy Economics* **31**, S254–S267. (DOI: 16/j.eneco.2009.09.008). Available at: http://www.sciencedirect.com/science/article/pii/S0140988309001649.

Kyle P., and S.H. Kim (2011). Long-term implications of alternative light-duty vehicle technologies for global greenhouse gas emissions and primary energy demands. *Energy Policy* **39**, 3012–3024. (DOI: 10.1016/j.enpol.2011.03.016). Available at: http://www.sciencedirect.com/science/article/pii/S0301421511001960.

Lackner K.S. (2009). Capture of carbon dioxide from ambient air. *The European Physical Journal Special Topics* **176**, 93–106. (DOI: 10.1140/epjst/e2009-01150-3). Available at: http://dx.doi.org/10.1140/epjst/e2009-01150-3.

Lampin L.B.A., F. Nadaud, F. Grazi, and J.-C. Hourcade (2013). Long-term fuel demand: Not only a matter of fuel price. *Energy Policy* **62**, 780–787. (DOI: 10.1016/j.enpol.2013.05.021). Available at: http://www.sciencedirect.com/science/article/pii/S0301421513003534.

Landis F., and T. Bernauer (2012). Transfer payments in global climate policy. *Nature Climate Change* **2**, 628–633. Available at: http://go.nature.com/49j2ys.

Latham J. (1990). Control of global warming? *Nature* **347**, 339–340. (DOI: 10.1038/347339b0). Available at: http://dx.doi.org/10.1038/347339b0.

Latham J., K. Bower, T. Choularton, H. Coe, P. Connolly, G. Cooper, T. Craft, J. Foster, A. Gadian, L. Galbraith, H. Iacovides, D. Johnston, B. Launder, B. Leslie, J. Meyer, A. Neukermans, B. Ormond, B. Parkes, P. Rasch, J. Rush, S. Salter, T. Stevenson, H.L. Wang, Q. Wang, and R. Wood (2012). Marine cloud brightening. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* **370**, 4217–4262. (DOI: 10.1098/rsta.2012.0086). Available at: ://WOS:000307462300005 http://rsta.royalsocietypublishing.org/content/370/1974/4217.full.pdf.

Latham J., P. Rasch, C.-C. Chen, L. Kettles, A. Gadian, A. Gettelman, H. Morrison, K. Bower, and T. Choularton (2008). Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **366**, 3969–3987. (DOI: 10.1098/rsta.2008.0137). Available at: http://rsta.royalsocietypublishing.org/content/366/1882/3969.abstract.

Leck E. (2006). The impact of urban form on travel behavior: a meta-analysis. *Berkeley Planning Journal* **19**.

Leimbach M., N. Bauer, L. Baumstark, and O. Edenhofer (2010). Mitigation costs in a globalized world: climate policy analysis with REMIND-R. *Environmental Modeling and Assessment* **15**, 155–173.

Lenton T.M., and N.E. Vaughan (2009). The radiative forcing potential of different climate geoengineering options. *Atmospheric Chemistry and Physics* **9**, 5539–5561. (DOI: 10.5194/acp-9-5539-2009). Available at: http://www.atmos-chem-phys.net/9/5539/2009/.

Levine M., D. Urge-Vorsatz, K. Blok, L. Geng, D. Harvey, S. Lang, G. Levermore, A. Mongameli Mehlwana, S. Mirasgedis, A. Novikova, J. Rilling, and J. Yoshino (2007). Residential and commercial buildings. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Liang Q.M., and Y.-M. Wei (2012). Distributional impacts of taxing carbon in China: Results from the CEEPA model. *Applied Energy* **92**, 545–551. (DOI: 10.1016/j.apenergy.2011.10.036).

Lin A. (2013). Does Geoengineering Present a Moral Hazard? *Ecology Law Quarterly, Forthcoming*.

Loschel (2002). Technological change in economic models of environmental policy: a survey. *Ecological Economics* **43**, 105–126. (DOI: 10.1016/S0921-8009(02)00209-4).

Lubowski R.N., and S.K. Rose (2013). The potential of REDD+: Economic modeling insights and issues. *Review of Environmental Economics and Policy* **In press**.

Lucas P.L., D. van Vuuren, J.G.J. Olivier, and M.G.J. den Elzen (2007). Long-term reduction potential of non-CO2 greenhouse gases. *Environmental Science & Policy* **10**, 85–103. (DOI: 16/j.envsci.2006.10.007). Available at: http://www.sciencedirect.com/science/article/pii/S1462901106001316.

Luderer G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler (2013a). Implications of weak near-term climate policies on long-term climate mitigation pathways. *Accepted for publication in Climatic Change*.

Luderer G., C. Bertram, K. Calvin, E. Cian, and E. Kriegler (2013b). Implications of weak near-term climate policies on long-term mitigation pathways. *Climatic Change*, 1–14. (DOI: 10.1007/s10584-013-0899-9). Available at: http://dx.doi.org/10.1007/s10584-013-0899-9.

Luderer G., V. Bosetti, M. Jakob, M. Leimbach, J. Steckel, H. Waisman, and O. Edenhofer (2011). The economics of decarbonizing the energy system—results and insights from the RECIPE model intercomparison. *Climatic Change*, 1–29. (DOI: 10.1007/s10584-011-0105-x). Available at: http://dx.doi.org/10.1007/s10584-011-0105-x.

Luderer G., V. Bosetti, M. Jakob, M. Leimbach, J.C. Steckel, H. Waisman, and O. Edenhofer (2012a). The economics of decarbonizing the energy system—results and insights from the RECIPE model intercomparison. *Climatic Change*, 1–29.

Luderer G., E. DeCian, J.-C. Hourcade, M. Leimbach, H. Waisman, and O. Edenhofer (2012b). On the regional distribution of mitigation costs in a global cap-and-trade regime. *Climatic Change*. (DOI: 10.1007/s10584-012-0408-6). Available at: http://www.springerlink.com/content/631knj4440358644/.

Luderer G, R. Pietzcker, Bertram C, Kriegler E, Meinshausen M, and Edenhofer O (2013). Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters, in press*.

Luderer G., V. Krey, R. Pietzcker, K. Calvin, J. Merrick, J.V. Vliet, K. Wada, and S. Mima (2014). The role of renewable energy in climate change mitigation: results from the EMF 27 scenarios. *Accepted for publication in Climatic Change* **In press.**

Luft G. (2013). To drill or not to drill. *Foreign Policy*.

Lüken M., O. Edenhofer, B. Knopf, M. Leimbach, G. Luderer, and N. Bauer (2011). The role of technological availability for the distributive impacts of climate change mitigation policy. *Energy Policy* **39**, 6030–6039. Available at: http://www.sciencedirect.com/science/article/pii/S0301421511005258.

Lunt D.J., A. Ridgwell, P.J. Valdes, and A. Seale (2008). "Sunshade world": a fully coupled GCM evaluation of the climatic impacts of geoengineering. *Geophysical Research Letters* **35**.

Luokkanen M., S. Huttunen, and M. Hilden (2013). Geoengineering, news media and metaphors: Framing the controversial. *Public Underst Sci*. (DOI: 10.1177/0963662513475966).

MacCracken M.C. (2009). On the possible use of geoengineering to moderate specific climate change impacts. *Environmental Research Letters* **4**, 045107–045107. (DOI: 10.1088/1748-9326/4/4/045107). Available at: http://stacks.iop.org/1748-9326/4/i=4/a=045107?key=crossref.da5ed101ba1ff398d9f9a3684bb03f3f.

MacMartin D.G., D.W. Keith, B. Kravitz, and K. Caldeira (2013). Management of trade-offs in geoengineering through optimal choice of non-uniform radiative forcing. *Nature Climate Change*, 365–368. (DOI: 10.1038/nclimate1722). Available at: http://dx.doi.org/10.1038/nclimate1722.

MacMynowski D.G., D.W. Keith, K. Caldeira, and H.J. Shin (2011). Can we test geoengineering? *Energy & Environmental Science* **4**, 5044–5052. (DOI: 10.1039/C1ee01256h). Available at: ://WOS:000297562300032 http://pubs.rsc.org/en/content/articlepdf/2011/ee/c1ee01256h.

Macnaghten P., and B. Szerszynski (2013). Living the global social experiment: An analysis of public discourse on solar radiation management and its implications for governance. *Global Environmental*

Change **23**, 465–474. (DOI: 10.1016/j.gloenvcha.2012.12.008). Available at: http://linkinghub.elsevier.com/retrieve/pii/S0959378012001483.

Majd S., and R.S. Pindyck (1987). Time to build, option value, and investment decisions. *Journal of financial Economics* **18**, 7–27.

Manne A.S., and R.G. Richels (2001). An alternative approach to establishing trade-offs among greenhouse gases. *Nature* **410**, 675–677. (DOI: 10.1038/35070541). Available at: http://dx.doi.org/10.1038/35070541.

Mansur E., R. Mendelsohn, and W. Morrison (2008). Climate change adaptation: A study of fuel choice and consumption in the US energy sector. *Journal of Environmental Economics and Management* **55**, 175–193.

Marangoni G., and M. Tavoni (2013). Bridging the clean energy R&D gap to 2C. *submitted to Climate Change Economics*.

Di Maria C., and E. Werf (2007). Carbon leakage revisited: unilateral climate policy with directed technical change. *Environmental and Resource Economics* **39**, 55–74. (DOI: 10.1007/s10640-007-9091-x). Available at: http://www.springerlink.com/content/v875281128q26r16/.

Markandya A., B.G. Armstrong, S. Hales, A. Chiabai, P. Criqui, S. Mima, C. Tonne, and P. Wilkinson (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation. *The Lancet* **374**, 2006–2015. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0140673609617153.

Massetti E., and M. Tavoni (2011). The Cost Of Climate Change Mitigation Policy In Eastern Europe And Former Soviet Union. *Climate Change Economics* **2**, 341–370. Available at: http://www.worldscientific.com/doi/pdf/10.1142/S2010007811000346.

