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Author(s):	CLAs:	Nebojsa Nakicenovic (Austria/ Serbia and Montenegro), Brian Fisher (Australia)	
	LAs:	Knut Alfsen (Norway), Jan Corfee Morlot (USA), Francisco de la Chesnaye (USA), Jean-Charles Hourcade (France), Kejun Jiang (China), Mikiko Kainuma (Japan), Emilio La Rovere (Brazil), Ashish Rana (India), Keywan Riahi (Iran), Richard Richels (USA), Detlef Van Vuuren (Netherlands), Rachel Warren (UK)	
	CAs:	Phillipe Ambrosi, Fatih Birol, Daneil Bouille, Christa Clapp (USA), Bas Eickhout (Netherlands), Yuzuru Matsuoko, Anna Matysek (Australia), Brian O'Neill, High Pitcher, Shilpa Rao, Steven Rose (USA), Ferenc Toth	
	REs:	John Weyant (USA), Mustafa Babiker (Kuwait)	
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Chapter 3 Issues related to mitigation in the long-term context

EXECUTIVE SUMMARY

This chapter documents baseline and stabilization scenarios in the literature since the publications of the IPCC Special Report on Emissions Scenarios (SRES, Nakicenovic *et al.*, 2000) and Third Assessment Report (TAR, Morita *et al.*, 2001). It reviews the use of the SRES reference and TAR stabilization scenarios and compares them with new scenarios that have been developed by the modelling community during the last five years. Of special relevance is a how representative the SRES ranges of driving forces and emissions are of the newer scenarios in the literature. Other important aspects of this review include methodological, data and other advances since the time the SRES scenarios were developed. The focus of the chapter is on scenarios that stabilize atmospheric concentrations of GHG and other relevant anthropogenic substances that are radiatively active in the atmosphere such as sulfur aerosols. New multigas stabilization scenarios represent a significant change in the new literature compared to TAR.

The main finding from the comparison of SRES and new scenarios in the literature is that the uncertainties as represented by the ranges of main driving forces and emissions have not changed very much. Overall, the range of emissions scenarios reported before and after TAR in scenarios without climate policy seems not to have changed appreciably.

Population scenarios from major demographic institutions are lower, but they have not been fully implemented so far in the emissions scenarios in the literature. However, this will have to be considered in any new scenario exercise. Moreover, in the scenarios that used lower projections - changes in other drivers of emissions resulted in similar emission levels.

Regional medium-term (2030) economic projections for the some developing country regions are currently lower than the highest scenarios used in TAR. Otherwise, economic growth perspectives have not changed much even though they are among most intensely debated aspects of SRES scenarios.

In the debate of the use of exchange rates (MER or PPP), the assumptions of per capita GDP and of technological convergence are the major determinants in the absolute levels of long-term emission projections. A number of studies concur that the actual choice of exchange rates in and of itself does not have an appreciable effect upon on long-term emission projections. Furthermore, very few of the new scenarios are calibrated in purchasing power parities (PPP) so that most of the literature is still based on market exchange rates.

There have been some changes in the distribution of the carbon dioxide emissions. There are now more scenarios that explore both the upper and the lower of the SRES emissions changes. There are also many more new scenarios that include all gases and not only carbon dioxide. The new multigas literature shows that multigas reduction strategies give substantially lower costs than CO_2-only strategies.

For most other drivers, scenarios published since TAR show a similar range as those published before TAR. A major exception is formed by emissions of SO_y and NO_x. As short-term trends have moved down, the range of projections for both are currently lower than the range published before TAR.A small number of new scenarios have begun to explore emission pathways for black and organic carbon.

The way substitution of gases is specified determines the role of short-lived gases in reduction over time. The use of GWPs as done in current policies leads to a high level of methane reduction over the short-term.

The costs of stabilization depends on the stabilization target and level, the baseline and the portfolio of technology considered and the rate of technology change. For stabilization at 4.5 W-m^2 costs range in between *x-y (quantification for other targets will be added).*

- Different stabilization targets can lead to somewhat different strategies in emission reduction.
- New studies exploring more stringent stabilization levels indicate that a wider portfolio of technologies is needed. Those could include nuclear, CCS and BECCS.

Baseline land-related GHG emissions are projected to increase with increasing cropland requirements at the expense of forest area due to global food demand, which grows at a decreasing rate, and shifts in dietary preferences towards meat consumption. Global long-term land-use scenarios are scarce in numbers but growing, with the majority of the new literature since SRES contributing new forestry and biomass scenarios. Overall, global integrated assessment and computable general equilibrium scenario models are beginning to more directly and realistically model the competing regional and global driving forces of dynamic land use and land use change as well as the biophysical productivity of land. Most post-SRES global scenarios project significant changes in agricultural land caused primarily by changes in food demand and the structure of supply as moderated by international trade.

Recent stabilization studies have found that including land-use mitigation options (both non-CO_2 and CO_2) provided greater flexibility and cost-effectiveness. Land-use is crucial in climate stabilization for its significant atmospheric inputs & withdrawals (emissions, sequestration, and albedo). Even if land activities are not considered as mitigation alternatives by policy, land's long-run atmospheric influence is substantial, as is its susceptibility to changes in the atmospheric condition. Scenarios suggest various roles for forestry in terms of timing and overall significance for mitigation. Biomass production from dedicated lands could contribute substantially to achieving stabilization targets, with potential defined by key factors, in particular oil prices, food demand, and conversion capacity.

Different sets of mitigation options reflect in varying shares of nuclear energy, CCS, hydrogen, and biomass across different country scenarios. In the countries with low energy intensity levels in 2000, drastic CO_2 reductions are achieved by carbon intensity improvement means like shift to natural gas in the UK, renewable energy in the Netherlands, and CCS in certain scenarios in France, Germany, the UK, and some other countries. The scenarios that report quantitative results with drastic CO_2 reduction targets of 60-80 per cent in 2050 require an increase in the rates of improvement of energy intensity and carbon intensity by two to three times their historical levels.

