Chapter:	6	
Title:	Assessing Transformation Pathways	
(Sub)Section:	All	
Author(s):	CLAs:	Leon CLARKE, Kejun JIANG
	LAs:	Mustafa BABIKER, Keigo AKIMOTO, Geoffrey BLANFORD, Karen FISHER-VANDEN, Jean-Charles HOURCADE, David KEITH, Volker KREY, Elmar KRIEGLER, Andreas LÖSCHEL, Sergey PALTSEV, Steven ROSE, Priyadarshi R. SHUKLA, Massimo TAVONI, Bob VAN DER ZWAAN, Detlef VAN VUUREN
	CAs:	Katherine Calvin, Subash Dhar, Gunnar Luderer, Ian Sue Wing, Laura Sokka
Remarks:	First Order Draft (FOD)	
Version:	1	
File name:		
Date:	25 July 2012	Template Version: 3

Table of changes

No	Date	Version	Place	Description	Editor
1	TT.MM.JJJJ	01		initial Version	

Comment on text by TSU to reviewers

This chapter has been allocated 65 template pages, currently it counts 85 pages (excluding this page and the bibliography), so it is **20 pages over target.** Reviewers are kindly asked to indicate where the chapter could be shortened.

Colour code used

Turquoise highlights are inserted comments from Authors or TSU i.e. [AUTHORS/TSU: ….]

Chapter 6: Assessing Transformation Pathways

Contents

Executive Summary

There are many transformation pathways to stabilization of greenhouse gas concentrations at a level that will prevent dangerous anthropogenic interference with the climate. None of these pathways is exclusively “the right pathway”, and choices will govern which pathway is followed. These choices include, among other things, the long-term stabilization goal, the timing of the path to meet that goal, the degree to which concentrations might temporarily exceed (or “overshoot”) the goal, the technologies that will be deployed to reduce emissions, the degree to which mitigation is coordinated across countries, the policy approaches used to achieve these goals within and across countries, the treatment of land use, and the manner in which mitigation is meshed with other national and societal priorities such as energy security and sustainable development. In addition, the pathways will be influenced by a range of forces about which we have only limited knowledge today, for example, economic growth, population growth, technological change, and social and political change. Given these uncertainties and the broad range of choices that might be made in the face of this uncertainty, it is not surprising that the literature on long-term transition pathways sketches out a wide range of often very different possible pathways that might be followed to meet any long-term stabilization goal.

Transformation pathways can be distinguished from one another by a range of characteristics. Weighing the characteristics of different pathways is the way in which deliberative decisions about transformation pathways would be made. Although measures of macro-economic costs such as GDP losses or changes in total personal consumption have been put forward as key deliberative decision-making factors, these are far from the only characteristics about transition pathways that matter for making good decisions. The broader socio-economic implications of mitigation go well beyond economic costs, conceived narrowly. Transition pathways inherently involve a range of tradeoffs that link to other national and societal priorities including, among other things, both energy and food security, sustainable development, the distribution of economic costs, local air pollution and other environmental factors associated with different technology solutions (e.g., nuclear power, coal-fired CCS), and economic competitiveness.

Although near-term mitigation levels may vary among regions for a variety of reasons, in the long term, all countries must ultimately bring their emissions toward zero to meet any stabilization goal. This means that although all countries must ultimately undertake substantial reductions in emissions, the total quantity of emissions reductions required from the currently developing regions will ultimately be larger, and with larger total mitigation costs, than those for the developed regions. *[High Agreement, Robust Evidence]* This is due to the fact that emissions from the currently developing regions are projected to be larger than those form the currently developed regions over the coming century and will therefore require more mitigation. This characteristic of the distribution of baseline emissions has other important implications for transformation pathways, including an increasing need for coordinated international action to meet more stringent long-term goals in particular. At the same time, it is important to note, however, that how responsibility for reduction of emissions among different countries is allocated, and the allocation of financial responsibility in particular, is a political decision and one that must include the appropriate incentives for different countries to take on mitigation actions and that must consider a wide range of factors, not limited to development and equity considerations.

Although virtually any long-term stabilization goal is theoretically possible to achieve hundreds to thousands of years into the future, a desire to meet particular goals by the end of this century or before, along with the degree to which this goal can be temporarily exceeded, will constrain the set of mitigation options over the next 20 to 40 years, including the options to explicitly delay mitigation or limits on mitigation as a result of differing national and regional commitments. For example, emissions peak prior to 2020 in virtually all scenarios leading to a 2.6 W/m2 long-term goal and emissions by 2050 are well below those of today [AUTHORS: Note to reviewers: Statement will be refined in second-order draft. See note in introduction on preliminary dataset.]. Emissions peak prior to 2030 in virtually all scenarios leading to a 3.7 W/m2 long-term goal and emissions by 2050 are at or below those of today [AUTHORS: Note to reviewers: Statement will be refined in second-order draft. See note in introduction on preliminary dataset.]. *[High Agreement, Robust Evidence]*

Table 6.ES.1. Characteristics of scenario categories. Note that the results shown are not requirements for specific climate outcomes. They are scenario results dependent upon modeling and assumptions, including assumptions regarding the timing of policy action. [AUTHORS: Note to reviewers: Please see discussion of preliminary dataset in the introduction.]

Category	Radiative Forcing in 2100 (W/m^2)	RCP	Peak Emissions	Emissions level relative to 2005		
				2020	2030	2050
Category 0	<2.5		TBD	TBD	TBD	TBD
Category 1	2.5-3.0	RCP 2.6	2010-2020	101 (87-120)	87 (70-115)	38 (27-47)
Category 2	3.0-3.5		2010-2020	105 (90-122)	97 (72-134)	47 (33-73)
Category 3	3.5-4.0		2010-2030	112 (100-127)	115 (99-127)	78 (51-94)
Category 4	4.0-5.0	RCP 4.5	2021-2058	118 (107-127)	129 (112-154)	118 (73-185)
Category 5	5.0-7.0	RCP 6.0	2050-2100	130 (115-145)	154 (132-175)	169 (132-207)
Category 6	>7	RCP 8.5	2050-2100	138 (127-150)	169 (146-188)	198 (166-219)

Stabilization will ultimately require dramatic changes in the world's energy system, including a dramatic expansion in the deployment of low-carbon energy sources. The rate of transformation will depend on the stabilization goal. In addition, mitigation pathways will be characterized by varying technology strategies across regions and over time; there is no single dominant technology strategy for mitigation. The deployment of low-carbon sources will be dramatically higher than current deployment of these same sources. *[High Agreement, Robust Evidence]*

Although macroeconomic costs are not necessarily the most fundamental decision-making criteria for the evaluation of transformation pathways, they are an important criterion and, in addition, they are an indicator of the level of difficulty or disruption that would be associated with particular transformation pathways.

Macroeconomic cost estimates for meeting stabilization goals vary widely, depending, among other things, on the nature of technological options, the underlying analysis approach, the policy options used for mitigation, the degree of international participation, and the nature of the drivers of emissions such as behavior, population growth, and economic growth. *[High Agreement, Robust Evidence]* The uncertainty in cost estimates is larger at deeper levels of reduction, because such estimates must be based on characterizations of energy and other systems that are very different from those of today. *[Medium Agreement, Medium Evidence]*

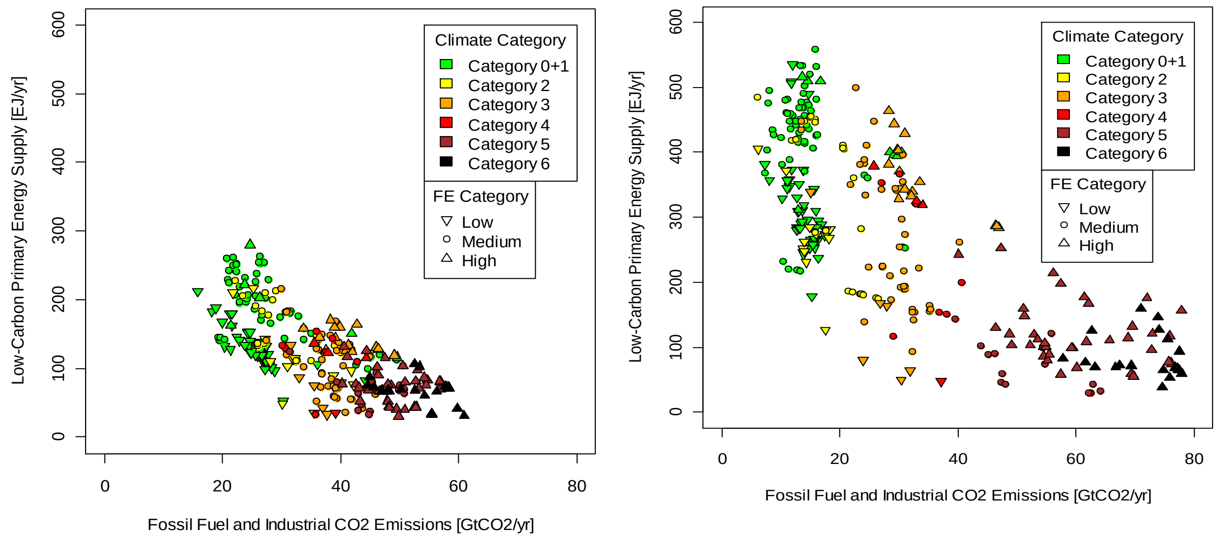

Figure 6.ES.1. Global low carbon primary energy supply (direct equivalent) in the reviewed long-term transformation pathways by 2030 (left) and 2050 (right) as a function of fossil and industrial CO2 emissions. The colour coding is based on categories of climate stabilization as defined in Section 6.2.2. [AUTHORS: Note to reviewers: This definition will be provided in the SOD; for now, the key point is that these final energy categories help to parse the space.]

Table 6.ES.2. Macroeconomic Costs of Transformation Pathways.

				Percentage Increase in Costs with Delayed Participation		Percentage Increase in Costs with Limited Technology		
Category	RF in 2100	Overshoot or Not-to-Exceed	Cost range in Idealized Scenarios	EMF 22	Other	No CCS	No New Nuclear	Limited Efficiency and Renewables
1	2.4 to 2.8	NTE						
		Overshoot						
2	2.8 to 3.4	NTE						
		Overshoot						
3	3.4 to 4.0	NTE						
		Overshoot						
4	4.0 to 5.0	NTE						
		Overshoot						
5	5.0 to 7.0	NTE						
--	> 7.0	NTE						

[AUTHORS: Note to Reviewers: To be Completed for the Second-Order Draft.]

All other things being equal, the costs of mitigation increase disproportionately with increasing stringency of the long-term stabilization goal. *[High Agreement,Robust Evidence]* In addition, limits on the availability of cost and performance of important mitigation technologies can substantially increase the costs of mitigation. For example, macroeconomic costs for scenarios without CCS and nuclear power are estimated to be as much as two to three times higher than comparable scenarios with full availability of these technologies [AUTHORS: Note to reviewers: Statement will be refined in second-order draft. See note in introduction on preliminary dataset.] *[Medium Agreement, Robust Evidence]*. Finally, approaches to mitigation that do not lead to emissions reduction where and when they are least expensive – as would happen in regimes in which some countries act earlier than others – can dramatically increase the macroeconomic costs of stabilization, and therefore indicate substantially greater challenge in meeting these goals. *[High Agreement, Robust Evidence]*

Technology alone will not stabilize greenhouse gas concentrations. Virtually all baseline scenarios in the literature include substantial improvements in technology. Yet virtually all baseline scenarios lead to radiative forcing above 5.0 W/m2 by the end of the century and rising. *[High Agreement, Robust Evidence]*

Many integrated models are unable to produce scenarios that lead to 2.6 W/m2 stabilization when there are limits on technology availability or non-idealized policy regimes in which some countries delay mitigation actions. *[High Agreement, Robust Evidence]* Although such model infeasibility does not provide a definitive assessment of real-world feasibility, except in very specific cases of actual physical infeasibility, it does provide an important indication of the challenge faced in meeting more challenging long-term stabilization goals.

A failure to include land use change emissions into the mitigation regime could dramatically increase the difficulty of meeting long term goals, and it could potentially lead to dramatic changes in the global land surface. *[High Agreement, Medium Evidence]*

Overshoot pathways toward stabilization allow for greater flexibility in near-term emissions. However, such pathways are characterized by radiative forcing levels that exceed the long-term goal for extended periods, with associated increases in climate change. Further, such pathways increased flexibility in the near-term implies deeper reductions in the long-term. The ability to store CO2 using bioenergy with CCS or other CDR technologies facilitates overshoot pathways, but overshoot pathways do not depend exclusively on bioCCS. *[High Agreement, Robust Evidence]*

6.1 Introduction

[AUTHORS: Note to reviewers. Much of the material in this chapter is based on a survey of scenarios collected in a database meant explicitly for use in Chapter 6 in AR5. This database is preliminary. This means that that the specific numbers in many of the figures are subject to change as we move from the first-order draft to the second-order draft. There are two reasons that this data set is preliminary. The first is that the authors of this chapter were only able to collect a portion of the available scenarios for this first-order draft. There will be a concerted effort to expand data collection efforts moving into the second-order draft and to have a more exhaustive and robust database of scenarios. The second reason that this data set is preliminary is that there are several important multi-model scenario development exercises currently underway that will be completed in time to meet the IPCC WGIII deadline but that are not yet publicly available. We have collected preliminary scenarios from these multi-model scenario exercises on a case-by-case basis and with the explicit permission by the associated authors to use such scenarios. Hence, many of these scenarios are reflected in the current draft, but many are not, and those that are reflected in the current draft may evolve as the associated studies move toward completion.

We would like to emphasize that despite the preliminary nature of the scenario ensemble data, the structure, key messages, and general themes of the chapter are not expected to change substantially moving to the second-order draft. Hence, we encourage reviewers to provide comments on the current draft acknowledging that the underlying dataset will be markedly improved going into the second-order draft, but also understanding that the structure, key messages, and general themes are not expected to change substantially based on the additional information we will collect for the second-order draft.]

Stabilizing greenhouse gas concentrations at a level that will prevent dangerous anthropogenic interference with the climate will ultimately require deep reductions in greenhouse gas emissions. CO2 emissions, in particular, must eventually be brought to or below zero. [Comment:

geoengineering; non-CO2s don't have to be brought to zero.] Emissions reductions of this magnitude will undoubtedly require large-scale transformations in human societies, from the way that we produce and consume energy to how we use the land surface. However, bringing CO2 emissions to zero is the long-term requirement, the timing of which depends heavily on the level at which greenhouse gas concentrations are eventually stabilized. All other things being equal, lower stabilization levels will require a more rapid transformation. A natural question in this context is what will be the transformation pathway toward stabilization; that is, how do we get from here to there?

The topic of this chapter is transformation pathways. In particular, the chapter is motivated by three questions at the core of decision-making regarding the timing and character of emissions mitigation. First, what long-term stabilization levels are feasible given current concentrations and the potential capabilities to reduce emissions? Second, what are the potential characteristics of transformation pathways – for example, emissions trajectories, macro-economic costs, energy systems transitions, land use patterns, co-benefits, and risks –that might lead to particular long-term stabilization levels? Finally, how do actions taken today influence the options to follow particular transformation pathways in the future?

Two concepts that emerge from the literature on transformation pathways are particularly important for framing any answers to these questions. The first of these concepts is there is no single pathway to stabilization of greenhouse gas concentrations at a level that will prevent dangerous anthropogenic interference with the climate. Instead, the literature on transformation pathways makes clear there are a range of such pathways, and choices will govern which pathway is followed in the end. These choices include, among other things, the long-term stabilization goal, the timing of the path to meet that goal and the degree to which concentrations might temporarily overshoot the goal, the technologies that will be deployed to reduce emissions, the degree to which mitigation is coordinated across countries, the policy approaches used to achieve these goals within and across countries, the treatment of land use, and the manner in which mitigation is meshed with other national and societal priorities such as energy security and sustainable development. Indeed, particularly given lack of knowledge today about how many important forces might evolve – for example, economic growth, population growth, technological change, and social and political change – it is not surprising that the literature on long-term transition pathways sketches out a wide range of often very different possible pathways that might be followed to meet any long-term stabilization goal.

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

A question that is often raised about particular stabilization goals and transformation pathways to those goals is whether the goals or pathways are "feasible". However, feasibility is often a subjective concept that is also best understood within this context of multiple pathways that can be distinguished by a range of characteristics. Although there are clear biogoephyiscal constraints that influence the physical feasibility of meeting particular long-term goals, particularly for pathways that do not "overshoot" the long-term goal, many evaluations of feasibility beyond these biogeophysical constraints are bound up in perceptions of the degree to which other characteristics of particular transformation pathways might influence the ability of, or desire of, human societies to follow them. Important characteristics include macro-economic costs, social acceptance of new technologies that underpin particular transformation pathways, the rapidity at which social and technological systems would need to change to follow particular pathways, political feasibility, and linkages other national priorities.

Although the topic of this chapter is long-term transformation pathways, decision-makers today can only make decisions today. A long-term perspective provides the context for near-term decisions, but many of the decisions associated with these pathways will take place beyond the reach of those making the decisions today. An important question for decision makers is therefore how near-term decisions will influence which transformation pathways could be followed by future decision makers. Some decisions may leave open a range of options, while others may constrain the future set of options for stabilization and approaches to stabilization. An important goal of this chapter is therefore to highlight the degree to which decisions today will influence the possibility of future transitions.

Actions to mitigate climate change are the result of choices. For decision makers to deliberate on choices today, they must understand the possible pathways to meet different concentration stabilization levels, the implications of these pathways for the many criteria by which they might be evaluated, and the linkage between actions today and the choices that will be present tomorrow. These are the organizing topics of this chapter. Within this framing, the remaining sections discuss the following specific topics: the tools that are used to project transition pathways (primarily large-scale integrated models); the counterfactual baseline projections of worlds without climate action that are used as the starting point for development of transition pathways and that help to define the space of possible transformation pathways; the broad suite of emissions pathways that might lead to different stabilization levels; the various characteristics of these pathways including associated economic costs, technology systems, land use and land use change, societal changes, national and international policy approaches, and linkages to sustainable development; the degree to which actions today influence the options to follow particular transformation pathways in the future; and the linkage between the high-level, long-term perspective in this chapter and nearer-term, bottom-up sectoral analyses.

6.2 Tools of Analysis

6.2.1 Introduction

The transformation pathway scenarios highlighted in this chapter were generated primarily by large-scale, integrated models. These models are designed to capture many of the key interactions among technologies, relevant human systems (e.g., energy, agriculture, the economic system), and between human systems and the important physical processes associated with climate change (e.g., the carbon cycle). The degree to which models capture these variations differs across models, with some focusing largely on key human systems such as the energy system and others including broader sets of systems. Regardless, capturing these interactions is important as they define the environment in which human societies might undertake mitigation and provide an important degree of internal consistency. In addition, these integrated models explore interactions over at least several decades to a full century into the future and at a global scale. This degree of spatial, sectoral, and temporal coverage is crucial for establishing the strategic context for transformation pathways.

However, the use of large-scale IAMs also comes with weaknesses. Most importantly, maintaining a long-term, integrated, and often global perspective involves tradeoffs in terms of detail. For example the models included in this chapter do not represent all the forces that govern decision making at the national- or even the firm- or individual-scale, in particular in the short-term. Similarly, these models must work at a more aggregate level than, for example, power-system models or engineering models, and must therefore employ stylized representations of many details that influence the deployment and use of technologies. More broadly, these models typically assume market behavior, thus non-market factors influencing decisions are not effectively represented. Finally, these models are not built to capture many social and political forces that can influence the way the world evolves (e.g., shocks such as the oil crisis of the 1970s). An outcome of these simplifications is that these models are most useful for generating integrated global and regional scenarios in the medium- and long-term, e.g., beyond the year 2020. For shorter time horizons, market analyses or short-term national analyses that explicitly address all existing policies and regulations are likely more suitable tools of analysis.

6.2.2 Uncertainty and the interpretation of large scenario ensembles

The interpretation of large ensembles of scenarios from different models, different studies, and different versions of individual models is a core component of the analysis of transformation pathways in this chapter. This interpretation must be handled carefully. There is an unavoidable ambiguity in interpreting these ensembles in the context of uncertainty and prediction. On the one hand, scenarios generated from these models and explored in this chapter do not represent a random sample of possible scenarios that can be used for formal uncertainty analysis. Each scenario was developed for a specific purpose and therefore 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 related. In addition, some modeling groups have generated substantially more scenarios than others. Indeed, most of the scenarios included in this chapter were generated as part of model intercomparison exercises which impose specific assumptions, often regarding long-term goals policy approaches to mitigation, but also in some cases regarding fundamental drivers like technology, population growth, and economic growth. 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 the scenarios should not be interpreted as representing a truly random sample, that does not mean that they do not contain information about uncertainty. In scenario ensemble analyses such as this, it is important to acknowledge the tension between the fact that, on the one hand, the associated scenarios are not truly a random sample with explicit information on uncertainty and, on the other hand, the fact that the variations among the scenarios is largely a result of our lack of knowledge about key forces that might shape the future. Hence, although they are not explicitly representative of uncertainty, they do provide real and often clear insights about uncertainty. (Krey and Clarke, 2011a).

6.2.3 Interpretation of model infeasibility

As noted above, a question that is often raised about particular stabilization goals and transformation pathways to those goals is whether the goals or pathways are “feasible.” Scenarios generated from models can be helpful in assessing feasibility, but they are generally most useful in providing inputs to assessments of feasibility rather than providing a definitive answer. This is particularly true given that the models used to generate transformation pathways typically do not consider many societal and political factors that are relevant to assessments of feasibility (Bosetti et al. 2010; (Ha-Duong, 1997).

At the same time, it is also true that particular stabilization goals may be infeasible in the case of particular models under particularly aggressive stabilization goals or particularly challenging technological or policy constraints. Model infeasibility will arise repeatedly in this chapter, and it must be interpreted carefully. Model infeasibility is an important input to our understanding of real-world feasibility, however, it is generally not definitive. In some cases, model infeasibility provides a clear indication of real-world infeasibility, as is the case, for example, when a particular not-to-exceed radiative forcing target is exceeded prior to the initiation of mitigation. However, in many cases, model infeasibility only provides a rough indicator of the challenge associated with meeting a particular stabilization goal, and it should be interpreted as such. Model infeasibility may be due to failures in the solution mechanism for particularly challenging scenarios, constraints on the rates at which models can retire or add new equipment, or exceedingly high prices in the model (Clarke et al., 2009). Although these are all factors that influence subjective assessments of the challenge associated with meeting particular stabilization goals, the results are all dependent on model assumptions and model construction. Indeed, in many cases, one model may be able to produce scenarios while another will not.

6.2.4 Key Characteristics of Integrated Assessment Models

Modeling approaches to generate transformation pathways can be very different, and these differences can have important implications for the scenarios that emerge from models. The remainder of this subsection highlights key differences in model characteristics and their implications for model results below. Models producing scenarios reviewed in this chapter are provided in Table 6.1.

Economic coverage, interactions, and associated mitigation cost measures: One of the more important ways that models differ is in terms of the degree of detail with which they represent the economic system and the degree of interaction they represent across economic sectors. For understanding the scenarios in this chapter, it is useful to separate the models into two categories. General equilibrium (GE) models capture all sectors of the economy. Partial equilibrium (PE) models, on the other hand, only capture a subset of economic sectors. Most commonly, PE models focus on the energy sector, and sometimes also on the agriculture and forestry sectors, given the important role that these sectors play in climate mitigation. A perturbation due, for example, to the imposition of a carbon policy, will have ripple effects throughout the economy. A GE model will capture these ripple effects and generate an overall impact on economic growth. A PE model, on the other hand, is unable to capture the full economic impact of policy, as the economic growth path is exogenous and therefore unresponsive to policy or other changes to the scenario such as those associated with improvements in technology. This means that GE models can provide a range of cost and welfare measures, including implications for GDP or consumption, whereas PE models must use a smaller set of cost metrics, such as the area under the marginal abatement cost function. The implications of the two approaches on the cost of mitigation are less clear. On the one hand, because a GE models includes feedbacks to the full economy, costs should be higher in GE models than in PE models. On the other hand, GE models may include more possibilities for substitution in sectors outside of those represented in PE models, and this would tend to reduce costs. This issue is discussed in more detail in Section 6.2.4.

Foresight: Models also differ in the degree to which the future is considered when making current decisions. Models with perfect foresight (i.e., a model with intertemporal optimization) 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. Thus, a model with perfect foresight will have lower economic costs from a carbon tax than a recursive dynamic model. The trajectory of emissions will also be different between a perfect foresight model and a dynamic recursive model. This is driven by how investment is determined in each of the models. Investment in a model with intertemporal optimization is influenced by the rate of time preference, the curvature of the utility function, and the terminal year condition. In a dynamic recursive model, investment is typically determined by a fixed savings rate or by equating the marginal propensity to consume and the marginal propensity to invest. As a result of the discounting influences associated with the rate of time preference and diminishing marginal utility, consumption tends to be higher and investment tends to be lower in the earlier years in a model with intertemporal optimization than in a dynamic recursive model.

Representation of trade: There are a number of ways trade can be represented in models, each with an implication for the cost of reaching a particular stabilization target. Compared to the other approaches, modeling trade assuming goods are homogeneous and traded at one world price (Heckscher-Ohlin) or assuming one global producer (quasi-trade) will result in lower cost to meet a stabilization target because perfect substitutability of goods across regions is assumed. On the other end of the spectrum, models assuming imperfect substitution between imported and domestically produced goods (Armington) or incorporating region-specific supply curves where instead of explicit trade across regions, each region has an import supply curve will result in higher cost of reaching the stabilization target. This ranking reflects how easy it is for goods to flow across regions. Additionally, modeling trade of both energy and non-energy goods will result in more flexibility and thus lower cost than if only one or the other was traded

Model flexibility: Greater capital mobility implies that the model can more easily adjust to policy. Thus, reaching a stabilization target or responding to a carbon tax will lead to lower economic costs than a model with less capital mobility, sector-specific capital, or capital vintaging.[1] All else equal, greater substitutability across energy technologies will result in lower cost of abatement. Elasticity of substitution across energy technologies in a nested CES structure is one way to define this ease of substitutability, but other important factors influencing this substitutability is the existence of technology specific fixed factors (e.g., uranium in the case of nuclear) and the elasticity of the supply curve for this fixed factor. Because of the existence of a fixed factor, output of this energy technology will not be as dependent on factors such as capital and labor that are demanded by other producing sectors. The existence of fossil fuel resource constraints will dampen the use of the resource and thus lead to lower baseline emissions. This will mean that a stabilization target will be easier to achieve. However, it isn't just whether a resource constraint exists or the depletion of resources is modeled. It also depends on the how the constraint is modeled—e.g., supply curve—and what supply elasticity is implied.

Sectoral, regional, and technology detail. Models with one monolithic economic sector are implicitly assuming perfect substitutability across subsectors. Thus, factors such as capital and labor can flow freely across subsectors. Adding sectoral detail reduces this mobility since CES production functions are typically assumed which imply non-perfect substitutability. As a result, reaching a stabilization target or imposing a carbon tax will be more costly in a model with more sectoral detail since it is more difficult to reallocate factors of production to less carbon intensive sectors. The same flexibility story applies when we consider regional detail. Reallocation across regions is easier if there is only one global region. Adding regional detail, through the Armington trade structure, means we are unable to freely reallocate resources across regions. Thus, reaching a stabilization target or imposing a carbon tax will be more costly in a model with more regional detail. Similarly, less energy detail would imply more substitutability across energy types.[2] Thus, meeting a stabilization target or imposing a carbon tax on a model with more energy detail will result in a larger impact on the economy than a model with less energy detail. Lastly, more GHG detail in the model can imply two things. First, including non-CO_2 gases would mean there would be another source of abatement options to meet a specific stabilization target. This will lower the cost of abatement. However, including non-CO_2 gases would mean that a policy targeting emissions (both CO_2 and non-CO_2) would be more costly than a policy just targeting CO_2 emissions.

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[1] This may not necessarily be the case with sector-specific policies (see Lanzi and Sue Wing (2012))

[2] An energy sector with a nested Cobb-Douglas production function or a CES production function with infinite elasticity (i.e., perfect substitutability) would both result in one monolithic energy sector.

Table 6.1. Characteristics of a sample of models generating transformation pathways

Model	Economic coverage and feedback	Foresight	Optimization / Simulation	Representation of trade	Model flexibility	Sectoral, regional, energy, and GHG detail	Cost measures
AIM-Enduse	Partial equilibrium	Myopic	Optimization	Trade in primary and secondary energy	(1), (2), (3), (5)	24 (energy-related) sectors; 32 regions; 5 GHGs	Energy system cost mark-up
DNE21	Partial equilibrium	Intertemporal optimization	Optimization	Trade in primary and secondary energy	(2), (3), (5)	4 sectors; 10 regions; 13 GHGs	Energy system cost mark-up
GCAM	Partial equilibrium	Myopic	Optimization	Trade in energy and non-energy goods	(1), (2), (5)	11 sectors; 14 regions; 13 GHGs	Area under marginal abatement cost curve
IMACLIM	General equilibrium	Myopic	Optimization	Trade in all goods	(1), (2), (3), (5)	12 sectors; 12 regions; CO2 only	Welfare loss, GDP loss, consumption loss, equivalent variation
MESSAGE	General equilibrium	Intertemporal optimization	Optimization	Trade in primary energy, secondary energy, and energy goods	(1), (2), (3), (5)	1 sector; 11 regions; 13 GHGs	Consumption loss, GDP loss, energy system cost mark-up, area under marginal abatement cost curve
Phoenix	General equilibrium	Myopic	Optimization	Trade in all goods: H-O (oil and gas); Armington for all other goods	(4), (5)	27 sectors (5 energy); 24 regions; CO2 only	Welfare loss, GDP loss, consumption loss, equivalent variation
POLES	Partial equilibrium/ econometric	Myopic	Simulation	Trade in primary energy, secondary energy, and energy goods	(2), (3), (4), (5)	15 sectors; 7 regions; 6 GHGs	Area under marginal abatement cost curve
ReMIND	General equilibrium	Intertemporal optimization	Optimization	Trade in energy and non-energy goods	(1), (5)	1 sector; 11 regions; 5 GHGs	Consumption loss, GDP loss, welfare loss
TIAM-ECN	Partial equilibrium	Intertemporal optimization	Optimization	Trade in primary and secondary energy and energy goods	(3), (5)	5 sectors; 15 regions; 3 GHGs	Energy cost increases; energy system cost mark-ups
WITCH	General equilibrium	Intertemporal optimization	Optimization	Trade in oil and non-energy goods	(3), (4), (5)	3 sectors; 13 regions; 6 GHGs	Consumption loss, GDP loss, welfare loss, energy system cost mark-ups

(1) Discrete technology choices with high substitution; (2) system integration constraints on energy technology substitution; (3) expansion and decline constraints on energy technology substitution; (4) discrete technology choices with low substitution; (5) resource constraint.

6.2.5 Overview of the scenario ensemble for this assessment

[AUTHORS: To be completed in the next draft.]

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

6.3.1 Baseline Scenarios

6.3.1.1 Introduction to baseline scenarios

Baseline scenarios are projections (not a predictions or forecasts) of greenhouse gas emissions and their key drivers, including growth population, economic output, energy demand, and technology availability, as they might evolve in a future with no explicit policy intervention, or with only specific (e.g. already enacted) policies applied. Baseline scenarios play the important role of establishing the projected scale and composition of the future energy system as a reference point for measuring the extent and nature of required mitigation for a given physical stabilization target. Accordingly, the resulting estimates of mitigation effort and costs in a particular stabilization scenario are always conditional upon the associated baseline. Despite the large uncertainty in projecting economic activity and technological progress over a century or more, analysis over these timeframes is necessary to fully assess the human and Earth system processes involved in climate stabilization. Although the range of baseline scenarios in the literature is broad, it may not represent the full potential range of possibilities. Moreover, it is not meaningful to assign probabilities to emissions paths in the literature range.[3] Most modelling studies are anchored on baseline scenarios intended to reflect median or 'best-guess' pathways for key emissions driver pathways, although recent exercises have included some sensitivity cases with faster declines in energy intensity.[4]

6.3.1.2 Baseline emissions and radiative forcing projections

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

[3] One reason it is not meaningful to assign probabilities based on frequency in the literature is that some models publish more scenarios than others, which introduces an arbitrary weighting. More generally, the choices made by the community of modeling teams do not constitute a statistical sample.

[4] One reason the range in the literature should not be interpreted as encompassing the full set of possibilities is that corresponding sensitivities with slower energy intensity decline are not systematically analyzed.