Matthews H.D. (2010). Can carbon cycle geoengineering be a useful complement to ambitious climate mitigation? *Carbon Management* **1**, 135–144. (DOI: 10.4155/cmt.10.14). Available at: http://dx.doi.org/10.4155/cmt.10.14.

Matthews H.D., and K. Caldeira (2007). Transient climate–carbon simulations of planetary geoengineering. *Proceedings of the National Academy of Sciences* **104**, 9949–9954. (DOI: 10.1073/pnas.0700419104). Available at: http://www.pnas.org/content/104/24/9949.abstract.

Matthews H.D., L. Cao, and K. Caldeira (2009). Sensitivity of ocean acidification to geoengineered climate stabilization. *Geophysical Research Letters* **36**. (DOI: 10.1029/2009gl037488). Available at: ://WOS:000266518100002 http://www.agu.org/pubs/crossref/2009/2009GL037488.shtml http://www.agu.org/journals/gl/gl0910/2009GL037488/2009GL037488.pdf.

McClellan J., D.W. Keith, and J. Apt (2012). Cost analysis of stratospheric albedo modification delivery systems. *Environmental Research Letters* **7**, 034019.

McCollum D., and al (2013). Investments, offsets, and incentives: an analysis of the 2°C target and what it takes to achieve it. **submitted to Climate Change Economics**.

McCollum D., N. Bauer, K. Calvin, A. Kitous, and K. Riahi (2013a). Fossil resource and energy security dynamics in conventional and carbon-constrained worlds. *Climatic Change* **submitted**.

McCollum D., N. Bauer, K. Calvin, A. Kitous, and K. Riahi (2013b). Fossil resource and energy security dynamics in conventional and carbon-constrained worlds. *Climatic Change* **120**. (DOI: 10.1007/s10584-013-0939-5).

McCollum D.L., V. Krey, P. Kolp, Y. Nagai, and K. Riahi (2014a). Transport electrification: a key element for energy system transformation and climate stabilization. *Climatic Change* **In Press**. (DOI: DOI 10.1007/s10584-013-0969-z).

McCollum D., V. Krey, and K. Riahi (2011). An integrated approach to energy sustainability. *Nature Climate Change* **1**, 428–429. (DOI: 10.1038/nclimate1297). Available at: http://dx.doi.org/10.1038/nclimate1297.

McCollum D., V. Krey, K. Riahi, P. Kolp, A. Grubler, M. Makowski, and N. Nakicenovic (2013c). Climate policies can help resolve energy security and air pollution challenges. *Climatic Change* **119**, 479–494. (DOI: 10.1007/s10584-013-0710-y). Available at: http://dx.doi.org/10.1007/s10584-013-0710-y.

McCollum D., Y. Nagai, K. Riahi, G. Marangoni, K. Calvin, R. Pietzcker, J. Van Vliet, and B. Van der Zwaan (2014b). Energy investments under climate policy: a comparison of global models. *Accepted for publication in Climate Change Economics*.

McCusker K.E., D.S. Battisti, and C.M. Bitz (2012). The Climate Response to Stratospheric Sulfate Injections and Implications for Addressing Climate Emergencies. *Journal of Climate* **25**, 3096–3116. (DOI: 10.1175/Jcli-D-11-00183.1). Available at: ://WOS:000303822700003 http://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-11-00183.1.

McFarland J.R., S. Paltsev, and H.D. Jacoby (2009). Analysis of the Coal Sector under Carbon Constraints. *Climate Change and Energy Policy* **31**, 404–424. (DOI: 10.1016/j.jpolmod.2008.09.005). Available at: http://www.sciencedirect.com/science/article/pii/S0161893808001002.

McGlashan N., N. Shah, B. Caldecott, and M. Workman (2012). High-level techno-economic assessment of negative emissions technologies. *Special Issue: Negative emissions technology* **90**, 501–510. (DOI: 10.1016/j.psep.2012.10.004). Available at: http://www.sciencedirect.com/science/article/pii/S0957582012001164.

McLaren D. (2012). A comparative global assessment of potential negative emissions technologies. *Special Issue: Negative emissions technology* **90**, 489–500. (DOI: 10.1016/j.psep.2012.10.005). Available at: http://www.sciencedirect.com/science/article/pii/S0957582012001176.

Meinshausen M. (2006). What does a 2°C target mean for greenhouse gas concentrations? - A brief analysis based on multi-gas emission pathways and several climate sensitivity uncertainty estimates. In: *Avoiding Dangerous Climate Change: Key Vulnerabilities of the Climate System and Critical Thresholds; Part II. General Perspectives on Dangerous Impacts; Part III. Key Vulnerabilities for Ecosystems and Biodiversity; Part IV. Socio-Economic Effects; Part V. Regional Perspectives; Part VI. Emission Pathways; Part VII. Technological Options.* H.J. Schellnhuber,, W.P. Cramer,, (eds.), Cambridge University Press, pp.265–279, .

Meinshausen M., B. Hare, T.M. Wigley, D. Vuuren, M.J. Elzen, and R. Swart (2006). Multi-gas Emissions Pathways to Meet Climate Targets. *Climatic Change* **75**, 151–194. (DOI: 10.1007/s10584-005-9013-2). Available at: http://dx.doi.org/10.1007/s10584-005-9013-2.

Meinshausen M., N. Meinshausen, W. Hare, S.C.B. Raper, K. Frieler, R. Knutti, D.J. Frame, and M.R. Allen (2009). Greenhouse-gas emission targets for limiting global warming to 2 degrees C. *Nature* **458**, 1158–1162. (DOI: 10.1038/nature08017). Available at: http://www.ncbi.nlm.nih.gov/pubmed/19407799.

Meinshausen M., S.C.B. Raper, and T.M.L. Wigley (2011a). Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmospheric Chemistry and Physics* **11**, 1417–1456. (DOI: 10.5194/acp-11-1417-2011). Available at: http://www.atmos-chem-phys.net/11/1417/2011/.

Meinshausen M., S.J. Smith, K. Calvin, J.S. Daniel, M.L.T. Kainuma, J.-F. Lamarque, K. Matsumoto, S.A. Montzka, S.C.B. Raper, K. Riahi, A. Thomson, G.J.M. Velders, and D. van Vuuren (2011b). The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* **109**, 213–241. (DOI: 10.1007/s10584-011-0156-z). Available at: http://www.springerlink.com/index/10.1007/s10584-011-0156-z.

Meinshausen M., T.M.L. Wigley, and S.C.B. Raper (2011c). Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 2: Applications. *Atmos. Chem. Phys.* **11**, 1457–1471. (DOI: 10.5194/acp-11-1457-2011). Available at: http://www.atmos-chem-phys.net/11/1457/2011/.

Melillo J.M., J.M. Reilly, D.W. Kicklighter, A.C. Gurgel, T.W. Cronin, S. Paltsev, B.S. Felzer, X. Wang, A.P. Sokolov, and C.A. Schlosser (2009). Indirect Emissions from Biofuels: How Important? *Science* **326**, 1397–1399. (DOI: 10.1126/science.1180251). Available at: http://www.sciencemag.org/content/326/5958/1397.abstract.

Mercado L.M., N. Bellouin, S. Sitch, O. Boucher, C. Huntingford, M. Wild, and P.M. Cox (2009). Impact of changes in diffuse radiation on the global land carbon sink. *Nature* **458**, 1014–1017. Available at: http://dx.doi.org/10.1038/nature07949http://www.nature.com/nature/journal/v458/n7241/suppinfo/nature07949_S1.html.

Messner S. (1997). Endogenized technological learning in an energy systems model. *Journal of Evolutionary Economics* **7**, 291–313. (DOI: 10.1007/s001910050045).

Metcalf G., M. Babiker, and J. Reilly (2004). A Note on Weak Double Dividends. *Topics in Economic Analysis and Policy* **4**. (DOI: 10.2202/1538-0653.1275).

Metz B., O. Davidson, H. de Coninck, M. Loos, and L. Meyer (2005). *IPCC special report on carbon dioxide capture and storage*. Intergovernmental Panel on Climate Change, Geneva (Switzerland). Working Group III.

Meyer A. (2000). *Contraction & convergence: the global solution to climate change*. Green Books, Bristol, UK, (ISBN: 1870098943).

Miketa A., and L. Schrattenholzer (2006). Equity implications of two burden-sharing rules for stabilizing greenhouse-gas concentrations. *Energy Policy* **34**, 877–891. (DOI: 10.1016/j.enpol.2004.08.050). Available at: http://www.sciencedirect.com/science/article/pii/S0301421504002861.

Mitchell D.L., and W. Finnegan (2009). Modification of cirrus clouds to reduce global warming. *Environmental Research Letters* **4**. (DOI: 10.1088/1748-9326/4/4/045102). Available at: ://WOS:000272900500047.

Molden D. (2007). *Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan, and Colombo: International Water Management Institute., (ISBN: 978-1-84407-396-2). Available at: http://www.iwmi.cgiar.org/assessment/ http://www.iwmi.cgiar.org/assessment/files_new/synthesis/Summary_SynthesisBook.pdf.

Monjon S., and P. Quirion (2011). Addressing leakage in the EU ETS: Border adjustment or output-based allocation? *Ecological Economics* **70**, 1957–1971. (DOI: 10.1016/j.ecolecon.2011.04.020). Available at: http://www.sciencedirect.com/science/article/pii/S0921800911001893.

Montgomery W.D. (1972). Markets in licenses and efficient pollution control programs. *Journal of Economic Theory* **5**, 395–418. Available at: http://ideas.repec.org/a/eee/jetheo/v5y1972i3p395-418.html.

Moore J.C., S. Jevrejeva, and A. Grinsted (2010). Efficacy of geoengineering to limit 21st century sea-level rise. *Proceedings of the National Academy of Sciences* **107**, 15699–15703. (DOI: 10.1073/pnas.1008153107). Available at: http://www.pnas.org/content/107/36/15699.abstract.