Decarbonization trends are persistent in majority of intervention and non-intervention scenarios. The medians of scenario sets indicate decarbonization rates of about 0.9 (pre 2001) and 0.6 (post 2001) compared to historical rates of about 0.3 per cent per year. On the upper end of the range decarbonization rates of up to 2.5 per cent per year are observed in more stringent stabilization scenarios, where complete transition away from carbon intensive fuels is considered.

Long-term stabilization scenarios highlight the importance of technology improvements, advanced technologies, learning-by-doing, and endogenous technology change for both for achieving the stabilization targets as well as cost reduction. While the technology improvement and use of advance technologies have been employed in scenarios largely exogenously in most of the literature, new literature covers learning-by-doing and endogenous technological change. The latter show results to be different by the ways of deployment of technologies while maintaining their key role in achieving stabilization and reduction of cost.

The assessment of scenario database for role of technology, as also the newer literature, affirms that there is significant technological change and diffusion of new and advanced technologies already assumed in the baselines and additional technological change 'induced' through various policies and measures in the mitigation scenarios. Decarbonization trends are persistent in majority of intervention and non-intervention scenarios. The technological options assumed in the models for decarbonization need further R&D, large-scale deployment and greater institutional and policy incentives in order to reduce their costs, improve performance and achieve social acceptability.

Due to long life times of energy and infrastructure capital stock, diffusion of carbon-saving technologies takes many decades. This is the reason why in the short-term, emissions either continue to increase or reach a maximum in most of the stabilization scenarios. Deeper reductions occur in latter decades as carbon-saving technologies acquire larger market shares due to mitigation measures and policies introduced in stabilization scenarios.

Many studies confirm that it is essential to have both (technology) "push" and (demand) "pull" policies for technological diffusion. Full replacement of dominant technologies in the energy systems is generally a long process. Achieving such a transition in the future toward lower GHG intensities is one of the major technological challenges addressed in the scenarios. Long-term stabilization scenarios highlight the importance of technology improvements, advanced technologies, learning-by-doing, and endogenous technology change for both for achieving the stabilization targets as well as cost reduction.

The baseline choice is crucial in determining the nature and cost of stabilization. This influence is largely due to different assumptions made about technological change in the baseline scenarios. Literature identifies low-cost technology clusters allowing for endogenous technological learning with uncertainty. This suggests that a decarbonised economy may not cost any more than a carbon-intensive one, if technological learning curves are taken into account.

Dynamics in developing countries, in particular their pursuance of development goals are the main driving forces behind the endogenous technological change in these countries. The development policies adopted are like climate opportunities, as they generate endogenous change and create a path-dependence for induced change through climate policies.

Long-term mitigation policy and decision making in a risk management framework is informed by concern about climate change impacts and integrated assessments. These assessments consider the relationship between geophysical climate change, climate impact predictions, adaptation potentials and costs of emissions reductions. In particular they are informed by the (physical or monetized) benefits of avoided climate change damages.

Stabilisation of GHG concentrations at * or lower results in avoidance of key climate impacts. Ranges of outcomes of mitigation or stabilisation scenarios can be linked with key vulnerabilities over the three temperature ranges considered in WG2 Chapter 19 (>4 C; 2-4 C; 0-2 C from 1990) . A variety of integrated assessment approaches exist to assess mitigation benefits in the context of policy decisions related to alternative long term climate goals and risk management strategies.

Analyses which use monetization suggest social costs of carbon are positive but the range of values is wide and is strongly dependent on modelling methodology, value judgements and assumptions (see also Ch. 20). Adaptation is scale-dependent and hence more difficult to characterise in global modelling and is thus largely under - studied in long-term emission scenario literature. Yet, overall, the small but growing literature to consider both adaptation and mitigation suggests that adaptation and mitigation are complementary.

Large uncertainties persist related to the cost of mitigation, the efficacy of adaptation and the extent to which the negative impacts of climate change, including those related to rate of change, can be avoided. When viewed from a risk management perspective, the extent of the desirable hedging strategy will depend on the stakes, the odds and societies' attitudes to risks. A risk-taking society might choose to delay action and take the (small) risk of triggering significant and possibly irreversible abrupt change impacts over the long-term. If society is risk averse – that is, interested in avoiding downside risk or worst case outcomes – this would suggest a preference for hedging behaviour, or more and earlier mitigation to lower the risk of abrupt climate change.

The scenarios show that a multigas approach and inclusion of carbon sinks will be less costly than policies depending upon CO_2 abatement only. This is especially true with reduction goals based on the possibility of abrupt climate change. That is, when a policy concern is the avoidance of a near-term climate threshold, increased focus needs to be on the shorter lived gases, eg, CH4. This more diversified approach provides greater flexibility in the timing of the reduction program.

Near term mitigation and adaptation decisions are related to long term climate goals
The issue for today's policy makers is not what the best climate policy is for the next century. It is what the best climate policy is for today given the uncertainty about the long term goals. There will be ample opportunity for learning and mid-course corrections as new information becomes available. Hence, analysis of near-term decisions should not be decoupled from analysis which considers the long term as well.

3.1 Emissions scenarios

The evolution of future greenhouse gas emissions and their underlying driving forces is highly uncertain. This is reflected in the very wide range of future emissions pathways across (more than 750 emissions) scenarios in the literature. This chapter assesses this literature focusing especially on new multigas baseline scenarios since the publication of the IPCC Special Report on Emissions Scenarios (SRES, Nakicenovic *et al.*, 2000) and on new multigas mitigation scenarios since the publication of the IPCC Third Assessment Report (TAR Working Group III, Ch. 2, Morita *et al.*, 2001). This literature is referred to as 'post-SRES' scenarios.