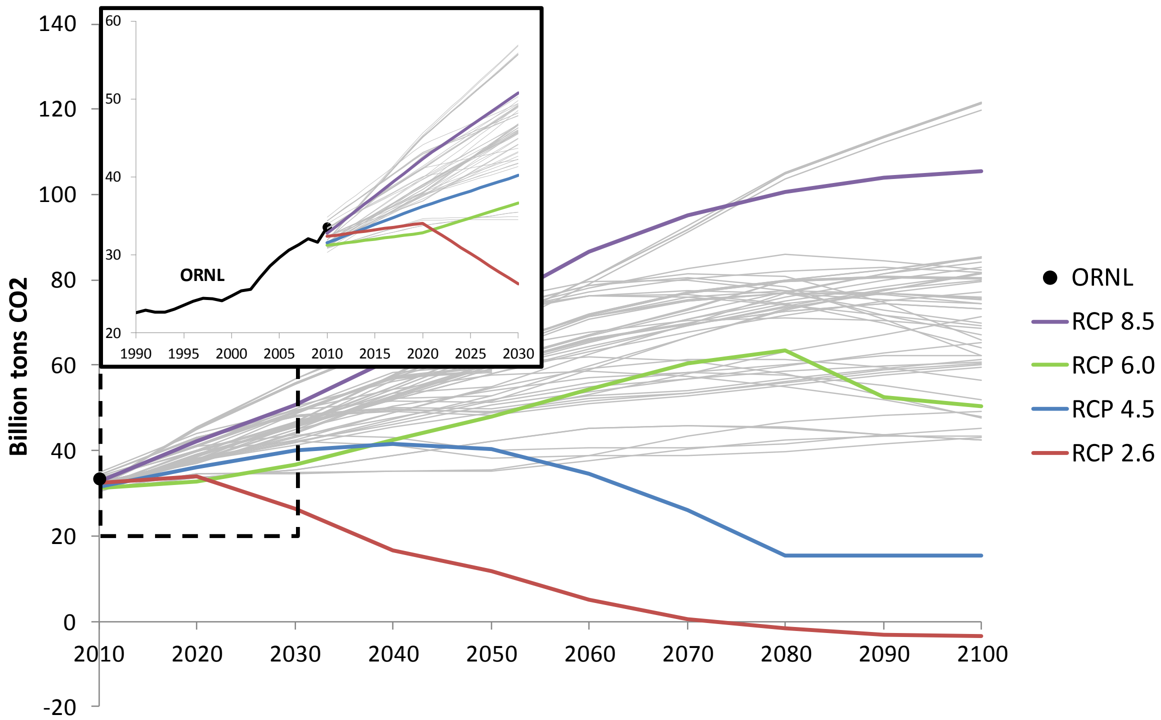
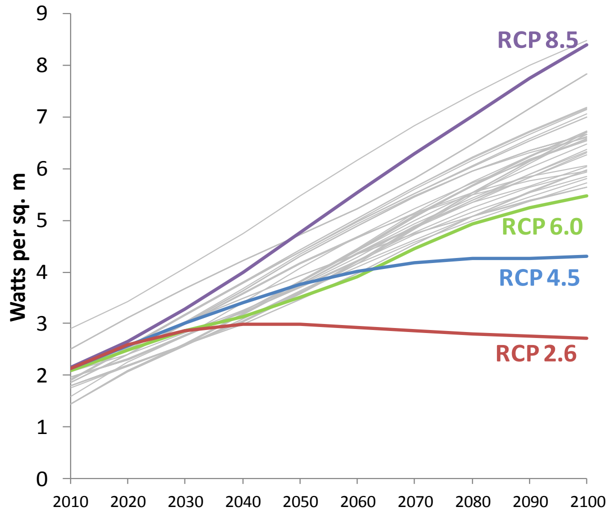


Figure 6.1. Global emissions of fossil and industrial CO2 in recent baseline scenario literature (grey lines) compared to history (ORNL) and RCP scenarios (RCP, 2009). [AUTHORS: Note to reviewers: Please see discussion of preliminary dataset in the introduction.]



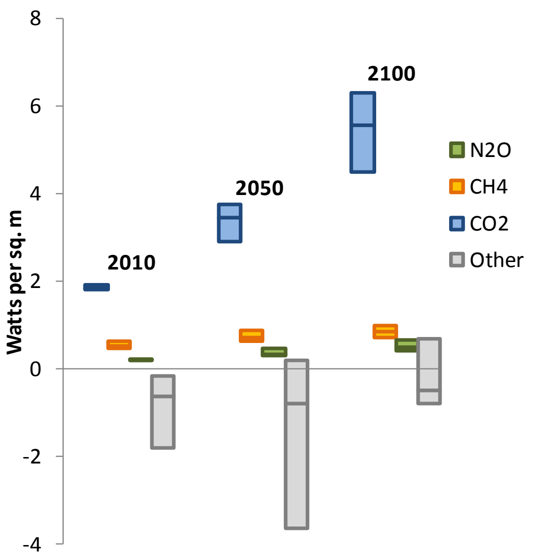


Figure 6.2 (left). Total radiative forcing in baseline scenario literature compared to target stabilization levels associated with the RCP scenarios. [AUTHORS: Note to reviewers: Please see discussion of preliminary dataset in the introduction.]

Figure 6.3 (right). Median and range of baseline radiative forcing by component. Other includes other gases and non-gas forcing agents. [AUTHORS: Note to reviewers: Please see discussion of preliminary dataset in the introduction.]

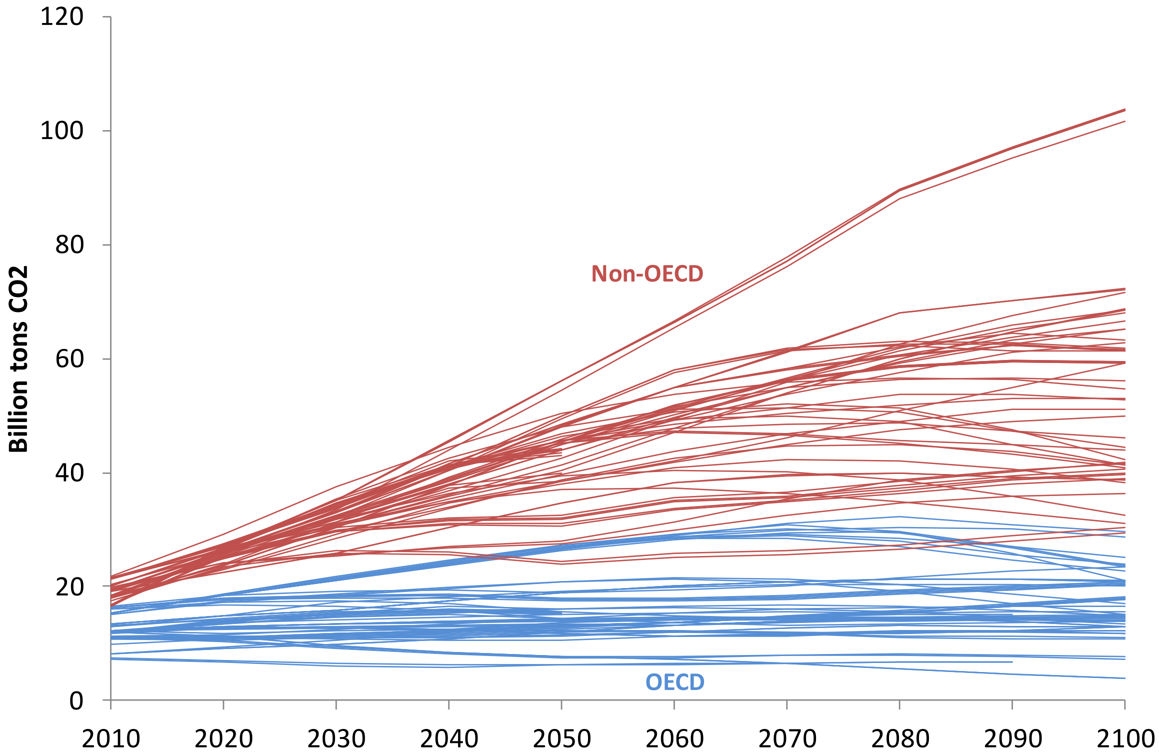


Figure 6.4. Comparison of OECD (in blue) and non-OECD (in red) fossil and industrial CO2 emissions projections in baseline scenario literature. [AUTHORS: Note to reviewers: Please see discussion of preliminary dataset in the introduction.]

As a result of increasing emissions, radiative forcing continues to grow throughout the century in the baseline, far exceeding the more stringent range of potential stabilization goals (Figure 6.2)**.** In all cases, radiative forcing exceeds the target stabilization levels of 3.7 W/m2 (which corresponds to 550 CO2-e) between 2040 and 2050, and the 2.6 W.m2 level (which corresponds to 450 CO2-e) is surpassed between 2020 and 2030. Forcing in the baseline grows at a roughly linear rate of 0.5 W/m2 per decade across all literature scenarios, with the dominant share from CO2. There is significant discrepancy as to the current level of total forcing, primarily due to uncertainty about the contribution of aerosols and other non-gas agents (Figure 6.3) but likely also due in part to differences in calibration data sources. All of the reference scenarios discussed here include improvements to technology (as discussed in the next section as well as in Section 6.4), which are often quite substantial. Thus there is strong evidence that technological change in the absence of explicit policy intervention is not sufficient to bring about stabilization of greenhouse gas concentrations.

A result that is robust across all baseline scenarios is that the majority of emissions over the century occur in those regions currently outside the OECD (Figure 6.4). This group consists of China, India, Russia, Brazil, South Africa, Indonesia and other developing countries throughout Asia, Latin America, and Africa. Because of its large and growing population and rates of economic growth relatively faster than the industrialized OECD countries, this group of regions is almost certain to have the dominant share of world energy demand over the course of the next century. Although the regional definitions employed by integrated assessment models vary considerably, most allow a similar separation of projections into the OECD group and the non-OECD group. While emissions in the OECD remain roughly constant, nearly all growth in future baseline emissions is projected to occur in the non-OECD countries.

6.3.1.3 The drivers of baseline emissions

The wide range of baseline emissions paths seen in the literature, while not suggestive of the full uncertainty range, reflects different assumptions across the modelling community on certain key parameters. Figure 6.5 highlights this decomposition for four major regions, which include two post-industrialized economies experiencing relatively slow growth and two emerging economies with much more rapid growth, provides a good synopsis of the factors driving variation in model baselines (see (Blanford et al., in press). There is comparatively little variation across model scenarios in projected population growth, with many models relying on the same reference projection from the United Nations. However, there is substantial variation in the projections of per capita income and energy intensity, particularly in China and India. All models assume increasing per capita income and declining energy intensity, thus the relative strength of these two opposing effects, which is embodied by per capita energy, plays the most important role in determining the growth of emissions in the baseline. The carbon intensity of energy is projected in most baseline scenarios to change little over time. Although there are a few exceptions in which renewable energy sources become competitive without policy incentives (usually due to a combination of aggressively declining technology costs and steeply rising fossil fuel prices driven by scarcity), most models project the current share of fossil-based energy to persist. In a few baseline scenarios, the fossil mix becomes more carbon intensive, for example due to replacement of conventional petroleum with heavier oil sands or coal-to-liquids technology.

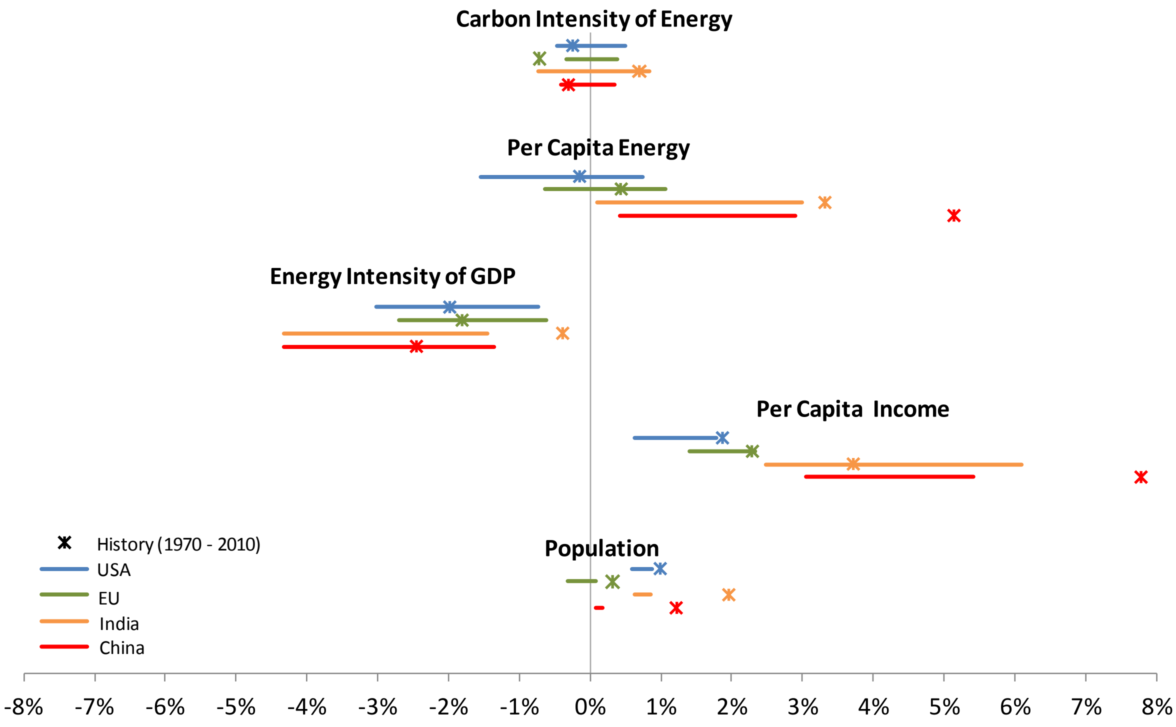


Figure 6.5. Range of average annual growth rates between 2010 and 2050 for Kaya decomposition indicators in baseline scenario literature. [AUTHORS: Note to reviewers: Please see discussion of preliminary dataset in the introduction.]

Figure 6.6 shows baseline scenario projections for average annual growth rates between 2010 and 2050 of per capita income growth and energy intensity decline simultaneously. The range projected in both dimensions is larger, and shifted towards higher rates, for the two emerging economies. There is a mild correlation between the two indicators, suggesting that baseline projections with faster growth in income also assume faster decline in energy intensity. The diagonal lines indicate isoquants for per capita energy growth rate. It is interesting to observe that for a given rate of growth in per capita energy (a strong determinant of baseline emissions), models vary widely across the spectrum of low-income / high-intensity (upper left) to high-income / low-intensity (lower right). This suggests that different development storylines could underlie the same emissions path.

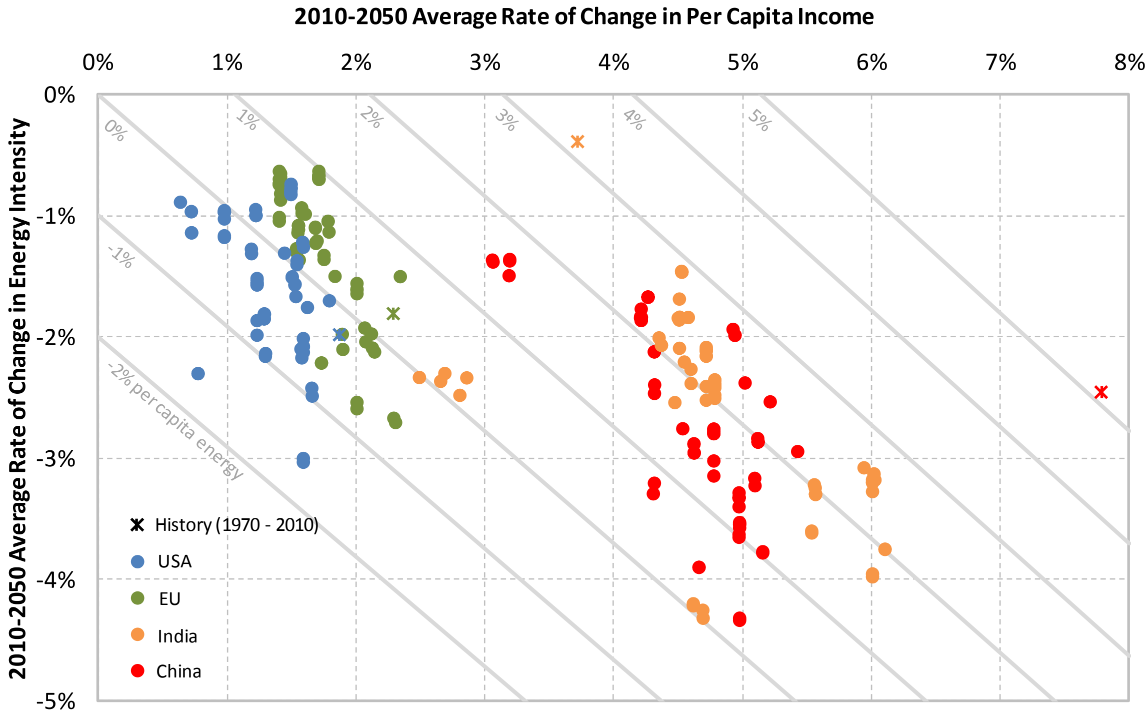


Figure 6.6. Comparison of average annual rates of change in per capita income, energy intensity of GDP, and per capita energy between 2010 and 2050 in baseline scenario literature. [AUTHORS: Note to reviewers: Please see discussion of preliminary dataset in the introduction.]

Changes in aggregate energy intensity over time in baseline model scenarios are the net result of several individual trends, including both improvements in end-use energy efficiency of technology and structural changes in the composition of energy demand. Structural changes can work in both directions: there may be increased demand for energy-intensive services such as air-conditioning as incomes rise, while on the production side of the economy there may be shifts to less energy-intensive services as countries become wealthier. Although increasing energy intensity has been observed for some countries during certain stages of development, the net effect is usually negative, and in general energy intensity has declined consistently over time (see Chapter 5). Both technological and structural change can be driven by changes in energy prices, but to a significant extent both are driven by other factors such as technical progress and changing preferences with rising incomes.

Most integrated assessment models are able to project structural and technical change only at an aggregate level, although some include explicit assumptions for certain sectors. More detailed projections for the possible evolution of energy intensity at the sectoral level are discussed in Chapters 8, 9, and 10 on transportation, buildings, and industry, respectively. The relationship between these bottom-up assessments and the assumptions made by integrated assessment models is discussed below in Section 6.7. [AUTHORS: Note: may be useful to add a baseline subsection in 6.7.]

6.3.2 Overview of Stabilization (including overshoot pathways)

6.3.2.1 Comparing Different Types of Stabilization Scenarios

The goal of international climate policy as defined in UNFCCC art.2 is to stabilize greenhouse gas concentrations at a level that avoids dangerous anthropogenic interference of the climate system

(UNFCCC, 1992). Consistent with this UNFCCC goal, the analysis of transformation pathways in this assessment focuses on those that lead to stabilization of greenhouse gas concentrations or associated radiative forcing. The majority of scenarios in the literature are also focused on stabilization of greenhouse gases or radiative forcing. However, it is important to note that there are types of long-term scenarios, including those that concentrate on temperature stabilization (see Section 6.3.2.5) and those that explicitly balance the costs and benefits of climate mitigation (see Section 6.3.3). Another important distinction between transformation pathways is whether the pathways exceed the long-term radiative forcing goal before decreasing to meet that goal (overshoot scenarios) or whether radiative forcing never exceeds the long-term goal (not-to-exceed scenarios).

There is no unique definition of greenhouse gas concentrations, and the way models handle stabilisation targets differs across models. Some use a full forcing approach while other models lack a representation of other greenhouse gases or even a carbon cycle and thus use intermediate products such as cumulative emissions as target. The manner in which the target is formulated can be very important for mitigation strategy. For example, more inclusive definitions allow for substitution among the gases (exploiting the so-called what flexibility) (e.g. as explored in EMF-21, (Weyant et al., 2006) but also have consequences for timing (aerosols provide a negative forcing offsetting the GHG forcing, but this negative forcing is likely to be reduced) (e.g. Van Vuuren and Riahi, 2011).

Scenarios base on different targets are not strictly comparable, and comparing among them provides substantial challenges. Realizing the limitation, for this synthesis we have grouped the scenarios into 6-7 categories, based on the radiative forcing level in 2100, and linked to other goals such as CO2 concentrations of cumulative CO2 budgets (**Table 6.2**). These scenario categories are consistent with the four RCPs and therefore provide a means for linkage between the three working groups in AR5. Far more low-stabilization-goal scenarios are now available than during AR4 (the assessment at the time included only 6 scenarios from 3 model groups).

Table 6.2. Categories of scenarios and the approach to comparing across scenarios with different long-term goals.

	Radiative forcing	RCP	CO2 budget (2000-2100)	No of scenarios	2100 CO2 concentration	CO2 forcing
Cat 0.	<2.5		<1000		380	
Cat 1.	2.5-3.0	RCP2.6	1000-1600	140	400	2.0
Cat 2.	3.0-3.5		1600-2150	48	410	2.1
Cat 3.	3.5-4.0		2150-2750	85	470	2.8
Cat 4.	4.0-5.0	RCP4.5	2750-3850	22	560	3.7
Cat 5.	5.0-7.0	RCP.6	3850-6150	78	700	4.9
Cat 6.	>7	RCP8.5	>6150	36	800	5.6

[AUTHORS: A note to reviewers: In the next draft, we will distinguish more clearly between not-to-exceed and overshoot scenarios in the binning of scenarios. In addition, we will more clearly explain how the way that scenarios with different targets were linked together; that is, how the table was developed.]

6.3.2.2 The timing of emissions reductions for transformation pathways

A crucial question with respect to long-term emission reductions is the timing of emission reductions. Many models use some form of optimization to determine emission pathways over time – either by formal intertemporal optimization or by, for instance, prescribing the Hotelling rule for the carbon price[5]. In any case, factors that determine the optimality of timing include the valuation of future costs versus current costs, the allowance of overshoot, transition rates and the assumed technology portfolio. With respect to the technology mix, especially, the combination of bio-energy and carbon capture and storage (BECCS) has shown to play an important role in overshoot scenarios (see below), since it permits to reach negative CO2 emissions in the long term (van Vuuren et al., 2007; Edenhofer et al., 2010; Azar et al., 2010). This allows compensating higher emission level in the 2010-2050 period.

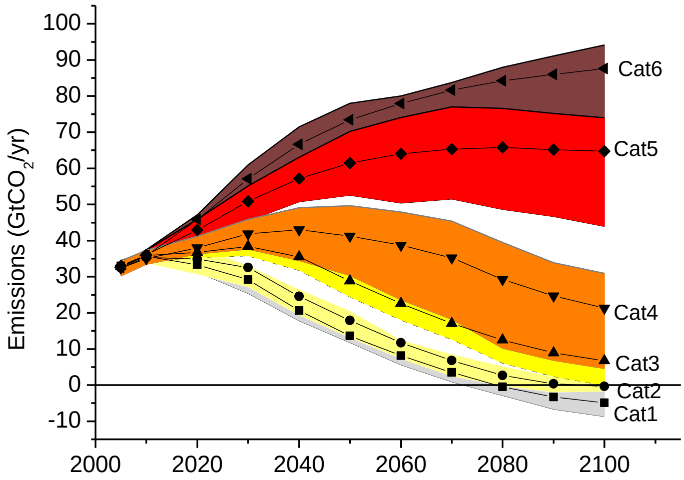


Figure 6.7. CO_2 emission pathways of the various categories. [AUTHORS: Note to reviewers: We aim to distinguish overshoot in this and subsequent figures and Table 3. The results of category 2 are now very close to those of category 1. This is likely to be a sampling issue. We will look into this in the next draft when we have a larger sample size to work with and when we distinguish between overshoot and not-to-exceed scenarios].

Table 6.3. Characteristics of scenario categories. [AUTHORS: Note to reviewers: Please see discussion of preliminary dataset in the introduction.]

	Peak	Emissions level (2005 = 100)		
		2020	2030	2050
Category 1	2010-2020	101 (87-120)	87 (70-115)	38 (27-47)
Category 2	2010-2020	105 (90-122)	97 (72-134)	47 (33-73)
Category 3	2010-2030	112 (100-127)	115 (99-127)	78 (51-94)
Category 4	2021-2058	118 (107-127)	129 (112-154)	118 (73-185)
Category 5	2050-2100	130 (115-145)	154 (132-175)	169 (132-207)
Category 6	2050-2100	138 (127-150)	169 (146-188)	198 (166-219)

Table 6.3 and **Figure 6.7** show key characteristics of the different scenarios. Cumulative emissions over the period up to 2050 or 2100 as actually been proposed to form the basis for climate policy

[5] The latter assumes that the carbon price increases with the discount rate over time. It has been shown for simple models that describe the climate problem as a simple extraction problem, that this is the optimal result. There are, however, reasons why some more complicated models may get a somewhat different result, including constraints in emission reductions, learning dynamics and additional criteria and dynamics in the climate system (e.g. no overshoot).

(Allen et al., 2009; Meinshausen et al., 2009). Scenarios in the lowest category show obviously the most ambitious emission reduction strategy. On average, scenarios in this category show a peak in global emissions before 2020 and emission reductions of 50 to 70% by 2050 (compared to 2005). The 2020 emissions of these scenarios vary around the 2000 level. For category II, the observed features in 2020 are not very different from category I. After 2020 more differences can be noted. For the third category, the 2020 emissions are about 12% above the 2005 level. In 2050, quite a wide reduction range is shown ranging from 0-50%. The higher categories of stabilization scenarios have subsequently higher emissions. In particular, category 5 and 6 are in the short-run not very different from baseline emission pathways.

There are several reasons for the wide ranges noted in **Table 6.3** and Figure 6.7. Models differ, among other things, in technology representations (Section 6.2.7), socioeconomic drivers (Section 6.2.1), and economic consequences of climate policy (Section 6.2.4). This implies that models will make different trade-offs across time and across different gases. Clearly, this corresponds to a similar flexibility in the real world, where policy-makers somehow need to find an desirable trade-off between the probability of reaching climate targets, climate risk, the ability to reduce short-term emissions, costs, and the uncertainty of long-term technology performance. Some differences in results across IAM models might be directly related to the representation of the climate system in these models (van Vuuren et al., 2009).

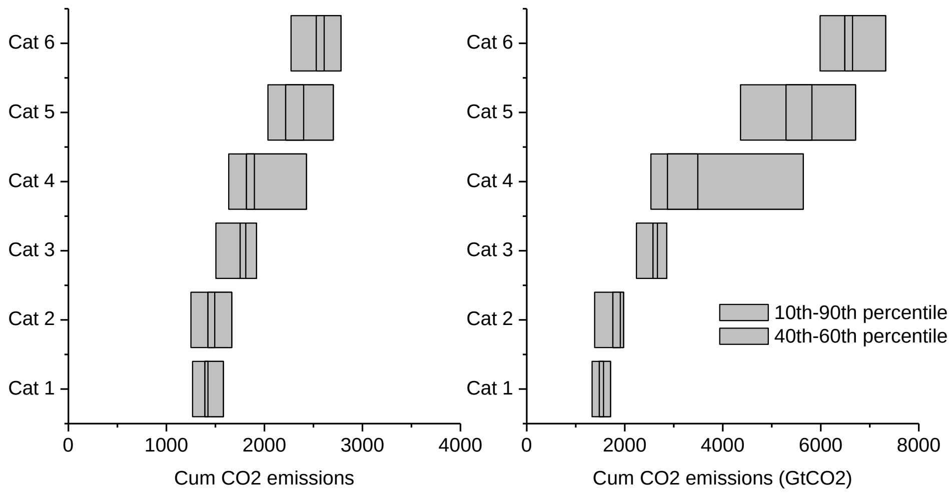


Figure 6.8. Cumulative CO2 Emissions 2000-2050 and 2000-2100. [AUTHORS: Note to reviewers: Please see discussion of preliminary dataset in the introduction.]

6.3.2.3 The allocation of emission reductions among radiatively important substances

In the construction of transformation scenarios, emission reductions are allocated across different gases and therefore across different sectors based on the costs and potential for emission reductions measures. Because different scenarios and models are based on different assumptions about costs and potentials, transformation pathway scenarios differ in terms of the reductions in these gases (**Figure 6.7**). Although emission reductions of CO_2 shown to be correlated with the different mitigation categories (see the previous sections), the correlation is less strong for CH_4 and N_2O. There are several reasons for this. First, CO_2 emissions dominate total forcing (Section 6.2.1), and therefore its emissions need to correlate well with the categories. Second, the emissions of CH_4 and N_2O are expected to increase less rapidly in the future (Section 6.2.1). Third, most studies expect that while there are cheap options to reduce non-CO_2 gases on the short-term, the emission reduction is severely constrained by several hard to mitigate sources such as lifestock and emissions associated with fertlizers. Nonetheless, CH_4 and N_2O emissions roughly correlate with the CO_2

emissions. For f-gases, the less ambitious mitigation scenarios expect a very rapid growth of emissions. For the lowest categories, this emission growth is significantly reduced, but emissions are not reduced further than the 2005 emission level.

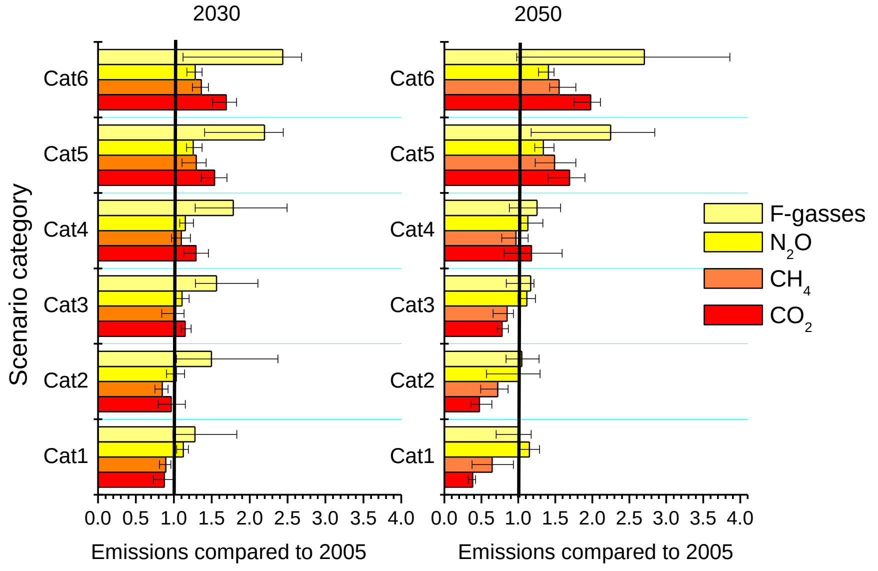


Figure 6.9. Emissions reductions in greenhouse gases in 2030 and 2050 across scenarios.
[AUTHORS: Note to reviewers: Please see discussion of preliminary dataset in the introduction.]

An additional key factor explaining the reduction across different gases is the way that emissions reductions from non-CO2 greenhouse gases are incorporated into the economic decision making for reductions. Many models allocate emission reductions on the basis of GWPs, similar to current climate policies. Recently some papers have looked into the impact of changing this metric from SAR to AR4 values [results will be included in next version]. In this case, the marginal price of emissions reductions for the non-CO2 greenhouse gases is simply a multiple of the CO2 price and rises and falls proportionally with the CO2 price. There are also models that determine the relative reduction of different gases based on the overall cost optimization across time. If the latter approach is applied toward long-term radiative forcing goals, the emissions of short-lived gases tends to be postponed compared to models using GWPs. Several alternative ways of optimizing the contribution of short and long-lived gases have been proposed, including the use of alternative metrics (such as the GTPs) and excluding short-lived gases from the overall portfolio (Shine et al., 2007). Research is going on in looking to the issue of allocation across gases from different angles. For instance, it has been argued that if might be attractive to focus more on climate forcing agents that also cause air pollution (black carbon and ozone precursors such as methane) (UNEP and WMO, 2011). A similar strain of research is to see whether air pollution policies can be formulated in such a way that it does not work against climate policy (in other words, making sure that emission reductions of sulphur coincide with those of positive forcing agents like black carbon and ozone precursors).

6.3.2.4 Negative emissions and overshoot stabilisation pathways

Overshoot scenarios allow for less aggressive mitigation in the near-term but then call for more severe reductions in the long-term. The long-term impact of climate change correlates well with CO_2 emission budgets, either over the entire 21st century or even the 2000-2050 emissions (Allen et al., 2009; Meinshausen et al., 2009). This implies a rather stringent coupling of short-term action to long-term concentrations, unless net anthropogenic CO_2 emissions can be negative so that concentrations can be reduced much faster than through the natural carbon cycle. In such a situation overshoot pathways are substantially advantaged by the presence of technologies that will allow for negative emissions.

Technologies for producing negative emissions are sometime referred to as Carbon Dioxide Removal (CDR) technologies, and they include a very wide range of technologies, including those comparable to normal mitigation options such as biomass energy with carbon storage (BECS) and reforestation as well as options such as ocean iron fertilization, biomass burial, and direct air capture (some of these technologies are discussed in more detail in Section 6.8). With the exception of BECCS and afforestation the recent integrated assessment and scenario literature has minimal treatment of CDR or SRM technologies, though there are some early treatments (Dowlatabadi and Morgan, 1993). The important consequences of negative emissions from BECS for emission profiles can be seen in Figure 6.9. Net negative emissions occur in scenarios in the second half of the century, and these allow for more modest 2020 and 2050 emission reductions. For instance, the category I scenarios with negative emissions show an increase in 2020 of 14%, while scenarios without negative emissions have a reduction of 15%. Net negative emissions occur in scenarios in the second half of the century, and these allow for more modest 2020 and 2050 emission reductions.