Moreno-Cruz J.B., and D.W. Keith (2012). Climate policy under uncertainty: a case for solar geoengineering. *Climatic Change*, 1–14. (DOI: 10.1007/s10584-012-0487-4). Available at: http://dx.doi.org/10.1007/s10584-012-0487-4.

Moreno-Cruz J.B., K.L. Ricke, and D.W. Keith (2011). A simple model to account for regional inequalities in the effectiveness of solar radiation management. *Climatic Change* **110**, 649–668. (DOI: 10.1007/s10584-011-0103-z).

Moss R., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks (2010). The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747–756. (DOI: 10.1038/nature08823). Available at: http://dx.doi.org/10.1038/nature08823.

Murphy D.M. (2009). Effect of Stratospheric Aerosols on Direct Sunlight and Implications for Concentrating Solar Power. *Environmental Science & Technology* **43**, 2784–2786. (DOI: 10.1021/es802206b). Available at: ://000265172800022.

Myhre G., J.S. Fuglestvedt, T.K. Berntsen, and M.T. Lund (2011). Mitigation of short-lived heating components may lead to unwanted long-term consequences. *Atmospheric Environment* **45**, 6103–6106. (DOI: 10.1016/j.atmosenv.2011.08.009). Available at: http://www.sciencedirect.com/science/article/pii/S1352231011008296.

Nabel J.E.M.S., J. Rogelj, C.M. Chen, K. Markmann, D.J.H. Gutzmann, and M. Meinshausen (2011). Decision support for international climate policy – The PRIMAP emission module. *Environmental Modelling & Software* **26**, 1419–1433. (DOI: 10.1016/j.envsoft.2011.08.004). Available at: http://www.sciencedirect.com/science/article/pii/S1364815211001873.

Nagashima M., R. Dellink, E. van Ierland, and H.-P. Weikard (2009). Stability of international climate coalitions â€" A comparison of transfer schemes. *Ecological Economics* **68**, 1476–1487. (DOI: 10.1016/j.ecolecon.2008.10.006). Available at: http://www.sciencedirect.com/science/article/pii/S0921800908004680.

Nakicenovic N., A. Grubler, and A. McDonald (1998). *Global Energy Perspectives.* Cambridge University Press, Cambridge.

Narula K., Y. Nagai, and S. Pachauri (2012). The role of Decentralized Distributed Generation in achieving universal rural electrification in South Asia by 2030. *Energy Policy* **47**, 345–357. (DOI: 10.1016/j.enpol.2012.04.075). Available at: http://www.sciencedirect.com/science/article/pii/S0301421512003801.

Nelson, and et al. CLimate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences* **in review**.

Nemet G.F., and A.R. Brandt (2012). Willingness to pay for a climate backstop: Liquid fuel producers and direct CO2 air capture. *The Energy Journal* **33**. Available at: http://ideas.repec.org/a/aen/journl/33-1-a03.html.

Nemet G.F., T. Holloway, and P. Meier (2010). Implications of incorporating air-quality co-benefits into climate change policymaking. *Environmental Research Letters* **5**, 014007. Available at: http://stacks.iop.org/1748-9326/5/i=1/a=014007.

Nemet G.F., and D.M. Kammen (2007). U.S. energy research and development: Declining investment, increasing need, and the feasibility of expansion. *Energy Policy* **35**, 746–755. (DOI: 10.1016/j.enpol.2005.12.012). Available at: http://www.sciencedirect.com/science/article/pii/S0301421505003551.

Nerlich B., and R. Jaspal (2012). Metaphors We Die By? Geoengineering, Metaphors, and the Argument From Catastrophe. *Metaphor and Symbol* **27**, 131–147. (DOI: 10.1080/10926488.2012.665795). Available at: http://dx.doi.org/10.1080/10926488.2012.665795.

Newell R.G., A.B. Jaffe, and R.N. Stavins (1999). The Induced Innovation Hypothesis and Energy-Saving Technological Change. *The Quarterly Journal of Economics* **114**, 941–975. (DOI: 10.1162/003355399556188). Available at: http://qje.oxfordjournals.org/content/114/3/941.abstract.

Nordhaus W.D. (2002). Modeling induced innovation in climate change policy. In: *Technological Change and the Environment*. A. Grubler, N. Nakicenivic, W.D. Nordhaus, (eds.), RFF Press, Washington, DC.

Nordhaus W.D., and J. Boyer (2000). *Warming the World: Economic Models of Global Warming*. Mit Press, (ISBN: 9780262640541). Available at: http://books.google.fi/books?id=GbcCZHGQliwC.

Nurse K. (2009). *Trade, climate change and tourism: Responding to ecological and regulatory challenges*. International Centre for Trade and Sustainable Development.

Nusbaumer J., and K. Matsumoto (2008). Climate and carbon cycle changes under the overshoot scenario. *Global and Planetary Change* **62**, 164–172. (DOI: 10.1016/j.gloplacha.2008.01.002). Available at: http://www.sciencedirect.com/science/article/pii/S092181810800012X.

O'Neill B.C., K. Riahi, and I. Keppo (2010). Mitigation implications of midcentury targets that preserve long-term climate policy options. *Proceedings of the National Academy of Sciences of the United States of America* **107**, 1011–1016. (DOI: 10.1073/pnas.0903797106). Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-75749097741&partnerID=40&md5=def770349e00627d9c89a8cd5f069d62.

OECD (2008). *OECD environmental outlook to 2030*. OECD Publishing Paris, France.

OECD (2009). *The economics of climate change mitigation: policies and options for global action beyond 2012.* Paris, France, (ISBN: 9789264056060).

Onigkeit J., N. Anger, and B. Brouns (2009). Fairness aspects of linking the European emissions trading scheme under a long-term stabilization scenario for CO2 concentration. *Mitigation and Adaptation Strategies for Global Change* **14**, 477–494. (DOI: 10.1007/s11027-009-9177-6). Available at: http://dx.doi.org/10.1007/s11027-009-9177-6.

Orr F.M. (2009). Onshore Geologic Storage of CO2. *Science* **325**, 1656–1658. (DOI: 10.1126/science.1175677). Available at: http://www.sciencemag.org/content/325/5948/1656.abstract.

Oschlies A., M. Pahlow, A. Yool, and R.J. Matear (2010). Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice. *Geophysical Research Letters* **37**, L04701. (DOI: 10.1029/2009GL041961). Available at: http://dx.doi.org/10.1029/2009GL041961.

Otto V.M., A. Löschel, and J. Reilly (2008). Directed technical change and differentiation of climate policy. *Energy Economics* **30**, 2855–2878. (DOI: 10.1016/j.eneco.2008.03.005). Available at: http://www.sciencedirect.com/science/article/pii/S0140988308000480.

Otto V.M., and J. Reilly (2008). Directed technical change and the adoption of CO2 abatement technology: The case of CO2 capture and storage. *Energy Economics* **30**, 2879–2898. Available at: http://ideas.repec.org/a/eee/eneeco/v30y2008i6p2879-2898.html.

Pacala S., and R. Socolow (2004). Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science* **305**, 968–972. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-4043100553&partnerID=40&md5=70dd98a14b5b13a84f5a0218fa08f628.

Paltsev S., J. Reilly, H.D. Jacoby, A.C. Gurgel, G.E. Metcalf, A.P. Sokolov, and J.F. Holak (2008). Assessment of US GHG cap-and-trade proposals. *Climate Policy* **8**, 395–420. Available at: http://globalchange.mit.edu/pubs/abstract.php?publication_id=988.

Paltsev S., J. Reilly, H.D. Jacoby, and K.H. Tay (2007). How (and why) do climate policy costs differ among countries? In: *Human-Induced Climate Change*. M.E. Schlesinger, H.S. Kheshgi, J. Smith, F.C. de la Chesnaye, J.M. Reilly, T. Wilson, C. Kolstad, (eds.), Cambridge University Press, pp.282–293, (ISBN: 9780511619472). Available at: http://dx.doi.org/10.1017/CBO9780511619472.

Pan J. (2005). Meeting Human Development Goals with Low Emissions : An Alternative to Emissions Caps for post-Kyoto from a Developing Country Perspective. *International Environmental Agreements: Politics, Law and Economics* **5**, 89–104. (DOI: 10.1007/s10784-004-3715-1). Available at: http://dx.doi.org/10.1007/s10784-004-3715-1.

Pan J. (2008). Welfare dimensions of climate change mitigation. *Global Environmental Change* **18**, 8–11. (DOI: 10.1016/j.gloenvcha.2007.11.001). Available at: http://www.sciencedirect.com/science/article/pii/S0959378007000696.

Pan Y., R.A. Birdsey, J. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz, O.L. Phillips, A. Shvidenko, S.L. Lewis, J.G. Canadell, P. Ciais, R.B. Jackson, S.W. Pacala, A.D. McGuire, S. Piao, A. Rautiainen, S. Sitch, and D. Hayes (2011). A Large and Persistent Carbon Sink in the World's Forests. *Science* **333**, 988–993. (DOI: 10.1126/science.1201609). Available at: http://www.sciencemag.org/content/333/6045/988.abstract.

Patt A.G., D. van Vuuren, F. Berkhout, A. Aaheim, A.F. Hof, M. Isaac, and R. Mechler (2009). Adaptation in integrated assessment modeling: where do we stand? *Climatic Change* **99**, 383–402.

(DOI: 10.1007/s10584-009-9687-y). Available at: http://www.springerlink.com/content/q0026gu420415704/.

PBL (2012). *Roads from Rio+20. Pathways to achieve global sustainability goals by 2050*. Netherlands Environmental Assessment Agency (PBL), The Hague.

Pentelow L., and D.J. Scott (2011). Aviation's inclusion in international climate policy regimes: Implications for the Caribbean tourism industry. *Developments in Air Transport and Tourism* **17**, 199–205. (DOI: 10.1016/j.jairtraman.2010.12.010). Available at: http://www.sciencedirect.com/science/article/pii/S0969699710001195.