The SRES scenarios were representative of some 500 emissions scenarios in the literature at the time of their publication in 2000. Of special relevance in this review is a how representative the SRES ranges of driving forces and emission levels are of the newer scenarios in the literature and how representative are the TAR stabilization levels and mitigation options compared with the new multigas stabilization scenarios. Other important aspects of this review include methodological, data and other advances since the time the SRES scenarios were developed.

An important source of the new scenarios are modelling networks that were organized to assess various questions associated with multigas mitigaton scenarios. In particular, this chapter uses the results of the Energy Modeling Forum (EMF-21) scenarios and the new Innovation Modelling Comparison Project (IMCP) network scenarios. In contrast to SRES and post-SRES scenarios, these new modelling comparison activities are not based on fully harmonized scenario assumptions but rather on 'modeller's choice' scenarios. Thus, further uncertainties have been introduced due both to different assumptions and different modelling approaches. Another emerging complication is that even baseline (also called reference) scenarios include some explicit policies directed at emissions reduction. Even at the time scenarios in the literature were assessed within SRES, it was not always possible to clearly differentiate between the baseline scenarios and those that include climate-related policies. This has become ever more difficult with the Kyoto Protocol entering into the force and other climate-related policies that are being implemented in many parts of the world. Some of the new baseline scenarios in the literature include such policies and measures as the integral component of scenario assumptions.

Another difficulty is that the information and documentation of the scenarios in the literature varies considerably. This hampers straightforward comparisons. Some scenarios are based on elaborate modelling approaches, others on simpler (integrated) models; some are comprehensive in covering the driving forces and emissions, others cover only so few of them; some are well documented while others report only some of the data.

The main finding from the comparison of SRES and the new scenarios in the literature is that the uncertainties as represented by the ranges of main driving forces and emissions have not changed very much. The main change is that population projections are now generally lower, but they have not been fully implemented so far in many of the new emissions scenarios in the literature. Economic growth perspectives have not changed much even though they are among the most intensely debated aspects of the SRES scenarios. In particular, very few of the new scenarios are calibrated in purchasing power parities (PPP). Most of the emissions scenario literature is still based on market exchange rates (MER). There have been some changes in the distribution of the carbon dioxide emissions. There are now more scenarios that explore both the upper and the lower bounds of the SRES emissions trajectories. There are also many more new scenarios that include all of the greenhouse gases and not simply carbon dioxide.

3.1.1 The definition and purpose of scenarios

Scenarios describe possible future developments. They can be used in an exploratory manner or for a scientific assessment in order to understand the functioning of an investigated system (Carpenter *et al.*, 2005). Researchers are often interested in exploring hypothesized interactions and linkages between key variables by using scenarios analysis. On the other hand scenarios can be utilized as part of a decision-making or planning process and for bridging the gap between the scientific and the policy-making communities. In this case upcoming decisions need to be highlighted and different choices and their outcomes can be explored. Here the scenarios can be used either in a more informative or educational way. Or, depending on the process employed, they can be used to challenge assumptions on the functioning of certain processes and illustrate different views held by participants in the scenario building exercise (Carpenter *et al.*, 2005).

In the context of the IPCC assessments, scenarios are directed at exploring possible future emissions pathways, their main underlying driving forces and how these might be affected by policy interventions. The IPCC evaluation of emissions scenarios in 1994 identified four main purposes of emissions scenarios (Alcamo *et al.*, 1995):

- To provide input for evaluating climatic and environmental consequences of alternative future GHG emissions in the absence of specific measures to reduce such emissions or enhance GHG sinks;
- To provide similar input for cases with specific alternative policy interventions to reduce GHG emissions and enhance sinks;
- To provide input for assessing mitigation and adaptation possibilities, and their costs, in different regions and economic sectors; and
- To provide input to negotiations of possible agreements to reduce GHG emissions.

There are many definitions of scenarios in the literature. They differ a lot depending on the purpose of the scenarios and how they were developed. For example, the SRES report (Nakicenovic *et al.*, 2000) defines a scenario as a plausible description of how the future might develop, based on a coherent and internally consistent set of assumptions ('scenario logic') about the key relationships and driving forces (e.g. rate of technology changes or prices). The SRES report defines the whole set of scenarios as 'alternative images of the future' used to explore future developments (in greenhouse gas emissions and its driving forces). SRES scenarios consist of two integrated elements, qualitative narratives (or stories) about the future and quantitative elaborations of these stories, based on formal modeling. These two elements together define 'an internally consistent and reproducible set of assumptions' about key driving forces, relationships and outcomes.

The definition of scenarios in SRES differs from several alternative uses of scenarios found in the literature. For example, some studies in the literature apply the term 'scenario' to 'best-guess' or forecast types of projections. Such studies do not aim primarily at exploring alternative futures, but rather at identifying most likely outcomes. Probabilistic studies represent a different approach, in which the range of outcomes is based on a consistent estimate of the probability density function (pdf) for crucial input parameters. In these cases, outcomes are associated with an explicit estimate of likelihood, albeit one with a substantial subjective component. Examples include probabilistic projections for population (Lutz *et al.*, 2001) and CO_2 emissions (Webster *et al.*, 2002; O'Neill, 2004).

3.1.1.1 Types of scenarios

The scenario literature can be split into two largely non-overlapping streams - quantitative modelling and qualitative narratives (Morita *et al.*, 2001). Figure 3.1 illustrates this heterogeneity (Nakicenovic *et al.*, 2000). This dualism mirrors the twin challenges of providing systematic and replicable quantitative representation, on the one hand, and contrasting social visions and non-quantifiable descriptors, on the other (Raskin *et al.*, 2005). It is particularly noteworthy that recent developments in scenario analysis are beginning to bridge this difficult gap (Nakicenovic et. al., 2000; Morita *et al.* 2001; Swart and Raskin. 2004; and Carpenter *et al.*, 2005). These developments are denoted in the Figure 3.1 by the overlapping area that encompasses both models and stories.