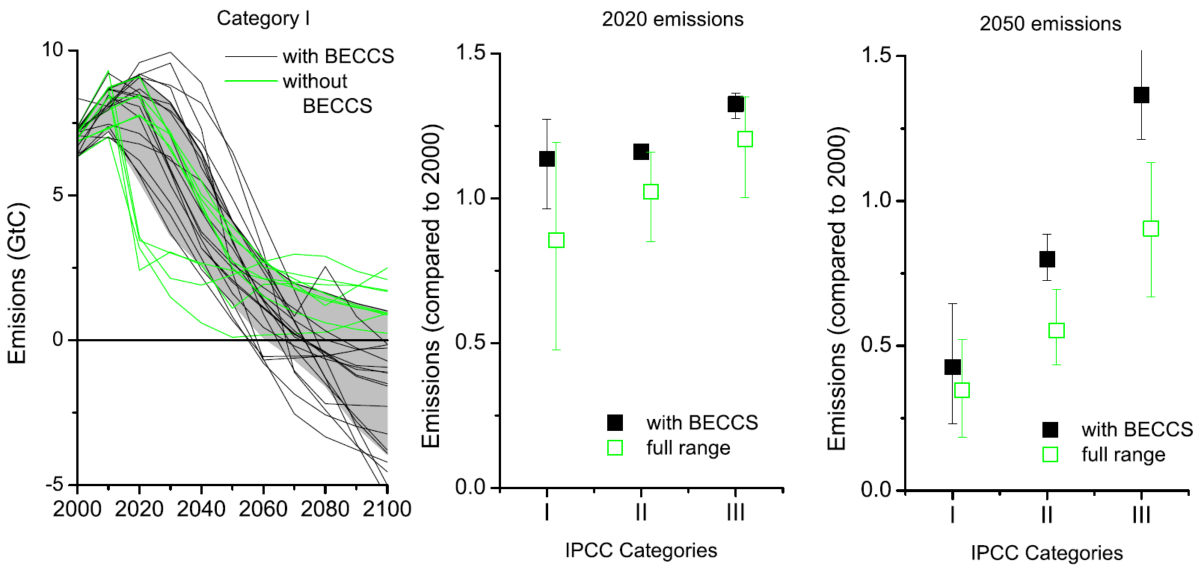


Figure 6.10. Left panel: development of CO2 emission in GtC in scenarios of category I (grey area is 15–85% percentile). Middle and right panels: average emissions levels of category I–III scenarios by 2020 and 2050 (compared to 2000). Scenarios with BECCS are shown in green and scenarios without BECCS in black. Error bands in the middle and right-hand panels indicated 15–85% percentile. (van Vuuren and Riahi 2011) [AUTHORS: Note to reviewers: the current Figure is from the published paper; to be supplemented with more recent scenarios from EMF27 and other sources for FOD/SOD].

Perhaps the most important aspect of CDR is the fact that by breaking the near one-to-one link between emissions and future concentrations, decisions about mitigation can be deferred until uncertainty about climate sensitivity is resolved. Keith et al (2005) show that in an optimal decision framework with climate sensitivity uncertainty the existence of CDR technologies alters near term strategy even though net emissions are not negative until after 2100 (Keith et al., 2005).

6.3.2.5 Temperature stabilization scenarios

The scenarios discussed in this assessment are based on stabilization of greenhouse gases. However, an alternative approach is to stabilize temperatures. Temperature stabilization pathways can differ in important ways from greenhouse gas stabilization pathways. One important difference is that, particularly for low temperature targets, greenhouse gas concentrations can exceed the long-term goal even in not-to-exceed temperature stabilization scenarios. This is due the fact that temperature lags concentrations (den Elzen and van Vuuren, 2007). Hence, temperature stabilization scenarios often fall into the category of concentration overshoot scenarios. Another important difference arises from the fact that the temperature implications of different concentration goals are highly uncertain. Hence, various studies have attempted to relate different targets by using either probability-distribution-functions for climate sensitivity, or, more dynamically, the results of small climate models calibrated to the results of more complex models (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). These studies emphasize that any temperature target needs to be expressed in terms of a probability with which the target needs to be achieved.

6.3.2.6 Solar radiation management (SRM) and stabilization scenarios

Another option to control the increase of climate radiative forcing is by directly altering the radiative forcing, for instance by increasing the number of aerosols in the atmosphere a technique now called Solar Radiation Management (SRM). In Section 6.8 we discuss the benefits and risks associated with these options. In the context of the stabilisation scenarios explored here, it is important to point out that these options are currently not often explored in IAM model analysis. Important reasons for this are that SRM technologies are only in a very preliminary stage of development and that decisions regarding SRM typically involve an assessment of risks versus benefits, instead of an assessments of costs that currently forms the focus of most IAM analysis (Barrett, 2008). Clearly, the use of SRM would imply that relationships between greenhouse gas emissions and radiative forcing that underlies much of the discussion of literature so-far would be partly broken. A much wider range of emission scenarios could still be consistent with a certain forcing level as long as the SRM would still be applied.

The potential future use of SRM has important implications when considered in conjunction with the uncertainty in climate sensitivity. The large carbon-climate inertia means that near term decisions about abatement are driven by estimates of future impacts that depend on uncertain future climate change. Absent SRM, near term decisions may be strongly contingent on the low-probability high-consequence “tail” of the probabilistic distribution of climate sensitivity and climate impacts. Because SRM can be implemented quickly (decades) whereas reduction in concentrations takes place on century-timescales it might, in principle, be implemented after uncertainty is partially resolved. This attribute of SRM makes it valuable in managing climate risk even if the costs and damages of SRM were comparable to the costs of mitigation and the damages climate change (Moreno-Cruz and Keith, 2012). SRM entails risks related to the specific methods employed to produce the radiative forcing (e.g., ozone loss from sulphate aerosols), and the radiative forcing from SRM is cannot precisely counteract the radiative forcing from greenhouse gases so SRM’s ability to compensate climate change is necessarily imperfect (Section 6.8).

6.3.2.7 The representations of carbon cycle and climate in models used to generate transformation pathways

One of the reasons to perform the RCP experiments was to compare the IAM climate results (temperature, GHG emission levels) for different forcing levels to the final results obtained by the complex climate models (Hibbard et al., 2007; Moss et al., 2010). Results of RCP model runs, but also model runs of comparable scenarios have recently become available for comparison. The result shows, in general, the outcomes of the complex climate models are consistent with the expected IAM results. Figure 6.8 compares the original emissions according to the RCPs with the ‘back-calculated’ CO_2 emission budgets in the complex models (on the basis of the prescribed concentration levels). In each case, the emission levels of the IAMs seem to lie well within those of the more complex models. This is in fact consistent with the in-depth analysis of the climate and carbon cycle components of IAMs compared to complex models that came to a similar conclusion.

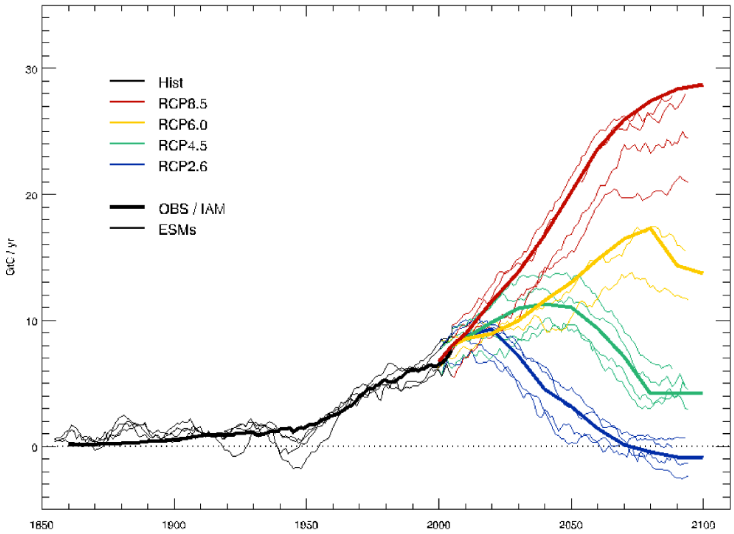


Figure 6.11. Calculated greenhouse gas emissions for the Representative Concentration Pathways as calculated by Earth System Models [AUTHORS: Note to reviewers: a more general figure will be added in next draft.]

6.3.3 Transformation Pathways in the Context of Impacts and Adaptation

The transformation pathways discussed in this chapter involve mitigation pathways to reach long-term stabilization goals. Mitigation is typically examined separately from impacts and adaptation. Indeed, the vast majority of the studies on transformation pathways, including those reviewed in this chapter, have been conducted assuming little or no climate impacts on underlying human and natural systems. A natural question is therefore to what degree would including impacts and adaptation alter the nature of the transformation pathways discussed in this chapter.

The primary way that impacts and adaptation have been considered in mitigation analysis is in the context of cost-benefit analysis. These studies assess the economic implications of mitigation as well as climate damages to identify the optimal trajectory of emissions reductions over time that will maximize welfare (i.e., net benefit). Climate feedbacks must be incorporated in order to trade off abatement costs with climate damages to determine the optimal level of mitigation. However, cost-benefit studies are fundamentally different from the studies of transformation pathways leading to a long-term stabilization goal that are explored in this chapter. In fact, no cost-benefit study finds an optimal level of mitigation that stabilizes atmospheric concentrations. Instead, concentrations continue to rise throughout the modeling period. For this reason, the studies that focus on cost-benefit are not appropriate for the discussion of transformation pathways in this chapter. In addition, the bulk of analyses using cost-benefit analysis are conducted using highly-simplified models without the structural detail necessary to explore the nature of energy system or agricultural and land use transitions.

Although the importance of considering impacts and adaptation responses when determining the optimal level of mitigation in a cost-benefit framework is obvious, it is less obvious what role impacts and adaptation have in transformation pathways. As discussed further below, mitigation, impacts and adaptation are interlinked in several important ways and should be considered jointly in the context of achieving stabilization targets. For instance, climate impacts and adaptation responses will affect the baseline perhaps warranting a different mitigation strategy.

Figure 6.12 offers a framework for thinking about the interlinkages of climate impacts, mitigation and adaptation responses in integrated assessment. Emissions mitigation strategies target the reduction in emissions generated by human activities (A). Sequestration strategies, another form of mitigation, target the reduction in greenhouse gas (GHG) concentrations as a result of emissions from human activities (B). Geoengineering strategies (a form of adaptation) attempt to decouple

GHG concentrations from climate variables such as temperature (C), and climate variables from physical impacts such as drought and hurricanes (D). These physical impacts result in changes to sectoral productivities (E) and ultimately economic losses (F), both of which are targets of adaptation strategies.

It is useful to distinguish between three types of adaptation strategies. Type I captures general equilibrium responses to price changes that, through substitution, can mitigate economic losses from productivity shocks. Type II includes protective and defensive adaptation responses that reduce shocks to productivity due to physical impacts. Lastly, Type III includes adaptive and coping expenditures that mitigate impacts further down the chain, similar to Type I, by reducing economic losses due to productivity shocks.

Few studies model the three types of adaptation depicted in **Figure 6.12** explicitly. Although many integrated assessment models are capable of capturing adaptation responses of the Type I (general equilibrium response) variety (e.g., (Darwin, 1999; Eboli et al., 2010), only a few capture adaptation responses of the Type II or Type III variety [e.g., AD-DICE (de Bruin et al., 2009), AD-WITCH (Bosello et al (2010b), and PAGE (Hope, 2006)]. A hybrid modeling approach has been used by some to capture other types of adaptation. For instance, Darwin and Tol (2001) combine the FARM and FUND models to capture both type I and II adaptation, Bosello et al (2010a) combines the AD-WITCH model with the ICES CGE model to capture all three types of adaptation, and Ciscar et al (2011) combine physical-impact models with the GEM-E3 CGE model to capture all three types of adaptation.

There are a number of reasons for the lack of models with explicit representation of adaptation responses. First, adaptation responses are inherently regional and sectoral and many models do not have the regional and sectoral detail to capture the variation in climate impacts and responses. Second, proactive adaptation decisions are inherently intertemporal which explains why a number of models that include adaptation (e.g., AD-DICE and AD-WITCH) also include intertemporal decision making. Lastly, there is desperate lack of data and empirical evidence on impacts and adaptation necessary for model calibration. Although there has been an uptick in the number of empirical studies on impacts and adaptation recently, these studies are not done with the intent of being incorporated into IAMs. As a result, they lack the regional and sectoral coverage to be useful for model calibration and typically collapse the (E) and (F) linkages in **Figure 6.12**, instead regressing temperature on productivity or economic losses. This disconnect between empirical work and models necessitates heroic efforts on the part of the modeler to bring empirical knowledge on impacts and adaptation responses into IAMs.

As represented by the blue dashed lines in **Figure 6.12**, these strategies and responses compete for investment and R&D resources, leading to potential trade-offs as discussed further below. Also, as captured by the red dashed lines, climate change feedbacks will affect the set of available mitigation and adaptation options, and thus optimal decision-making in a cost-benefit framework.

Omitting climate impacts and adaptation responses from transformation pathways is likely to lead to biased results for three main reasons. First, climate impacts could limit the feasibility of emissions mitigation options. For instance, water required for thermal cooling in the case of nuclear power and stream flow required for hydroelectric power could face severe shortages as a result of climate change. Both are important carbon-free sources of electric power. Also, climate change could negatively impact biofuel crop productivities, another important source of carbon-free energy. Unfortunately, there are no published modeling studies that account for the effects of climate impacts and adaptation responses on the set of viable mitigation strategies to reach stabilization targets (Fisher-Vanden et al., 2011). Therefore, there is little information by which to judge how the omission of impacts and adaptation responses would alter the results reviewed in this chapter.

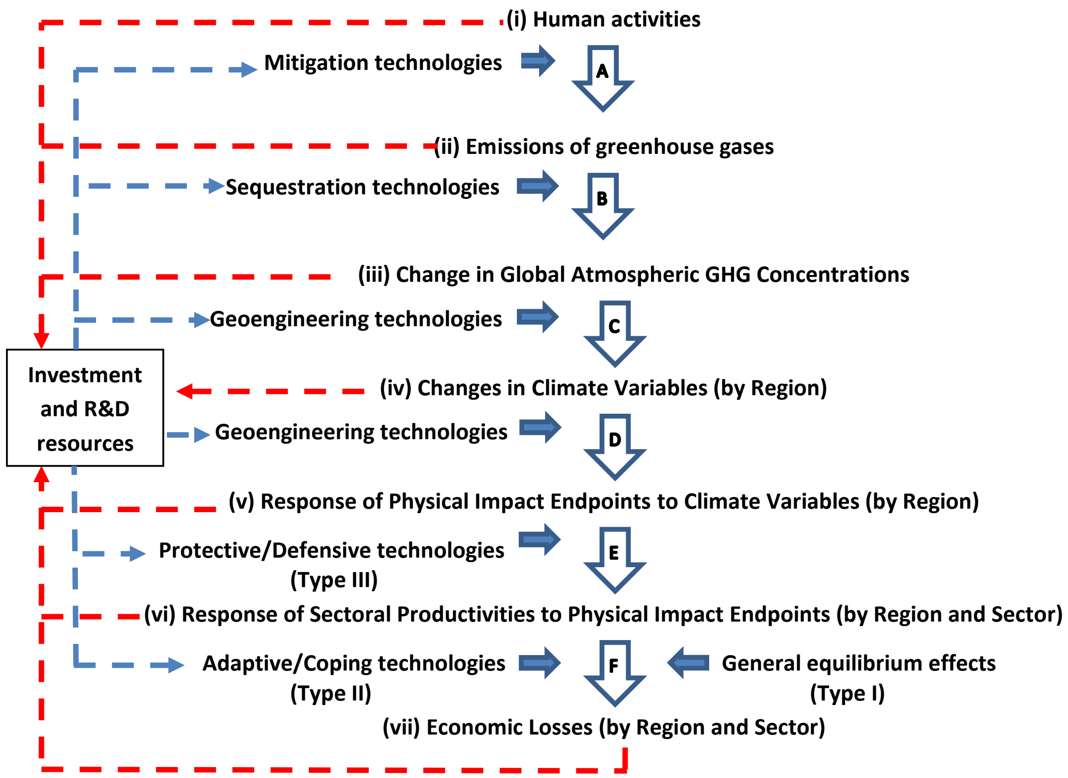


Figure 6.12. Climate Impacts and Adaptation in Integrated Assessment. Adapted from: Fisher-Vanden, Sue Wing, Lanzi, and Popp (2011)

Second, adaptation responses to climate change could exacerbate emissions from human activities, requiring deeper cuts in emissions to reach atmospheric stabilization targets. For example, a warmer climate is likely to lead to higher demand for air conditioning (Mansur et al, 2005) which will lead to higher emissions if this increased electricity demand is met by electric power generated with fossil fuels. There is a limited number of studies that account for changes in baseline emissions as a result of adaptation responses. In these studies, higher emissions from increased air conditioning as a result of higher temperatures are captured (Bosello et al., 2010b; Eboli et al., 2010); Antoff et al, 2011). Although these studies account for higher emissions as a result of adaptation behavior, none of these studies examine what this implies for meeting stabilization targets. Again, the implications for transformation pathways are ambiguous.

Finally, mitigation strategies will need to compete with adaptation strategies for scarce investment and R&D resources. This will also lead to higher abatement costs. A number of studies account for competition for investment and R&D resources. In cost-benefit modeling studies like de Bruin et al (2009) and Bosello et al (2010a, 2010b), adaptation and mitigation are both decision variables and compete for investment resources. Competition for investment resources is also captured in studies measuring the economic impacts of climate impacts, but rather than competing with mitigation investments, competition is between investment in adaptation and consumption (Bosello et al., 2007) and other capital investments (Darwin and Tol, 2001). Some simulation studies that estimate the economic cost of climate damages add adaptation cost to the cost of climate impacts and do not capture crowding out of other expenditures (Hope, 2006). No existing study, however, examines how this crowding out will affect an economy’s ability to invest in mitigation options to reach stabilization targets. The scenarios discussed in this chapter also do not account for crowding out and therefore could underestimate the cost of meeting stabilization targets.

6.3.4 The macroeconomic costs of mitigation in an idealized context

6.3.4.1 Overview of issues associated with estimating the economic costs of transformation pathways

Emissions mitigation requires actions that would not be taken without explicit efforts to reduce greenhouse gas emissions. Mitigation actions will therefore require behavioural changes and the use of alternative technologies, both of which can lead to economic costs to producers and consumers, potentially decreasing total economic output and the consumption of goods and services by individuals. It is therefore common to estimate the economic costs of mitigation against a counterfactual baseline scenario without climate policy. These economic costs relative to a counterfactual baseline are an important criterion by which different transformation pathways can be evaluated.

Several caveats are important when interpreting economic cost estimates. First, these costs are not the only criterion by which pathways might be evaluated. Transformation pathways inherently involve a range of trade-offs that link to other national and societal priorities including, among other things, both energy and food security, sustainable development, the distribution of economic costs, local air pollution, and other environmental factors associated with different technology solutions (e.g., nuclear power, coal-fired CCS), and economic competitiveness [Links to other chapters or sections]. Second, most cost estimate focus only on a constrained set of direct market effects and do not take into account important ancillary costs or benefits of mitigation actions, such as health benefits from reduced air pollution or changes in landscapes, e.g., from energy crop plantations. These mostly non-market costs and benefits could be substantial. Third, assumptions about market distortions and policies in place in the counterfactual baseline can affect cost estimates. Reduced or negative mitigation costs, for example, require the hypothesis of policies that remove additional global scale market imperfections beyond climate change. Finally, these cost estimates only capture the costs of mitigation; they do not capture the benefits of containing the growth in greenhouse gas concentrations and therefore reducing climate change. It is against these benefits that all the different potential costs of mitigation must ultimately be weighed (see Section 6.2.3 and Working Group II Contribution to the AR5).

There is no single metric for reporting the costs of mitigation, and the metrics that are available are not directly comparable (see Section 0; see Chapter 3 for a more general discussion). In economic theory the most direct cost measure is a change in welfare due to changes in the amount and composition of consumption of goods and services by individuals. Important measures of welfare change include “equivalent variation” and “compensating variation”, which attempt to discern how much individual income would need to change to keep consumers just as well off after the imposition of a policy as before. However, these are quite difficult to calculate, so a more common welfare measurement is change in consumption, which captures the total amount of money consumers are able to spend on goods and services. Another common metric is the change in gross domestic product (GDP). However, GDP is a less satisfactory indicator of overall cost than those focused on individual income and consumption, because it is a measure of output, which includes not only consumption, but also investment, imports and exports, and government spending. A final common measure is the “deadweight loss” or “area on the marginal abatement cost function”, which suffers from similar limitations as GDP. As discussed in Section 0, different modeling frameworks are capable of producing different cost estimates. Therefore, when comparing across scenarios from different models, some degree of incomparability must necessarily result. In representing costs across scenarios in this chapter, consumption losses are used preferentially when available from general equilibrium models, and costs represented by the area under the marginal abatement cost function or additional energy system costs are used for partial equilibrium measures.

One popular measure used to evaluate the economic implications of mitigation actions is the emissions price, often presented in per metric ton of CO_2 or, in case of multiple gases, per metric ton of CO_2-equivalent. However, it is important to emphasize that emissions prices are not cost measures. There are two important reasons why emissions prices are not a meaningful representation of costs. First, emissions prices measure marginal cost; that is, the cost of an additional unit of emissions reduction. However, total costs represent the costs of all mitigation that took place at lower cost than the emissions price. Without explicitly accounting for these "inframarginal" costs, it is impossible to know how the carbon price relates to total mitigation costs. Second, emissions prices can interact with other policies and measures, either regulatory policies directed at greenhouse gas reduction (for example, renewable portfolio standards or subsidies to carbon-free technologies) or other taxes on energy, labor, or capital. If mitigation is achieved partly by these other measures, the emissions price will not take into account the full costs of an additional unit of emissions reductions, and will indicate a lower marginal cost than is actually warranted.

It is often important to calculate the total cost of mitigation borne over the life of the policy. To compare costs over time, conventional economic practices apply a discount rate to future costs on the basis that money today would earn a return over time. The discount rate, which represents how much less society values the future payments in comparison to the present payments of the same size, is a key parameter, and there are different views on what the appropriate rate is for climate policy [Possible references if needed: (Portney & Weyant 1999; Stern 2007; Nordhaus 2006 and Chapter 3). Transformation pathways in the literature have been derived under a range of assumptions about discount rates. For the purpose of comparing temporal aggregates of mitigation costs in this Section, we will consistently use a discount rate of 5% to calculate the net present value of a consumption or output stream, or the mitigation costs over time.

6.3.4.2 Global economic costs of climate stabilization in idealized implementation scenarios

The economic implications of mitigation depend on a wide range of factors. To begin the treatment of costs, it is useful to first develop a benchmark cost based on the assumption of an idealized approach to mitigation in which mitigation is undertaken where and when it is most effective and in which there are no explicit limits on the deployment of particular technologies such as nuclear power or fossil energy with CCS. Such an idealized scenario is achieved by assuming the existence of a ubiquitous price on carbon that is applied across the globe in every sector of every country (achieved either through a global carbon price or emissions trading with assuming transparent markets and no transaction costs), and that rises at a rate that minimizes the discounted cost of mitigation. Although this particular scenario is improbable, it is valuable in that it leads to a low cost approach to mitigation and therefore serves as a benchmark against which other scenarios with non-idealized policy structures or limits on technology might be compared. However, departures from all or many of these assumptions are likely to occur, particularly in the short term. Examples are imperfect competition in the energy sector, and imperfect implementation of mitigation policies such as fragmented carbon markets inducing carbon leakage.

It is important to note that although the idealized scenarios provide low cost estimates, they do not necessarily provide least cost estimates. The ubiquitous carbon price may interact with other existing policies such as other energy policies, mitigation options available in the model default, and the recycling of revenues from emissions pricing. A carbon price combined with policies directly addressing these other factors could potentially result in even lower costs.

The remainder of this section explores the economic implications of mitigation in scenarios with these idealized assumptions. The following sections then explore, in turn, the influence on costs of the policy instruments used for mitigation, the influence of international participation, and the influence of limits to technology availability.

A first observation is that there is significant variation in cost estimates between scenarios even though they all assumed idealized implementation frameworks (Figure XX). Although the bulk of scenarios estimates costs below 2.5% of net present consumption and gross output, respectively, a small set of scenarios (red crosses) shows costs 3-4 times higher. This difference in costs may be traced back to a range of assumptions embedded in the structures of the individual models, and is further discussed below. There are also other assumptions beyond the assumption of an idealized implementation framework that contribute to the uncertainty in the cost estimates. These include underlying socioeconomic drivers such as population growth and economic growth, assumptions about technology cost and performance, and assumptions about resources and international trade.. Efforts to better understand the sources for differences in cost estimates are an important research area. However, it is also important to acknowledge the resulting uncertainty, because it highlights the fact that not only are the benefits of climate mitigation uncertain, so are the costs. [AUTHORS: NOTE to reviewers: in the SOD, we plan to *better explore the dependence of cost estimates on additional categories to climate stabilization such as overshoot, availability of negative emissions technologies, baseline emissions and baseline final energy demand*].

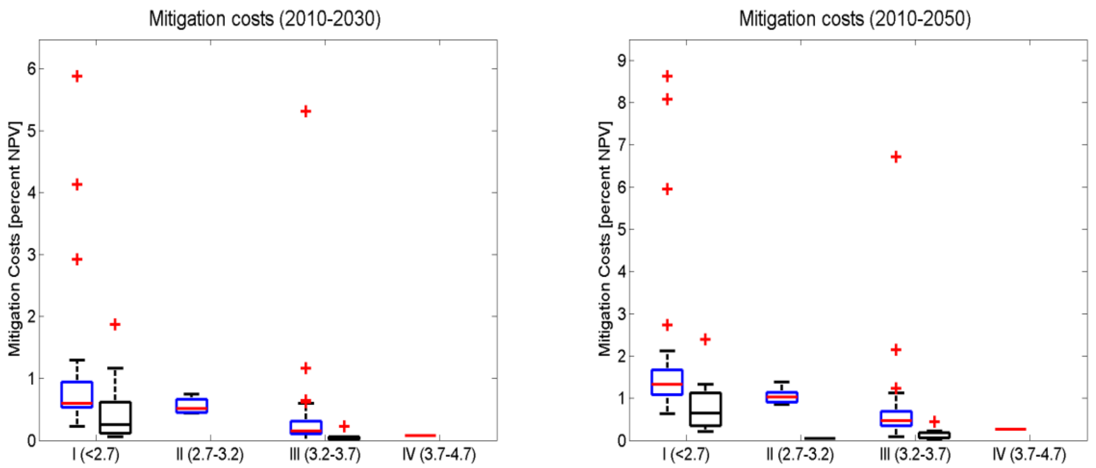


Figure 6.13. Global mitigation costs ranges for four different climate stabilization categories as defined in Section 6.2.2. Shown are net present value (NPV) consumption losses (blue box plots; general equilibrium models) and abatement costs (black box plots; partial equilibrium models) as percentage of net present baseline consumption and gross world output, respectively, (all discounted with 5% / yr) for the period 2010-2030 (left panel) and 2010-2050 (right panel). Boxes contain the 25th – 75th percentile range of cost estimates, whiskers include all estimates within 1.5 that range above / below the box. Scenarios outside the whisker range are shown by the crosses. Sample size of scenarios differs across climate categories and type of cost measure (32/10, 5/1, 42/11, 1/0 for consumption losses/abatement costs in CatI-IV). [AUTHORS: NOTE to reviewers: This information is preliminary and will be updated with a more extensive dataset in the SOD which will include larger samples underlying the boxplots. Please see discussion in Section 6.1.]

A further observation is that the costs of mitigation are highly dependent on the level of stabilization; that is, mitigation cost estimates increase significantly with stringency of climate stabilization (**Figure 6.13** and **Figure 6.14**). Although cost estimates range up to 1% of net present consumption in Category III (3.2-3.7 W/m2 total radiative forcing), they go up to 2.5% for stringent climate stabilization at or below 2.7 W/m2 (Category I; ca. 450 ppm CO2-equiv or below) for the period 2010-2050 (excluding the high cost model estimates).

Cost ranges across all models and scenarios do not fully depict the increase in costs with stringency, because they do not control for the model and study used to create the cost estimates. It is therefore instructive to look at the cost increases projected by individual models in a given study, as shown in **Figure 6.14**, which represents increases in mitigation costs relative to the costs of climate stabilization at Category III (3.2-3.7 W/m2 total radiative forcing). Mitigation costs increase by a factor of approx. 2-5 when moving from Category III (ca. 550 ppm CO_2-equiv) to stringent climate stabilization at or below 2.7 W/m2 (Category I; ca. 450 ppm CO_2-equiv or below). In general, the increase in costs with stringency of emissions reductions is non-linear; that is, costs increase more than proportionally with the increase in stringency.

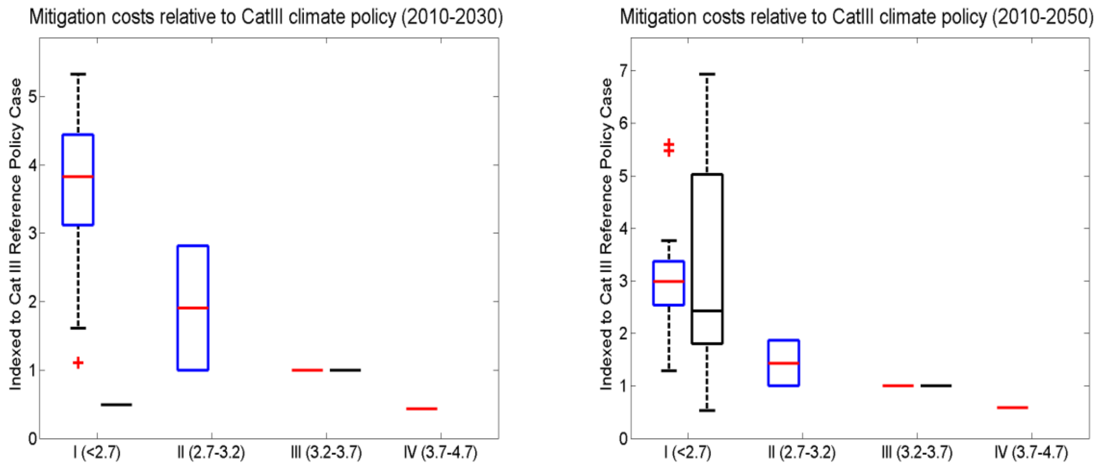


Figure 6.14. (PRELIMINARY DATA): Global mitigation cost increases relative to reference level of climate stabilization (Category III = 1) for the period 2010-2030 (left panel) and 2010-2050 (right panel). Shown is the range of ratios of mitigation costs over mitigation costs for Category III stabilization. Ratios were only calculated when available from a given model and study. See figure caption 6.11 for an explanation of the cost metrics and boxplots used. Sample size of scenarios differs across climate categories and type of cost measure (32/8, 5/1, 42/9, 1/0 for consumption losses/abatement costs in CatI-IV). [AUTHORS: Note to reviewers: The scenario database is in a preliminary stage, and shown cost ranges are subject to change. Please see discussion in Section 6.1.]

Another important observation is that the degree of variation in costs increases as the stringency increases. In other words, scenarios indicate greater consensus regarding the nature of mitigation costs at lower stabilization levels than those at higher levels. This increase in variation reflects the challenge associated with modeling energy and other human systems that are dramatically different than those of today. Although all stabilization scenarios must ultimately bring greenhouse gas emissions toward zero, stringent scenarios must do this sooner. These deep reductions, in turn, are associated with energy and other systems that will be very different than those of today.

The flexibility of the model to almost fully substitute carbon intensive energy technologies with low carbon energy technologies is a key determinant of mitigation costs for stringent mitigation policies. It is largely determined by the availability of low carbon alternatives and by substitution possibilities. Since models differ in their representation of abatement options in the various sectors and for the various greenhouse gases (see Section 6.2.2), their scenarios may have very different implications for reductions of carbon dioxide emissions from fossil fuel combustion and industrial processes. It is therefore useful to investigate mitigation costs as a function of cumulative CO_2 abatement in these sectors (Figure 6.15). Partial equilibrium (abatement costs in black) and general equilibrium models (consumption losses in green) show roughly linear cost increases up to 80% cumulative reduction relative to baseline over the 21^{st} century. Even for up to 90% reduction of baseline emissions, costs are at or below 4% of net consumption over the period 2010-2100. However, three dynamic recursive computable general equilibrium models show generally higher costs (particularly when aggregated over the full century) that in addition are strongly increasing beyond some threshold of 30% (2010-50) to 50% (2010-2100) cumulative emissions reductions (red dots). The non-linear increase further amplifies the cost differences to the other models, explaining the upper tail of cost estimates across models. An analysis shows that those models need higher carbon prices to achieve similar levels of emissions reductions, indicating a more limited flexibility to substitute fossil fuels. In addition, they show higher economic impacts for a given level of carbon price. The results indicate that those models that capture economy wide costs and at the same time have limited flexibility to reduce carbon intensity show significantly higher mitigation costs for achieving stringent abatement levels

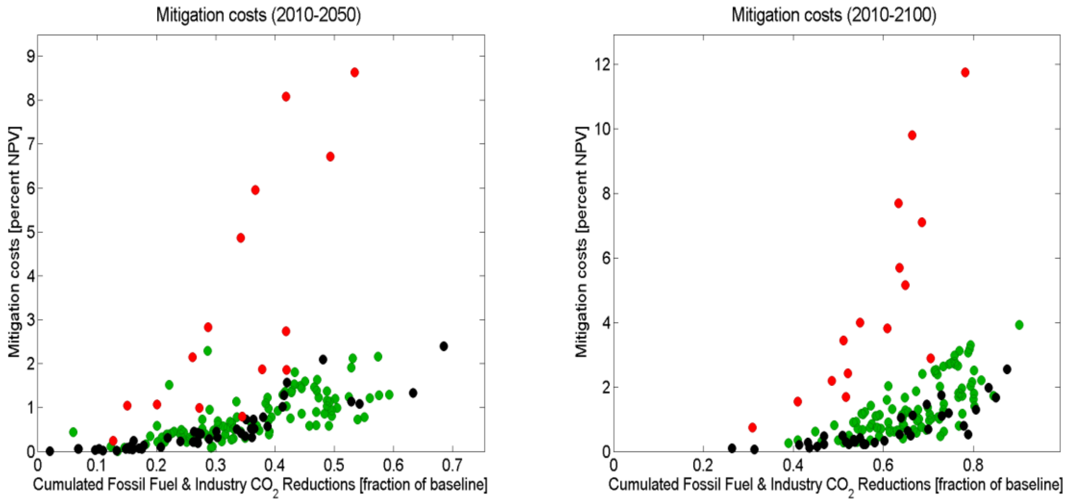


Figure 6.15. Global mitigation costs as a function of cumulative fossil fuel and industry CO2 emissions reductions (fraction of cumulated baseline emissions) over the period 2010-2050 (left panel) and 2010-2100 (right panel). Mitigation costs are reported in NPV consumption losses (green and red dots) or abatement costs (black dots) in percent of net present consumption and gross world output, respectively (all discounted at 5%). [AUTHORS: Note to reviewers: The scenario database is in a preliminary stage, and shown cost ranges are subject to change. Please see discussion in Section 6.1.]