Persson T.A., C. Azar, D. Johansson, and K. Lindgren (2007). Major oil exporters may profit rather than lose, in a carbon-constrained world. *Energy Policy* **35**, 6346–6353. (DOI: 10.1016/j.enpol.2007.06.027). Available at: http://www.sciencedirect.com/science/article/pii/S0301421507002583.

Persson T.A., C. Azar, and K. Lindgren (2006). Allocation of CO2 emission permits—Economic incentives for emission reductions in developing countries. *Energy Policy* **34**, 1889–1899. Available at: http://www.sciencedirect.com/science/article/pii/S0301421505000601.

Peterson S., and G. Klepper (2007). *Distribution matters: Taxes vs. emissions trading in post Kyoto climate regimes*. Germany. Available at: http://hdl.handle.net/10419/4076.

Phylipsen G., J. Bode, K. Blok, H. Merkus, and B. Metz (1998). A Triptych sectoral approach to burden differentiation; GHG emissions in the European bubble. *Energy Policy* **26**, 929–943. (DOI: 10.1016/S0301-4215(98)00036-6). Available at: http://www.sciencedirect.com/science/article/pii/S0301421598000366.

Pielke Jr R.A. (2009). An idealized assessment of the economics of air capture of carbon dioxide in mitigation policy. *Environmental Science & Policy* **12**, 216–225. Available at: http://www.sciencedirect.com/science/article/pii/S1462901109000161.

Pierce J.R., D.K. Weisenstein, P. Heckendorn, T. Peter, and D.W. Keith (2010). Efficient formation of stratospheric aerosol for climate engineering by emission of condensible vapor from aircraft. *Geophysical Research Letters* **37**. (DOI: 10.1029/2010gl043975). Available at: ://WOS:000282318200003.

Pietzcker R., T. Longden, W. chen, S. Fu, E. Kriegler, P. Kyle, and G. Luderer (2013). Long-term transport energy demand and climate policy: Alternative visions on Transport Decarbonization in Energy-Economy Models. *Energy* **Accepted**. (DOI: 10.1016/j.energy.2013.08.059).

Pindyck R.S. (1982). Adjustment costs, uncertainty, and the behavior of the firm. *The American Economic Review* **72**, 415–427.

Pittel K., and D.T.G. Rübbelke (2008). Climate policy and ancillary benefits: A survey and integration into the modelling of international negotiations on climate change. *Ecological Economics* **68**, 210–220. (DOI: 10.1016/j.ecolecon.2008.02.020). Available at: http://www.sciencedirect.com/science/article/pii/S0921800908001110.

Popp D. (2006a). ENTICE-BR: The effects of backstop technology R&D on climate policy models. *Energy Economics* **28**, 188–222.

Popp D. (2006b). Innovation in climate policy models: Implementing lessons from the economics of R&D. *Energy Economics* **28**, 596–609. (DOI: 10.1016/j.eneco.2006.05.007). Available at: http://www.sciencedirect.com/science/article/pii/S0140988306000648.

Popp D., J.P. Dietrich, H. Lotze-Campen, D. Klein, N. Bauer, M. Krause, T. Beringer, D. Gerten, and O. Edenhofer (2011a). The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. *Environmental Research Letters* **6**, 034017. (DOI: 10.1088/1748-9326/6/3/034017). Available at: http://iopscience.iop.org/1748-9326/6/3/034017/.

Popp D., I. Hascic, and N. Medhi (2011b). Technology and the diffusion of renewable energy. *Energy Economics* **33**, 648–662. (DOI: doi: 10.1016/j.eneco.2010.08.007). Available at: http://www.sciencedirect.com/science/article/pii/S0140988310001283.

Popp A., S. Rose, K. Calvin, D. Vuuren, J. Dietrich, M. Wise, E. Stehfest, F. Humpenöder, P. Kyle, J. Vliet, N. Bauer, H. Lotze-Campen, D. Klein, and E. Kriegler (2013). Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, 1–15. (DOI: 10.1007/s10584-013-0926-x). Available at: http://dx.doi.org/10.1007/s10584-013-0926-x.

President's Science Advisory Committee. Environmental Pollution Panel (1965). *Restoring the Quality of Our Environment: Report*. White House.

Preston C.J. (2013). Ethics and geoengineering: reviewing the moral issues raised by solar radiation management and carbon dioxide removal. *Wiley Interdisciplinary Reviews-Climate Change* **4**, 23–37. (DOI: 10.1002/wcc.198). Available at: ://WOS:000312734100003 http://onlinelibrary.wiley.com/store/10.1002/wcc.198/asset/198_ftp.pdf?v=1&t=hdercskk&s=4f70e8f4ee6b1e4241bfa59d8aab79d17acf58be.

Rafaj P., W. Schöpp, P. Russ, C. Heyes, and M. Amann (2012). Co-benefits of post-2012 global climate mitigation policies. *Mitigation and Adaptation Strategies for Global Change*, 1–24. (DOI: 10.1007/s11027-012-9390-6). Available at: http://dx.doi.org/10.1007/s11027-012-9390-6.

Ramanathan V., and G. Carmichael (2008). Global and regional climate changes due to black carbon. *Nature Geoscience* **1**, 221–227. (DOI: 10.1038/ngeo156). Available at: http://www.nature.com/ngeo/journal/v1/n4/full/ngeo156.html.

Ramanathan V., and Y. Xu (2010). The Copenhagen Accord for limiting global warming: criteria, constraints, and available avenues. *Proceedings of the National Academy of Sciences of the United States of America* **107**, 8055–8062. (DOI: 10.1073/pnas.1002293107).

Rao N.D. (2013). Distributional impacts of climate change mitigation in Indian electricity: The influence of governance. *Energy Policy* **61**, 1344–1356. (DOI: 10.1016/j.enpol.2013.05.103). Available at: http://www.sciencedirect.com/science/article/pii/S0301421513004588.

Rao S., S. Pachauri, F. Dentener, P. Kinney, Z. Klimont, K. Riahi, and W. Schoepp (2013). Better air for better health: Forging synergies in policies for energy access, climate change and air pollution. *Global Environmental Change* **23**, 1122–1130. (DOI: 10.1016/j.gloenvcha.2013.05.003). Available at: http://www.sciencedirect.com/science/article/pii/S0959378013000770.

Rasch P.J., S. Tilmes, R.P. Turco, A. Robock, L. Oman, C.C. Chen, G.L. Stenchikov, and R.R. Garcia (2008). An overview of geoengineering of climate using stratospheric sulphate aerosols. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* **366**, 4007–4037. (DOI: 10.1098/rsta.2008.0131).

Rau G.H., and K. Caldeira (1999). Enhanced carbonate dissolution:: a means of sequestering waste CO2 as ocean bicarbonate. *Energy Conversion and Management* **40**, 1803–1813. (DOI: 10.1016/S0196-8904(99)00071-0). Available at: http://www.sciencedirect.com/science/article/pii/S0196890499000710.

Rau G.H., K.G. Knauss, W.H. Langer, and K. Caldeira (2007). Reducing energy-related CO2 emissions using accelerated weathering of limestone. *Energy* **32**, 1471–1477. (DOI: 10.1016/j.energy.2006.10.011). Available at: http://www.sciencedirect.com/science/article/pii/S0360544206002982.

Reddy B.S., P. Balachandra, and H.S.K. Nathan (2009). Universalization of access to modern energy services in Indian households—Economic and policy analysis. *Energy Policy* **37**, 4645–4657. (DOI: 10.1016/j.enpol.2009.06.021). Available at: http://www.sciencedirect.com/science/article/pii/S0301421509004340.

Reilly J., J. Melillo, Y. Cai, D. Kicklighter, A. Gurgel, S. Paltsev, T. Cronin, A. Sokolov, and A. Schlosser (2012). Using Land To Mitigate Climate Change: Hitting the Target, Recognizing the Trade-offs. *Environ. Sci. Technol.* **46**, 5672–5679. (DOI: 10.1021/es2034729). Available at: http://dx.doi.org/10.1021/es2034729.

Reilly J., S. Paltsev, B. Felzer, X. Wang, D. Kicklighter, J. Melillo, R. Prinn, M. Sarofim, A. Sokolov, and C. Wang (2007a). Global economic effects of changes in crops, pasture, and forests due to changing climate, carbon dioxide, and ozone. *Energy Policy* **35**, 5370–5383. (DOI: 10.1016/j.enpol.2006.01.040).

Reilly J., S. Paltsev, B. Felzer, X. Wang, D. Kicklighter, J. Melillo, R. Prinn, M. Sarofim, A. Sokolov, and C. Wang (2007b). Global economic effects of changes in crops, pasture, and forests due to changing climate, carbon dioxide, and ozone. *Energy Policy* **35**, 5370–5383. (DOI: 10.1016/j.enpol.2006.01.040). Available at: http://www.sciencedirect.com/science/article/pii/S0301421507002388.

Reisinger A., P. Havlik, K. Riahi, O. Vliet, M. Obersteiner, and M. Herrero (2012). Implications of alternative metrics for global mitigation costs and greenhouse gas emissions from agriculture. *Climatic Change*, 1–14. (DOI: 10.1007/s10584-012-0593-3). Available at: http://dx.doi.org/10.1007/s10584-012-0593-3.

Riahi K., F. Dentener, D. Gielen, A. Grubler, J. Jewell, Z. Klimont, V. Krey, D. McCollum, S. Pachauri, S. Rao, B. van Ruijven, D. van Vuuren, and C. Wilson (2012a). Energy Pathways for Sustainable Development. In: *The Global Energy Assessment: Toward a Sustainable Future.* IIASA, Laxenburg, Austria and Cambridge University Press, Cambridge, UK, .

Riahi K., F. Dentener, D. Gielen, A. Grubler, J. Jewell, Z. Klimont, V. Krey, D. McCollum, S. Pachauri, S. Rao, B. van Ruijven, D.P. van Vuuren, and C. Wilson (2012b). Chapter 17 - Energy Pathways for Sustainable Development. In: *Global Energy Assessment - Toward a Sustainable Future*.Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria pp.1203–1306, (ISBN: 9781 10700 5198 hardback 9780 52118 2935 paperback). Available at: www.globalenergyassessment.org.