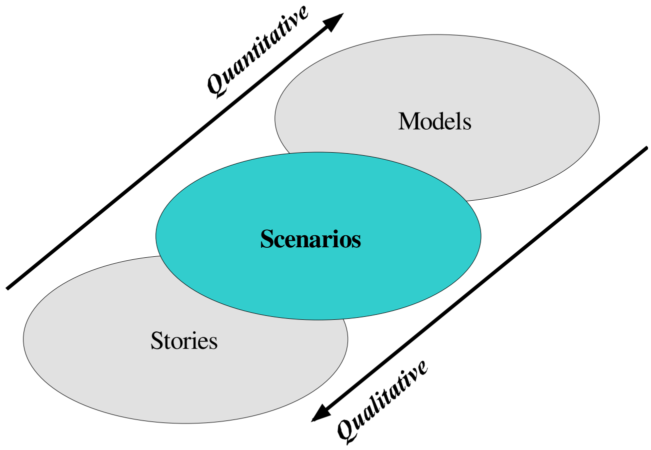


Figure 3.1: *Schematic illustration of alternative scenario formulations, from narrative storylines to quantitative formal models. Source: Nakicenovic et al., 2000*

3.1.1.2 Narrative storylines and modelling

The literature based on narrative storylines that describe futures is very rich going back to the first global studies of the 1970s (e.g. Kahn *et al.*, 1976; Kahn and Weiner 1967) and is also well represented in more recent literature (e.g. Peterson, 1994; Gallopin *et al.* 1997; Raskin *et al.*, 1998; Glenn and Gordon, 1997). Well known are the Shell scenarios that are principally based on narrative stories with illustrative quantification of salient driving forces and scenario outcomes (Wack 1985a; Wack 1985b; Schwartz, 1992; Shell, 2005).

Catastrophic futures feature prominently in the narrative scenarios literature. They typically involve large-scale environmental or economic collapses, extrapolating current unfavourable conditions and trends in many regions.[1] Many of these scenarios suggest that catastrophic developments may draw the world into a state of chaos within one or two decades. Greenhouse-gas emissions might be low in such scenarios because of low or negative economic growth, but seem unlikely to receive much attention in any case, in the light of more immediate problems. This report does not analyze such futures except cases that do provide emissions pathways.

3.1.1.3 Global futures scenarios

As mentioned, global futures scenarios are deeply rooted in the long history of narrative scenarios. The direct antecedents of contemporary scenarios lie with the future studies of the 1970s (Raskin *et al.*, 2005). These responded to emerging concerns about the long-term sufficiency of natural resources to support expanding global populations and economies. This first wave of global scenarios included ambitious mathematical simulation models (Meadows *et al.*, 1972; Mesarovic and Pestel, 1974) as well as speculative narrative (Kahn *et al.*, 1976). At this time, scenario analysis was first used at Royal Dutch/Shell as a strategic management technique (Wack, 1985; Schwartz, 1992).

[1] Prominent examples of such scenarios include the 'Retrenchment' (Kinsman, 1990), the 'Dark Side of the Market World' or 'Change without Progress' (Schwartz, 1991), the Global Incoherence Scenario (Peterson, 1994), the 'New World Disorder' (Schwartz, 1996), the 'Barbarization' (Gallopin *et al.*, 1997), 'Dark Space' (Glenn and Gordon, 1999), and 'A Passive Mean World' (Glenn and Gordon, 1997 and 1999).

A second round of integrated global analysis began in the late 1980s and 1990s, prompted by concerns with climate change and sustainable development. These included narratives of alternative futures ranging from 'optimistic' and 'pessimistic' worlds to consideration of 'surprising' futures (Burrows *et al.*, 1991; Milbrath, 1989; the Central Planning Bureau of the Netherlands, 1992; Kaplan 1994; Svedin and Aniansson, 1987; Toth *et al.*, 1989). The long-term nature of the climate change issue introduced a new dimension and has resulted in a rich new literature of global emissions scenarios, extending to the IPCC IS92 scenarios (Pepper *et al.*, 1992; Leggett *et al.*, 1992) and most recent scenario comparisons projects (e.g. EMF and IMCP). The first decades of scenario assessment paved the way by showing the power - and limits - of both deterministic modelling and descriptive future analyses. A central challenge of global scenario exercises today is to unify these two aspects by blending the objectivity and clarity of quantification with the richness of narrative (Raskin *et al*., 2005).

3.1.2 Introduction to mitigation and stabilization scenario

Climate change intervention, control, or mitigation scenarios capture measures and policies for reducing GHG emissions with respect to some baseline (or reference) scenario. They contain emission profiles as well as costs associated with the emission reduction. Some give explicit portfolio of mitigation technologies, other more aggregate emissions reduction profiles. Stabilization scenarios are mitigation scenarios that aim at a pre-specified GHG reduction target or pathway. Usually the target is the concentration of CO_2, the CO_2-equivalent concentration of a 'basket' of gases (thus the name mulitigas), radiative forcing or temperature by 2100 or at some later date when atmospheric stabilization is actually reached (Morita *et al*., 2001).

Mitigation scenarios are an essential tool for the assessment of policies and measures that would be required to reduce future GHG emissions. In this report, the terminology is used from the IPCC evaluation of emissions scenarios (Alcamo *et al*., 1995) and SRES (Nakicenovic *et al*., 2000). Those scenarios that include some form of policy intervention are referred to as mitigation or intervention scenarios, such as the 80 TAR scenarios (Morita *et al*., 2001), while those that do not assume any climate policy measures, such as the 40 SRES scenarios (Nakicenovic *et al*., 2000) are referred to as baseline, reference or non-intervention scenarios. Some mitigation scenarios investigate more radical emissions reductions required to stabilize atmospheric concentrations of GHG gases (in accordance with Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC, 1992)). As mentioned above, assessment of new multigas stabilization scenarios is a focus of this chapter.