6.3.4.3 Regional distribution of costs

In the idealized setting of a universal carbon price, the costs of mitigation will not be borne equally across countries and regions. The costs of climate stabilization for an individual region will depend on the baseline development of regional emissions and energy use, the mitigation requirement, the emissions reduction potential of the region, and terms of trade effects of climate policy, particularly in the energy markets. Due to this multitude of factors, the regional distribution of mitigation costs is more uncertain than globally aggregated mitigation cost estimates. Nonetheless, as discussed in Section 6.2.1 and 6.2.2, the majority of emissions reductions over the coming century will be borne by the currently developing countries, in large part because these are the countries that will produce the majority of the world's emissions without explicit efforts to reduce greenhouse gas emissions. As a result, these countries generally bear a larger weight of abatement costs in the energy sector and other sectors (**Figure 6.16**).

Economy wide mitigation costs measured in changes to welfare or consumption will include the effect of compensation and burden sharing schemes, respectively, if available. Such schemes can be introduced, e.g., via regional emissions allowances traded on a global carbon market. The choice of allowance allocations would determine the degree to which the abatement costs in the energy and other sectors are borne within a given country or financed through the sale of allowances. It has been shown that the impact of different allocation schemes on regional mitigation costs can be very large, particularly in those models that require a high global carbon price signal for achieving climate stabilization (Lüken et al. 2011; Luderer et al. 2012). These issues are discussed in greater detail in Section 6.2.6 and in Chapter 13.

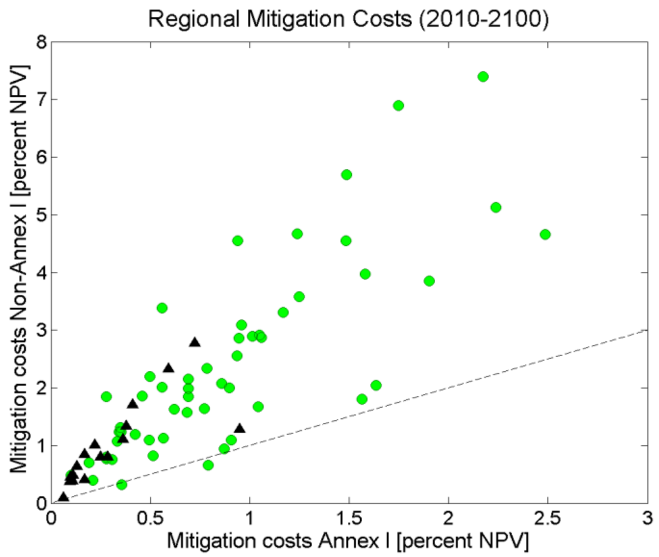


Figure 6.16. Comparison of mitigation costs borne by Annex I and Non-Annex I countries in a subset of idealized implementation scenarios that do not include burden sharing or compensation mechanisms. Consumption losses in percent of net present baseline consumption over 2010-2100 are shown in green, and abatement costs from partial equilibrium models in percent of net present gross regional product in black. Note that these costs do not represent the actual burden of regions, which can be influenced by the nature of compensation mechanisms. [AUTHORS: Note to reviewers: The scenario database is in a preliminary stage, and shown cost ranges are subject to change. Please see discussion in Section 6.1.]

6.3.4.4 Summary of cost estimates across models and studies

[AUTHORS: Note to reviewers: Summary will be prepared for the SOD]

Table 6.4. Overview of cost estimates [AUTHORS: Note: Will be finalized for the SOD. The current collection of results is not yet sufficient and the scenario database too preliminary to pull all numbers together consistently].

Category	RF in 2100	Overshoot or Not-to-Exceed	Cost range in Idealized Scenarios	Percentage Increase in Costs with Delayed Participation			Percentage Increase in Costs with Limited Technology		
				EMF 22	Delay until 2020	Delay until 2030	No CCS	No New Nuclear	Limited Efficiency and Renewables
1	2.4 to 2.8	NTE							
		Overshoot							
2	2.8 to 3.4	NTE							
		Overshoot							
3	3.4 to 4.0	NTE							
		Overshoot							
4	4.0 to 5.0	NTE							
		Overshoot							
5	5.0 to 7.0	NTE							
--	> 7.0	NTE							

6.3.5 Policy structures for mitigation

Mitigation actions can be incentivized or required by a variety of policy structures and instruments. Chapter 3 provides a discussion of main instruments. On one side of a spectrum are pure market structures, where emissions constraints are introduced and decisions on where and how to reduce emissions are left to the market. On the other side are command-and-control regulations that require specific technologies and/or performance standards. Any policy structure that imposes a constraint on emissions creates a value to the right to emit, something that economists call a scarcity rent. As discussed in Section 6.2.4, mitigation actions also impose economic cost to a society. In this subsection we consider different policy structures and economic rents and costs that they create, focusing on different criteria to measure their effectiveness. We also explore the factors that influence regional choices of mitigation approaches, as we are interested in understanding why might approaches other than those that are most economically efficient be chosen.

6.3.5.1 Effectiveness of policy instruments

Policy structures and instruments can be assessed based on several criteria (Baumol and Oates, 1988); Hahn and Stavins, 1991). Specific dimensions that can be applied uniformly across the different policy instruments are economic costs (economic efficiency), distributional impacts, and environmental effectiveness. Economic efficiency is determined by cost minimization (achieving certain targets at the lowest possible cost), cost-effectiveness (cost relative to emissions abated), implementation, monitoring and transaction costs, and co-benefits of a policy. Distributional impacts are assessed based on impacts of a policy on different regions, income groups, age- and gender-specific categories, whether the instrument generates revenues and how they are used, distribution of mitigation burden across sources and sectors, shift of incidence and spillover effects. Environmental effectiveness is estimated by a potential for emission abatement and scalability, the level of stringency, and the scope of leakage.

The literature makes clear that incomplete coverage is more costly. The way to minimize the costs of mitigation is to undertake mitigation where and when it is least expensive (Montgomery, 1972). Approaches that exclude sectors or regulate reductions by sector will have higher costs than those that give a consistent incentive for mitigation across the full economy (Paltsev et al., 2008). Incomplete coverage can have several dimensions: some economic sectors and activities might be excluded (for example, an instrument can be applied to energy-intensive sectors only, energy sectors only, with different options for an inclusion/exclusion of land use processes); some temporal decisions can be prohibited (for example, banking and/or borrowing of emission permits issued at different periods of time may not be allowed); some countries or regions may decide not to participate (implications are discussed in Section 6.2.6)

Figure 6.17 shows an example of a policy that targets the EU 20% emissions reduction in 2020 (Böhringer et al., 2009). If implemented at the lowest possible cost, the 20% reduction would lead to 0.5-2% by 2020. A policy with two carbon prices (one for the emissions trading scheme, ETS, that covers a subset of energy-intensive sectors and one for non-ETS) could increase costs by up to 50%. A policy with 28 carbon prices (one for the ETS, one each for each EU state for non-ETS) could increase costs by another 40%.

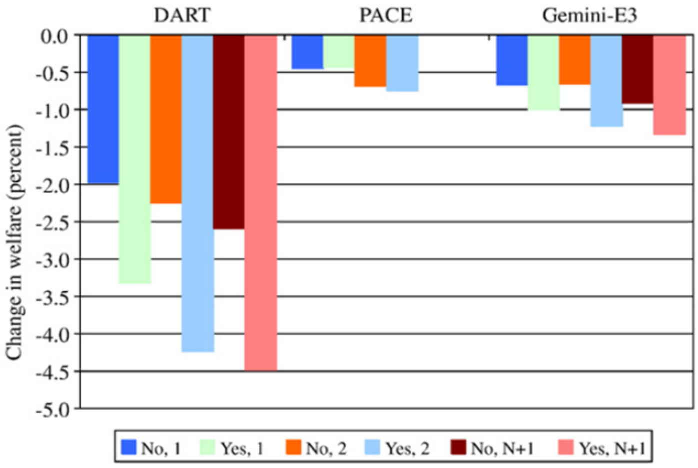


Figure 6.17. The change in welfare in the EU in 2020 according to three different models: 1 = uniform price for ETS and non-ETS emissions; 2 = separate prices for ETS and non-ETS emissions; N+1 = one Europe-wide price for ETS emissions, different prices for non-ETS emissions in different EU states; no = no target for the share of renewables in energy supply; yes = target for the share of renewables in energy supply.

The literature also makes clear that predicting the technology winners is difficult. The most economically-efficient climate policy remains cap-and-trade policy or carbon tax (Goulder and Parry, 2008). When idealized economy-wide cap-and-trade system or carbon tax is replaced by regulations that target certain industries or technologies, economic costs (and energy mix) change substantially. Figure 6.17 shows that standards requiring certain amount of renewables in the energy mix could raise the costs of emissions reduction by 90%. Similar findings are coming from numerous studies that focus on different regions, sectors and technologies. [AUTHORS: NOTE: cite EMF 24 papers that are forthcoming]. Figure 6.18 provides a comparison of economic costs and environmental effectiveness when cap-and-trade policy is combined with fuel economy standards for passenger vehicles (Karplus et al., 2012). It underscores the potentially large costs of a policy aimed at a particular sector and technology relative to a broad policy that allows flexibility.

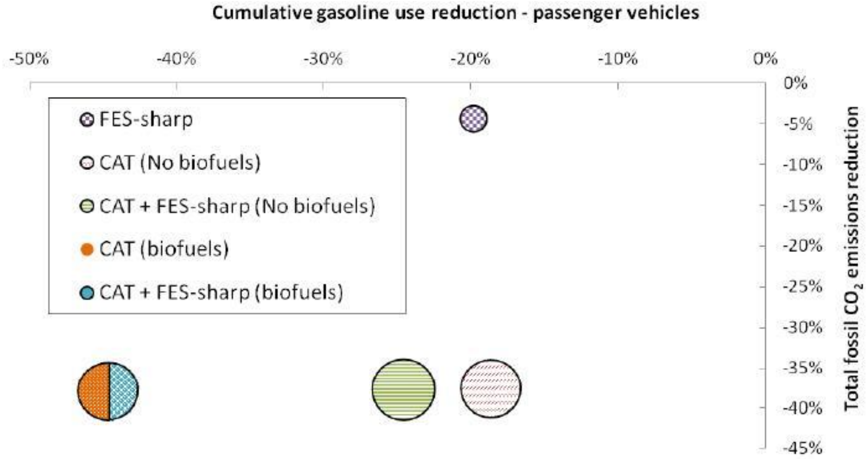


Figure 6.18. A comparison of the cumulative change in gasoline use, total fossil CO2 emissions, and household consumption from 2005 to 2050 under fuel economy standard (FES) and cap-and-trade (CAT) policy with and without advanced biofuels available. The size of the circle corresponds to the magnitude of policy cost.

To reduce costs, policies should address not just carbon from the energy system, but also from land use. Efficient structures and instruments do not focus on energy and industry only, but they also include terrestrial carbon sinks and sources (Bosetti et al., 2011). Land can be a source of emissions, but can be also a sink of carbon. Incorporation of sinks brings some challenges into a design of a land-including policy instruments, but some adjustments for sink treatments can solve the design issues (Reilly and Asadoorian, 2007). However, agreeing on baseline land emissions may bring some political challenges. The inclusion of land-use change emissions in emission trading systems would create incentives to control both direct and indirect land-use emissions and enhance land sinks. The significant trade-off with this integrated land use approach is that prices for agricultural products may rise because of higher land prices (Reilly et al., 2012).

6.3.5.2 Distributional Implications

Distributional implication of policy instruments may vary by income group and by region. (Rausch et al., 2010) show that the impacts of climate policy on U.S. households of different income may vary, and consumers are impacted by two major channels: on the expenditure side - when lower income households pay for energy use higher portions of their income; and income side – when government transfers and returns to investments are affected. (Rausch et al., 2011) also show that variance of impacts within an income group is very substantial. Looking at average cost measures neglects the wide variation in costs to consumers and hide the fact that some households will be big losers and some households will gain from a mitigation policy. Such variation within an income group is larger than variation between the income groups.

Distributional impacts may vary with a different policy instrument. The cross-country distribution of mitigation burden and the extent of spillovers depend on whether countries adopt a uniform policy instrument or different policy instruments (Jacoby et al., 2010). Different allocation schemes in a cap-and-trade system affect different economic agents in a different way (Hahn and Stavins, 2012). Combining cap-and-trade system with a fuel standard (like corporate fuel efficiency, CAFE, standard in the U.S.) leads to different impacts by region and income group. When land is used to mitigate climate change and agricultural products become more expensive, a share of income spent on food for wealthier regions continues to fall, but for the poorest regions, higher food prices lead to a rising share of income spent on food (Reilly et al., 2012).

6.3.5.3 Institutional Feasibility

Economic cost and political feasibility are criteria by which regions and countries might choose their approaches to mitigation. Political considerations make some instruments difficult to implement or infeasible. For example, in the U.S. it is very unpopular to introduce gasoline taxes even though they can reach the same effects in terms of fuel and emissions reduction at much smaller overall economic cost. Incomplete participation, delayed actions, incomplete sectoral coverage, combining with regulatory approaches increase the costs substantially (at least 2-10 times). Instead of efficiently pricing greenhouse gases, policy makers have favored measures that implicitly or explicitly subsidize low carbon fuels (Holland et al., 2011). Hybrid policy instruments are sometimes employed to overcome such implementation difficulties (Goers et al., 2010). The persistence of these alternatives in spite of their higher costs lies in the political economy of carbon policy (Aldy and Stavins, 2012).

6.3.6 International Strategies and Stabilization

6.3.6.1 The nature of international action for climate mitigation

Many transformation scenarios are based on the assumption of perfect where and when flexibility; that is, the ability to undertake emissions reductions where and when they would be least expensive. This would imply larger reductions, even in the near-term, in the developing countries, in large part because these countries are now responsible for the majority of greenhouse gas emissions moving forward (see Section 6.2.1 and 6.2.2). In reality, climate policy at the international level will certainty deviate from this idealized scenario. Full cooperation among all world regions to transform the global energy and land use systems at minimum cost is very difficult to achieve (see Chapter 13), and a range of decision criteria beyond simply minimizing global cost will undoubtedly figure into the decisions countries make regarding their levels of mitigation. Hence, the reality of international strategies for mitigation, at least in the near-term, is one of different countries taking on different actions at different times, with some countries reducing emissions more quickly than others. Without consideration of the means of implementing mitigation (see Section 6.2.5), our understanding of real-world international strategies will imply countries undertaking mitigation levels that deviate, perhaps substantially, from the idealized scenario in which mitigation is undertaken where and when it is least expensive. This raises questions about the influence of these fragmented policy regimes on transformation pathways.

6.3.6.2 The overall implications of international climate architectures on the achievement of long-term climate stabilization goals

Several modelling results (Keppo and Rao, 2007; Edmonds et al., 2008; Clarke et al., 2009; Tol, 2009; van Vliet et al., 2009a; Richels et al., 2009; Bosetti, Carraro, and Tavoni, 2009b; Calvin, Patel, et al., 2009b; Krey and Riahi, 2009b) indicate that the timing and the rate of international participation in climate mitigation will have a significant effect on the feasibility of achieving climate stabilization policies. For example, the EMF22 modeling comparison has provided one of the most comprehensive assessment of this issue by comparing two stylized cases of immediate global participation and marked delayed participation by developing countries (to 2030 and 2050 for BRICs and other developing countries respectively), for different climate targets and ways of achieving them. The results indicate that many models were not able to produce scenarios with delayed participation of large developing countries for the more stringent long-term goals. For example, half of models found it impossible to meet the 550 Co2-e target with delayed participation, unless the concentration target could be overshot. For the most stringent 450 ppm-eq, the effect of delayed participation was even more significant. There were three reasons why models could not reach the goals: physical infeasibility (climate target is exceeded prior to the initiation of mitigation in late countries in a not-to-exceed scenario), model solution (model cannot be solved), and high initial price (the initial price in 2012 is higher than 1000$/tCO2). Although only the first of these reasons truly indicates that a goal might be physically infeasible, failure to meet a target based on the second two criteria most certainly illustrate the degree to which delayed action will inhibit the ability to meet particular long-term stabilization targets.

6.3.6.3 The implications of international climate architectures on the global costs of stabilization

An important criterion by which to distinguish alternative transformation scenarios is the cost of mitigation. A wide range of studies has emphasized that the increase in the overall mitigation costs is positively affected by the size of the non-participating regions' abatement potential, the length of delay, and the stringency of the overall climate objective. In particular, the literature indicates that the total global cost of mitigation can increase substantially with fragmented international action (**Figure 6.19**). For a given level of mitigation commitment, the additional costs are a tradeoff between higher mid-term emissions and the more rapid and aggressive mitigation effort needed once a large coalition forms. As a result, the extent of the penalty depends on whether the climate target can be overshot or not, and to the discounting of future versus actual losses.

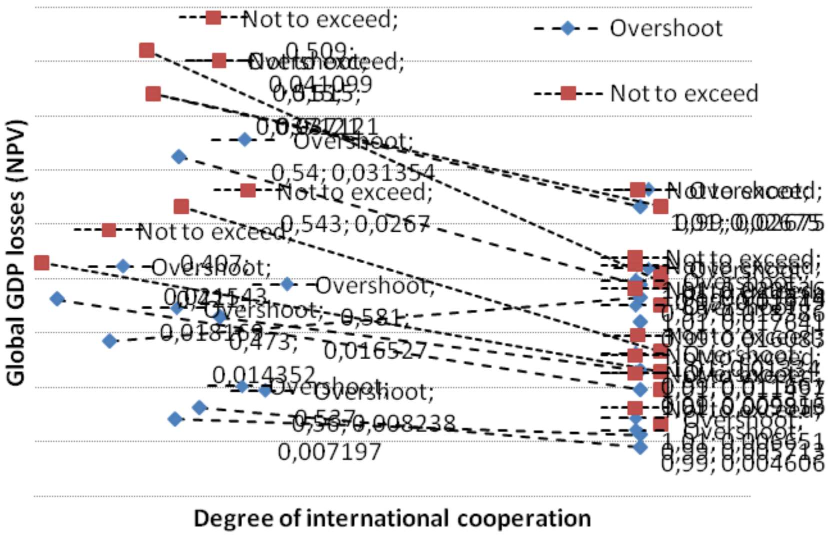


Figure 6.19. Global policy costs as a function of the level of international cooperation. The x axis shows the fraction (cumulative to 2050) of BAU emissions covered by the international climate policy. The y axis shows global losses of GDP in net present value terms (at 5% discounting). The same set of models ran a full participation case (level of cooperation=1, for clarity the markers are plotted around 1), and a fragmented one, which are connected by dashed lines for the models who could find a feasible solution. The climate stabilization target is 3.7 W/m^2, with either concentration target that can be overshot or not exceeded. Source: EMF22'.

Increased mitigation costs will mostly fall on early joiners. However, an important result in several models and studies is that costs can also increase for late entrants (**Figure 6.20**). Such countries or regions would benefit in early periods because of the lower mitigation obligation and advantageous terms of trade. However, if long-term goals are truly to be met, they must act extraordinarily quickly once they begin to take action. And this rapid action can more than compensate for the reduced costs from limited near-term mitigation, and would increase for all major regions the maximum policy costs over time (see coloured bars). The degree to which the late entrants costs might increase with delayed participation depends on the extent of carbon intensive technologies and infrastructure put in place during the no action period (Clarke et al., 2009) and the speed at which emissions must be reduced after they begin to take action.

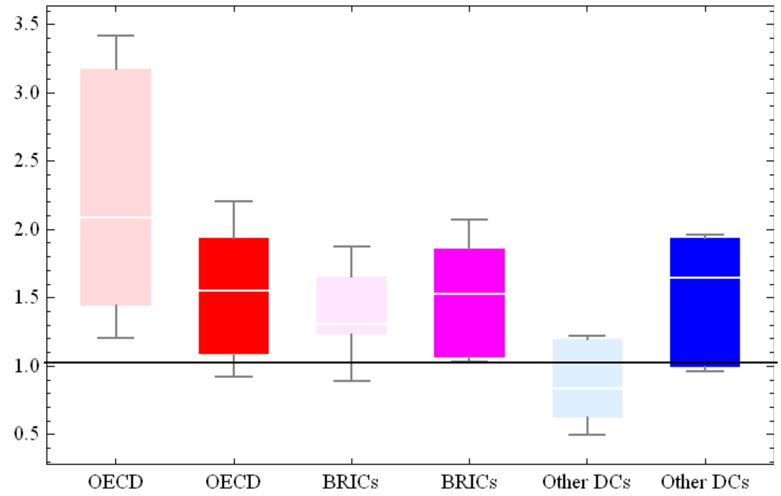


Figure 6.20. Penalty of fragmented participation for 3 representative regions. The y axis shows the ratio of GDP losses between fragmented and full participation scenarios. When bigger than 1, it indicates that fragmented participation is costlier than full participation. Costs are calculated both in NPV terms (light coloured bars) and as maximum losses over time (coloured bars). Box plots indicate variations across models (median, 25% and 75%, and maximum and minimum). The climate stabilization target is 3.7 W/m^2 with overshoot. In the fragmented scenarios, OECD join immediately the climate policy, BRICs in 2030 and other DCs in 2050. Source: EMF22

The notion of fragmented near-term international strategies toward stringent mitigation goals raises a relative contradiction in incentives and further increases the sense that such policy approaches will reduce the chances that stringent goals will be met. Very particular circumstances must be in place for countries to see little benefit in mitigation in the near-term and then to undertake dramatic action in the longer-term. Indeed, studies have shown that the ability to foresee the coming target is essential for reducing the costs of mitigation for late entrants. For example, inter-temporal dynamic models suggest that in the face of a future mitigation commitment it is optimal to anticipate abatement, reducing the adjustment costs of confronting climate policy with a more carbon intensive capital stock (Richels, Blanford, and Rutherford 2009; Bosetti, Carraro, and Tavoni 2009). Most generally, although studies have demonstrated that particular goals can still be met under fragmented international action, these same studies have also demonstrated the inherent inconsistency in the nature of late entrants if such long-term goals are truly to be met.

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

When accounting for national interest, the literature suggests that climate coalitions which are self enforcing and stable can be effective only in the presence of significant compensatory transfers. Schemes like international emission trading, technology agreements have been showed to be quite successful in inducing cooperation (Carbone et al., 2009). The financial transfers that would result depend on the burden sharing and on regional abatement opportunities but have been shown to be potentially significant. For example, in the above mentioned EMF22 the transfers in an international emission permit market for a 550 ppmv CO2-e case are found to be in the range of several hundred billions of U.S. dollars per year, see Figure below.

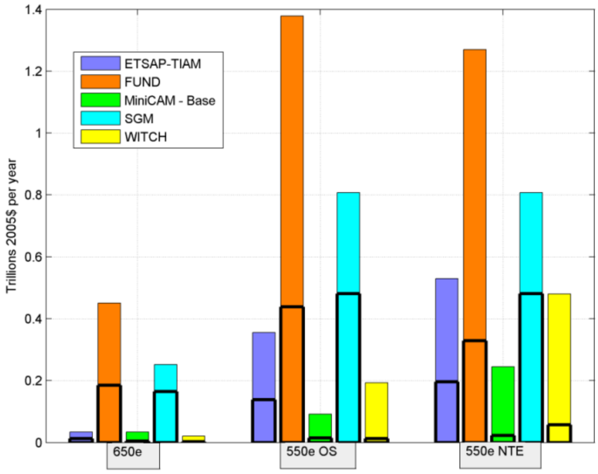


Figure 6.21. Average financial transfers from OECD in an international carbon market (2020-2050). The blacked part represents the transfers to BRICs.

The transfers associated with different burden sharing schemes have a direct impact on the geographical distribution of climate policy costs, which are found to be rather sensitive to the given allocation scheme, especially for the major emerging economies.

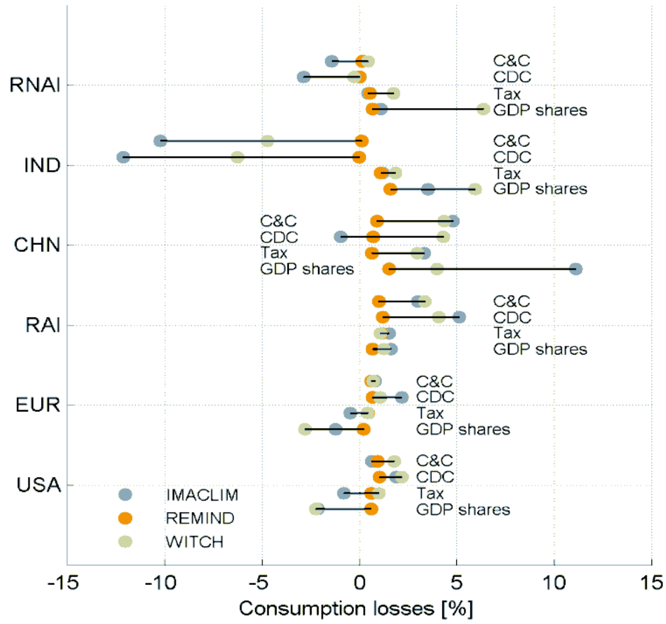


Figure 6.22. Policy costs for different allocation schemes (C&C=Contraction and Convergence, CDC=Common but differentiated Convergence, Tax=Uniform Carbon Tax, GDP Shares= equal emission right of emission per unit of GDP) from the RECIPE project for a 450 ppm-CO2 stabilization target, for key regions.

6.3.6.4 The implications of international climate architectures on emissions pathways and mitigation levels across regions

An important implication of fragmented policy regimes is that the allocation of emissions reductions both across regions and over time will differ from the idealized scenario. In the near-term, emissions reductions will be undertaken more heavily in those countries participating in action, not surprisingly, and total global mitigation will be pushed toward the future. If long-term goals are to be met, however, the degree to which mitigation at a global level is pushed to the future may be limited. The long-term constraint enforces a degree of mitigation discipline, meaning that much of the result of fragmented action, assuming again that a particular goal will be met, is to speed up mitigation efforts for the early entrants and delay them for the late entrants (Figure 6.23). As discussed above, when the delayed entrants begin to undertake reductions, they do so at a rate far more rapid than they would have otherwise.

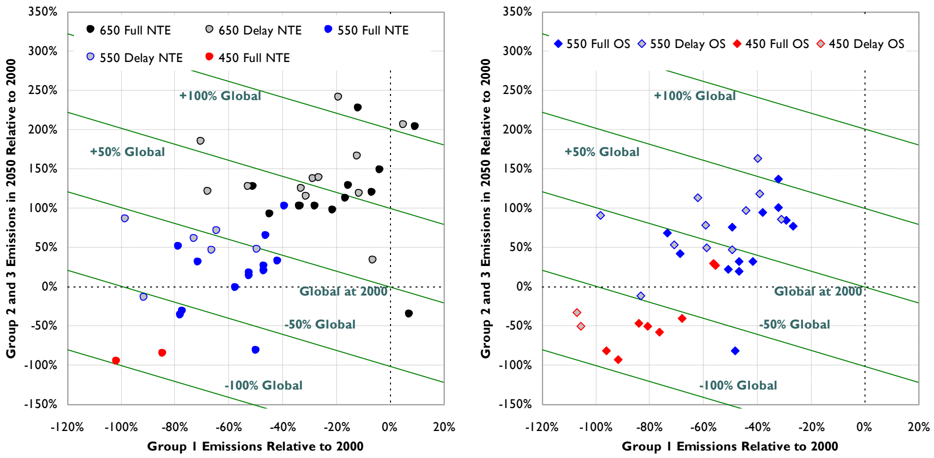


Figure 6.23. Emissions across regions and in total in the not-to-exceed and overshoot scenarios from EMF 22. [AUTHORS: Note to reviewers: This is a placeholder figure, and we will explore whether a better figure is more appropriate in the second-order draft.]

6.3.7 Energy Sector Technology Transitions

6.3.7.1 Low-carbon energy supply along transformation pathways

There is a clear linkage between the long-term stabilization goal and the amount of freely-emitting fossil fuel energy that can be used in the energy sector. The long-term climate stabilization goal constrains the amount of cumulative GHG emissions over the course of the coming decades to century and thereby the use of freely-emitting fossil energy (Figure 6.24), see also (Fischedick et al., 2011a; Krey and Clarke, 2011b)]. Although the relationship is quite strong, some flexibility in the limits on the use of freely-emitting fossil energy remains, as reflected by the ranges shown in Figure 6.24. Factors that lead to this flexibility include the difference in the (direct and indirect) carbon content of the various fossil fuels (e.g., natural gas has a lower carbon content per unit of energy than coal, but upstream GHG emissions in the production of fossil fuels also play a role); the potential to achieve negative emissions by utilizing bioenergy with CCS or forest sink enhancements (Sections 6.2.2 and 6.2.8), which allow for greater emissions of freely-emitting fossil energy; differences in the timing of mitigation as a result of differing underlying model structures, assumptions about technologies, drivers and mechanisms to allocate mitigation effort optimally over time (e.g., discounting); and representations of physical systems such as the carbon cycle.

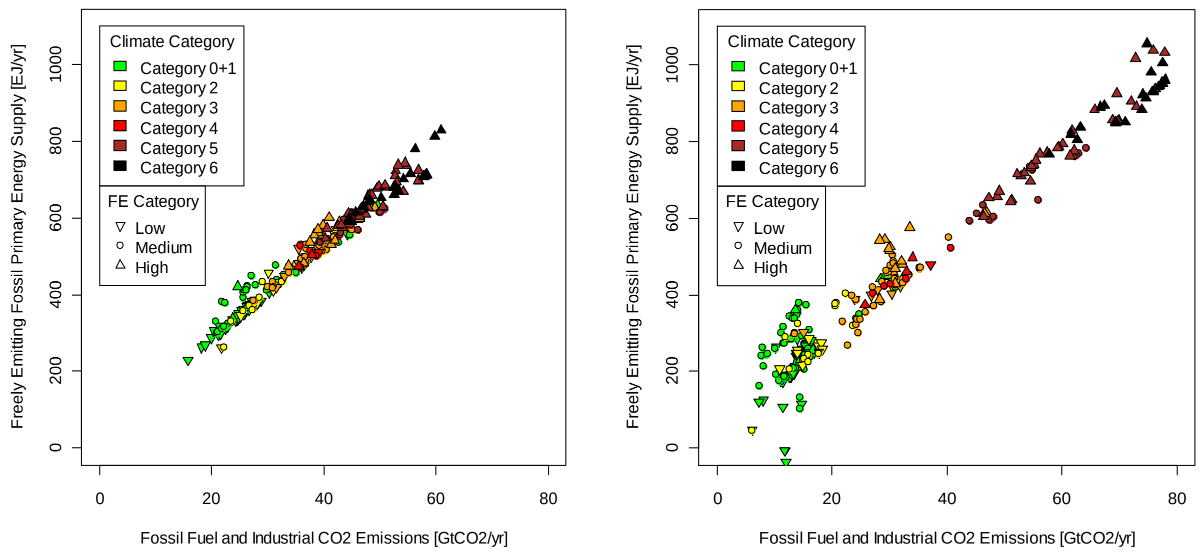


Figure 6.24. Global freely emitting fossil primary energy supply (direct equivalent) in the reviewed long-term transformation pathways by 2030 (left) and 2050 (right) as a function of fossil and industrial CO2 emissions. The colour coding is based on categories of climate stabilization as defined in Section 6.2.2. The different symbols relate to different levels of final energy use in the scenarios. [AUTHORS: Note to reviewers: Please see note in the introduction regarding the preliminary nature of the scenario dataset.]

While the use of freely emitting fossil energy is tightly constrained by the climate target, there is no similar limitation that applies to the total primary energy used as long as the remaining energy consumption does not add significantly to the GHG emissions budget associated with the climate target. Therefore, the use of low-carbon energy – which we define here as the sum of renewable energy, nuclear energy, and fossil energy with CCS (see also Fischedick et al., 2011b) – is far less well correlated with the CO2 emissions from fossil fuel use and industrial processes (Figure 6.25) and therefore with the long-term stabilization goal. Despite the looser coupling, there is a strong tendency that low carbon energy use needs to increase with more stringent climate targets to substitute for the accompanying decrease in freely emitting fossil energy. The deployment levels of low carbon energy technologies are substantially higher than today in the vast majority of scenarios, even under baseline conditions, but in particular so for the most stringent climate stabilization scenarios of climate categories 1 and 0.