Riahi K., E. Kriegler, N. Johnson, C. Bertram, M. Den Elzen, J. Eom, M. Schaeffer, J. Edmonds, and et al. (2014). Overview WP2 - Locked into Copenhagen Pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Accepted for publication in Technological Forecasting and Social Change*.

Riahi K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, and P. Rafaj (2011). RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Climatic Change* **109**, 33–57. (DOI: 10.1007/s10584-011-0149-y). Available at: http://www.springerlink.com/index/10.1007/s10584-011-0149-y.

Richels R.G., G.J. Blanford, and T.F. Rutherford (2009). International climate policy: a “second best” solution for a “second best” world? *Climatic Change* **97**, 289–296. (DOI: 10.1007/s10584-009-9730-z). Available at: http://www.springerlink.com/content/jv3v2901605435p7/.

Richels R., T. Rutherford, G. Blanford, and L. Clarke (2007). Managing the transition to climate stabilization. *Climate Policy* **7**, 409–428.

Rickels W., G. Klepper, J. Dovern, G. Betz, N. Brachatzek, S. Cacean, K. Güssow, J. Heintzenberg, S. Hiller, C. Hoose, G. Klepper, T. Leisner, A. Oschlies, U. Platt, A. Proelß, O. Renn, W. Rickels, S. Schäfer, and M. Zürn (2011). *Large-Scale Intentional Interventions into the Climate System? Assessing the Climate Engineering Debate. Scoping report conducted on behalf of the German Federal Ministry of Education and Research (BMBF)*. Kiel Earth Institute, Kiel.

Ridgwell A., J.S. Singarayer, A.M. Hetherington, and P.J. Valdes (2009). Tackling Regional Climate Change By Leaf Albedo Bio-geoengineering. *Current Biology* **19**, 146–150. (DOI: 10.1016/j.cub.2008.12.025). Available at: ://WOS:000263012600026 http://ac.els-cdn.com/S0960982208016801/1-s2.0-S0960982208016801-main.pdf?_tid=5a0f2dea-4465-11e2-85bd-00000aab0f26&acdnat=1355321466_2eaa9816676e95e26b236063691b02cb.

Robock A., M. Bunzl, B. Kravitz, and G.L. Stenchikov (2010). A Test for Geoengineering? *Science* **327**, 530–531. (DOI: 10.1126/science.1186237).

Robock A., A. Marquardt, B. Kravitz, and G. Stenchikov (2009). Benefits, risks, and costs of stratospheric geoengineering. *Geophysical Research Letters* **36**, L19703. Available at: http://www.agu.org/pubs/crossref/2009/2009GL039209.shtml.

Robock A., L. Oman, and G.L. Stenchikov (2008). Regional climate responses to geoengineering with tropical and Arctic SO2 injections. *J. Geophys. Res.* **113**, D16101. (DOI: 10.1029/2008JD010050). Available at: http://dx.doi.org/10.1029/2008JD010050.

Roe M.J. (1994). *Strong managers, weak owners: The political roots of American corporate finance*. Princeton University Press (Princeton, NJ), (ISBN: 0691036837).

Rogelj J., W. Hare, J. Lowe, D. van Vuuren, K. Riahi, B. Matthews, T. Hanaoka, K. Jiang, and M. Meinshausen (2011). Emission pathways consistent with a 2 °C global temperature limit. *Nature Clim. Change* **1**, 413–418. (DOI: 10.1038/nclimate1258). Available at: http://dx.doi.org/10.1038/nclimate1258.

Rogelj J., D.L. McCollum, B.C. O/’Neill, and K. Riahi (2013a). 2020 emissions levels required to limit warming to below 2 degrees. *Nature Clim. Change* **3**, 405–412. (DOI: 10.1038/nclimate1758). Available at: http://dx.doi.org/10.1038/nclimate1758.

Rogelj J., D.L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi (2013b). Probabilistic cost estimates for climate change mitigation. *Nature* **493**, 79–83. (DOI: 10.1038/nature11787). Available at: http://dx.doi.org/10.1038/nature11787.

Rogelj J., D.L. McCollum, and K. Riahi (2013c). The UN’s “Sustainable Energy for All” initiative is compatible with a warming limit of 2 [deg]C. *Nature Clim. Change* **3**, 545–551. Available at: http://dx.doi.org/10.1038/nclimate1806.

Rogelj J., M. Meinshausen, and R. Knutti (2012). Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Clim. Change* **2**, 248–253. (DOI: 10.1038/nclimate1385). Available at: http://dx.doi.org/10.1038/nclimate1385.

Rogner M., and K. Riahi (2013). Future nuclear perspectives based on MESSAGE integrated assessment modeling. *Energy Strategy Reviews* **1**, 223–232. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84877352603&partnerID=40&md5=d0e3c7792c0b8848cc89d78ca6a29a59.

Rose S.K., H. Ahammad, B. Eickhout, B. Fisher, A. Kurosawa, S. Rao, K. Riahi, and D.P. van Vuuren (2012). Land-based mitigation in climate stabilization. *Energy Economics* **34**, 365–380. (DOI: 10.1016/j.eneco.2011.06.004). Available at: http://www.sciencedirect.com/science/article/pii/S0140988311001265.

Rose S.K., E. Kriegler, R. Bibas, K. Calvin, D. Popp, D. Van Vuuren, and J. Weyant (2014a). Bioenergy in energy transformation and climate management. *Accepted for publication in Climatic Change* **In press**. (DOI: DOI: 10.1007/s10584-013-0965-3).

Rose S.K., R. Richels, S. Smith, K. Riahi, J. Strefler, and D. van Vuuren (2014b). Non-Kyoto Radiative Forcing in Long-Run Greenhouse Gas Emissions and Climate Change Scenarios. *Accepted for publication in Climatic Change*. (DOI: DOI: 10.1007/s10584-013-0955-5).

Ross A., and D.H. Matthews (2009). Climate engineering and the risk of rapid climate change. *Environmental Research Letters* **4**. (DOI: 10.1088/1748-9326/4/4/045103). Available at: http://stacks.iop.org/1748-9326/4/i=4/a=045103?key=crossref.a779f8e536316a2ab72c782972a5a6cb.

Royal Society (2009). *Geoengineering the climate: Science, governance and uncertainty*. The Royal Society, London.

Van Ruijven B.J., D.P. van Vuuren, B.J.M. de Vries, M. Isaac, J.P. van der Sluijs, P.L. Lucas, and P. Balachandra (2011). Model projections for household energy use in India. *Clean Cooking Fuels and Technologies in Developing Economies* **39**, 7747–7761. (DOI: 10.1016/j.enpol.2011.09.021). Available at: http://www.sciencedirect.com/science/article/pii/S0301421511007105.

Russ P., and P. Criqui (2007). Post-Kyoto CO2 emission reduction: The soft landing scenario analysed with POLES and other world models. *Energy Policy* **35**, 786–796. Available at: http://www.sciencedirect.com/science/article/pii/S0301421506001145.

Sagar A.D., and B. van der Zwaan (2006). Technological innovation in the energy sector: R&D, deployment, and learning-by-doing. *Energy Policy* **34**, 2601–2608. (DOI: 10.1016/j.enpol.2005.04.012).

Sathaye J., O. Lucon, A. Rahman, J. Christensen, F. Denton, J. Fujino, G. Heath, M. Mirza, H. Rudnick, A. Schlaepfer, and A. Shmakin (2011). Renewable Energy in the Context of Sustainable Development. In: *IPCC Special Report on Renewable EnergySources and Climate Change Mitigation*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Schaeffer M., L. Gohar, E. Kriegler, J. Lowe, K. Riahi, and D. Van Vuuren (2013). Mid- and long-term climate projections for fragmented and delayed-action scenarios. *Accepted for publication in Technological Forecasting and Social Change* **In press.**

Schaeffer M., T. Kram, M. Meinshausen, D. van Vuuren, and W.L. Hare (2008). Near-linear cost increase to reduce climate-change risk. *Proceedings of the National Academy of Sciences* **105**, 20621 –

20626. (DOI: 10.1073/pnas.0802416106). Available at: http://www.pnas.org/content/105/52/20621.abstract.

Schaeffer R., A.S. Szklo, A.F. Pereira de Lucena, B.S. Moreira Cesar Borba, L.P. Pupo Nogueira, F.P. Fleming, A. Troccoli, M. Harrison, and M.S. Boulahya (2012). Energy sector vulnerability to climate change: A review. *Energy* **38**, 1–12. (DOI: 10.1016/j.energy.2011.11.056). Available at: http://www.sciencedirect.com/science/article/pii/S0360544211007870.

Schäfer A. (2005). Structural change in energy use. *Energy Policy* **33**, 429–437. (DOI: doi: 10.1016/j.enpol.2003.09.002). Available at: http://www.sciencedirect.com/science/article/pii/S0301421503002799.

Schelling T.C. (1996). The economic diplomacy of geoengineering. *Climatic Change* **33**, 303–307. (DOI: 10.1007/bf00142578). Available at: ://WOS:A1996VB19700004.

Schellnhuber H.J., D. Messner, C. Leggewie, R. Leinfelder, N. Nakicenovic, S. Rahmstorf, S. Schlacke, J. Schmid, and R. Schubert (2009). *Solving the climate dilemma: The budget approach*. Berlin, Germany. 25 pp.

Schmidt H., K. Alterskjær, D. Bou Karam, O. Boucher, A. Jones, J.E. Kristjánsson, U. Niemeier, M. Schulz, A. Aaheim, F. Benduhn, M. Lawrence, and C. Timmreck (2012). Solar irradiance reduction to counteract radiative forcing from a quadrupling of CO2: climate responses simulated by four earth system models. *Earth Syst. Dynam.* **3**, 63–78. (DOI: 10.5194/esd-3-63-2012). Available at: http://www.earth-syst-dynam.net/3/63/2012/.