For the purposes of this chapter, a scenario is identified as a mitigation or intervention scenario if it meets one of the following two conditions:

- it incorporates specific climate change targets, which may include absolute or relative GHG limits, GHG concentration levels (e.g., CO_2 or CO_2-equivalent stabilization scenarios), or maximum allowable changes in temperature or sea level; and
- it includes explicit or implicit policies and/or measures of which the primary goal is to reduce CO_2 or a broader range of GHG emissions (e.g., a carbon tax, carbon cap or a policy encouraging the use of renewable energy).

Some scenarios in the literature are difficult to classify as mitigation (intervention) or baseline (reference or non-intervention), such as those developed to assess sustainable development paths. These studies consider futures that require radical policy and behavioural changes to achieve a transition to a postulated sustainable development pathway; Greenpeace formulated one of the first such scenarios (Lazarus *et al*., 1993). Many sustainable development scenarios are also included in this assessment. Where they do not include explicit policies, as in the case of SRES scenarios, they can be classified as baseline or non-intervention scenarios. For example, the SRES B1 family of reference scenarios can be characterized as having many elements of sustainability transition that lead to generally low GHG emissions even though the scenarios do not include policies or measures explicitly directed at emissions mitigation.

In addition to these ambiguities about what constitutes a baseline scenario without climate polices, a new and emerging classification problem is that some climate policies are being increasingly adopted throughout the world. Ever since the Kyoto Protocol entered into force on 16 February 2005 policies directed at implementation of emissions reductions commitments by the Parties can no longer be considered to be additional climate policies and need to become part of a reference scenario. An immediate complication than becomes what to assume for policy setting post 2012 when the Kyoto commitment period ends given that there is no firm guidance on what will replace the announced arrangements. Moreover, it is not easy to separate climate polices from other policies in many instances and sometimes it is simply not possible to do so.

Another type of mitigation (intervention or climate policy) scenario approach specifies future ‘worlds’ that are internally consistent with some specified climate target (e.g., a global temperature increase of no more than 1°C by 2100), and then works backwards to develop feasible emission trajectories and emission driver combinations leading to these targets. Such scenarios, also referred to as ‘safe landing’ or ‘tolerable windows’ scenarios, imply the necessary development and implementation of climate policies intended to achieve these targets in the most efficient way (Morita *et al*., 2001). A number of such new multigas stabilization scenarios are assessed in this chapter.

Confusion can arise when the inclusion of ‘non-climate-related’ policies in a reference (non-intervention) scenario has the effect of significantly reducing GHG emissions. For example, energy efficiency or land use policies that reduce GHG emissions may be adopted for reasons that are not related to climate policies and may therefore be included in a non-intervention scenario. Such a scenario may have GHG emissions that are lower than some intervention scenarios. The root cause of this potential confusion is that, in practice, many policies can both reduce GHG emissions and achieve other goals (so-called multiple benefits). Whether such policies are assumed to be adopted for climate or non-climate policy related reasons in any given scenario is determined by the scenario developer based on the underlying scenario narrative. While this is a problem in terms of making a clear distinction between intervention and non-intervention scenarios, it is at the same time an opportunity. Because many decisions are not made for reasons of climate change alone, measures implemented for reasons other than climate change can have a large impact on GHG emissions, opening up many new possibilities for mitigation (Morita *et al*., 2001).

3.1.3 Development trends and the lock-in effect of infrastructure choices

An important consideration in scenario generation is the nature of the economic development process and whether and to what extent developing countries will follow the development pathways of industrialized countries with respect to energy use and GHG emissions. The “lock-in” effects of infrastructure, technology and product design choices made by industrialized countries in the post-world war II period of low energy prices are responsible for the major recent increase in world GHG emissions. On the supply side, the share of less developed regions in the world production of highly energy intensive goods, such as steel and aluminium, has been consistently increasing. A simple mimicking by developing countries of the development paradigm established by industrialized countries could lead to an unsustainable increase of global GHG emissions (see Ch. 2). As high carbon infrastructure and technological choices develop, the so-called lock-in effects make it increasingly difficult for developing countries to shift toward low carbon development pathways (Halsnaes *et al*., 2003; Jung *et al*., 2000).

Commercial energy demand/GDP elasticities in industrialized countries have first increased in successive stages of industrialization, with acceleration during the fifties and sixties, but have sharply decreased since then, due to different factors: relative growth of services in GDP share, technical progress induced by higher oil prices and energy conservation efforts, among others.

In developing countries, as a major part of the needed infrastructure to meet development needs is still to be built, the spectrum of future options is considerably wider than in industrialized countries (e.g. on energy, see IEA, 2004). The spatial distribution of the population and economic activities is still not settled, opening the possibility of adopting urban/regional planning and industrial policies directed toward rural development and strengthening the role of small and medium sized cities, thus reducing the extent of rural exodus and the degree of demographic concentration in large cities. The large amount of natural resources available in developing countries could be tapped through the use of modern technology leading to more decentralized development patterns, as in the case with respect to the huge opportunities supplied by the prospects of biotechnology. The main issue here is the magnitude and viability to tap the potential for technological 'leapfrogging' whereby developing countries can bypass emissions-intensive intermediate technology and jump straight to cleaner technologies. There are large technical possibilities for less energy intensive development patterns in the long run leading to low carbon futures in the South compatible with national objectives (see e.g. La Rovere *et al*., 2002).

On the other hand, the barriers to a more sustainable development in the developing countries can hardly be underestimated, going from financial constraints to cultural behaviours in industrialized as in developing countries, including the lack of appropriate institution building. One of the key findings of the reviewed literature is the long-term implications for GHG emissions of short and medium-term decisions about the building of new infrastructure, particularly in developing countries (see e.g. La Rovere and Americano, 2002; IEA, 2004).