It is important to note that the quantity of low-carbon energy required is also influenced by the degree that energy consumption is altered along a transformation pathway. Energy demand reductions will occur both in responses to higher energy prices brought about by mitigation as well as by approaches to mitigation focused explicitly on reducing energy demand. When taking into account the level of total energy consumption (Figure 6.25), it becomes clear that higher low carbon energy technology deployment tends to go along with higher final energy use and vice versa. Hence the relative importance of energy supply and demand technologies varies across transformation pathways (see Section 6.2.7.2).

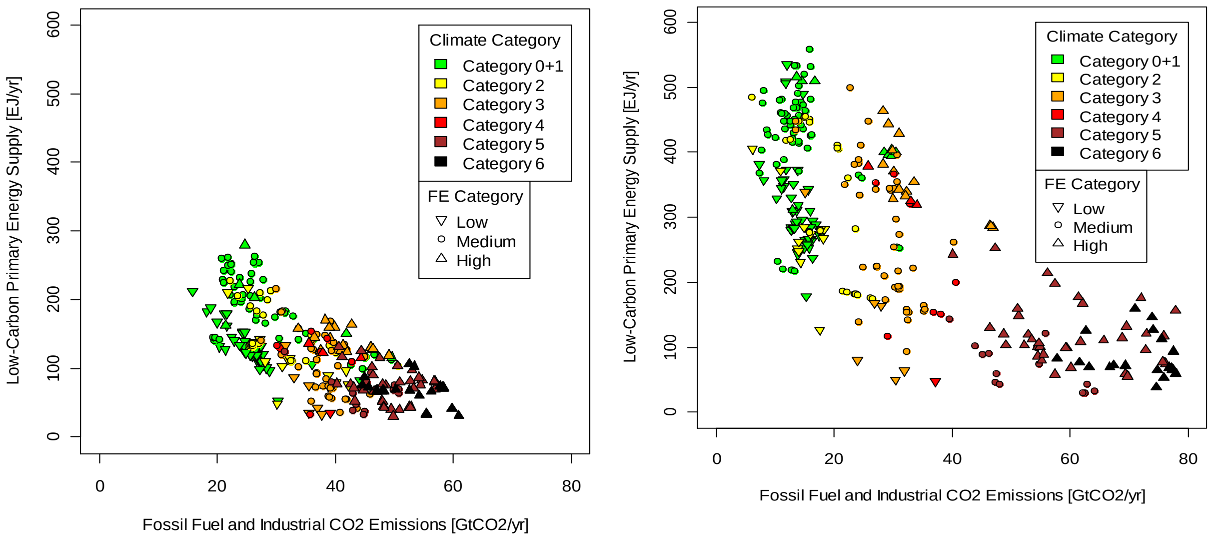


Figure 6.25. Global low carbon primary energy supply (direct equivalent) in the reviewed long-term transformation pathways by 2030 (left) and 2050 (right) as a function of fossil and industrial CO2 emissions. The colour coding is based on categories of climate stabilization as defined in Section 6.2.2. The different symbols relate to different levels of final energy use in the scenarios. [AUTHORS: Note to reviewers: This definition will be provided in the SOD; for now, the key point is that these final energy categories help to parse the space. Please see note in the introduction regarding the preliminary nature of the scenario dataset.]

On the energy supply side, different technologies and technology clusters compete with each other for the provision of low carbon energy (Figure 6.26). Moving from baselines to climate category 3 and further to category 0 and 1, the role of fossil energy (coal and hydrocarbons) decreases across scenarios (Figure 6.26, left panel). At the same time, the degree to which this is accomplished depends to a large degree on the models and the assumptions used to generate scenarios, and it is particularly tightly linked to the importance of fossil CCS in a specific pathway. For example, in the electricity sector (Figure 6.26, right panel), some pathways maintain roughly equal shares of renewable, fossil CCS and nuclear power, while other pathways tend to move into the upper corner, thereby relying mostly on renewable electricity generation. These different behaviours can be traced back to differences in model structures, assumptions about technological change, energy resources – renewable, fossil and nuclear – and CO2 storage potentials, both at the global and regional levels (Fischedick et al. 2011; Krey and Clarke 2011). However, a robust finding is the significant transformation of the electricity generation mix under the intermediate 550 ppm CO2-equiv target which is only modestly changed under the more stringent 450 ppm CO2-equiv target.

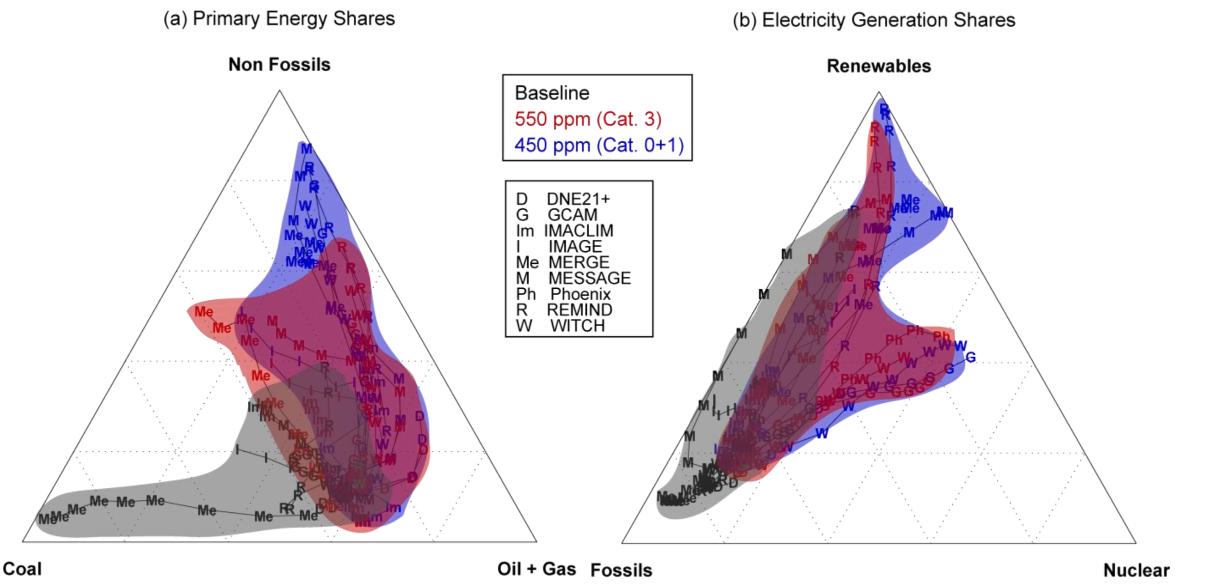


Figure 6.26. Primary energy (a) and electricity generation shares (b) by technology cluster in different transformation pathways between 2005 up to 2100. Letters correspond to different models. The green letters denote the base year shares, consecutive letters show the development in the future in 10-year steps where the black letters correspond to baseline scenarios, red to climate category 3 scenarios and blue to climate category 1 scenarios. [AUTHORS: Note to reviewers: Results are preliminary from the ongoing EMF27 modelling comparison]

Many low-carbon supply technologies, such as nuclear power, CO2 storage, hydro or wind power, sometimes face public acceptance issues and other barriers that may limit or slow down their deployment. Despite technical maturity and competitive costs societies may therefore choose to exclude one or several options form the portfolio which may lead to mitigation cost increases or unattainability of low climate targets. Such reduced technology portfolio scenarios have been studied in the literature and will be discussed in more detail in Section 6.2.7.3 with a focus on economic implications. The changes in the configuration of the energy system strongly depend on the technology portfolios in the full portfolio cases which by themselves vary significantly across models. Section 7.12 discusses some illustrative examples for different energy supply side portfolios.

6.3.7.2 Energy end use sectors along transformation pathways

Transformation pathways indicate two roles for energy demand sectors in climate mitigation. One of these roles is to facilitate the use of low-carbon fuels in end uses. In particular, across transformation pathways, a robust result is that there is an increase in the share of electricity in final energy consumption (Figure 6.27). With increasing stringency of the climate target, the share of electricity in final energy use significantly increases beyond the baseline level. Because electricity generation can be decarbonized at relatively modest extra costs (compared to other fuels), electrification of the end-use sectors is a way of reducing GHG emissions from the entire energy system (e.g., Sugiyama, 2012).

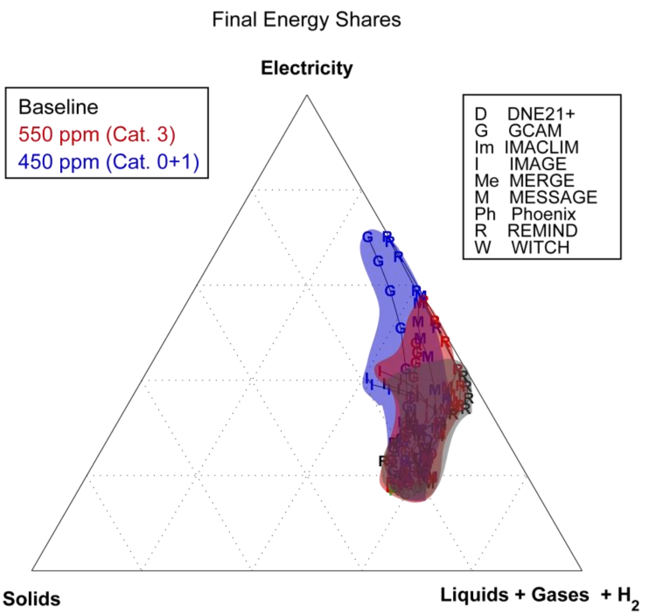


Figure 6.27. Final energy shares for three different groups of energy carriers – solids, liquids/gases/hydrogen, electricity – in different transformation pathways between 2005 up to 2100. Letters correspond to different models. The green letters denote the base year shares, consecutive letters show the development in the future in 10-year steps where the black letters correspond to baseline scenarios, red to climate category 3 scenarios and blue to climate category 1 scenarios. [AUTHORS: Note to reviewers: Results are preliminary from the ongoing EMF27 modelling comparison]

The other important role of end use sectors in climate mitigation is to reduce energy demand, thereby reducing the need for low-carbon energy. Virtually all scenarios indicate meaningful reductions in energy demand as an economically-efficient element of mitigation (Figure 6.28). An important question regarding energy demand reductions is the role that such reductions might play in mitigation relative to the role of decarbonisation of energy supply. There are considerable differences between scenarios when it comes to the relative importance of reductions of carbon intensity (measured as the fossil fuel and industrial CO2 emissions per unit of primary energy supply) and energy intensity (measured as final energy use per unit of GDP) – two important factors in the Kaya identity – compared to the corresponding baseline. However, in all transformation pathways assessed here, by 2050 the relative reduction of carbon intensity is larger than the relative reduction in energy intensity. In some cases the relative carbon intensity reduction is exceeding the relative energy intensity reduction by a factor of more than four.

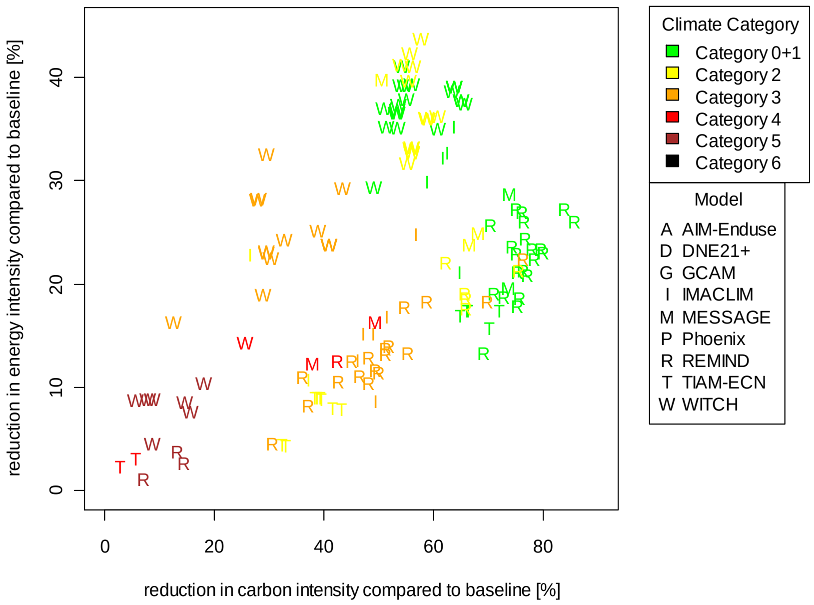


Figure 6.28. Reduction in carbon intensity of primary energy supply vs. reduction in final energy intensity of GDP compared to baseline in 2050 for different climate stabilization categories. [AUTHORS: Note to reviewers: Please see note in the introduction regarding the preliminary nature of the scenario dataset.]

6.3.7.3 The economic and model infeasibility implications of technological change and technology portfolios choices

The choice of technologies for use in mitigation is not a simple economic one of minimizing mitigation costs. The choice is also related to a range of other societal priorities such as energy security, safety, and competitiveness. In addition, the choice will be influenced by what technologies are actually available for mitigation, and this will be the result of a complex and uncertain process of technological change. Hence, an important consideration in evaluating transformation pathways is the influence of different assumptions about technology availability or performance on the costs of mitigation.

Several multi-model studies, EMF27, ADAM (Knopf et al., 2009; Edenhofer et al., 2010) and RECIPE (Luderer et al., 2011) have explored the influence of technology availability and performance. EMF27 is the largest of these studies and also the most recent [in its final stage during summer 2012]. Therefore, the results shown here most heavily rely on this study and are compared with the earlier ones. In addition, individual research papers and reports have done similar work, sometimes in more detail, but typically constrained to a single model (e.g. Calvin, Edmonds, et al., 2009; Krey and Riahi, 2009a; van Vliet et al., 2009b; Riahi et al., 2012).

The primary result of these analyses is to confirm that mitigation costs are heavily influenced by the nature of the available mitigation technologies (Figure 6.29 and Figure 6.30). Of importance, the influence of technology generally increases with increasing stringency of the climate target.[6] Mitigation costs tend to increase more for specific constrained technology portfolios than in the default (full technology portfolio) cases where on average a doubling of mitigation costs is reported moving from the 550 to the 450 ppm CO2-equiv target. The response in mitigation costs varies to some degree by technology, however, the ranges reported by the different models tend to strongly overlap (see Section 6.2.4 and Fisher et al., 2007)). Although the increase in total costs is

[6] Due to different types of models participating in the EMF27 modeling comparison, different mitigation costs measures have been applied for different models: energy system costs and additional direct mitigation costs for partial equilibrium models, consumption losses for general equilibrium models.

substantially higher at the tighter stabilization level (Figure 6.29), this is in fact largely a product of the fact that mitigation is simply much more costly at the tighter stabilization goal (see Section 6.4), as evidenced by the fact that the relative increase in costs is not nearly so different across stabilization goals (Figure 6.30).

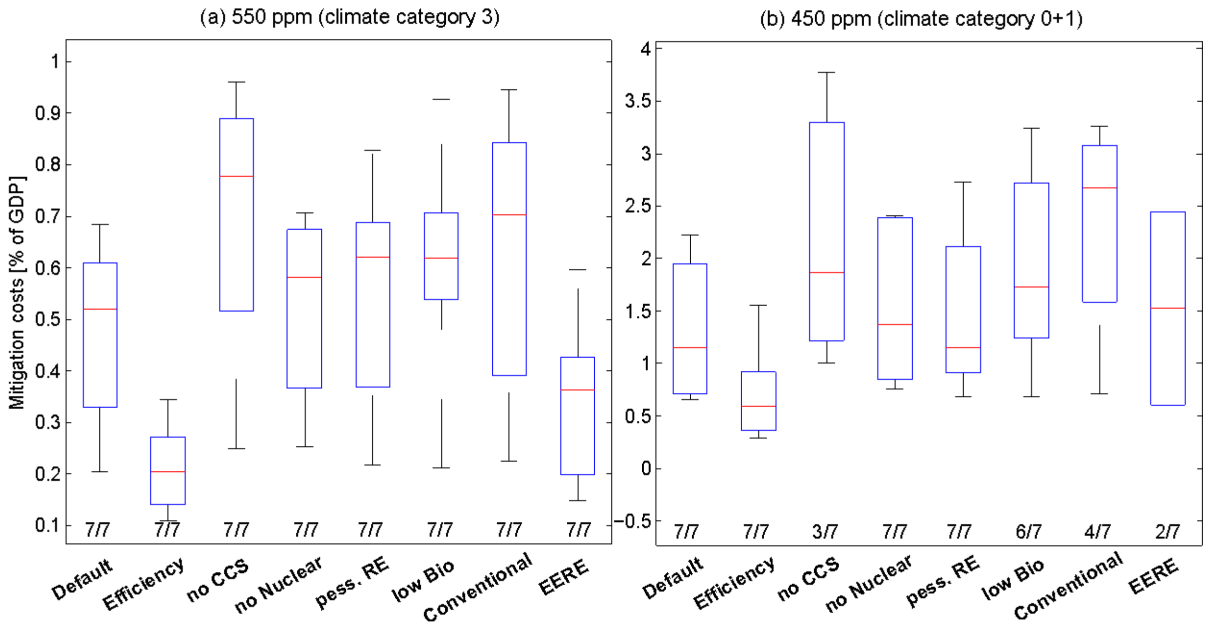


Figure 6.29. Mitigation costs as a fraction of GDP (discounted @5%, between 2010 and 2100) in case of technology portfolio variations for a 550 ppm (a) and a 450 ppm (b) CO2-equiv stabilization target. The numbers at the bottom of both panels indicate the number of models that attempted the reduced technology portfolio scenarios and how many in each sample were feasible. [AUTHORS: Note to reviewers: Results are preliminary from the ongoing EMF27 modelling comparison]

In the assessment of costs it is important to note that model infeasibility (see below) needs to be taken into account in the interpretation of results to avoid a serious underestimation of costs (Tavoni and Tol, 2010). For example some models did not reach the 450 ppm CO2-equiv target without CCS or low bioenergy supplies which means that the range indicated for this case is actually downward biased, because only the cost increases of models that were able to still achieve the target are included.

Unavailability of CCS tends to be associated with the most significant cost increase in the 450 ppm target. This high value of CCS in the scenarios is relate to several factors: (i) CCS is a versatile technology which can be combined with electricity, synthetic liquids and gas and hydrogen production from several feedstocks, (ii) CCS can act as bridge technology that is compatible with existing fossil-fuel dominated supply structures, and (iii) in combination with biomass negative emissions can be generated which is potentially attractive in the longer term (see Section 6.2.2). Nonetheless, other supply side technologies also have an important influence on costs.

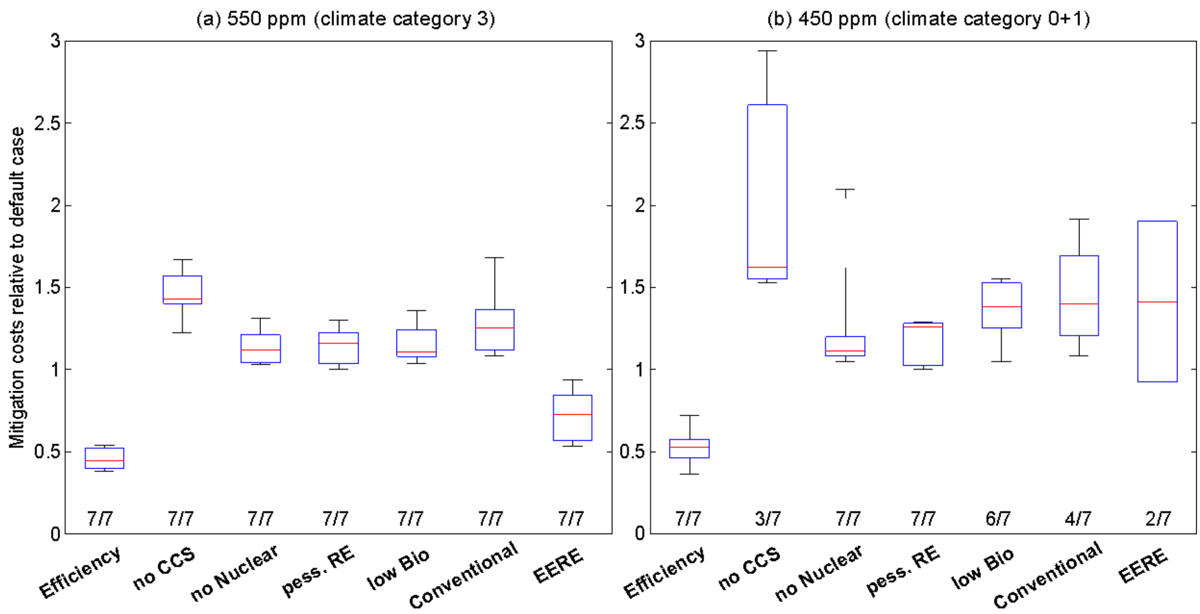


Figure 6.30. Relative mitigation cost increase (discounted @5%, between 2010 and 2100) in case of technology portfolio variations compared to the default (full portfolio) 550 ppm (a) and the default 450 ppm (b) CO2-equiv stabilization scenarios. The numbers at the bottom of both panels indicate the number of models that attempted the reduced technology portfolio scenarios and how many in each sample were feasible. The conventional scenario combines pessimistic assumptions for bioenergy and other RE with availability of CCS and nuclear and the higher energy intensity pathway. On the other hand, the energy efficiency and renewable energy (EERE) case combines optimistic bioenergy and other RE assumptions with a low energy intensity future and non-availability of CCS and nuclear. [AUTHORS: Note to reviewers: Results are preliminary from the ongoing EMF27 modelling comparison]

Demand-side technologies also demonstrate an important influence on the costs of mitigation. For example, in EMF 27, reductions in the energy intensity pathway led to substantial reductions in the costs of mitigation. It should be noted, however, that the costs for implementing this more energy efficient future have not been taken into account by all models, leading to a potential downward bias of these estimate.

Further, returning to the point that the role of demand side measures are important not just for reducing energy consumption, but also for facilitating the use of low-carbon fuels, a number of individual studies have looked into the importance of specific demand side technologies for reaching low GHG concentration levels. For example, Riahi et al. (2012) by allowing electricity or hydrogen in transportation, along with the associated supply side conversion technologies, increases the flexibility on the supply side by opening up additional supply routes to the transportation sector and therefore reduces mitigation costs.

In addition to increasing the costs of mitigation, the nature of available technologies can also influence the feasibility of meeting targets in other ways, and this can be represented by the degree of model infeasibility (see section 6.2.2 for a discussion of model infeasibility) that emerges for different stabilization goals and different technology assumptions (see the percentage of model able to meet a particular goal with different technology combinations for EMF 27 at the bottom of Figure 6.29 and Figure 6.30). In general, limited technology portfolios have not led to model infeasibilities for the 550 ppmv CO2-e scenarios. However, at the tighter, 450 ppmv CO2-e constraint, many models could not produce scenarios with limited technology portfolios. In particular, the absence of CCS made these scenarios particularly challenging.

6.3.8 Land and stabilization

6.3.8.1 Baseline emissions and sequestration

Baseline land-related emissions and sequestration are an important uncertainty with implications for transformation portfolios and costs. For instance, higher baseline land-use change emissions represent more emissions that must be mitigated, but also increased land conversion pressure and therefore higher costs for mitigation (e.g., Sohngen and Sedjo, 2006). Land-use and land management affect the climate through radiative forcing via GHG emissions (CO2 and non-CO2), carbon sequestration, land albedo (reflectivity), and aerosol and tropospheric ozone precursor emissions (primarily from open-burning of biomass). Non-CO2 GHG emissions come from croplands (synthetic and organic fertilizer use, rice paddies), livestock production (manure and enteric), and fossil fuel combustion associated with management and transport. Carbon sequestration occurs below ground in soils and above ground in growing biomass (e.g., crops, grasses and trees) and stocks can be increased or released to the atmosphere naturally and as a result of human activity (soil tillage change, land conversion, forest harvest and management). (See Chapter 11 for details regarding sources and emissions.)

Uncertainty about land-related baseline CO2 emissions and sequestration is significant historically (Houghton et al., 2012; Pan et al, 2011) and in projections. The latest baseline projections for land related CO2 emissions show an enormous range across integrated assessment models, which begins with historical years (Figure 6.31). Like AR4, most projections suggest declining annual CO2 emissions over time. In part, this is driven by technological change, as well as projected declining rates of agriculture area expansion, which, in turn, is related to the expected slowing in population growth. However, unlike AR4, all models suggest that globally, we have passed LUCF peak emissions. There is also somewhat larger variability later in the century, including a strong net sink starting in 2050. The revised range is 1.0 – 4.5 GtCO2/yr in 2020 and (-0.5) – 3.5 GtCO2/yr in 2050.

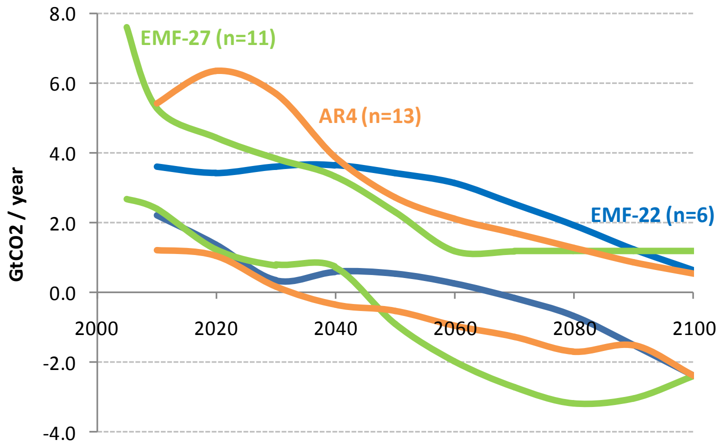


Figure 6.31. Baseline ranges of LUCF CO2 emissions (GtCO2/year). Sources: AR4 (Fisher et al., 2007), EMF-22 (Clarke et al., 2009), EMF-27 (green, preliminary results placeholder, not for distribution). Note: outlier projection removed from EMF-27 data. Also, of the 11 EMF-27 projections, 8 went to 2100.

6.3.8.2 Climate policy transformation

The literature suggests a significant cost-effective, and possibly essential, mitigation role for land in transformation. A key interaction between land and energy system transformation is through bioenergy and land-use change, such that more emissions from land will imply greater fossil and industrial emissions reductions, and vice versa. The competition for land to produce bioenergy, store carbon in land, produce agricultural products, and provide other ecosystems services provides a complicated and important area of consideration in transformation pathways.

Projections of potential land-related GHG mitigation suggest significant promise (supply) and potential decarbonization role within transformations (quantity supplied), in particular when bioenergy is included (Rose et al., 2012). Transformation projections of net land-use emissions and land-use are largely defined by the reference scenario and mitigation policy assumptions regarding eligible abatement options and regions covered. Most transformation scenarios assume immediate, global, and comprehensive availability of land related mitigation options. In these cases, models are assuming a global terrestrial carbon stock incentive or a global forest protection policy, as well as global agriculture mitigation policies. Bioenergy is also being deployed, sometimes at significant levels. Recent literature has illustrated that more realistic non-comprehensive and delayed pathways for land-related GHG mitigation policy offer less mitigation potential, at least in the near-term, and there are potentially adverse consequences (e.g., Rose and Sohngen 2011; Tyner et al. 2010; Calvin et al. 2009).

GHG mitigation opportunities in land are of one of three types: emissions reductions, terrestrial carbon stock enhancement, or biomass displacement of fossil-fuel based energy. Bio-based products are also a possibility, but one not yet modeled. For a more complete discussion of mitigation technologies, as well as mitigation supply potential, see Chapter 11.

A survey of results from models with explicit representations of land (Rose et al., 2012) found that, across the surveyed scenarios, land-related strategies contributed 21 to 59% of total cumulative abatement to 2030, with forest strategies contributing 0 to 25%, agricultural CH_4 -1 to 7%, agricultural N_2O 1 to 23%, and bioenergy 2 to 26% of total abatement. To 2050, all land-related strategies contributed 14 to 72% of total cumulative abatement, with forestry 14 to 55%, agricultural CH_4 0 to 9%, agricultural N_2O 1 to 13%, and bioenergy 4 to 24%. Over the century, bioenergy was the dominant strategy, followed by forestry, and then agriculture. Bioenergy mitigation levels reached as high as 3.7, 7.3, and 25.7 $GtCO_2$/year in 2030, 2050, and 2100 respectively. In a separate study, Klein et al. (2011) report bioenergy abatement of approximately 37 $GtCO_2$/year in 2100.

More generally, transformation pathway studies have produced total global land-use CO_2 emissions reductions of up to 5 and 6 $GtCO_2$/year in 2030 and 2050 respectively (Fisher et al., 2007); L. Clarke et al., 2009), with up to 10 $GtCO_2$/year having also been estimated (Wise et al., 2009), in scenarios in which terrestrial carbon is subject to the same immediate and global price as fossil and industrial emissions. In contrast, scenarios with delayed global regional participation and bioenergy incentives but without incentives/accounting for terrestrial carbon stocks have produced sizable increases in emissions. For instance, emissions increases of 4 and 6 $GtCO_2$/year in 2030 and 2050 respectively have been estimated from scenarios with staggered global regional forest carbon policies (Calvin et al. 2009). This issue is discussed more below.

To better understand the potential of land-use CO_2 emission reductions and sequestration in transformation pathways, it is helpful to juxtapose them with carbon prices. Intuitively, the literature projects greater reductions with more stringent climate targets and higher CO_2 prices (**Figure 6.32**). And, across models, there is evidence of a positive correlation between reductions with carbon prices. However, some models estimate large reductions with a low carbon price, while others estimate low reductions despite a high carbon price. In large part, these divergent views are due to differences in modeling. Overall, while a tighter target and higher carbon price results in an increase in land-use CO_2 reductions, the relationship within models is non-linear and declining. Thus, reductions increase at a decreasing rate. This is indicative of the rising relative cost of land abatement and subsequent increasing reliance on energy system abatement and energy consumption reductions. This is a result also found in (Rose et al., 2012).

The value of land-use CO_2 reductions has not been broadly evaluated to date. There are however a few estimates or proxies. (Jakeman and Fisher, 2006) estimated that including land-use change and forestry mitigation options reduced global real GDP losses associated with achieving stabilization to 2.3% in 2050 (US$3.6 trillion in 2003 dollars), versus losses of 7.1% (US$11.2 trillion) and 3.3%

(US$5.2 trillion) for CO2-only and multi-gas (without forest sinks) scenarios respectively. Wise et al. (2009) provide another indicator with CO2 prices in 2050 up to four times those from stabilization policies that excluded land-use carbon.

More recently, the literature has begun exploring more realistic fragmented policy contexts and identifies a number of policy coordination issues. There are many dimensions to policy coordination: technologies, regions, climate and non-climate policies, and timing. For instance, increased bioenergy incentives without terrestrial carbon stock incentives (Wise et al., 2009; Reilly et al., 2012) or global forest protection policy (Popp, Dietrich, et al., 2011) suggests a large potential for leakage with the use of energy crops. The leakage comes primarily in the form of displacement of pasture, grassland, and natural forest. There is also food cropland conversion. However, providing bioenergy, while protecting terrestrial carbon stocks, could result in a significant increase in food prices.

In general, implementing land mitigation policies will be challenging. In addition to the leakage associated with coordinating mitigation activities, staggered adoption of land mitigation policies will likely have leakage implications (e.g., Calvin et al. 2009; Rose and Sohngen 2011). Regional abatement supply costs are also affected by regional participation/non-participation as the opportunity costs of abatement are impacted by relative production costs (Golub et al., 2009). And, fragmented and delayed forest carbon policy could even accelerate deforestation (Rose and Sohngen, 2011).

To understand bioenergy's transformation role, it is important to understand bioenergy's role within the energy system. The research results surveyed in (Rose et al., 2012) found bioenergy contributing up to 15% of cumulative primary energy over the century during stabilization. **Figure 6.33** shows more recent annual results, where bioenergy is projected to provide 20 to 250 EJ in 2050 (10 to 30% of total primary energy) and 10 – 330 EJ in 2100 (20 to over 40%) for immediate global action scenarios. The modeling reports an increasing dependence on bioenergy with lower climate change targets, both in a given year as well as earlier in time. When modeled, bioenergy combined with carbon capture and storage features prominently (Figure 6.2.8 – 3), and bioenergy could be the dominant land-related mitigation strategy (e.g., Rose et al., 2012). **Figure 6.33** also illustrates the uncertainty in baseline bioenergy, as well as the incremental increases from baseline for 450 ppm CO2eq climate policies.

The models universally project that the majority of bioenergy primary energy, regardless of the end-use, will occur in developing and transitional economies (60-75% in non-OECD in 2050, 60-82% in 2100), including bioenergy with CCS, and bioenergy share of total regional electricity and liquid fuels could be significant. There is no single vision about where biomass is projected to be cost-effectively deployed within the energy system, due in large part to uncertainties about relative technology options and costs over time. Some models prefer to use biomass for electricity, while others prefer to use if for biofuels, as well as hydrogen. For immediate participation 550 ppm CO2eq scenarios, the EMF-27 scenarios estimated bioelectricity's share of regional electricity in 2050 as 0-11% in the OECD, 0-22% REF, 0-26% MAF, 0-20% LAM, and 0-10% ASIA; and biofuels share of regional liquid fuels as 0-31% in the OECD, 0-73% REF, 0-35% MAF, 0-43% LAM, and 0-25% ASIA (EMF-27 study, forthcoming).