Scholte S., E. Vasileiadou, and A.C. Petersen (2013). Opening up the societal debate on climate engineering: how newspaper frames are changing. *Journal of Integrative Environmental Sciences* **10**, 1–16. (DOI: 10.1080/1943815X.2012.759593). Available at: http://dx.doi.org/10.1080/1943815X.2012.759593.

Searchinger T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu (2008). Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science* **319**, 1238 –1240. (DOI: 10.1126/science.1151861). Available at: http://www.sciencemag.org/content/319/5867/1238.abstract.

Shen Y., T. Oki, N. Utsumi, S. Kanae, and N. Hanasaki (2008). Projection of future world water resources under SRES scenarios: water withdrawal / Projection des ressources en eau mondiales futures selon les scénarios du RSSE: prélèvement d'eau. *Hydrological Sciences Journal* **53**, 11–33. (DOI: 10.1623/hysj.53.1.11). Available at: http://www.tandfonline.com/doi/abs/10.1623/hysj.53.1.11.

Shiklomanov I.A., and J.C. Rodda (2003). *World Water Resources at the Beginning of the 21st Century*. Cambridge, UK.

Shindell D., J.C.I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S.C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L. Pozzoli, K. Kupiainen, L. Höglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan, K. Hicks, N.T.K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler (2012). Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science* **335**, 183–189. (DOI: 10.1126/science.1210026). Available at: http://www.sciencemag.org/content/335/6065/183.abstract.

Shine K.P., T.K. Berntsen, J.S. Fuglestvedt, R.B. Skeie, and N. Stuber (2007). Comparing the climate effect of emissions of short- and long-lived climate agents. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **365**, 1903–1914. (DOI:

10.1098/rsta.2007.2050). Available at: http://rsta.royalsocietypublishing.org/content/365/1856/1903.abstract.

Shrestha R.M., and S.R. Shakya (2012). Benefits of low carbon development in a developing country: Case of Nepal. *The Asia Modeling Exercise: Exploring the Role of Asia in Mitigating Climate Change* **34, Supplement 3**, S503–S512. (DOI: 10.1016/j.eneco.2012.03.014). Available at: http://www.sciencedirect.com/science/article/pii/S0140988312000588.

Shukla P.R., and V. Chaturvedi (2012). Low carbon and clean energy scenarios for India: Analysis of targets approach. *Energy Economics* **34**, S487–S495. (DOI: 10.1016/j.eneco.2012.05.002). Available at: http://www.sciencedirect.com/science/article/pii/S0140988312001028.

Shukla P.R., and S. Dhar (2011). Climate agreements and India: aligning options and opportunities on a new track. *International Environmental Agreements: Politics, Law and Economics* **11**, 229–243. Available at: http://ideas.repec.org/a/spr/ieaple/v11y2011i3p229-243.html.

Shukla P.R., S. Dhar, and D. Mahapatra (2008). Low-carbon society scenarios for India. *Climate Policy* **8**, S156–S176. (DOI: 10.3763/cpol.2007.0498). Available at: http://www.tandfonline.com/doi/abs/10.3763/cpol.2007.0498.

Shukla P.R., A. Garg, and S. Dhar (2009). Integrated regional assessment for South Asia: A Case Study. In: *Knight, C.G. & Jäger, J. (eds). Integrated Regional Assessment of Climate Change*. Cambridge University Press, .

Skea J. (2010). Valuing diversity in energy supply. *Large-scale wind power in electricity markets with Regular Papers* **38**, 3608–3621. (DOI: 10.1016/j.enpol.2010.02.038). Available at: http://www.sciencedirect.com/science/article/pii/S0301421510001199.

Skea J.I.M., and S. Nishioka (2008). Policies and practices for a low-carbon society. *Climate Policy* **8**, S5–S16. (DOI: 10.3763/cpol.2008.0487). Available at: http://www.tandfonline.com/doi/abs/10.3763/cpol.2008.0487.

Smale R., M. Hartley, C. Hepburn, J. Ward, and M. Grubb (2006). The impact of CO2 emissions trading on firm profits and market prices. *Climate Policy* **6**, 31–48.

Smetacek V., C. Klaas, V.H. Strass, P. Assmy, M. Montresor, B. Cisewski, N. Savoye, A. Webb, F. d'Ovidio, J.M. Arrieta, U. Bathmann, R. Bellerby, G.M. Berg, P. Croot, S. Gonzalez, J. Henjes, G.J. Herndl, L.J. Hoffmann, H. Leach, M. Losch, M.M. Mills, C. Neill, I. Peeken, R. Rottgers, O. Sachs, E. Sauter, M.M. Schmidt, J. Schwarz, A. Terbruggen, and D. Wolf-Gladrow (2012). Deep carbon export from a Southern Ocean iron-fertilized diatom bloom. *Nature* **487**, 313–319. (DOI: 10.1038/nature11229). Available at: http://dx.doi.org/10.1038/nature11229.

Smith K.R., M. Jerrett, H.R. Anderson, R.T. Burnett, V. Stone, R. Derwent, R.W. Atkinson, A. Cohen, S.B. Shonkoff, D. Krewski, C.A. Pope III, M.J. Thun, and G. Thurston (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants. *The Lancet* **374**, 2091–2103. (DOI: 10.1016/S0140-6736(09)61716-5). Available at: http://www.sciencedirect.com/science/article/pii/S0140673609617165.

Smith S.M., J.A. Lowe, N.H.A. Bowerman, L.K. Gohar, C. Huntingford, and M.R. Allen (2012). Equivalence of greenhouse-gas emissions for peak temperature limits. *Nature Clim. Change* **2**, 535–538. (DOI: 10.1038/nclimate1496). Available at: http://dx.doi.org/10.1038/nclimate1496.

Smith S.J., and A. Mizrahi (2013). Near-term climate mitigation by short-lived forcers. *Proceedings of the National Academy of Sciences* **110**, 14202–14206. Available at: http://www.pnas.org/content/110/35/14202.abstract.

Smith S.J., and P.J. Rasch (2012). The long-term policy context for solar radiation management. *Climatic Change*. (DOI: 10.1007/s10584-012-0577-3). Available at: http://www.springerlink.com/index/10.1007/s10584-012-0577-3.

Socolow R.H., M. Desmond, R. Aines, J. Blackstock, O. Bolland, T. Kaarsberg, L. Lewis, and et al. (2011). *Direct Air Capture of CO2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs*. The American Physical Society, Washington DC.

Spracklen D.V., S.R. Arnold, and C.M. Taylor (2012). Observations of increased tropical rainfall preceded by air passage over forests. *Nature* **489**, 282–285. Available at: http://dx.doi.org/10.1038/nature11390.

SRREN I. (2011). *Renewable Energy Sources and Climate Change Mitigation. Special report of the International Panel on Climate Change*. Intergovernmental Panel on Climate Change.

Steckel J.C., R.J. Brecha, M. Jakob, J. Strefler, and G. Luderer (2013). Development without energy? Assessing future scenarios of energy consumption in developing countries. *Ecological Economics* **90**, 53–67. (DOI: 10.1016/j.ecolecon.2013.02.006). Available at: http://www.sciencedirect.com/science/article/pii/S0921800913000670.

Stephens J., and D. Keith (2008). Assessing geochemical carbon management. *Climatic Change* **90**, 217–242. (DOI: 10.1007/s10584-008-9440-y). Available at: http://dx.doi.org/10.1007/s10584-008-9440-y.

Stirling A. (1994). Diversity and ignorance in electricity supply investment: Addressing the solution rather than the problem. *Energy Policy* **22**, 195–216. (DOI: 10.1016/0301-4215(94)90159-7). Available at: http://www.sciencedirect.com/science/article/pii/0301421594901597.

Stirling A. (2010). Multicriteria diversity analysis: A novel heuristic framework for appraising energy portfolios. *Energy Security - Concepts and Indicators with regular papers* **38**, 1622–1634. (DOI: 10.1016/j.enpol.2009.02.023). Available at: http://www.sciencedirect.com/science/article/pii/S0301421509000901.

Stocker T.F., Q.F. Dahe, and al. (2013). *Climate Change 2013: The Physical Science Basis*. WMO & UNEP. Available at: http://www.climatechange2013.org/.

Stolaroff J.K., S. Bhattacharyya, C.A. Smith, W.L. Bourcier, P.J. Cameron-Smith, and R.D. Aines (2012). Review of Methane Mitigation Technologies with Application to Rapid Release of Methane from the Arctic. *Environmental Science & Technology* **46**, 6455–6469. (DOI: 10.1021/es204686w). Available at: http://dx.doi.org/10.1021/es204686w.

Stone D.A., M.R. Allen, P.A. Stott, P. Pall, S.K. Min, T. Nozawa, and S. Yukimoto (2009). The Detection and Attribution of Human Influence on Climate. *Annual Review of Environment and Resources* **34**, 1–16. (DOI: 10.1146/annurev.environ.040308.101032). Available at: ://000272082000002.

Strachan N., T. Foxon, and J. Fujino (2008). Low-Carbon Society (LCS) modelling. *Climate Policy* **8**, S3–S4. (DOI: 10.3763/cpol.2008.0538). Available at: http://dx.doi.org/10.3763/cpol.2008.0538.

Strachan N., and W. Usher (2012). Failure to achieve stringent carbon reduction targets in a second-best policy world. *Climatic Change* **113**, 121–139. (DOI: 10.1007/s10584-011-0267-6). Available at: http://dx.doi.org/10.1007/s10584-011-0267-6.

Sugiyama M. (2012). Climate change mitigation and electrification. *Energy Policy* **44**, 464–468. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84858282448&partnerID=40&md5=8eb2b2c62b2fa5f1a4266d0796931bcf.