3.1.4 Economic growth and convergence

Determinants of long-term GDP per person are labour force and its productivity projections. Labour force utilization depends on factors such as working-age, structural unemployment and hours worked per worker. Demographic change is still the major determinant of the baseline labour supply (Martins and Nicoletti, 2005). Long-term projections of labour productivity primarily depend on capacity building and the advance of the technological frontier related to capital deepening.

The growth theory of the 1980s and 1990s reiterated the view that knowledge is the only means of production that is not subject to diminishing returns (Marshall, 1890; Clark, 1923). It brought about a marked change in the analysis of aggregate production functions, examining production functions that show increasing returns because of an expanding stock of human capital and as a result of specialization and investment in 'knowledge' capital (Meier, 2001; Aghion and Howitt, 1998). According to this interpretation, economic 'catch-up' and convergence strongly depend on the forces of 'technological congruence' and 'social capability' between the productivity leader and the followers (see the subsequent sub-section on institutional frameworks and Section 3.4 on the role of technological change).

The economic convergence literature has been using a standard neoclassical economic growth setup to discuss the question of future world per person income distribution and productivity levels, following the methods first used by Solow (1956). Abramovitz (1986) and Baumol (1986) found evidence of convergence between the richest countries, but not for the world as a whole. Other research efforts documented ‘conditional convergence’, meaning that countries appeared to reach their own steady states at a fairly uniform rate of two per cent per year (Barro, 1991; Mankiw *et al*, 1992). Jones (1997) found that the future steady-state distribution of per person income will be broadly similar to the 1990 distribution. Important differences would continue to arise among the bottom two-thirds of the income distribution, confirming the trend observed since the sixties. Jones’ analysis also highlighted the importance of total factor productivity (TFP) levels and convergence for the evolution of income distribution. Catch-up, and even overtaking in per person incomes, as well as changes in leaders in the world distribution of income are among some of the expected findings in this literature. However, limits to this convergence are also highlighted. Quah (1993, 1996) found that the world is moving toward a bimodal income distribution. Jones’ model results about the future steady-state distribution of per person income levels indicate additional divergence at the bottom and convergence and overtaking at the top. Countries in the upper half of the world income distribution are expected to feature additional catch-up to the United States (with several economies overtaking the US levels) while the other economies would remain close to their relative income levels (Jones, 1997). Some recent assessments demonstrate divergence, not convergence (World Bank, 2002; Halloy *et al.*, 2005; UN-SD, 2005).

Convergence is limited for a number of reasons, such as imperfect mobility of factors (notably labour); different endowments (notably human capital); market segmentation (notably services); and limited technology diffusion (different incentives). Therefore only limited catch-up can be factored in baseline (no-policy) scenarios: while capital quality is likely to push up productivity growth in most countries, especially in those lagging behind, labour quality is likely to drag down productivity growth in a number of countries, unless there are massive investments in education. However, appropriate policies may play an important role in accelerating the convergence process, creating incentives for human capital formation and the adoption of new technologies (Martins and Nicoletti, 2005). Apart from the standard neoclassical standpoint, different perspectives on the convergence issue can be obtained from economists such as Nelson and Fagerberg, who argue within an evolutionary paradigm (Fagerbeg, 1995; Fagerberg *et al.*, 2005; UNIDO, 2005). It should be acknowledged that the old theoretical controversy about steady-state economics and limits to growth still continues (Georgescu-Roegen, 1971).

The assumptions in the SRES scenarios about world income convergence were found to be consistent with historical evidence for regional income convergence in OECD regions (Barro and Sala-i-Martin, 1997; Riahi, 2005). The annual rate of income convergence between 11 world regions in the SRES scenarios falls within the range of less than 0.5 per cent in A2 scenario family to less than 2.0 per cent in A1 (both in purchasing power parity and market exchange rate metrics). In the period 1950-1990, 90 regions in Europe have shown annual rate of income convergence close to 2 per cent. Gruebler *et al.* (in press) note problems that might arise as a consequence of these comparisons of convergence at different levels of spatial aggregation. Their analysis shows that extending the above discussions to national or subnational level would suggest that income disparities are even larger than suggested by simple inter-regional comparisons and that scenarios of (relative) income convergence are highly sensitive to the spatial level of aggregation used in the analysis. What might seem a “high” relative income convergence at the level of 11 world regions is substantially smaller at the level of 185 countries. Discussion of long-term trends and scenarios of income disparities and income gap closures needs to consider both intercountry and intracountry variation in income levels. However, these are not yet reflected in the convergence and scenario literature, which to date has exclusively focused on model results on aggregate world regions and comparative national-level statistics. An important finding from the sensitivity analysis performed is that less convergence generally yields higher emissions. In B2, an income ratio (between 11 world regions, in market exchange rates) of 7 corresponds to CO_2 emissions of 14.2 GtC in 2100, while shifting this income ratio to 16 would lead to CO_2 emissions of 15.5 GtC in 2100. Results pointing to the same direction were also obtained for A2. This can be explained by slower TFP growth, slower capital turn over, and less ‘technological congruence’ leading to slower adoption of low emissions technologies in developing countries. On the other hand, as climate stabilization scenarios require global application of climate policies and convergence in adoption of low emissions technologies, they are less compatible with low economic convergence scenarios (Riahi, 2005).

3.1.5 Development pathways and GHG emissions

Over the long run, the links between economic development and GHG emissions depend not only on the rate of growth (measured in aggregate terms), but also on the nature and structure of this growth. Comparative studies aiming to explain these differences help to determine the main factors that will ultimately influence the amount of GHG emissions, given a certain overall rate of economic growth (Jung *et al.*, 2000):

- structural changes in the production system, namely the role of high or low energy-intensive industries and services: the energy intensity of industries such as steel, non ferrous metals, chemicals and pulp and paper is between four and six times the energy intensity of the other industries.
- technological patterns in sectors such as energy, transportation, building, agriculture and forestry: the treatment of technology in economic models has so far received most of the efforts and triggered the most difficult debates within the scientific community working in this field (Edmonds and Clarke, 2005; Grubb *et al.*, 2005; Shukla, 2005; Worrell, 2005. Köhler *et al.*, 2006).
- geographical distribution of activities: the geographical distribution encompasses both human settlements and urban structures in a given territory, and has a twofold impact on the evolution of land use, and on mobility needs and transportation requirements.
- consumption patterns: existing differences between countries are mainly due to inequalities in income distribution, but for a given income per person, parameters such as housing patterns, leisure styles, or the durability and rate of obsolescence of consumption goods will have a critical influence on long-run emission profiles.
- trade patterns: the degree of protectionism and the creation of regional blocks can influence the access to the best available technologies, inter alia, and constraints on financial flows can limit the capacity of developing countries to build their infrastructure.