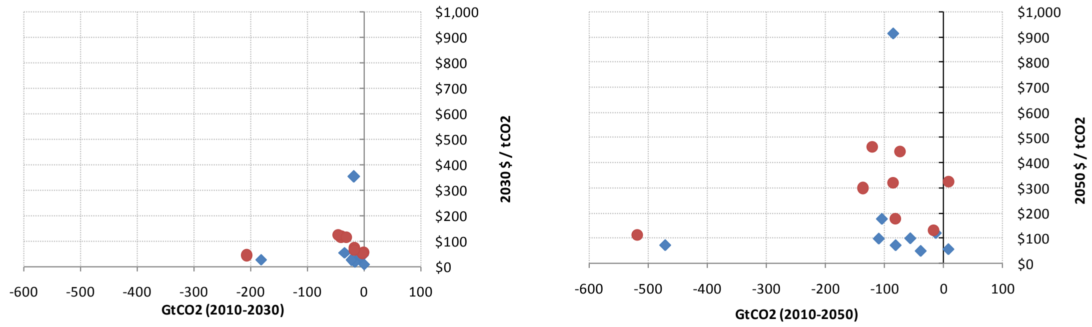


Figure 6.32. Projected cumulative land-use CO2 emissions reductions 2010-2030 and 2010-2050 relative to 2030 and 2050 estimated carbon prices. Blue results for 4.5 W/m2 targets. Red results for 3.7 W/m2 targets. Source: EMF-27 (preliminary results). Not all models reported results for both climate targets. Results for scenarios with immediate global comprehensive participation policies with no artificial constraints on total primary bioenergy. [AUTHORS: Note to reviewers: Results are preliminary from the ongoing EMF27 modelling comparison]

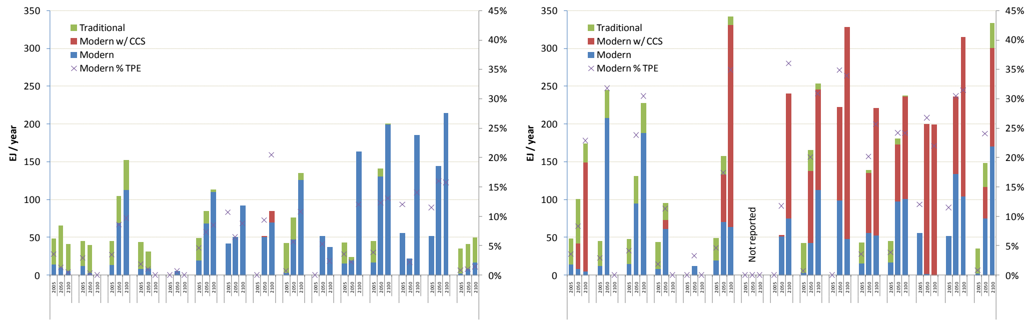


Figure 6.33. Global biomass primary energy for 2005, 2050, and 2100 from 15 models from baseline (left) and 450 ppm CO2e (right) scenarios. Crosses are biomass share of total primary energy. Source: EMF-27 (preliminary results). [AUTHORS: Note to reviewers: Results are preliminary from the ongoing EMF27 modelling comparison]

A particularly important issue with respect to bioenergy is the use of bioenergy in conjunction with carbon dioxide capture and storage. BioCCS could be very helpful (and valuable) for getting to lower targets (especially in later half of century), and as an overshoot response technology that even affects the degree of overshoot. Whether it is essential for climate management, or even sufficient, is unclear. Some results provide anecdotal evidence that BioCCS and REDD abatement may be essential for very low climate change objectives. For instance, Clarke et al. (2009) found that a 2.6 W/m2 stabilization target was only feasible for two models—both included BioCCS. In addition, van Vuuren and Riahi (2011) found that the vast majority of 2.6 W/m2 scenarios included BioCCS. Overall, IAMs would like bioenergy to be a significant part of energy transformation and climate management. However, the bioenergy transformation suggested by modeling is challenging and problematic due to the regional scale of deployments, and implementation challenges, including institution and program design, land-use policy coordination, emissions leakage, and potential non-climate social implications.

6.3.8.3 Implementation issues

There are significant challenges to accessing the potential estimated above. Among other things, there are large fundamental historical scientific uncertainties about terrestrial carbon stocks and fluxes (e.g., (Henry et al., 2011); Houghton et al., 2012) that combined with uncertainty about economic behavior, complicate estimation of mitigation potential, as well as actual mitigation project implementation, and could lead to order of magnitude differences in land-use changes (e.g., Sathaye et al., 2011); Lubowski and Rose, in review). Similarly, the state of institutions, protocols, approval processes, and country implementation capability are poor (e.g., Sathaye et al., 2011). As a result, there are likely significant mitigation project risk and transactions costs. A few efforts have attempted to quantify these factors (RFF Forest Carbon Index, REF; EPRI mitigation investment delivery risks, REF), but these costs are not yet included in scenarios modeling. In addition, as discussed above, integrated assessments of the role of forests and land in climate stabilization policies have, in general, abstracted from institutional details of climate policy and assumed ideal carbon market designs. Policy is unlikely to unfold that way and the new literature mentioned above has suggested that it matters. Interactions between policies, regions, and over time will affect forestry, agricultural, and bioenergy mitigation potential and net GHG effectiveness. Together, these issues imply that there is likely less available mitigation potential than suggested above, and possibly unavoidable negative emissions consequences associated with getting programs in place.

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 their radiative effects on the earth's heat balance is a long-term endeavour. There is substantial inertia in both the physical system (e.g. carbon accumulation and uptake) and the energy system (e.g. long-lived fossil-based capital stock), thus transformation pathways must be evaluated over long time horizons. There is also substantial uncertainty in our understanding of both the physical system and the technologies and preferences that will characterize the future energy system. Accordingly, whether a particular target can be met, and what the cost will be of meeting it, will depend on decisions to be made and uncertainties to be resolved over many decades. The transformation to atmospheric stabilization is best understood as a process of sequential decision-making and learning. The most relevant decisions are those that must be made in the near-term with the understanding that new information and opportunities for strategic adjustments will arrive often.

6.4.2 Near-term emissions and long-term transformation pathways

There is a very broad range of near-term emissions levels that could be consistent with a given long-term stabilization target (Figure 6.34). Some stabilization scenarios are constructed to follow a cost-minimizing allocation of emissions reductions over time. Even among optimal pathways for a particular long-term target, near-term emissions levels depend on factors such as the availability of technology (both near-term and long-term), trade-offs between sectors such as energy and land-use, and the evolution of non-CO2 gases and non-gas forcing agents. In particular, models or scenarios that assume the future availability of a negative emissions energy conversion technology, such as electric generation from sustainably grown biomass with carbon capture and storage, tend to show optimal stabilization pathways with higher near-term emissions than models without such an option (see section 6.2.2). Models employ a wide range of assumptions about the mitigation potential for non-CO2 greenhouse gases, such as methane and nitrous oxide emissions from agriculture. In some models there are significant residual emissions of these gases that cannot be abated, which forces greater and earlier reductions in energy-related CO2 to meet the same target. There is also considerable uncertainty on the role of aerosol forcing, so that models assuming a larger magnitude negative offset can meet the same forcing target with higher atmospheric levels of CO2.

The ranges depicted in Figure 6.34 include both optimal and non-optimal pathways toward the various long-term stabilization categories. In addition to the factors described above underlying variation in the optimal near-term emissions level associated with a long-term target, constraints on so-called "when-" and "where-" flexibility lead to larger (and typically) higher ranges. This class of non-optimal stabilization pathways have received significant attention and analysis since the publication of the AR4. One important variable is the extent of international participation in the near-term. Scenarios with incomplete international participation have higher pathways in the near-term than would be optimal with full participation from the outset. In most of these scenarios, participating countries compensate partially during the initial phase, but the global pathway is shifted in time, resulting in steeper reductions later to meet the target (see Clarke et al., 2009). Another possibility is that even with full participation, policies constrain near-term emissions at levels higher than in an optimal setting. In Figure 6.35, the optimal ranges are exceeded during the near-term period (through 2030) where emissions follow a myopic pathway (see AMPERE reference). By 2050 the optimal and non-optimal ranges have converged, although in the longer run the non-optimal pathways may require deeper reductions.

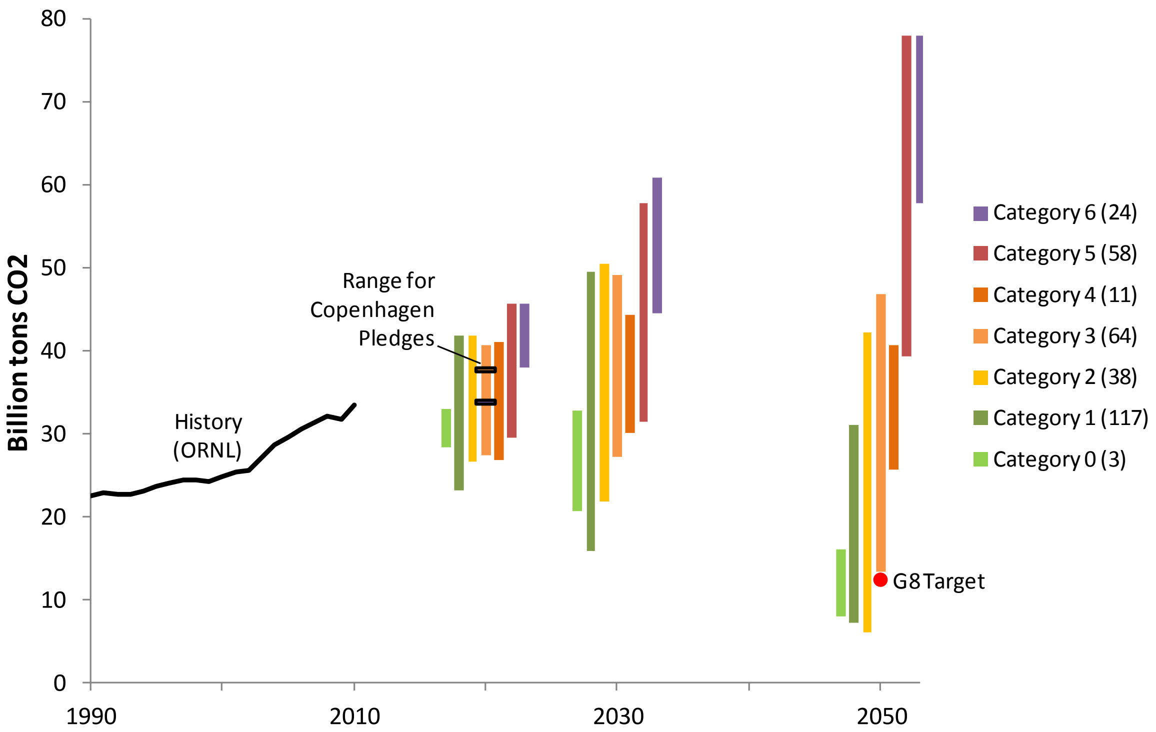


Figure 6.34. Global fossil and industrial CO2 emissions. Ranges are shown for 2020, 2030, and 2050 representing published scenarios falling into the respective long-term radiative forcing categories described in Section 6.2.2. The legend includes in the number of scenarios reported for each category. Also shown are the historical emissions path, the range of 2020 emissions consistent with the Copenhagen Accord (as defined in the AMPERE protocol), and the 2050 target articulated by the G8 of a 50% reduction relative to 2000. [AUTHORS: Note to reviewers: Please see discussion of preliminary dataset in the introduction.]

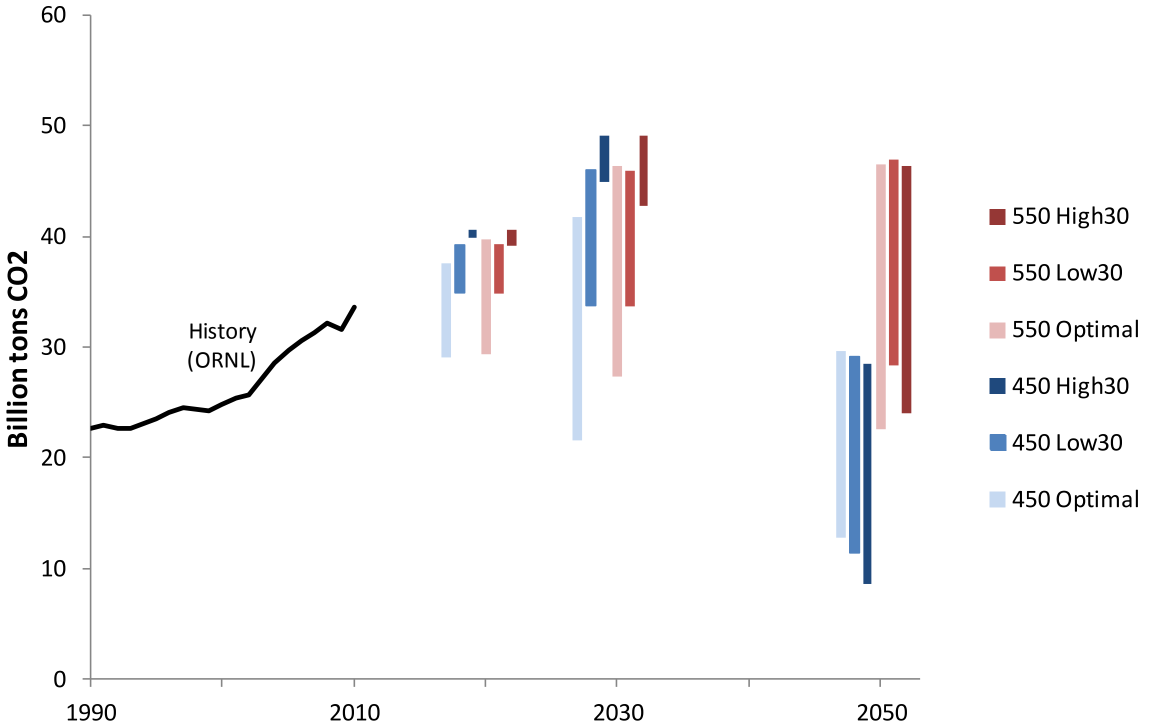


Figure 6.35. Global fossil and industrial CO2 emissions from AMPERE project. Ranges are shown for 2020, 2030, and 2050 for six AMPERE scenarios. One set corresponds to a long-term target of 450 CO2-e stabilization (or 2.6 W/m2), the other to a 550 CO2-e (3.7 W/m2) target. The AMPERE project compares cost-minimizing implementation (denoted Optimal) with myopic pathways in which specific emissions targets are enforced in 2020 (corresponding to the Copenhagen Accord) and in 2030 (denoted Low30 and High30). [AUTHORS: Note to reviewers: Please see discussion of preliminary dataset in the introduction.]

Cost-minimizing stabilization scenarios can be useful as a benchmark against which to compare proposed near-term mitigation actions. However, it is important to note they do not necessarily indicate whether a particular near-term emissions goal is or is not sufficient to reach a long-term stabilization goal. Deviating from the cost-minimizing near-term emissions profile will increase global costs of meeting a long-term stabilization goal, but near-term emissions need not necessarily be in the optimal range for a long-term goal to be met. Still, some models have found that under certain conditions, including constraints on near-term abatement or on technology availability, a particular long-term target in fact cannot be met. The analysis of more and more stringent targets combined with increasing attention to more realistic limited-flexibility assumptions for the near term has resulted in a more frequent finding of infeasibility. This type of result is difficult to represent in a literature review, because in general only scenarios that are found to be feasible are published. For example, while the range for the optimal 450 CO2-e pathway in the AMPERE results shown in Figure 6.35 reflects five models, the range for the low myopic path through 2030 reflects only four models, and the range for the high 2030 path reflects only two. This suggests that three out of five models found that radiative forcing could not be kept below the target in the long-term if emissions followed the specified higher pathway through 2030.

A few studies have attempted systematically to include infeasible outcomes. Clarke et al. (2009) find that only five out of 10 models were able to meet a 450 CO2-e target allowing for overshoot before 2100 with full participation, and only two of 10 models found the overshoot 450 CO2-e target feasible when delayed action by some participants was imposed. O'Neill et al. (2010) explore a scenario space of several 2050 emissions targets against several long-term stabilization targets and map out the feasibility frontier as assessed by one integrated assessment model. Nonetheless, there is the potential for a reporting bias towards models with more favourable assumptions (Tavoni and Tol, 2010).

Figure 6.34 shows, alongside the projected emissions in stabilization scenarios, a stylized representation of recently adopted or articulated policy targets. In Figure 6.35, the range of 2020 emissions in the non-optimal scenarios corresponds to the Copenhagen targets by construction. In comparison to the optimal pathways in 2020, the Copenhagen target emissions range is higher than the 450 pathway and roughly consistent with the 550 pathway. In the 2050 timeframe, the target proposed by the G8 of a 50% reduction relative to 2000 for global emissions falls at the lower end of the ranges for the most stringent long-term categories. Some broad conclusions can be drawn from the literature of published scenarios about *option value* that are especially relevant for near-term decision-making. There is some evidence that an emissions pathway through 2020 that follows the pledges in the Copenhagen Accord preserves the option of achieving a long-term target in the range of 450 CO2-e (Category 1). There is also evidence that, based on less than systematic reporting of infeasibilities, near-term emissions pathways that continue to rise through 2030 might not preserve the option of keeping long-term forcing below such a level.

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

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

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

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

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

6.5 Integrating technological and societal change

6.5.1 Integrating technological change

The development and deployment of new energy technologies, and overcoming the barriers to their widespread adoption, is central to the transition towards cleaner and more efficient forms of energy production and consumption. The importance of technological change raises important questions about the best way to improve the technologies needed for deep emissions reductions and the degree to which current efforts in this regard are adequate to the upcoming challenge. Important questions also surround the appropriate timing of investments in technological change relative to efforts to reduce emissions.

Various steps can be discerned in the life of a technology, from invention through innovation, demonstration, commercialization, diffusion and maturation (Grübler et al., 1999). This is a complex process of interactions between technological and societal developments. Although the process has received extensive attention and analysis, a clear systematic understanding has so far proven elusive. Nonetheless, it is broadly accepted that both R&D and the accumulation of experience through learning-by-doing play important roles in the mechanisms behind technological change. These two main drivers of technological innovation are complementary yet inter-linked (e.g., Sagar and van der Zwaan, 2006). Major changes in existing technology are unlikely if no directed R&D efforts are made. Yet R&D spending that successfully leads to new technological concepts without the acquisition of experience through actual deployment makes it impossible for these innovations to diffuse and mature.

The representation of technological change in the modelling frameworks used to generate transformation pathways falls short of the reality of the process of technological change. Many scenarios assume that technology evolves with calendar time, foreseeing cost reductions which progress over the century and depend on the maturity and prospects of each greenhouse gas abatement option. In this “exogenous” specification, technological change evolves independently of policy measures or investment decisions. In addition to technological progress, assumptions about technological change may depict structural changes in the energy system (Richels and Blanford, 2008) or reflect specific decarbonization patterns for different world regions based on stages of economic development (Jacoby et al. 2009). Regardless of the approach, scenarios based on exogenous technological change cannot provide insights into the manner in which technological change interacts with the measures by which mitigation is achieved.

A considerable number of studies have been dedicated to endogenizing technological change in transformation pathways models, that is, allowing for some portion of technological change to be influenced by policies or other elements of the scenario such as deployment rates. Models featuring endogenous technical change predict that the pace of cost reduction will not be independent of the undertaken policy actions. These efforts can roughly be divided into four approaches: price-induced technological change in the spirit of Hicks (1966), learning curves and learning-by-doing introduced by Wright (1936) and Arrow (1962), expenditures and subsidies of research and development (Goulder and Schneider 2000), and directed technical change formalized by Acemoglu (2002), 2011). Integrated assessment models using one or more of these approaches generate widely diverging results depending on their assumptions regarding R&D and learning-by-doing. These two processes occur predominantly at different stages of technological evolution and how to include plus balance them in transformation pathways models much determines their outcomes.

Messner (1997) and Mattsson and Wene (1997) introduced learning curves in an energy systems model of climate change, which subsequently was refined in other bottom-up models, while van der Zwaan et al. (2002) and Gerlagh et al. (2004) implemented learning curves in a top-down energy-climate model of optimal growth. Given that R&D investments are essential for bringing down the costs of known low-carbon techniques or generate new alternatives to fossil fuels, parallel efforts by top-down modellers focused on simulating R&D activities or stocks of knowledge, as done for instance by Goulder and Mathai (1998), (Popp et al., 2009) and Bosetti et al. (2009). Following these efforts, representation of learning-by-doing and R&D is now employed in many integrated assessment models (see for recent overviews Kahouli-Brahmi (2008); Clarke and Weyant 2011). As R&D and learning-by-doing are uncertain and poorly understood phenomena (Sagar and van der Zwaan, 2006), ongoing work investigates issues of uncertainties, which models have to account for more accurately. This holds particularly for major innovations resulting from R&D. Attempts to tackle these aspects are the contributions by e.g. Baker and Adu-Bonnah (2008). While learning-by-doing is recognized as a key phenomenon that determines the future costs of low-carbon energy technology, integrated assessment models must better account for the fact that our present understanding does not allow reliable extrapolations of learning curves and questions of causation exist between cost reductions and cumulative deployment (IEA/OECD, 2006; Stern, 2007).

Regardless of modeling approaches, however, virtually all transformation scenarios assume that technology will improve over time, especially for technologies with learning potential like renewables (Figure 6.36). There is generally more agreement about cost and performance improvements for mature technologies than for many emerging technologies upon which transformation pathways may depend. The cost changes are typically assumed to take place in similar proportion across countries and regions, as a result of the integration of global energy markets but also because of the difficulties of differentiating regional costs and progress; however, many models do differentiate costs across regions based, for example, on differences in availability of capital and labor costs. For models with endogenous technological change, climate stabilization policies lead to a faster and more pronounced decline in capital costs, depending on the learning potential of the specific technology (Figure 6.36).

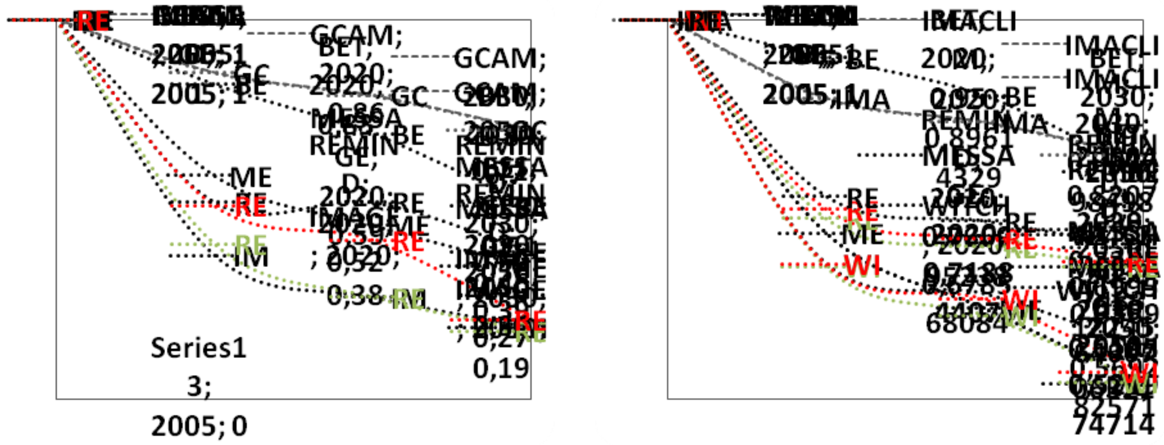


Figure 6.36. Evolution of capital costs of solar PV (left panel) and wind onshore (right panel) in the US to 2050, indexed at 1 in 2005. The black lines indicate BAU scenarios. For models featuring policy induced technical change, we also report 550-ppme (in red) and 450 ppm-e (in green) policies. For all other models, these are identical to the BAU cases. Note the different scale of the y axis of the two panels. Source: EMF27. Model legend: (BE=Bet, GC=Gcam, IM=Image, IMA=Imaclim, ME=Message, RE=Remind, WI=Witch). [AUTHORS: Note to reviewers: Results are preliminary from the ongoing EMF27 modelling comparison]

It is important to emphasize that technological change is not simply important for low-carbon energy supply technologies. Technological progress plays an important role also in determining the evolution of energy demand via changes in energy intensity or energy efficiency (see Section 6.2.1 and 6.2.7). Indeed, technological change related to climate mitigation is not relegated exclusively to the energy sector. For example, improvements in agricultural yields can have an important effect on the degree of mitigation required in the energy sectors and therefore on the costs of mitigation.

The literature shows that the rate and the direction of technological change play a major role in the feasibility of attaining climate stabilization[1–6]. The costs of climate policies are significantly influenced by the rate of technological evolution. For example, carbon prices for a given stabilization policy are rather sensitive to assumptions about technological progress of both energy efficiency and renewable energy (Figure 6.37). Increasing autonomous energy saving technical change by on average 50% yields carbon price reductions of 25-35%, depending on the climate policy scenario. On the other hand, slower technological progress in renewable (Cons. RE) would increase the carbon price index and its variation across models.

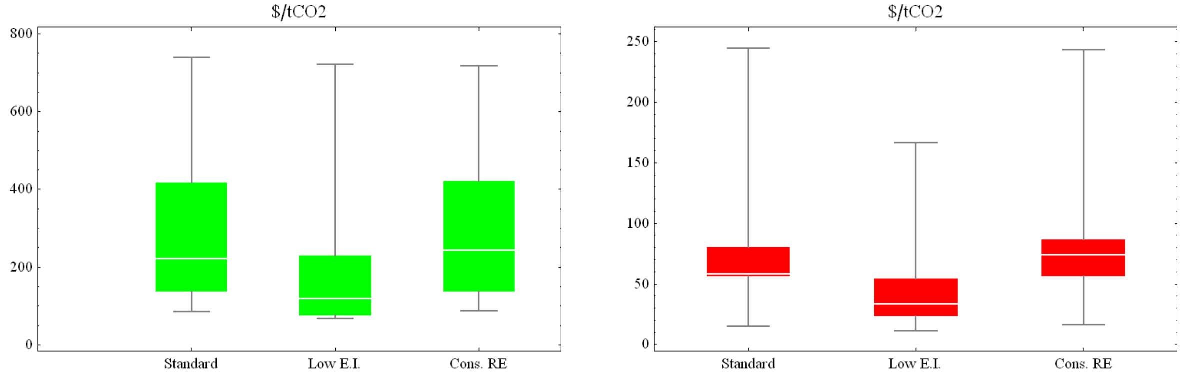


Figure 6.37. Carbon price (actualized in net present value at a 5% annual discount rate) in 450 ppm-e (left panel, in green) and 550 ppm-e (right panel, in red) stabilization scenarios under standard technical progress, as well as low energy intensity (Low EI) and conservative renewable (Cons. RE) technical progress. The box plot indicate median 25%, 75% and max and min. statistics across models. Please note the difference in scales between the two panels. Source: EMF27 [AUTHORS: Note to reviewers: Results are preliminary from the ongoing EMF27 modelling comparison]

However, autonomous technology might not be sufficient to limit climate change and dedicated resources and policies might be needed to induce it. Literature suggests that the benefits of technological change are sufficiently high to justify upfront investments and support in innovation and diffusion of low carbon mitigation options. Studies that have specifically looked at the role of investments in innovation and diffusion in energy efficiency and clean energy -and on how these are induced by policy- suggest that current rates of investment are too low. For example, an average increase between 3 and 6 times from current clean energy R&D expenditures, has been suggested to be the optimal one to achieve climate stabilization, see next Table (REFERENCE). The R&D gap is particularly important given that investments in OECD countries have been decreasing as a share of total national R&D budgets and currently, standing at about 4%. This gap would need to be directed to a well-diversified portfolio of investments, but especially to advanced transportation, which currently faces the steeper marginal costs of abatement.

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 (2010)	50-100 USD Billion/yr	To achieve the 'Blue Map' scenario in 2050. Roughly half of investments to advanced vehicles.
Bosetti et. al (2009)	70-90 USD Billions/yr	Average to 2050 for a range of climate stabilization targets. A large share to low carbon fuels..

Table 6.5. Optimal energy efficiency and clean energy R&D investments suggested in the literature as needed to attain climate stabilization policies. For reference, current public only R&D expenditures are approximately 10 USD Billions/yr.

The two way relation between mitigation and innovation raises the question of what is the proper policy intervention aimed at reducing CO2 emissions, while at the same time recognizing the role of innovation. The modelling literature of endogenous technical change indicates that relying solely on innovation policies would not be sufficient to achieve climate stabilization. On the other hand, climate policies such as carbon pricing could induce significant technological change, provided the policy commitment is credible, long term and sufficiently strong. This suggests that the implementation of mitigation policies is an important driver of the cost, and thus the feasibility, of additional mitigation in the future, but does not necessarily rule out the need for specific policies aimed at incentivizing R&D investments. Indeed, the joint use of R&D subsidies and climate policies has been shown to generate further benefits, in the order of 10-30% (REFERENCE). Alternatively, carbon taxes greater than the Pigouvian level are recommended when one accounts for market imperfections in the knowledge sector (REFERENCE). Market based policies complementing innovation policies are also important to avoid or reduce the effects of so called 'rebound effects'. On the other hand, command and control policies nudged to ensure that consumers adopt new technologies are relevant for promoting energy efficiency technical change, where behavioural anomalies play an important role (REFERENCE).

However, the unequivocal call for clean energy innovation policies can be somewhat questioned when the whole inventive activities, which also include endogenous technical progress for ''dirty'' inputs, are included. In such cases, the overall effect of a climate policy on innovation might not be straightforward, since clean energy R&D can crowd out other inventive activities, and result in lower welfare. The degree of substitutability between input of production has been shown to drive the final result (REFERENCE).

Innovation is also found to play an important role when accounting for uncertainty about future climate response, technological performance and policy implementation (REFERENCE). Innovation can provide hedging against uncertainty, since the required investments are relatively smaller than the physical one required for mitigation technologies.

6.5.2 Integrating Societal Change

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

The role of scientific and ethical controversies which block the large scale deployment, and even lead to the ban, of some carbon free options in many countries. This is the case for the nuclear energy (all the more so after Fukushima), and also for geological and biological carbon sequestration and for bio-energy (uncertainty about its carbon content along its life-cycle, intensification of industrial inputs, competition for land with food and feed production). Both lobbying and public perceptions influence long term technical choices. The risk is to select efficient techniques which cannot be socially accepted and/or may not deliver carbon free and environmentally safe options in due time. Technologies can be proven boomerang technologies [GoeschlPerino2009]; expected to be “clean” during the R&D process, they prove to be perceived as “dirty” even long after the industrial deployment. The conduct of these controversies is very context dependant and determines the pace and content of technical change.

Investment risks, business environment and human skills: the capacity of carbon prices to trigger investments on low carbon technologies is limited by the risks supported by industry when high upfront costs have to be funded in a context of a) long delay of maturation of investment b) uncertainty about prices, demand and technology performance c) limited access to capital and priority to equity value and d) lack of pre-existing technical skills and industrial capacity. Risks-adversed firms try and prevent to face sunk-costs in case their expectations do not realize and do not adopt technologies by merit order in function of their levelized costs as it is assumed by most models. This problem is analysed in economic literature on decision under uncertainty (Kahneman and Tversky 1979), Pyndick 1982, 1987). Hallegatte et al. (2008) show the importance of the difference in investment rules in a managerial economy (Roe 1994) and a shareholder economy (Jensen 1986). Hadjilambrinos (2000) and Finon (2009, 2012) show how differences in regulatory regimes may explain differences in technological choices in the electricity industries. Grübler (2010) show how institutional rigidities may lead to technological de-learning. Historically, political and institutional pre-conditions to changing decision routines to setting up organisational skills explains why similar countries as regards to their dependence to oil imports adopted very different responses to oil shocks (Hourcade, Kostopoulou 1994).

The many sources of energy efficiency gap: reliability of technologies, maintenance, quality of the end-use service, comfort and time (ii) information failures (iii) property rights like the tenant/landlord problem (iv) behavioral characteristics and their differentiation per level of income: high private discount rate in particular for low income classes under tight financial constraints; low attention to energy expenditures for high income classes.

Obstacles to carbon pricing. These obstacles relate to three redistributive issues: The first of these is industrial competition under uneven carbon constraints: the impact of a carbon price differs widely across sectors because of the heterogeneity of their energy intensity of the turnover of their capital stock. In case of asymmetry of carbon constraints, the risks of carbon leakages are then an argument for not imposing significant carbon prices on the energy intensive industry (Houser et al 2008, Smale & al 2006, Fischer & al 2011, Monjon & al 2011, Demailly & al 2008) . The key message of these studies is that a) after consideration of transportation costs, the impact is important for some segments of energy intensive industry b) because of the general equilibrium effects part of the adverse impacts of the economic welfare of a country are offset by change in terms of trade c) over the long run the competitiveness losses in energy intensive industry are compensated by gains in other industries d) uneven regional impacts remain due to the difficulty in finding substitutes for jobs lost in places where coal mining and energy intensive industry represent a large part of activity

The second obstacle is the uneven impacts on household's purchasing power which is one major cause of failures in adopting a carbon tax. The low middle classes are indeed specifically hurt by significant increases of energy prices especially when they are totally dependent from automobile for their daily travels because they live in remote areas, in low density cities or in urban suburbs (Combet et al 2010, Grainger et al 2010).