Sugiyama M., O. Akashi, K. Wada, A. Kanudia, J. Li, and J. Weyant (2014). Role of energy efficiency in climate change mitigation policy for India: Assessment of co-benefits and opportunities within an integrated assessment modeling framework. *Accepted for publication in Climatic Change* **In press.**

Swart R., M. Amann, F. Raes, and W. Tuinstra (2004). A Good Climate for Clean Air: Linkages between Climate Change and Air Pollution. An Editorial Essay. *Climatic Change* **66**, 263–269. (DOI: 10.1023/B:CLIM.0000044677.41293.39). Available at: http://dx.doi.org/10.1023/B%3ACLIM.0000044677.41293.39.

Swart R., and N. Marinova (2010). Policy options in a worst case climate change world. *Mitigation and Adaptation Strategies for Global Change* **15**, 531–549. (DOI: 10.1007/s11027-010-9235-0). Available at: http://dx.doi.org/10.1007/s11027-010-9235-0.

Tavoni M., E. De Cian, G. Luderer, J. Steckel, and H. Waisman (2012). The value of technology and of its evolution towards a low carbon economy. *Climatic Change* **114**, 39–57. Available at: http://dx.doi.org/10.1007/s10584-011-0294-3.

Tavoni M., E. Kriegler, T. Aboumahboub, K. Calvin, G. DeMaere, T. Kober, J. Jewell, P. Lucas, G. Luderer, D. McCollum, and et al. (2014). The distribution of the major economies' effort in the Durban platform scenarios. *Accepted for publication in Climate Change Economics* **In press**.

Tavoni M., and R. Socolow (2013). Modeling meets science and technology: an introduction to a special issue on negative emissions. *Climatic Change* **118**, 1–14. (DOI: 10.1007/s10584-013-0757-9). Available at: http://dx.doi.org/10.1007/s10584-013-0757-9.

Tavoni M., and R. Socolow, (2012). Modeling meets science and technology: An introduction to a Special Issue on Negative Emissions. *submitted to Climatic Change*.

Tavoni M., and R.S.J. Tol (2010). Counting only the hits? The risk of underestimating the costs of stringent climate policy. *Climatic Change* **100**, 769–778. (DOI: 10.1007/s10584-010-9867-9). Available at: http://dx.doi.org/10.1007/s10584-010-9867-9.

Thollander P., J. Palm, and P. Rohdin (2010). Categorizing barriers to energy efficiency: an interdisciplinary perspective. *Energy efficiency. Sciyo, Croatia. Available at: http://www. intechopen. com/books/show/title/energy-efficiency*.

Tilmes S., J. Fasullo, J. Lamarque, D.R. Marsh, M. Mills, K. Alterskjær, H. Muri, J.E. Kristjánsson, O. Boucher, and M. Schulz (2013). The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres* **118**, 11–036.

Tilmes S., R.R. Garcia, D.E. Kinnison, A. Gettelman, and P.J. Rasch (2009). Impact of geoengineered aerosols on the troposphere and stratosphere. *J. Geophys. Res.* **114**, D12305. (DOI: 10.1029/2008JD011420). Available at: http://dx.doi.org/10.1029/2008JD011420.

Tol R.S.J. (1997). On the optimal control of carbon dioxide emissions: an application of FUND. *Environmental Modeling & Assessment* **2**, 151–163. Available at: http://dx.doi.org/10.1023/A%3A1019017529030.

Tol R.S.. (2009). The feasibility of low concentration targets: An application of FUND. *Energy Economics* **31**, S121–S130.

Townsend P.V., R.J. Harper, P.D. Brennan, C. Dean, S. Wu, K.R.J. Smettem, and S.E. Cook (2012). Multiple environmental services as an opportunity for watershed restoration. *Forest Policy and Economics* **17**, 45–58. (DOI: 10.1016/j.forpol.2011.06.008). Available at: http://www.sciencedirect.com/science/article/pii/S1389934111000888.

Tuana N., R.L. Sriver, T. Svoboda, R. Olson, P.J. Irvine, J. Haqq-Misra, and K. Keller (2012). Towards Integrated Ethical and Scientific Analysis of Geoengineering: A Research Agenda. *Ethics, Policy & Environment* **15**, 136–157. (DOI: 10.1080/21550085.2012.685557). Available at: http://dx.doi.org/10.1080/21550085.2012.685557 http://www.tandfonline.com/doi/abs/10.1080/21550085.2012.685557.

Turton H., and L. Barreto (2006). Long-term security of energy supply and climate change. *Energy Policy* **34**, 2232–2250. (DOI: 10.1016/j.enpol.2005.03.016). Available at: http://www.sciencedirect.com/science/article/pii/S0301421505001035.

UNCCD (2004). *United Nations Convention to Combat Desertification (UNCCD)*. Available at: http://www.unccd.int/en/Pages/default.aspx.

UNEP (2012). *The Emissions Gap Report 2012: UNEP Synthesis Report.* United Nations Environment Programme (UNEP), Nairobi, Kenya. Available at: http://igitur-archive.library.uu.nl/milieu/2013-0903-200557/2012gapreport.pdf.

UNEP and WMO (2011). *Integrated Assessment of Black Carbon and Tropospheric Ozone.* UNEP and WMO, Nairobi, Kenya.

UNFCCC (1997). *Paper no 1: Brazil; Proposed Elements of a Protocol to the United Nations Framework Convention on Climate Change*. UNFCCC, Bonn, Germany.

UNFCCC (2011a). Compilation of economy-wide emission reduction targets to be implemented by Parties included in Annex I to the Convention. *UNFCCC/SB/2011/INF.1/Rev.1.*

UNFCCC (2011b). Compilation of information on nationally appropriate mitigation actions to be implemented by Parties not included. *UNFCCC/ FCCC/AWGLCA/2011/INF.1*.

Uprety D.C., S. Dhar, D. Hongmin, B. Kimball, A. Garg, and J. Upadhyay (2012). *Technologies for Green House Gas Mitigation in Agriculture*. UNEP Risoe Centre, Risoe DTU National Laboratory for Sustainable Energy.

Urpelainen J. (2012). Geoengineering and global warming: a strategic perspective. *International Environmental Agreements-Politics Law and Economics* **12**, 375–389. (DOI: 10.1007/s10784-012-9167-0). Available at: ://WOS:000310168900005.

Vaillancourt K., and J.-P. Waaub (2004). Equity in international greenhouse gases abatement scenarios: A multicriteria approach. *Management of the Future MCDA: Dynamic and Ethical Contributions* **153**, 489–505. (DOI: 10.1016/S0377-2217(03)00170-X). Available at: http://www.sciencedirect.com/science/article/pii/S037722170300170X.

van Sluisveld et. al. (2013). A multi-model analysis of post-2020 mitigation efforts of five major economies. *Climate Change Economics*.

Vaughan N., and T. Lenton (2011). A review of climate geoengineering proposals. *Climatic Change* **109**, 745–790. (DOI: 10.1007/s10584-011-0027-7). Available at: http://dx.doi.org/10.1007/s10584-011-0027-7.

Venema H.D., and I.H. Rehman (2007). Decentralized renewable energy and the climate change mitigation-adaptation nexus. *Mitigation and Adaptation Strategies for Global Change* **12**, 875–900. (DOI: 10.1007/s11027-007-9104-7). Available at: http://dx.doi.org/10.1007/s11027-007-9104-7.

Verbruggen A., and M. Al Marchohi (2010). Views on peak oil and its relation to climate change policy. *The socio-economic transition towards a hydrogen economy - findings from European research, with regular papers* **38**, 5572–5581. (DOI: 10.1016/j.enpol.2010.05.002). Available at: http://www.sciencedirect.com/science/article/pii/S0301421510003514.

Victor D.G. (2008). On the regulation of geoengineering. *Oxford Review of Economic Policy* **24**, 322–336. (DOI: 10.1093/oxrep/grn018). Available at: ://WOS:000260555200006.

Virgoe J. (2009). International governance of a possible geoengineering intervention to combat climate change. *Climatic Change* **95**, 103–119. (DOI: 10.1007/s10584-008-9523-9). Available at: ://WOS:000267365400008.

Vliet J., M. Berg, M. Schaeffer, D. Vuuren, M. Elzen, A. Hof, A. Mendoza Beltran, and M. Meinshausen (2012). Copenhagen Accord Pledges imply higher costs for staying below 2°C warming. *Climatic Change* **113**, 551–561. (DOI: 10.1007/s10584-012-0458-9). Available at: http://dx.doi.org/10.1007/s10584-012-0458-9.

Van Vliet J., M.G.J. den Elzen, and D.P. van Vuuren (2009). Meeting radiative forcing targets under delayed participation. *Energy Economics* **31**, S152–S162. (DOI: 16/j.eneco.2009.06.010). Available at: http://www.sciencedirect.com/science/article/pii/S014098830900108X.

Van Vuuren D., J. Cofala, H.E. Eerens, R. Oostenrijk, C. Heyes, Z. Klimont, M.G.J. den Elzen, and M. Amann (2006). Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe. *Energy Policy* **34**, 444–460. (DOI: 10.1016/j.enpol.2004.06.012). Available at: http://www.sciencedirect.com/science/article/pii/S0301421504001867.

Van Vuuren D.P., S. Deetman, J. Vliet, M. Berg, B. Ruijven, and B. Koelbl (2013). The role of negative CO2 emissions for reaching 2 °C—insights from integrated assessment modelling. *Climatic Change* **118**, 15–27. (DOI: 10.1007/s10584-012-0680-5). Available at: http://dx.doi.org/10.1007/s10584-012-0680-5.

Van Vuuren D., S. Deetman, J. Van Vliet, M. van den Berg, B.J. van Ruijven, and B. Koelbl (2013). The role of negative CO2 emissions for reaching 2 C - insights from integrated assessment modelling. *Climatic Change* **In press**.

Van Vuuren D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith, and S.K. Rose (2011a). The representative concentration pathways: An overview. *Climatic Change* **109**, 5–31. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-80053903024&partnerID=40&md5=c3dd4f4dda4f04e0ccb47bd2a44d20a8.