These different relationships between development pathways and GHG emissions may or may not be captured in models used for long-term world scenarios, by changes in aggregated variables such as per person income or through more disaggregated economic parameters, e.g., the structure of expenses devoted to a given need such as heating, transport or food, or the share of energy and transportation in the production function of industrial sectors. This means that alternative configurations of these underlying factors can be combined to give internally consistent socioeconomic scenarios with identical rates of economic growth. It would be false to say that current economic models ignore these factors. They are to some extent captured by changes in economic parameters, such as the structure of household expenses devoted to heating, transportation or food; the share of each activity in the total household budget; and the share of energy and transportation costs in total costs in the industrial sector.

These parameters remain very important indeed, but the outcome in terms of GHG emissions will also depend on dynamic linkages between technology, consumption patterns, transportation and urban infrastructure, urban planning, and rural-urban distribution of population (see also Ch. 2 and 11 for a more extensive assessment of some of these issues). The lack of knowledge available about their dynamic linkages and about their interactions with economic policies over the long run must be underlined together with the intrinsic difficulty of predicting innovations and transformation of lifestyles in the long-term.

3.1.6 Institutional frameworks

Institutional frameworks are referred to as qualitative driving forces, since they are not readily measurable in quantitative terms. Institutions are the rules of the game in society, including the rules that organize markets and other mechanisms that allocate resources in society (Peet and Hartwick 1999, North 1990, 2005). Recent research has included studies on the role of institutions as a critical component in an economy's capacity to use resources optimally (Ostrom 1990; Ostrom *et al*. 2002) and interventions that alter institutional structure are among the most accepted solutions in recent times for shaping economic structure and its associated energy use and emissions. Three important aspects of institutional structure are: 1) the extent of centralization and participation in decisions; 2) the extent (spanning from local to global) and nature of decision mechanisms; and 3) processes for effective interventions (e.g., the mix of market and regulatory processes). In this regard, institutional structures vary considerably across nations even with similar levels of economic development. Although no consensus exists on the desirability of a specific type of institutional framework, experience suggests that more participative processes help to build trust and social capital to better manage the environmental 'commons' (World Bank, 1992, Beierle and Cayford, 2002; Ostrom *et al*., 2002; Rydin, 2003; NAS forthcoming). Other relevant developments may include greater use of market mechanisms and institutions to enhance global cooperation and more effectively manage global environmental issues (Keohane 1993, Ch. 12).

Recent development research has included studies on the role of institutions as a critical component in an economy's capacity to use resources optimally. Institutions are here in a broad sense being understood as the core allocation mechanism and as the structure of society that organizes markets and other institutions (Peet and Hartwick, 1999). A weak institutional structure on one hand basically explains why an economy can be in a position that is significantly below the theoretically efficient production frontier. Several economists suggest that the institutional structure can be understood as the so called 'missing link' in the production function that explains differences in economies' productive capacity (Meier, 2001). Furthermore, weak institutions also provide a basis for high transaction costs because frictions in economic exchange processes arise when institutions are weak.

The existence of weak institutions in developing countries has implications for the capacity to adapt to or mitigate climate change. A review of the social capital literature and the implications for climate change mitigation policies concludes that successful implementation of GHG emission reduction options in most cases will depend on additional measures to increase the potential market and the number of exchanges. This can involve strengthening the incentives for exchange (prices, capital markets, information efforts and the like), introduction of new actors (institutional and human capacity efforts), and reducing the risks of participating (legal framework, information, general policy context of market regulation). The measures all depend on the nature of the formal institutions, the social groups in society, and the interaction between them (Ch. 2 and Halsnæs, 2002).

Some of the climate change policy recommendations that are inspired by institutional economics include general capacity building programmes, and local enterprise and finance development for example in the form of soft loans, in addition to educational and training programmes (see Ch. 2, 12 and Halnaes *et al*., 2003).

In the presently less industrialized regions, there is a large and relatively unskilled part of the population that is not yet involved in the formal economy. In many regions industrialization leads to wage differentials that draw these people into the more productive, formal economy, in the process causing accelerated urbanization. This is why labour force growth in these regions contributes significantly to GDP-growth. The concerns relating to the informal economy are twofold: 1) whether historical development patterns and relationships among key underlying variables will hold constant in the projections period; and 2) whether there are important feedbacks between the evolution of a particular sector and the overall development pattern that would affect GHG emissions (Shukla, 2005).

Social and cultural processes influence the future in a myriad of ways. They shape institutions and how they function. Social norms of ownership and distribution have a vital influence on the structure of production and consumption. And most vitally, the social and culture processes determine the quality and extent of the so-called social 'infrastructure' sectors, such as education, which are paramount to capacity building and technological progress. Unlike institutions, social and culture processes are often more inflexible and difficult to influence. However, specific sectors like education are amenable to interventions. Barring some negative features, such as segregation for instance, there is no consensus as to the interventions that are necessary or desirable to alter social and cultural processes. On the other hand, understanding their role is crucial for assessing the evolution of the social infrastructure that underpins technological progress and human welfare (Jung *et al*., 2000) as well as evolving perceptions and social understanding of climate change risk (see Rayner and Malone, 1998; Douglas and Wildavsky, 1982; Slovic, 2000).