Both experiences of successful introduction of carbon taxes (Sterner 1994, Wier 2005) and of failure (Deroubaix 2006) show that the introduction of significant carbon pricing demands a social consensus to use a carbon tax as a component of a larger reform of fiscal systems which allow for indirect compensatory transfers through the reduction of other taxes or specific devices for the most vulnerable segments of society. Guivarch (2011) shows that they have to be complemented by policies apt to upgrade the adaptability of labour force to changing conditions (enhancement of the human capacity and organization of labour markets). The condition for fiscal reforms to be a useful lubricant for the technological transition is the quality of public debates about their recycling.

The non energy drivers of energy demand dynamics: part of the decoupling between energy and growth relates to the efficiency of end-use equipment, part is governed by structural changes. These are driven by the interplays between a) life styles and consumption patterns b) technical patterns in infrastructure sectors, energy intensive industry and food production c) the geographical distribution of activities which encompasses human settlements and urban forms and determines passengers mobility needs, freight transport requirements, the size of housings and their heating and cooling needs. These interplays are in part driven by powerful economic and institutional parameters like the prices of real estates, the price of land, transportation infrastructures and urban policies, the disintegration of the 1st and 2nd phases of material transformation, the just in time processes in manufacture industry or the changes in the food production processes.

Recent modeling exercises captured for example the trade-off between commuting costs and housing costs and their impact on the urban sprawl and the mobility needs (Gusdorf et al 2007, 2008). They show that the price of real estate is a driver of mobility demand as powerful as gasoline prices. Waisman et al. (2012) show that acting soon on transportation infrastructures is a way of controlling the induction of automobile dependant transportation patterns over the long run and cut by 45% in 2100 the carbon price necessary to achieve a 450 ppm target in scenarios in which large scale low cost biofuels are not available after 2040. A vision of the consolidated impact of urban forms on energy consumption (transportation, heating and air-conditioning) can be derived from meta-analysis of urban forms which show out a 0,2 to 0,4% elasticity of energy consumption to the density of the cities (Leck 2006) . Another critical sector here is agriculture and food production. Mitigating these trends has huge implications on both the price of land and the policies that govern the location of human settlements.

One key issue is that neither the changes of the business environment, nor reforms of the regulatory regimes in the infrastructure sectors (including electricity), nor fiscal reforms, financial reforms, labor policies, urban policies or agricultural policies will be adopted only for reasons of climate objectives. A policy integration is needed to align climate policies with other public objectives; otherwise carbon price signals will be swamped by many other powerful price and non-price signals. This integration also offers leeway to compensate for the transition costs of the transformation pathways and to find politically acceptable pareto-improving sets of reforms.

The challenge is to avoid self-reinforcing loops between technical choices, life-styles and institutions which result in a carbon intensive lock-in. This lock-in has been achieved in the past century in developed countries and cannot be unlock overnight. Early policy-mixes are necessary to avoid such institutional and technical lock-ins in emerging economies over the forthcoming decades.

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

6.6.1 Sustainable development and transformation pathways

Transformation pathways come in many form - from climate stabilization with multi-lateral cooperation, to regional policies seeking specific low carbon societies, to regional sustainability policies, and policies with multiple objectives. Transformation pathways toward greenhouse gas stabilization may have implications for achieving sustainable development goals. Sustainable development may also yield its own societal transformations, with implications for transformation (Shukla et al., 2008) pathways. Thus, it is pragmatic to inquire into the two-way relationship between climate transformation and sustainable development.

The degree to which SD is incorporated in the transformation pathway literature depends on the degree to which the models used to construct transformation pathways consider issues related to SD. Many issues related to sustainable development are incorporated, such as [examples]. In contrast, many other issues are generally not incorporated, including [examples].

6.6.2 Sustainable development, baseline Scenarios, and implications for transformation pathways

The cost of achieving a specific emissions pathway and associated policy interventions depends on the baseline from which emissions reductions occur. The baselines which include significant SD policies tend to produce lower emissions, greater resilience to climate change impacts and co-benefits like reduced local air pollution (Bollen et al., 2009) or improved employment opportunities (Stern, 2007). An important point demonstrated by most studies is that the level of carbon tax necessary to achieve a given climate target is lower if, in the baseline scenarios, a lower carbon intensity has been achieved through other policies related to: e.g. infrastructure, real estate markets, urban design, consumption behaviour and income distribution (Shukla, Dhar, and Mahapatra 2008; Haines et al. 2007) (Mathiesen et. al., 2010). Some have argued that the co-benefits are significant enough to render SD a precondition for climate-friendly transformation (Shukla and Dhar 2011).

Levers for gaining co-benefits differ across sectors. For example, in case of urban transport, CO_2 emission reductions happen from a wide portfolio of strategies encompassing travel demand, modal choices, fuels and vehicle efficiency (Bakker & Huizenga, 2010). Travel demand and choice of transport mode depend on land use planning interventions that alter density, diversity and design (Cervero and Kockelman, 1997) of urban space can reduce travel demand (Ewing and Cervero, 2010) and integrate public transit which can reduce CO_2 emissions; as well as deliver co-benefits from improved air quality and reduced congestion (Lefèvre, 2009; Dulal et al., 2011). In case of intercity travel, the empirical evidence, e.g. from Sweden, Germany and Japan, suggest that CO2 emissions are reduced in the long term by investing in infrastructures for high speed rails (Rozycki et al., 2003; Kato et al., 2005; Åkerman, 2011). In the building sector, CO2 emission reduction can happen through energy efficiency measures using in-situ technologies (e.g. improving insulation, improving efficiency of electrical appliances, CFL lights, etc.) and the measures are very cost effective (Urge-Vorsatz and Novikova, 2007; (Pérez-Lombard et al., 2008; Kneifel, 2010) including in developing countries (Li, 2008; Saidur, 2009). The implementation of these measures however requires policies (e.g. tighter building codes, incentive schemes) which can address the issue arising from fragmented building markets) (Pérez-Lombard et al., 2008; Li, 2008).

Assessment of the costs of 'Baseline Sustainable Development Policies and Actions' at an aggregate level in terms GDP is contentious. The issues of definitions and measurements of cost elements persist. The alternative baseline scenarios can be viewed as corresponding to multiple equilibriums.

First, in case of models allowing endogenous technical change, alternative technical systems can, over the long run, be produced at identical technical costs. Second, even in case of differences in technical costs, the overall economy (consumption and localization patterns, tariffs and fiscal systems, industrial specialization) the higher costs of a given energy system may not lead to lower GDP. Third, even if there are differences in baseline GDP, a lower GDP may be associated with a higher social welfare because of reduction of disruptions of local environment such as air and water quality which can be measured as ecosystem services (Boyd and Banzhaf 2007; Fisher, Turner, and Morling 2009), of a higher level of energy security and food security, a higher level of education and well-being and differences in individual and social preferences. The research in ecosystem services (Fisher et al., 2009) area lately however a common definition of what constitutes ecosystem services has not evolved. The concept of energy security, food security and other measures of welfare has been sometimes quantified using multi criteria approaches (Madlener et al., 2007).

The status of policies in different baselines is very different between regions. In developed countries the main issues are the restructuring of an important capital stock and the evolution of well-established consumption patterns; the emerging economies are at the crossroads between mimicking the development pathway followed by the developed countries in the past century (with an income elasticity of energy higher than one and progressively decreasing), a “leapfrogging” towards an energy/GDP ratio similar to the current level of industrialized countries; less developed countries have to go out of the “poverty trap” and the way they will do so will in part determined their capacity of choosing either to the alternative we just described for emerging economies.

The Integrated Assessment of Climate Stabilization scenarios from different baseline scenarios will allow separating the contribution of various development policies to the achievement of lower carbon content development pathways from the specific contribution of climate policies. However it should be underlined that: i) Policies which are analytically separated can be put as component of the same policy package for political acceptability reasons, and ii) the efficiency of a given climate policy tool can be greatly influenced by the content of the baseline scenario.

6.6.3 Other Approaches to the Assessment of SD and Climate Stabilization Scenarios

The conception of low carbon society (LCS) is closely tied to the sustainable development and green economy paradigms. LCS pathways typically include actions that are compatible with sustainable development principles and contribute to the stabilization of GHG concentration to avoid dangerous climate change (Skea and Nishioka, 2008). Strategies adopted in a low carbon society may vary among countries due to differences in energy resources, geographical conditions, state of economic development, and other factors. Implementing LCS actions, though, would require international cooperation for technology innovations and to finance for transfer and deployment of low carbon technologies, especially in developing countries.

The key distinguishing features of LCS vis-à-vis conventional transformation are altered policy perspective, governance approaches and institutional structures which aim at cooperation among economic, social and political agents to gain co-benefits vis-à-vis multiple socio-economic and environmental objectives and targets. LCS pathways impose lower costs after accounting for co-benefits (Shukla and Dhar, 2010); contrary to the conventional low carbon pathways which tend to be significantly costly compared to the business-as-usual transformation. Low carbon technologies (e.g. energy efficient infrastructures, appliances, next-generation automobiles and RETs) often have higher upfront costs; but in the long-run these additional costs are more than balanced by gains from fuel conservation, enhanced energy security, improved air quality etc. LCS implementation assumes diverse set of policies to encourage technology R&D, new financing mechanisms and transformation of urban and industrial structures.

Regional cooperation is vital to sustainable development. It allows sharing of common resources among nations such as the hydro- electric potential of rivers flowing across nations, creating regional electricity markets, and laying trans-country pipelines (Shukla, Garg, and Dhar 2009). The projects are pursued primarily for commercial reasons, but they, deliver other benefits like flood control, reduced trans-boundary pollution and higher climate mitigative and adaptative capacity. Regional assessment of SD and climate responses exist in developed (Battaglini et al., 2009; Lacher and Kumetat, 2011) and developing (Shukla and Dhar, 2009; Shukla et al., 2009) regions. These assessments show sizable gains from regional cooperation for sustainable development and climate change (Table 1, Section 6.5).

LCS scenarios and modelling assessments keep in view disaggregated geographical (global, national, sub-national), temporal (short to long term), sector-specific (agriculture, industry, electricity, transport, buildings), behavioural (lifestyle) and institutional (laws, governance) realities (objectives, targets, barriers). LCS studies focus on those important short-term policies, measures and actions which have significant implications on the long-term emissions pathways.

LCS framing and modelling aim to delineate a roadmap of climate policies and measures which when implemented can transform the in-situ existing socio-economic development to a sustainable low carbon society. LCS assessments delineate alternate socio-economic and technological transformations that deliver low emissions pathways that are consistent with an agreed GHG concentration stabilization target. In conventional assessments such targets impose additional economic costs (Shukla and Chaturvedi, 2012) as they perturb the competitive equilibrium.

The LCS roadmap is typically developed by back-casting method using the soft-linked modelling system which includes several models sharing information and interactively interfacing with stakeholder inputs (Kainuma et al., 2012). Typically the LCS assessment is built from bottom-up; wherein the national assessments are aggregated from local and provincial levels and global assessments are aggregated from national and regional levels. At each level, the targets vary as per the local conditions, needs and objectives. LCS modelling approach is applied in many countries; e.g. in Japan, China, India, Korea and Nepal as reported in Asia Modelling Exercise (Kainuma et al., 2012).

6.6.4 Aligning SD and Climate Change Policies and Actions to gain Co-benefits

Sustainable development and similar paradigms like ‘green growth’ provide the foundation and framework for designing international cooperative mechanisms to support the implementation of integrated development and climate change policies. The framework perceives managing climate change risks as an integral part of the governance actions to shape the future socio-economic development. It removes the artificial separation of climate change and the counterfactual baseline world which underlie the conventional approach of climate studies.

The framework mainstreams the climate change in the socio-economic development policies, measures and actions at global and national levels. The alignment is around the national development policies and global cooperative mechanisms to combat climate change such as R&D and technology transfer mechanisms as well as inclusion of wider stakeholder interests. The framework advocates reinforcing mutual policy initiatives undertaken by governments and the private sector which have major positive impacts on climate change mitigation and adaptation without them being initiated by the climate-centric policy mechanisms. The climate change policy implementation is further enhanced by aligning the international cooperation mechanisms with the regional and national policies and measures based on stakeholder interests and policy priorities including broader economic and social development issues (Halsnæs and Shukla, 2007).

Modelling studies show that sizable fraction of global mitigations are expected in the developing nations. Many of these nations are at a stage of transition from lower to medium income of economic development. Such transformation level is generally accompanied by the sustained high economic growth lasting over several decades. In the short-term, the high growth is sustained by the investments in basic infrastructures. This provides numerous opportunities for influencing the long-term development pathway. The policies and measures aligned to 'development' and 'climate' objectives thereby deliver substantial co-benefits and help avoid climate risks. Modelling studies show significantly reduced energy security risks and high co-benefits from improved air quality in the short-term in emerging nations (Shukla and Dhar, 2011). These advantages though are neither automatic nor assured and need conscious and careful coordination of policies and implementation strategies.

Modelling studies assessing explicit 'Sustainability' scenarios include additional policies which, besides carbon mitigation benefits, are aimed at delivering development co-benefits such as improved energy security, energy access and clean air. Such scenarios typically assume policies and measures that facilitate investments in energy efficient devices and 3R measures, life style changes, greening of production processes, targeted technology policies (Shukla and Chaturvedi, 2012) to promote low carbon energy technologies, e.g. renewable and nuclear; in contrast to conventional low carbon scenarios which rely exclusively on carbon price to achieve low carbon transformation. Targets setting require balancing subsidies to achieve target and its co-benefits. The net effect of co-benefits manifests in lower social cost of carbon (Figure 1, Section 6.5) in the sustainability scenario compared to the carbon price required to deliver identical mitigation in the low carbon conventional scenario (Shukla et al., 2008).

[AUTHORS: Top Add: Conclusions on 'regional considerations and differences' from the modelling studies assessed in previous Sections are needed to fill-in this section.]

SD interacts not only with mitigation, but also with impacts, adaptation, and vulnerability (see Section 6.2.3). Cleaner fuels help in reducing local pollution which in turn is beneficial to health of people (Haines et al., 2007; Mathiesen et al., 2011). Decentralised renewable energy can help in building adaptive capacity of communities (Venema and Rehman, 2007). Sustainable agricultural practices (e.g., conservation tillage, water management, etc.) help to improve drought resistance, soil conservation and soil fertility (Uprety et al., 2012).

The feasibility of a low carbon transformation pathway would depend on technological as well as social, political, institutional and economic contexts. Mitigation to achieve a low carbon pathway might doubly exacerbate climate risks by increasing climate consequences, slowing the pace of sustainable development and lowering the adaptive capacity. Institutions of a sustainable society aim at inclusive and extensive growth. They turn the pernicious trade-offs into opportunities that enhance both the mitigative and adaptive capacity. The alternative transformation pathways therefore must be compared in terms of risk profiles that are calibrated in multiple metrics of physical, economic, and social risks generated not only by climate change, but also by climate policy. In this context, sustainable development is an essential framework to align mitigation and adaptation policies and actions.

Table 6.6. Benefits from South Asia Regional Cooperation (2010-30). The assessment for South-Asia region showed that the monetary value of climate benefits and non-climate co-benefits through South-Asia regional energy cooperation can add nearly 1%of regional GDP equivalent each year between 2010 and 2030 (Shukla et al., 2009).

Total Benefit from 2010-30		**Annual Increase in Region's GDP (%)**
Energy saving (Direct Benefits)		
Energy Saved	59 Exa Joule	0.47
Investment in energy supply technologies		0.19
Investment in energy demand technologies		0.19
Environment (Indirect Benefits)		
CO_2 Saved	5.1 Billion Ton	0.09
Sulfur Dioxide (SO_2) Saved	50 Million Ton	0.03
Total Direct and Indirect Benefits		**0.97**
Spill-over Benefits		
Water	16 GW additional hydropower capacity	
Irrigation / Flood Control	From additional dams	
Competitiveness	Reduced per unit energy and electricity costs	

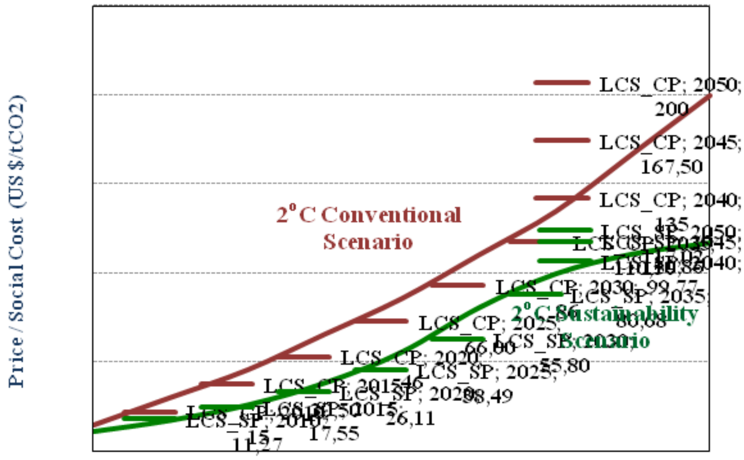


Figure 6.38. The global carbon price to achieve 2^{O}C stabilization target, derived from the global top-down model GCAM, following the conventional scenario approach, increases gradually reaching $83 in 2030 and $202 in 2050. The same amount of cumulative emission is achieved between 2010 and 2050 for India, at a 'social cost of carbon' which is $120 in 2050 for the 'sustainability' scenario, in an exercise using ANSWER-MARKAL model. The 'social price of carbon' is a shadow price that includes the co-benefits of aligning sustainable development and climate change policies and measures. The social cost of carbon governs the key investment decisions and is the carbon price effectively paid by the agents (Shukla and Dhar, 2011).

6.7 Risks of transformation pathways

[AUTHORS: Note: We will be coordinating with sector chapters on technology and operation risks, as well as social risks. This section therefore aspires to provide a summary across sectors of transformation risks]

Table 6.7. Deployment levels, growth of deployment and share in primary energy production for different energy technologies and stabilization pathways. The table lists the 5th to 95th percentile range from the scenarios with full technology availability [AUTHORS: Note: Preliminary data from the scenario database. 2010 estimates were corrected for differences in reporting conventions where apparent. Further work consolidating the database pending for the SOD.]

		Deployment [Primary energy in EJ/yr; nuclear, solar and wind energy reported in direct equivalent of energy output] [Sequestered carbon dioxide in GtCO2 reported for CCS]			**Expansion** [%/yr growth rate of deployment averaged over previous 20 year period]			**Share in primary energy production [%]**		
Technology	**Climate Outcome**	**2010**	**2030**	**2050**	**2010**	**2030**	**2050**	**2010**	**2030**	**2050**
Nuclear energy	<3.2 W/m^2	9-11	11-31	11-72	Add (IEA)	1 to 6	0.2 to 6	~2	2-6	2-10
	3.2-4.7 W/m^2		11-31	11-67		1 to 5	-0.2 to 6		2-4	1-7
CCS	<3.2 W/m^2	0	0.3-8	4-18	N/A	N/A	3 to 15	N/A	N/A	N/A
	3.2-4.7 W/m^2		0-3.5	1-15		N/A	7 to 36		N/A	N/A
Modern Bioenergy	<3.2 W/m^2	4-7	21-82	95-185	Add (SRREN)	4 to 14	3 to 9	~1	4-16	18-26
	3.2-4.7 W/m^2		7-45	29-120		3 to 9	4 to 12		1-7	5-16
Geothermal energy	<3.2 W/m^2	0.2-0.6	0.6-3.6	1-26	Add (SRREN)	1 to 12	1 to 13	<0.1	0.1-0.5	0.2-3.2
	3.2-4.7 W/m^2		0.6-2.2	0.9-7		1 to 8	1 to 9		0.1-0.3	0.2-0.7
Solar energy	<3.2 W/m^2	~1.5	1.5-29	8-87	Add (SRREN)	1 to 21	5 to 26	~0.3	0.3-5	1-13
	3.2-4.7 W/m^2		1.5-20	3-70		0 to 20	5 to 21		0.3-3	0.6-9
Wind energy	<3.2 W/m^2	1.1-1.5	4-19	16-45	Add (SRREN)	5 to 14	3 to 7	~0.3	0.7-3	3-6
	3.2-4.7 W/m^2		4-16	15-39		5 to 13	4 to 7		0.6-3	2-5
Coal energy	<3.2 W/m^2	120-140	70-190	35-115	Add	-3 to 1.5	-5 to 1	26-28	12-28	4-20
	3.2-4.7 W/m^2		100-215	70-220	(IEA)	-2 to 2	-3 to 1		15-30	8-25
Gas energy	<3.2 W/m^2	100-120	65-220	60-240	Add	-3 to 3	-2 to 2	20-24	15-33	12-30
	3.2-4.7 W/m^2		115-285	120-340	(IEA)	0 to 4	0 to 2		20-38	20-37
Oil energy	<3.2 W/m^2	170-190	140-245	95-210	Add	0 to 1	-4 to 1	34-38	26-44	14-34
	3.2-4.7 W/m^2		175-270	160-270	(IEA)	0 to 2	-1 to 1		27-45	19-44

The transformation of energy and land use in a climate stabilization pathway has to be scrutinized not only in terms of associated costs, benefits and opportunities, but also in terms of associated risks. Societal transformations related to the sustainability of transition have been object of investigation in recent years (German Advisory Council on Global Change (WBGU), 2011; Smart, 2011; Westley et al., 2011; Markard et al., 2012). It has been acknowledged in the literature that the complexity of the transformation towards a sustainable low-carbon world implies much more than technological changes. Although many transformation steps - related to societal change, changes in lifestyles, etc. - adhere to technologies, key elements of transformation processes sit elsewhere and so do important risks (German Advisory Council on Global Change (WBGU), 2011). Implementing the transformation process will require societal support and institutional capacity to mediate distributional conflicts and potentially introduce changes to energy service consumption. Most transformations in history - such as medium-range transformations from recent history like the

European integration, the IT revolution in the nineties, or the protection of the ozone layer - would not have been possible without acceptance and support of large parts of society (German Advisory Council on Global Change (WBGU), 2011). Most literature on transformations provides a rather broad picture of the process, including but not focusing on the aspect of risks of transformation pathways.

Risks can be associated with the scale, speed and structure of the transformation process. Since different levels of climate stabilization have different implications on the scale and speed of the energy and land transformation, those pathways may come with different levels of risk. A characterization of potential trade-offs between risks and benefits across different stabilization pathways can be important. While quantifying the risk of transformation pathways has not been done, useful information can be assembled that informs thinking about risk. Table 6.6 compares deployment levels (scale), the expansion and reduction of deployment levels (speed), and the share of individual technologies in the technology portfolio (structure) across different classes of stabilization pathways for a set of key energy technologies.

We distinguish between three different types of risk in this section:

- technology risks associated with increased deployment of individual technologies including resource and innovation uncertainty and environmental side effects,
- operational risk with respect to system reliability including both technological and societal constraints, and
- wider societal risks including institutional strain due to the speed of the transformation.

Our approach to risks of transformation pathways needs to be distinguished from broader risk analysis of climate policies. Key insights from the relevant literature are assessed in Chapter 2 of this volume. Those insights typically come from welfare analyses of the trade-off between climate damages and mitigation costs under uncertainty and risk aversion. Other studies have investigated hedging strategies for reaching climate policy targets. Those studies typically use probabilistic frameworks to measure risk as a function of the probability of different climate policy outcomes and the associated (welfare) losses.

The risks of transformation pathways need to be considered along with the reduction in risk from mitigating climate change. Climate change impacts and associated risks, and the reduction thereof for different levels of climate stabilization, are discussed in the Working Group II Assessment report. Here we focus exclusively on risks within transformation pathways—for technologies, system operation, and society. There are risks associated with increased deployment of low carbon technologies and rapid decommissioning of high carbon technologies, as well as reduced risk from decreased deployment of fossil fuel technologies.

6.7.1 Technology and operational risks

Increased deployment of any technology is subject to environmental, resource, system, innovation, and public and regulatory uncertainty and constraints. These uncertainties and constraints could prevent, delay, and, in general, increase the cost of the technology. Risks from increased deployment comprise:

- Physical resource scarcity that could create investment uncertainty and supply chain bottlenecks, and therefore higher than expected costs. These include inputs to deployment, such as equipment, skilled labourers, and materials (e.g., rare earths for batteries, turbines, solar cells (e.g. DOE, 2010, Critical materials strategy);
- Financial resource scarcity due to uncertainty about policy, availability of capital in the financial markets, state of public finance, and unclear risk sharing between public and private sectors;
- Innovation barriers, including a delay of commercial availability, slow innovation cycles, and

- higher than expected costs due to lack of technological improvement; Regulatory constraints and uncertainty, e.g., land and water use, nuclear waste, and air pollution policies;
- Environmental risks, including nuclear waste, uranium mining, chemical waste, water quality, soil quality, biodiversity, CO2 leakage, changes in seismic activity, and micro climate effects;
- Security risk, such as the risk of nuclear proliferation
- Public acceptance

[AUTHORS: Note: Here we will provide a summary of results on technology risks “at scale” from Chap. 7-10. Such a summary was not possible for the FOD given the timing of chapter drafts]

System level risks do not relate to individual technologies, but to the reliability of operating the transformed system at scale. Transformation pathways can imply rapid and dramatic changes in the energy system. What do these changes (both increases and decreases) mean for system operation? Sustainable transformation pathways could require radical shifts in governance and management regimes of the current system. There is also a status quo bias in the preference towards optimizing the existing system rather than innovating a new system (Westley et al., 2011). This in turn implies sluggishness and additional cost in conversion to the new system. If transformation leads to increased reliance on some technologies, this may imply increased operational risk due to intermittency, increased infrastructure, operational coordination, and inter-industry coordination. At an extreme is failure of a technology option or of achieving the policy objective. Failure scenarios are rarely available in the literature, let alone their probability. A useful indirect measure for the consequence of technology or policy failure is the cost increase of maintaining the climate policy target despite such failure (Arnell and Usher, 2011). This information can be inferred from mitigation scenarios with limited technology availability or fragmented climate policy action. On a system level, the probability of higher costs, underperformance, and even failure is related to the resilience or robustness of a system (against failure of a system component). Therefore, resilience indicators such as diversity of the portfolio can provide useful information. Strong dependence on a single technology or group of technologies carries risks, particularly if the characteristics of a large scale deployment of the technology are not well known. Energy transformation scenarios typically show that supply diversity is generally higher in mitigation pathways compared to the reference case – which is heavily relying on fossil fuels - until 2050. The picture is less clear for the second half of the 21st century where supply diversity differs considerable across mitigation scenarios.

[AUTHORS: Note: In future drafts, this section may discuss, as examples only, shares of fluctuating renewables to discuss grid integration.].

6.7.2 Societal risks of transformation pathways

Transformation pathways can have a strong impact on broader societal policy objectives, e.g., relating to sustainable development, such as:

- energy security;
- food security, including consideration of food price changes;
- water security, including consideration of water price changes;
- energy access, including consideration of energy price changes and restriction of energy services;

[AUTHORS: Note: Discussion needs to be added in close coordination with Section 6.5 Sustainable development. There may be a lack of indicators on the risk part that would help to link the discussion to the scenario database. In this case, the paragraph may be integrated in Section 6.5].

The transformation pathways induced by mitigation policies can harbor societal risk due to the scale and speed of transition in the energy and land use sectors. In history the speed of different large transformation processes varies significantly (German Advisory Council on Global Change (WBGU), 2011). While some factors such as economic structures or the availability of resources can change within a relatively short amount of time, others like social and mental structures can be very persistent and change at a significantly different speed (Grin et al., 2010). There is the risk of societal strain if the scale and speed of the transformation exceed the institutional capacity. It also includes regulatory and governance questions as the implementation of the transformation process may introduce new institutions as well as new market distortions and opportunities, and may change the role and influence of existing institutions.

[AUTHORS: Note: In future drafts, it may be possible to explore historical rates of technology transformation, and assess whether there have been situations of rapid expansions introducing societal risks.]

Land-use changes associated with transformation pathways can create social risks directly for consumers via commodity prices, as well as indirectly by affecting environmental quality. A price on carbon stored in land will cause substantial changes to competitiveness and revaluation of land-use options, possibly leading to substantial reallocations in land-use between food crops, bioenergy, and conservation (Harvey and Pilgrim, 2011; Popp, Dietrich, et al., 2011; Persson, 2012). Energy crop demands alone can lead to higher agricultural commodity prices, and combined with forest protection, can be pushed even higher (Popp, Hascic, et al., 2011; Reilly et al., 2012; Wise et al., 2009). This can create risks regarding food security especially threatening poor people (Azar, 2011). With benefits to land owners, there can be net positive changes in agricultural sector economic welfare (Baker et al., 2010). However, distributional effects are important considerations.

Mitigation strategies can bear risks regarding their distributional consequences (Labandeira et al., 2009; Boccanfuso et al., 2011; Liang and Wei, 2012). Distributional questions such as regressive effects on household income, depreciation of existing rents and introduction of new rents emerge from the changes to food and energy prices caused by mitigation strategies. Climate policies - just as many public policies - do not only have an impact on efficiency but also on equity (Labandeira et al., 2009; Boccanfuso et al., 2011). The latter effects play a crucial role for social acceptability and thus feasibility of climate mitigation policies. A carbon tax may increase the urban- rural gap and deteriorate the living standards of large parts of the population aggravating over time (Liang and Wei, 2012). Hence, there is the risk of social tensions and objection against mitigation policies from negatively affected parts of the population. According to the literature, distributional effects of a price on carbon can be either progressive (Oladosu and Rose, 2007; Labandeira et al., 2009) or regressive (Kerkhof et al., 2008; Callan et al., 2009) depending on the approach and region analysed.

6.8 Integrating sector analyses and transformation scenarios

6.8.1 Introduction and Methodological Issues

[AUTHORS: Note to reviewers: This section aims at integrating information from analyses presented in several chapters, most notably chapters 6 to 12. Due to its cross-cutting nature, parts of the section are still in an early stage of development and will require further coordination effort among the chapter writing teams to improve.]

Transformation scenarios which most of the analysis presented in this chapter is relying on puts an emphasis on integrating different sectoral and regional perspectives into a coherent picture that includes dependence and feedbacks between different human and natural systems. As discussed in Section 6.1, two important caveats must be kept in mind when interpreting the scenarios in this chapter. First, maintaining a global, long-term, integrated perspective involves trade-offs in terms of detail. For example, the models do not represent all the forces that govern decision making at the national or even the company or individual scale, in particular in the short-term. The level of sophistication in representing these details varies substantially across models. An outcome of these simplifications is that integrated global and regional scenarios are most useful for the medium- to long-term outlook, say from 2030 onwards. For shorter time horizons, more detailed national and sectoral analysis that explicitly addresses all existing policies and regulations are more suitable sources of information. This section addresses how the (long-term) transformation pathways relate to the (short- to medium-term) sectoral analysis, predominantly assessed in Chapters 7 through 12 of this report.

In the IPCC AR4, Chapter 11 (Barker et al., 2007) was charged with comparing the sectoral analysis (Chapters 4 to 10) with the long-term scenario analysis (Chapter 3, Fisher et al. (2007)). This was largely done by comparing economic mitigation potentials for different carbon price levels by 2030 between the sectoral chapters and the scenario chapter at the sectoral level and in total (Barker et al. (2007), Tables 11.4, 11.5 and Figure 11.3). For this comparison, sectoral mitigation potentials were calculated based on the point of emissions, i.e. emission reduction from secondary energy (e.g., electricity) savings in the end-use sectors were allocated to the supply sector (which is in fact the only unambiguous way of allocation, see also Box 6.1 for a discussion of allocation issues)[7]. For many sectors a considerable overlap of direct mitigation potentials was found, with a few exceptions, mostly the buildings sector where the sector-based assessments found considerably higher direct mitigation potentials compared to the integrated modelling approaches. Also for the agricultural and forestry sector the sectoral studies found considerably higher direct mitigation potentials compared to integrated models. In contrast, for the industrial sector, the situation was the other way around and higher potentials were found by the integrated models. The total estimates across all sectors showed good agreement between the two streams of analysis with the total of the sectoral studies being somewhat higher than the integrated models.

This section will go beyond a comparison of mitigation potentials, but will also look at other indicators such as energy use, land use, and service level indicators to improve comparability between the various studies. [AUTHORS: Note to reviewers: This should be viewed as an aspirational goal for the SOD and final draft. While it seems doable to improve the situation with respect to some indicators, e.g. energy use, it may turn out to be too ambitious to go down to the service level indicators which would be desirable. To take into account differences in drivers between and among sectoral and integrated modelling studies, normalization to the key drivers will be explored (e.g., per capita, per GDP). Other ideas include the use of price information and taking into account different base years of studies for mitigation costs and potentials (it matters a lot whether mitigation starts in 2005 or 2010 when comparing potentials for 2020) to improve the understanding of differences (and similarities).] In addition, the sectoral emissions and their reductions will not be combined to a total as this may result in double counting as well as combining incompatible assumptions in different sectoral studies, such as strong afforestation measures in the agriculture and forestry sector and high bioenergy use for mitigation in various energy sectors.