Van Vuuren D., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith, and S.K. Rose (2011b). The representative concentration pathways: an overview. *Climatic Change* **109**, 5–31. (DOI: 10.1007/s10584-011-0148-z). Available at: http://www.springerlink.com/index/10.1007/s10584-011-0148-z.

Van Vuuren D., M.G.J. den Elzen, P.L. Lucas, B. Eickhout, B.J. Strengers, B. Ruijven, S. Wonink, and R. Houdt (2007). Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change* **81**, 119–159. (DOI: 10.1007/s10584-006-9172-9).

Van Vuuren D., M. Hoogwijk, T. Barker, K. Riahi, S. Boeters, J. Chateau, S. Scrieciu, J. van Vliet, T. Masui, T. Blok, E. Blomen, and T. Kram (2009a). Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. *Energy Policy* **37**, 5125–5139. (DOI: 16/j.enpol.2009.07.024). Available at: http://www.sciencedirect.com/science/article/pii/S0301421509005394.

Van Vuuren D.P., M. Isaac, M.G.. den Elzen, E. Stehfest, and J. van Vliet (2010). Low stabilization scenarios and implications for major world regions from an integrated assessment perspective. *The Energy Journal* **31**, 165–192.

Van Vuuren D., J. Lowe, E. Stehfest, L. Gohar, A.F. Hof, C. Hope, R. Warren, M. Meinshausen, and G.-K. Plattner (2009b). How well do integrated assessment models simulate climate change? *Climatic Change* **104**, 255–285. (DOI: 10.1007/s10584-009-9764-2).

Van Vuuren D., and K. Riahi (2011). The relationship between short-term emissions and long-term concentration targets. *Climatic Change* **104**, 793–801. (DOI: 10.1007/s10584-010-0004-6). Available at: http://dx.doi.org/10.1007/s10584-010-0004-6.

Van Vuuren D.P., and E. Stehfest (2013). If climate action becomes urgent: the importance of response times for various climate strategies. *Climatic Change* **121**, 473–486. (DOI: 10.1007/s10584-013-0769-5). Available at: http://dx.doi.org/10.1007/s10584-013-0769-5.

Van Vuuren D., and Stehfest (2013). What if climate action becomes really urgent? *Climatic Change* **In press**.

Van Vuuren D., E. Stehfest, M.G.J. den Elzen, T. Kram, J. van Vliet, S. Deetman, M. Isaac, K. Klein Goldewijk, A. Hof, A. Mendoza Beltran, R. Oostenrijk, and B. Ruijven (2011c). RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change* **109**, 95–116. (DOI: 10.1007/s10584-011-0152-3). Available at: http://www.springerlink.com/index/10.1007/s10584-011-0152-3.

Wagner F. (2012). Mitigation here and now or there and then: the role of co-benefits. *Carbon Management* **3**, 325–327. (DOI: 10.4155/cmt.12.37). Available at: http://dx.doi.org/10.4155/cmt.12.37.

Waisman H., C. Guivarch, F. Grazi, and J. Hourcade (2012). The Imaclim-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight. *Climatic Change* **114**, 101–120. (DOI: 10.1007/s10584-011-0387-z). Available at: http://dx.doi.org/10.1007/s10584-011-0387-z.

WCED (1987). *Our Common Future, From One Earth to One World (Brundtland Report)*. United Nations World Commission on Environment and Development, Oslo.

Webster M., A. Sokolov, J. Reilly, C. Forest, S. Paltsev, A. Schlosser, C. Wang, D. Kicklighter, M. Sarofim, J. Melillo, R. Prinn, and H. Jacoby (2012). Analysis of climate policy targets under uncertainty. *Climatic Change* **112**, 569–583. (DOI: 10.1007/s10584-011-0260-0). Available at: http://dx.doi.org/10.1007/s10584-011-0260-0.

Wei M., S. Patadia, and D.M. Kammen (2010). Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy Policy* **38**, 919–931. (DOI: 10.1016/j.enpol.2009.10.044). Available at: http://www.sciencedirect.com/science/article/pii/S0301421509007915.

Ban-Weiss G.A., and K. Caldeira (2010). Geoengineering as an optimization problem. *Environmental Research Letters* **5**, 034009.

West J.J., A.M. Fiore, L.W. Horowitz, and D.L. Mauzerall (2006). Global health benefits of mitigating ozone pollution with methane emission controls. *Proceedings of the National Academy of Sciences of the United States of America* **103**, 3988–3993. Available at: http://www.pnas.org/content/103/11/3988.abstract.

West J.J., A.M. Fiore, V. Naik, L.W. Horowitz, M.D. Schwarzkopf, and D.L. Mauzerall (2007). Ozone air quality and radiative forcing consequences of changes in ozone precursor emissions. *Geophysical Research Letters* **34**, L06806. (DOI: 10.1029/2006GL029173). Available at: http://dx.doi.org/10.1029/2006GL029173.

West J.J., S.J. Smith, R.A. Silva, V. Naik, Y. Zhang, Z. Adelman, M.M. Fry, S. Anenberg, L.W. Horowitz, and J.-F. Lamarque (2013). Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change* **3**, 885–889.

Weyant J., F.C. de la Chesnaye, and G.J. Blanford (2006). Overview of EMF-21: Multigas Mitigation and Climate Policy. *The Energy Journal* **Multi-Greenhouse Gas Mitigation and Climate Policy**, 1–32.

Wigley T.M.L. (2005). The Climate Change Commitment. *Science* **307**, 1766–1769. (DOI: 10.1126/science.1103934). Available at: http://www.sciencemag.org/content/307/5716/1766.abstract.

Wigley T.M.L. (2006). A Combined Mitigation/Geoengineering Approach to Climate Stabilization. *Science* **314**, 452–454. (DOI: 10.1126/science.1131728). Available at: http://www.sciencemag.org/content/314/5798/452.

Wilkinson P., K.R. Smith, M. Davies, H. Adair, B.G. Armstrong, M. Barrett, N. Bruce, A. Haines, I. Hamilton, T. Oreszczyn, I. Ridley, C. Tonne, and Z. Chalabi (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *The Lancet* **374**, 1917–1929. (DOI: 10.1016/S0140-6736(09)61713-X). Available at: http://www.sciencedirect.com/science/article/pii/S014067360961713X.

Williams J.H., A. DeBenedictis, R. Ghanadan, A. Mahone, J. Moore, W.R. Morrow III, S. Price, and M.S. Torn (2012). The technology path to deep greenhouse gas emissions cuts by 2050: The pivotal role of electricity. *Science* **335**, 53–59. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84855488361&partnerID=40&md5=5d8e91d91b6592a2157cc3fceff978ab.

Winkler H., T. Letete, and A. Marquard (2011). A South African approach - responsibility, capability and sustainable development. In: *Equitable access to sustainable development: contribution to the body of scientific knowledge.* BASIC expert group, Beijing, Brasilia, Cape Town and Mumbai.

Wise M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S.J. Smith, A. Janetos, and J. Edmonds (2009a). Implications of limiting CO2 concentrations for land use and energy. *Science* **324**, 1183.

Wise M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S.J. Smith, A. Janetos, and J. Edmonds (2009b). Implications of Limiting CO2 Concentrations for Land Use and Energy. *Science* **324**, 1183 –1186. (DOI: 10.1126/science.1168475). Available at: http://www.sciencemag.org/content/324/5931/1183.abstract.

Woodcock J., P. Edwards, C. Tonne, B.G. Armstrong, O. Ashiru, D. Banister, S. Beevers, Z. Chalabi, Z. Chowdhury, A. Cohen, O.H. Franco, A. Haines, R. Hickman, G. Lindsay, I. Mittal, D. Mohan, G. Tiwari, A. Woodward, and I. Roberts (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *The Lancet* **374**, 1930–1943. (DOI: 10.1016/S0140-6736(09)61714-1). Available at: http://www.sciencedirect.com/science/article/pii/S0140673609617141.

World Bank (2013). *International Comparison Program Database*. World Bank, Washington DC, USA. Available at: http://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD.

Yamamoto H., M. Sugiyama, and J. Tsutsui (2014). Role of end-use technologies in long-term GHG reduction scenarios developed with the BET model. *Climatic Change* **In Press**. (DOI: DOI 10.1007/s10584-013-0938-6).

Zeebe R.E., and D. Archer (2005). Feasibility of ocean fertilization and its impact on future atmospheric CO2 levels. *Geophysical Research Letters* **32**, L09703. (DOI: 10.1029/2005GL022449). Available at: http://dx.doi.org/10.1029/2005GL022449.

Zhou Y., J. Eom, and L. Clarke (2013). The effect of global climate change, population distribution, and climate mitigation on building energy use in the U.S. and China. *Climatic Change* **119**, 979–992. (DOI: 10.1007/s10584-013-0772-x). Available at: http://dx.doi.org/10.1007/s10584-013-0772-x.

Zickfeld K., M. Eby, H.D. Matthews, and A.J. Weaver (2009). Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proceedings of the National Academy of Sciences* **106**, 16129 –16134. (DOI: 10.1073/pnas.0805800106). Available at: http://www.pnas.org/content/106/38/16129.abstract.

Zürn M., and S. Schäfer (2013). The Paradox of Climate Engineering. *Global Policy*. (DOI: 10.1111/1758-5899.12004).

Van der Zwaan B., R. Gerlagh, G. Klaassen, and L. Schrattenholzer (2002). Endogenous technological change in climate change modelling. *Energy Economics* **24**, 1–19. Available at: http://ideas.repec.org/a/eee/eneeco/v24y2002i1p1-19.html.

Van der Zwaan B.C.C., H. Rösler, T. Kober, T. Aboumahboub, K.V. Calvin, D.E.H.J. Gernaat, G. Marangoni, and D. McCollum (2014). A Cross-model Comparison of Global Long-term Technology Diffusion under a 2˚C Climate Change Control Target. *Accepted for publication in Climate Change Economics*.