In AR4 (Barker et al., 2007) the term bottom-up was used for the sectoral studies and the term top-down for the integrated scenarios (van Vuuren, Hoogwijk, et al. 2009). The scenarios chapter in AR4 (Fisher et al., 2007), referred to aggregated CGE-type models as top-down models while technology-rich systems engineering modelling approaches were classified as bottom-up (integrated) models. To avoid the use of identical terms for different things, we adopt the practice suggested in (Fischedick et al. (2011b), Box 10.1), and do not use these terms altogether as they are not capturing the differences between the two streams of analysis accurately and are in fact often misleading. Integrated models have considerably evolved since AR4 with the category of so-called hybrid models being much more common than a few years ago. Such models combine considerable technological and sectoral detail and at the same time include a macro-economic component that also captures feedbacks from the overall economic development. Instead, we will simply stick to the terms

[7] In the following, we will refer to this way of calculating the sectoral mitigation potential as *direct mitigation potential*.

sectoral analysis and integrated modelling, but in parallel will aim at classifying both approaches in terms of their degree of technology resolution.

6.8.2 Synthesis of Sectoral Analysis and Comparison with Transformation Pathways

This section combines information from the sectoral chapters and puts them into context of the transformation pathways. A number of different metrics can be employed to compare results from sectoral analyses with the outcomes of the literature on transformation pathways. However, only some of them are universally applicable across a number of sectors while others are very much sector-specific as the sectors provide very different services.

6.8.2.1 Sectoral Energy Use

For the energy end-use sectors (Chapters 8-10) final energy use is a straight forward metric that can be compared with results from the transformation pathways. Another metric available from a larger set of the integrated modelling literature is the development of total global electricity generation. The development of these energy sector indicators across a range of scenarios for different climate categories (cf. Section 6.2.2) is shown in Figure 6.39.

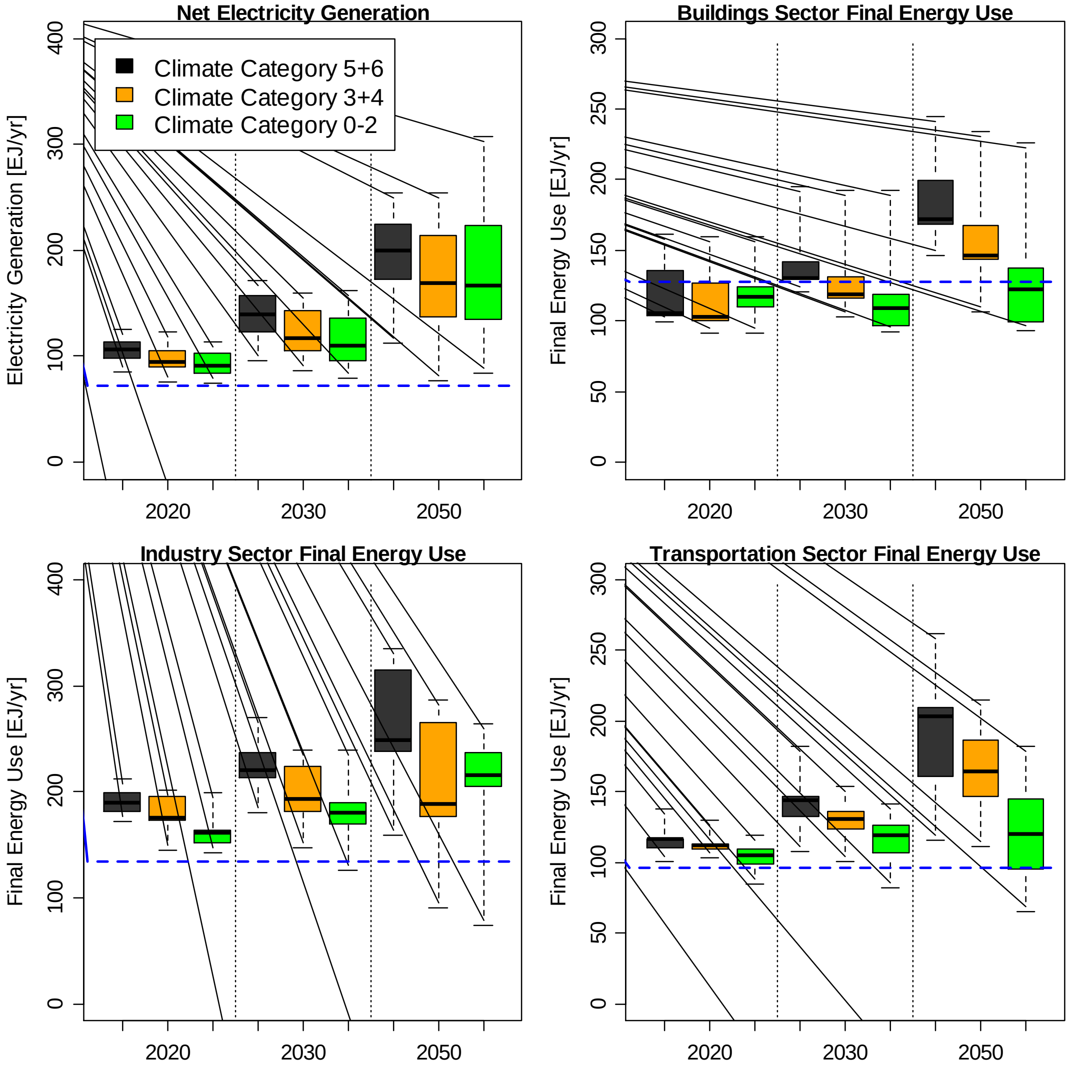


Figure 6.39. Total electricity generation and final energy use in the three end-use sectors (buildings, industry and transportation) by 2020, 2030 and 2050 in transformation scenarios from three different climate categories (see Section 6.2.2). The thick black line corresponds to the median, the coloured box to the inter-quartile range (25th to 75th percentile) and the whiskers to the total range across all

reviewed scenarios. The blue dashed lines refer to historical data as of 2009 (IEA, 2011a). [scenarios from preliminary AR5 database].

Energy Conversion

The energy conversion sector plays a key role for the development of GHG emissions, in particular because of its interaction with the end-use sectors. For example, an interesting feature of the electricity sector is that with increasing stringency of climate goals, total electricity generation is first reduced with improving energy efficiency, but eventually may increase again (Figure 6.39) due to increasing electrification of previously non-electrified sectors and services. As shown in Chapter 7.12.3 mitigation studies indicate that the decarbonisation of the electricity sector can be achieved at much higher pace than in the rest of the energy system. In stringent stabilization scenarios, the share of low-carbon energy sources for electricity generation increases from presently about 30% to more than 80% by 2050 (see Figure 7.25). However, at the local level numerous physical, technological as well as acceptance issues exist. Among the physical and technological barriers, remote locations of, in particular renewable energy resources, limited geological CO2 storage potential for the application of CCS and limits to the integration of fluctuating renewables in the short- to medium-term bear mentioning (Chapter 7.10.1). Public acceptance most prominently affects nuclear energy, but also other low carbon energy sources such as CO2 storage and renewable energy (see Chapter 7.9). Further, most of these technologies are capital intensive which may hamper their deployment in the absence of support from financial institutions, particularly in developing countries (Chapter 7.10.2).

Industry

According to sectoral analysis presented in Chapter 10, in the energy intensive industries energy intensities under best practices are approaching technical limits, with at most 25%-30% improvement left across all industries (Chapter 10, ES). Energy intensity in the iron and steel sector can be reduced some 35% of current levels; in the cement sector, energy intensity can be reduced by another 30%, mainly through the reduction in clinker to cement ratio (Chapter 10.7, Table 10.7). In the chemical and petrochemical industry, comparing a 4 degree and a 2 degree scenario from IEA, an energy intensity reduction of 22% is achievable (Chapter 10.7, Table 10.7). Global final energy demand in industry was 134 EJ/yr in 2010, and the demand in 2050 – even under the 2 degree scenario from IEA – is estimated to be in the range of 191-200 EJ/yr, thereby significantly exceeding today's levels (Chapter 10, Table 10.11). These findings are broadly consistent with the reported industrial final energy use from the transformation pathways, although the lower end of the range reported in the transformation pathways is significantly lower (about 75 EJ/yr in 2050, see Figure 6.39) than suggested by the detailed IEA analysis.

Buildings

A set of detailed building sector scenarios has been reviewed in Chapter 9.10.2 and reports a final energy use of the buildings sector in the range of 120-170 EJ/yr by 2030 under baseline conditions (150-220 EJ/yr by 2050) (Figure 9.17). By 2030 final energy savings of 10-25% compared to these levels are reported (Figure 9.18) with studies that focus on the provision of space heating, cooling and hot water reporting considerably higher savings compared to baseline of 37-50% in 2030. In addition, comprehensive (systemic) buildings sector studies presented in Chapter 9.6 report that final energy reductions by 2050 can be in the range of 30 to 50% compared to the baseline development, for space heating and cooling services values of up to 70% are reported (see Table 9.5). These values are generally compatible with the ranges reported in the transformation pathway literature, acknowledging that the reported values span a large range in both streams of analysis.

To realize the final energy reductions indicated above, a combination of different policies has been identified in Chapter 9.11. In particular, some of the existing implementation barriers, including the lack of skilled labour, the lack of monitoring and enforcement of existing legislation, and split incentives (Table 9.9), would need to be overcome (Chapter 9.9). A holistic approach, taking into account the entire lifespan of the building, is required to obtain the broadest impact possible in the building industry. A broad portfolio of policy instruments will be needed to remove these barriers, with many of them saving energy and emissions at no extra costs or even considerable lifecycle savings (Chapter 9.11).

Transport

In the transformation pathway literature the transport sector is typically described as being the most difficult of the end-use sectors to decarbonize. Fuel economy and carbon emissions standards are already widely used effectively in several OECD countries (Section 8.10.1). The improvement targets for LDV GHG emission per km in 2015 or 2016 are around 10-25% compared to 2008 (Figure 8.10.1). In 2010, the International Civil Aviation Organisation (ICAO) agreed on a non-binding, global aviation strategy to continuously improve fuel efficiency by an average of 1.5% per annum from 2009 until 2020; to achieve carbon neutral growth from 2020; and to reduce carbon emissions by 50% by 2050 compared to 2005 levels. A global CO2 standard for aircraft is under development for 2013 aiming to slow demand growth and hence avoid additional emissions of 190Mt CO2 annually (Section 8.10.4).

A transition to new fuel supply chains, a feature that many of the transformation pathways foresee as a strategy to decarbonize the transport sector, will require close coordination among fuel suppliers, vehicle manufacturers, and policymakers, as well from consumers. Historical analysis suggests that it takes 30-70 years to fully implement new infrastructures, but changes can occur quicker in specific regions and markets (Section 8.9.2.1). Changing the fuel supply infrastructure requires time, especially if this means switching on a massive scale from liquid fuels to gaseous fuels or electricity (Section 8.9.1).

Sectoral analysis suggests that up to 20% of transport demand can be reduced by more compact cities, modal shift and behavioural change (Section 8.9.1), options which are only partly represented in state of the art integrated scenarios.

Human Settlements

Transformation of places, populations, economies and the built environment vitally influence GHG pathways. Human settlements are getting increasingly urbanized globally, but the levels of urbanization vary across regions. Over half of the world's population was urban in 2009 (Section 12.1, UN (2010)). Urban areas generate more than 90% of the global economy. By 2050, urban population is projected to increase to 6.3 billion, from 3.4 billion in 2009, with growth concentrated in Asia (+ 1.7 billion), Africa (+ 0.8 billion) and Latin America and the Caribbean (+ 0.2 billion) (Section 12.2.1.1).

Across cities, there is a large variation in total and per capita emissions. The differences arise from multiple factors like energy mix, urban economic structures, local climate and geography, stage of economic development, state of public transport, urban form and density. Economic globalization is another force that is shaping urban pattern through myriad levers like capital and technology flows, governance reforms, infrastructure choices and changing production techniques and consumption patterns. Urban GHG mitigation plans include a broad range of strategies and activities. Spatial planning, a holistic approach, includes land use, urban, regional and environmental planning at different spatial scales (Section 12.5). Mitigation opportunities arise from multiple avenues like choices of land-use infrastructures, housing, energy efficiency, renewable energy and pollution control (Section 12.7.1). GHG mitigation from human settlements interact both, positively and negatively (Section 12.8), with many aspects of sustainable development. Climate change mitigation plans are often part of larger sustainability plans, mixed with urban development projects, or embedded in the spatial plans.

6.8.2.2 Sectoral CO2 Emissions

[AUTHORS: Direct GHG emissions by sector can be compared in a meaningful way between the different streams of analyses without any accounting ambiguities (see Figure 6.40). A comparison between the analyses presented in the sectoral chapters and the transformation pathways still needs to be performed toward the SOD.]

6.8.3 Regional (Sectoral) Analysis and Transformation Pathways

The global trends described in the previous section are often the result of very different regional dynamics. Whereas in developed regions even under baseline conditions, with modest or little climate policies in place, a reduction of final energy demand and resulting GHG emissions is projected in many studies, a strong increase in demands for services is foreseen in emerging economies and developing countries.

Industry

Industrial production will significantly increase in many regions of the world to satisfy growing demand in the next 40 years, particularly in Non-OECD regions (excluding China, where material demand is expected to flatten). For some materials demand is likely to double by 2050 or in some regions even to triple (e.g., cement in India) while in other regions only modest demand increase can be expected (e.g. OECD) or even demand on specific materials is expected to flatten (Section 10.11.2). Demand increases for energy-intensive materials combined with limited technical potentials for increasing efficiency lead to considerable growth in industrial final energy use. For example, in India, final energy use in industry in 2010 was 7 EJ/yr, which may be tripling until 2050 even if ambitious climate policies are adopted (Chapter 10, Table 10.11).

Transport

Closely related to urbanization, the mobility needs, complex choices and priority setting issues raised by the rapid growth of transport demand taking place in non-OECD countries highlights the importance of placing climate-related transport policies in the context of goals for sustainable urban development. Local history and social culture relate to the specific problem context and can shape the policy aspirations which determine what will ultimately become acceptable solutions (Section 8.10.6).

Human Settlements

The embedded emissions in settlement structures (Section 12.4.1.2) in developed countries are far higher compared to in the less developed countries (Müller et al., 2011). Under rapid urbanisation, developing countries can leapfrog by constructing sustainable settlements having low carbon intensive infrastructures and buildings. Reviving urban carbon sinks like urban forests, wetlands, parks, grasslands and green roofs also deliver co-benefits like reduced airborne pollution and heat island effect (Section 12.8.4). Waste generation is another area offering substantial mitigation in urban settlements (Section 12.4.3.11). The scenarios and modelling studies of the transformation pathways generally have macro, long-term and global view and therefore miss to explicitly include the drivers at finer scales. The low carbon society studies which focus on finer geographical scales find significant co-benefits from explicitly integrating mitigation activities in human settlements including infrastructure choices and spatial planning.

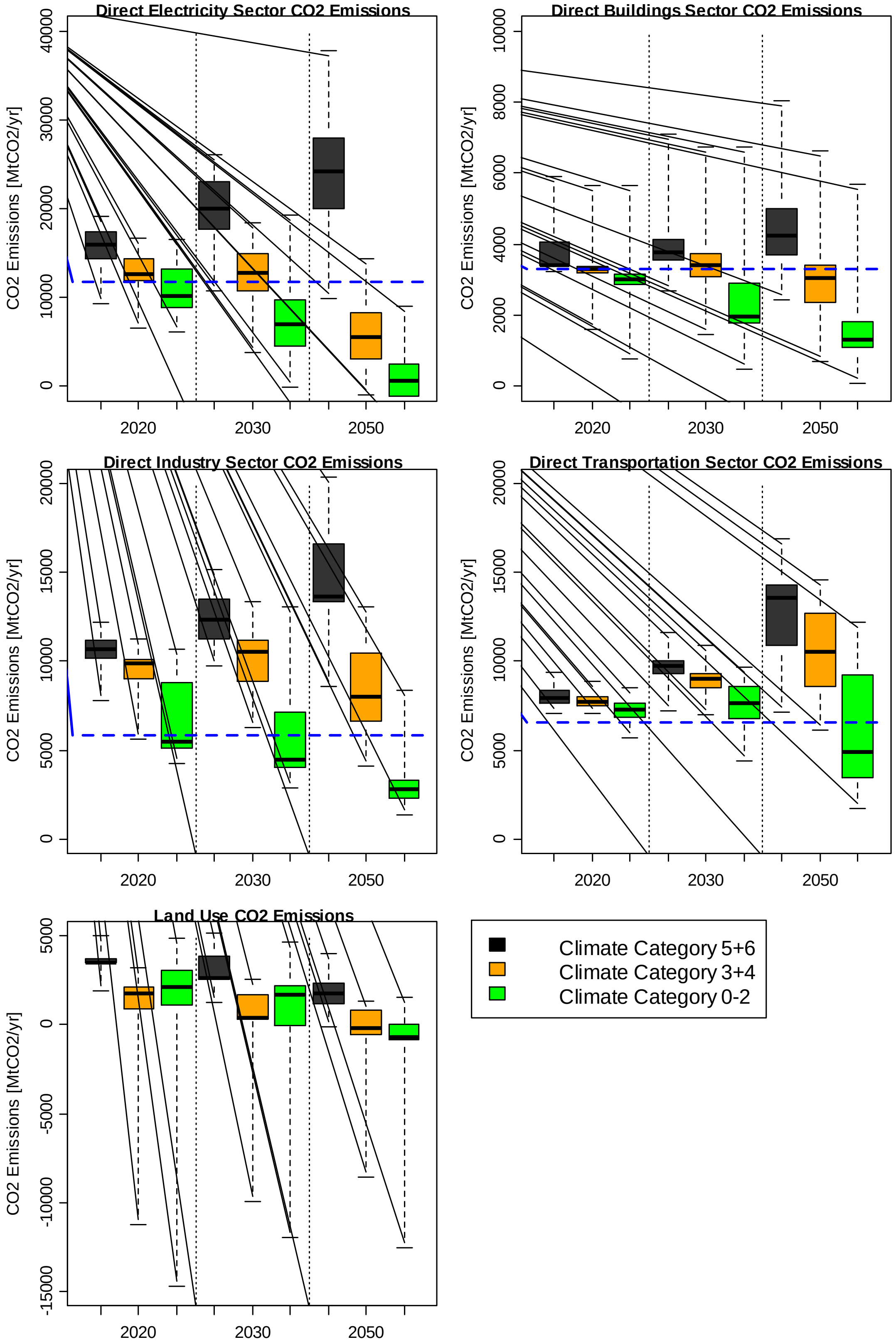


Figure 6.40. Direct CO2 emissions from the electricity sector, the three end-use sectors (buildings, industry and transportation) and the land-use sector by 2020, 2030 and 2050 in transformation scenarios from three different climate categories (see Section 6.2.2). The thick black line corresponds to the median, the coloured box to the inter-quartile range (25th to 75th percentile) and the whiskers to the total range across all reviewed scenarios. The blue dashed lines refer to historical data as of 2009 (IEA, 2011b). [scenarios from preliminary AR5 database].

6.8.3.1 Agriculture, Forestry and Other Land Use (AFOLU)

Agriculture production (12%) and land use change (12-20%) together contribute 24-34% of the global anthropogenic GHG emissions between years 2000-2010 (Ref. Sections 11.2.2 and 11.2.3). The top-down assessments show that AFOLU have significant cost-effective GHG mitigation options on production-side (Ref. Table 11.2) and demand-side (Ref. Table 11.4). The mitigation options differ greatly by activity, regions, system boundaries and the time horizon. Forestry mitigation options - including reduced deforestation, forest management, afforestation, and agro-forestry - are estimated to contribute between 1.27 and 4.23 Gt CO_2 / yr abatement in 2030 at carbon prices up to 100 US$ / t CO_2-eq; and nearly half of the mitigation (= 1.55 Gt CO_2 / yr) can occur at a costs under 20 US$ / t CO_2-eq. (Ref. Section 11.6.2; Figure 11.11).

Mitigation potentials in agriculture vary across regions and options. Economically viable mitigation opportunities in agriculture at 2030 show that at carbon prices of $100 a tonne of CO_2-eq, the mitigation potential is 4.30 Gt CO_2-eq / yr and restoration of organic soils is most promising among all options, followed by cropland management and grazing land management. At a price of around US$20 a tonne of CO_2-eq, cropland management seems to hold highest economic mitigation potential. The implementation of AFOLU mitigation measures can deliver myriad co-benefits. On the other hand, climate change feedbacks, such as thawing permafrost and CO_2 fertilization, will affect AFOLU emissions. The institutional and technological barriers and opportunities (Ref. Section 11.8) shall alter the realization of mitigation potential and co-benefits, though to a different extent for different transformation pathways.

Box 6.1. Attribution of GHG emission reductions to technologies and sectors.

A stream of the literature assigns GHG emission reductions to individual technologies or technology clusters. A prominent example is the paper by Paccala and Socolow (2004) which introduced the term “mitigation wedges” for this type of allocation of emission reductions to technologies, although there are earlier examples for this type of assignments. Such assignments are done based on various methodological approaches, for example, technology-specific marginal abatement cost curves (MACs, see Section 7.8.3 for a more detailed discussion of the methodological issues and a list of recent publications making use of the concept) or integrated modelling analysis (e.g. (Riahi and Roehrl, 2000; Shukla et al., 2008)). While the general idea of breaking down emission reduction to the technology level appears attractive at first glance – in particular when communicating results of analysis to decision makers – it has a number of methodological problems and is complicated by interdependencies among technologies within the energy system and also with other natural and human systems.

First, all emission reductions are calculated against a hypothetical baseline which determines the overall amount of emissions that can be avoided. Second, with the exception of very simple systems that, e.g., do not allow for changes in demand and supply of energy or other commodities simultaneously, an unambiguous allocation to individual technology activities is impossible. In many cases only the combination of certain technologies may actually lead to emission reductions. For example, electrification of transport is only a mitigation option if electricity generation is decarbonized at the same time. Splitting the realized emissions reduction of such system solutions between two (or more) technologies is always arbitrary, because neither of the two (or more) individually would lead to emissions reductions by themselves. A further complication arises that even if an agreement on a specific allocation algorithm is made, the different levels of aggregation of the underlying frameworks (sectoral and technology detail of models) introduce ambiguities in the allocation to technologies.

Therefore, in this chapter the allocation of emissions reductions to individual technologies or technology clusters is avoided and the results of such analyses should generally be interpreted with great care.

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

6.9.1 Carbon dioxide removal

A diverse set of methods might enable removal of CO_2 from the atmosphere. These methods vary greatly in their costs, environmental risks and potential scalability, as well as in depth of research about their potential and risks. The divergence between techniques is so great that it is essentially impossible to draw meaningful conclusions about CDR as a whole. Arguably there are only two methods—Biomass Energy with CCS (BECCS) and iron fertilization—for which there is sufficiently deep body of scientific and policy analytic literature to allow a confident summary of current understanding (Stephens and Keith, 2008; Swart and Marinova, 2010). The spectrum of CDR techniques may usefully be divided into three categories according to the fate of the stored carbon: (a) ocean waters, (b) land biosphere, (c) geosphere (Stephens and Keith, 2008). It must be noted, however, that other taxonomies may be more relevant for risk assessment and regulatory policy such as the division between encapsulated industrial technologies such as BECCS and direct air capture on one hand and ecosystem manipulation technologies such as biochar and iron fertilization on the other.

It is possible to increase the flux of carbon into the ocean deliberately manipulating biogeochemical cycling in the surface ocean. The most well researched idea is the possibility that (a) the addition of iron in the ocean surface in regions in which biological productivity is limited by iron can increase ocean surface productivity that would in turn (b) increase the export of carbon from the surface to the deep ocean. The net effect would be to accelerate the equilibration of atmospheric carbon with the deep ocean thus reducing the peak atmospheric concentrations experienced for a given input of fossil carbon.

Iron is a micronutrient in the sense that the mass radio of iron addition to carbon removal is of order 10^4-10^5 far larger than ratios for fertilization by macronutrients such as nitrogen and sulphur. This large molar ratio means that relatively little iron is required so the costs are expected to be low (Shepherd et al. 2009).

Large-scale experiments in the open ocean have shown unequivocally that the addition of iron can create short-term increases in biological productivity in the form of algal blooms (Boyd et al., 2007; Sarmiento et al., 2009). However the extent of the fertilization effect is highly variable. Surface fertilization alone provides no drawdown of atmospheric carbon unless there is an increase in the flux of carbon from the surface to the deep ocean in the form of settling biomass. Experimental evidence for increases in the export flux is substantially weaker than evidence for the algal blooms themselves (Boyd et al., 2007).

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

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

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

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

Direct capture of CO_2 from ambient air has been demonstrated at industrial scale only as a pre-treatment for cryogenic air separation, but not as a stand-alone process. Consequently there are no reliable estimates of the cost and performance of DAC if industrial scale technologies were to be developed, the only broad-based assessment of DAC technologies suggest that cost would be of order \$600/tCO_2 using current technologies (Socolow et al., 2011).

6.9.2 Solar Radiation Management

SRM role in climate policy is shaped by the fact that it acts quickly (Shepherd et al. 2009); (Keith, 2000; Swart and Marinova, 2010). The climate responds to changes in radiative forcing such as those induced by SRM on a timescale less than a decade, whereas the climates response to gradual change in emissions has a timescale of order a century. SRM can temporarily and imperfectly mask the climate change that arises from the accumulation of from long-lived greenhouse gases such as CO_2. Emissions mitigation necessarily has a much slower impact on climate because of the inertia inherent in the carbon cycle. Mitigation cannot substantial reduce climate risk on timescales of decades; but on the century timescale only the reduction in long lived GHGs can reduce the long-run climate risk. It is therefore a misconception to think of a simple one-time trade-off between SRM and mitigation, though there are trade-offs that must be considered between across century-scale climate policy (Wigley, 2006).

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

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

Only a few studies have quantitatively evaluated extent to which SRM can compensate for anthropogenic climate change on a regional basis. Early studies focused suggested large that SRM did a poor job reducing climate damages, and that that damages from SRM might be large (Robock et al., 2008). Later studies confirm that (a) SRM cannot accurately reverse GHG driven climate change and that (b) the divergence is larger at regional scales that it is on a global means basis (Ricke et al., 2010), but (c) one of the first studies to examine the effectives geoengineering in compensating for temperature or precipitation changes on a regional basis shows that SRM can compensate for increased GHG surprisingly well even at a regional level. Using analysis over 22 regions Moreno-Cruz et al found that a single (optimal) choice of SRM forcing could reduce the population-weighted mean squared deviation in temperature by 99% and in precipitation by 85% but both cannot be achieved simultaneously (Moreno-Cruz et al., 2012).

All studies to date have focused on compensation as measured by climate variable such as temperature and precipitation, understanding of the effectiveness—or lack thereof—of SRM in reducing climate damages will require studies that directly assess damages to more relevant quantities such as crop productivity.

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

6.10 Gaps in Knowledge and Data

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

[AUTHORS: Note to reviewers: The remainder of the text in this section simply raises three issues as placeholders as a starting point for a more thorough treatment in the SOD. Although these are simply placeholders, we would still appreciate comments on this section.]

Topic: Regional Comparability: The literature reviewed in this assessment is not based on a common set of global regions. This has limited the comparability among models and scenarios at a regional level.

Topic: Interactions with Impacts and Adaptation: The vast majority of scenarios take no account of impacts and adaptation, and those that do are in the context of very specific studies addressing very specific impacts. Given the potential for very large interactions between mitigation, impacts, and adaptation, it is important that future scenarios and analyses begin to take on these issues.

Topic: Modeling of links to other national and societal priorities: Mitigation will not take place within a vacuum. The degree to which actions might be taken will depend to a large degree on the degree to which they are consistent with or achieve other national priorities such as development (including sustainable development), national security, or non-climate environmental goals. Similarly, the implications of different mitigation strategies will depend on their links to these priorities. The scenarios in this chapter have been built to explore the core characteristics of climate mitigation, most notably, the costs, the energy system transitions, the agricultural system transitions, and the longer-term international policy approaches. Although there is some literature that attempts to link these scenarios to other priorities, this literature is limited in comparison. Future research in this direction would be valuable for future assessments.

6.11 Frequently Asked Questions

6.11.1 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?

It is true that it is impossible to bring climate change under control if doing so were to involve maintaining greenhouse gas concentrations below a level that has already been exceeded or will be shortly. However, in all other cases, the question of “feasibility” – whether it is possible to bring climate change under control – is more subjective, bound up with perceptions of the challenges associated with particular mitigation strategies. Important characteristics of mitigation strategies that influence assessments of feasibility include macro-economic costs, social acceptance of new technologies that underpin mitigation, the rapidity at which social and technological systems would need to change to bring greenhouse gas concentrations to particular levels, political feasibility of national and international policy approaches, and linkages between mitigation approaches and other national priorities such as energy security and development.

The nature of these characteristics, in turn, is dependent on many choices that will influence the transformation toward a lower-emissions future. Among the most fundamental of these is the level of greenhouse gas concentrations that is considered most appropriate to prevent dangerous anthropogenic interference with the climate. Other key factors include the timing of the path to bring greenhouse gas concentrations to this level, the degree to which concentrations might temporarily exceed (or “overshoot”) this level, the technologies that will be deployed to reduce emissions, the degree to which mitigation is coordinated across countries, the policy approaches used to achieve these goals within and across countries, the treatment of land use, and the manner in which mitigation is meshed with other national and societal priorities such as energy security and sustainable development.

Within this context, research indicates that efforts to meet a 2.6 W/m2 will be challenging under all strategies, but extraordinarily challenging without the option to overshoot this goal temporarily, substantial, near-term global emissions reduction, coordinated action to achieve these reductions, and a full complement of available technology options including CCS and nuclear power. Indeed, studies indicate a global emissions peak prior to 2020 to meet this goal, with associated dramatic near-term transformations in the energy system and social and institutional infrastructure for producing and consuming energy. Many modeling studies find 2.6 W/m2 impossible to produce without these requirements. [AUTHORS: Note to reviewers: Statement will be refined in second-order draft. See note in introduction on preliminary dataset.]

6.11.2 What are the most important technologies for mitigation? Is there a silver bullet technology?

There are many technology strategies for mitigation that can lead to stabilization at particular concentrations of greenhouse gases. This means that there is no single technology that is either required or that will serve as a "silver bullet", achieving mitigation without incurring meaningful macroeconomic costs or creating challenging transformations to the energy system and other important characteristics of human societies. For example, zero-carbon electricity sources such as nuclear power, fossil energy with CCS, and renewable power are potentially critical for mitigation, but they are not sufficient without technologies such as heat pumps and electric cars that can allow electricity to substitute for liquid and solid fuels. Similarly many end uses such as air travel may never be amenable to electricity, meaning that low-carbon liquid fuels such as those from bioenergy will be a critical part of the mitigation portfolio. Technologies that can reduce the energy required to provide basic services such as heating, cooling, lighting, and transportation are critical for reducing the need for low-carbon energy.

In this light, the role of technology should be seen as reducing the challenge of bringing climate change under control. The more technologies that are available for mitigation and the better and less expensive these technologies are, the lower will be the cost and the challenge of bringing climate change under control.

The one possible exception to this biomass coupled with carbon dioxide capture and storage. This technology makes it possible remove CO2 from the atmosphere. Many scenarios indicate that the availability of bioCCS would allow for more challenging stabilization goals, particularly in overshoot pathways, by allowing for net negative global emissions beyond mid-century.

6.11.3 How much would it cost to bring climate change under control?

Although measures of macro-economic costs such as GDP losses or changes in total personal consumption have been put forward as key deliberative decision-making factors, these are far from the only characteristics about transition pathways that matter for making good decisions. The broader socio-economic implications of mitigation go well beyond economic costs, conceived narrowly. Transition pathways inherently involve a range of tradeoffs that link to other national and societal priorities including, among other things, both energy and food security, sustainable development, the distribution of economic costs, local air pollution and other environmental factors associated with different technology solutions (e.g., nuclear power, coal-fired CCS), and economic competitiveness. Nonetheless, macroeconomic costs are an important criterion for evaluating transformation pathways and can serve as one indicator of the level of difficulty or disruption that would be associated with particular transformation pathways.

Macroeconomic cost estimates for meeting stabilization goals vary widely, depending, among other things, on the nature of technological options, the underlying analysis approach, the policy options implemented to reduce emissions, the degree of international participation, and the nature of the drivers of emissions such as behavior, population growth, and economic growth. The uncertainty in cost estimates is larger at deeper levels of reduction, because such estimates must be based on characterizations of energy and other systems that are very different from those of today. Assuming full technological availability and a coordinated global approach to mitigation in which mitigation is undertaken where it is least expensive, and starting immediately, most studies indicate a total net discounted global macroeconomic costs of less than XX% of GDP through 2050 to meet goals below 2.6 W/m2 [AUTHORS: Note to reviewers: Statement will be refined in second-order draft. See note in introduction on preliminary dataset.], although a minority of studies indicate costa as high at 8 percent of GDP over this period. Costs for a 3.7 W/m2 goal under these same circumstances generally fall below 1 percent of total global GDP [AUTHORS: Note to reviewers: Statement will be refined in second-order draft. See note in introduction on preliminary dataset.].

At the same time, these idealized circumstances are unlikely to materialize. Studies indicate that delays in global action or fragmented action regimes in which mitigation is not undertaken where and when it is least expensive or in which policy structures are not designed to minimize costs can all increase costs dramatically, more than XX% in some circumstances [AUTHORS: Note to reviewers: Statement will be refined in second-order draft. See note in introduction on preliminary dataset.]. Reductions in the availability of mitigation technologies can also reduce costs, more than doubling costs when key technologies such as CCS are not available [AUTHORS: Note to reviewers: Statement will be refined in second-order draft. See note in introduction on preliminary dataset.].

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