3.2 Baseline scenarios

3.2.1 Drivers of emissions

Trajectories of future emissions are determined by complex dynamic processes that are influenced by factors such as demographic and socio-economic development, and technological and institutional change. An often used identity to describe changes in some of these factors is based on the IPAT analysis (see Holdren, 2000; Ehrlich and Holdren, 1971) and is often called the Kaya-identity (Yamaji *et al*., 1991) which states that energy-related emissions are a function of population growth, GDP per person, changes in energy intensity, and carbon intensity of energy consumption. These factors are discussed in Section 3.2.1 to describe new information published on baseline scenarios since the TAR. There are more than 750 emission scenarios in the literature including almost 400 baseline (non-intervention) scenarios. Many of these scenarios were collected during the IPCC SRES and TAR processes (Morita & Lee, 1998a) and made available through the Internet

(Morita & Lee, 1998b). Systematic reviews of the baseline and mitigation scenarios were reported in the SRES (Nakicenovic *et al.*, 2000) and TAR (Morita *et al.*, 2001) respectively. The corresponding databases have been updated and extended recently (Nakicenovic *et al.*, 2006; Hanaoka *et al.*, 2006).[2] The recent scenario literature is discussed and compared with the earlier scenarios in this section. Land-use change as a driver of land-use related emissions is a particular focus in the section.

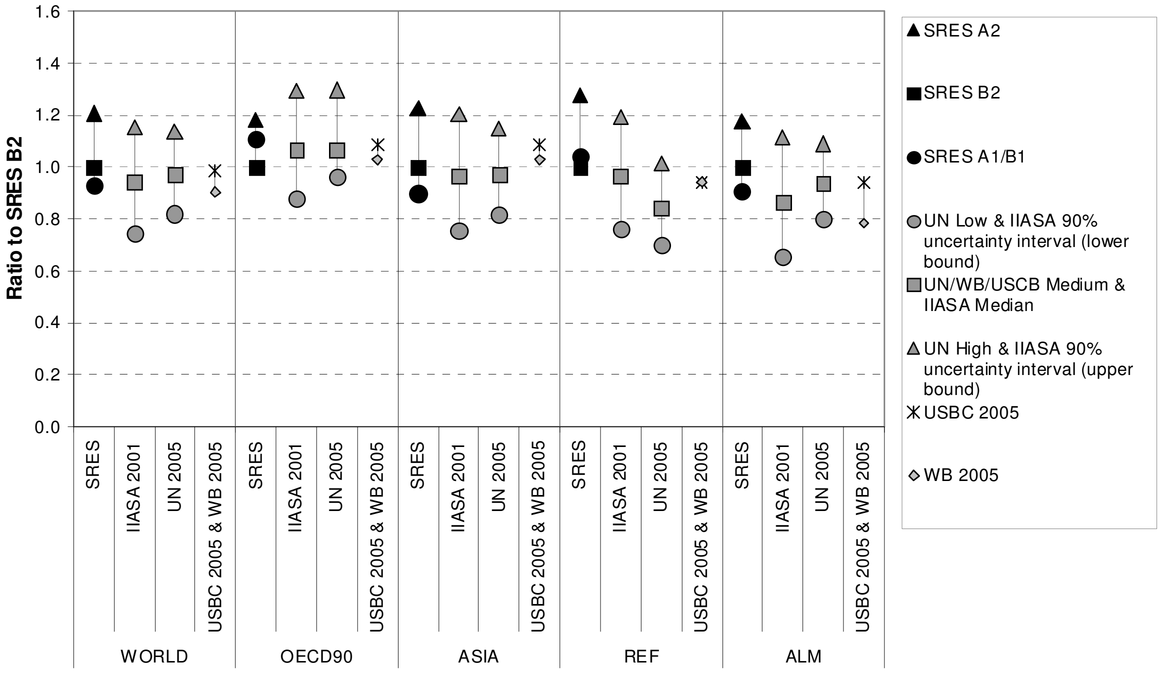
3.2.1.1 Population projections

Current population projections anticipate less global population growth than was expected at the time the Third Assessment Report (TAR) was published. Since the early 1990s demographers have revised their outlook on future population downward, based mainly on new data indicating that birth rates in many parts of the world have fallen sharply. Figure 3.2A compares the projections for 2050 used in SRES (as representative of older scenarios) to the most recent projections from major demographic institutions.

Recent projections indicate a small downward revision to the medium (or 'best guess') outlook and to the high end of the uncertainty range, and a larger downward revision to the low end of the uncertainty range (van Vuuren and O'Neill, in press). This global result is driven by changes in outlook for the Asia and the Africa-Latin America-Middle East (ALM) region. On a more detailed level, trends are driven by changes in the outlook for Sub-Saharan Africa, the Middle East and North Africa region, and the East Asia region, where recent data shows lower than expected fertility rates in these regions as well as a much more pessimistic view on the extent and duration of the HIV/AIDS crisis in sub-Saharan Africa. In contrast, in the OECD region updated projections are somewhat higher than previous estimates. This comes from changes in assumptions regarding migration in the case of the UN projections, or to a more optimistic projection of future life expectancy in the case of IIASA projections. In the Eastern Europe and Central Asia (Reforming economic, REF) region, projections have been revised downward, especially by the UN, driven mainly by recent data showing very low fertility levels and mortality that is quite high relative to other industrialized countries.

(A)

[2] It should be noted that the quality of data varies from scenario to scenario. For some scenarios the data come directly from the modelling teams. In other cases they have been assembled from the literature or from other scenario comparison exercises such as EMF 19, EMF 21, and IMCP. The scenarios published before the year 2000 were entered in the database during SRES and TAR. The data can be accessed on the following web-pages: (http://iiasa.ac.at/Research/TNT/WEB/scenario_database.html. and http://www-cger.nies.go.jp/scenario).



(B)

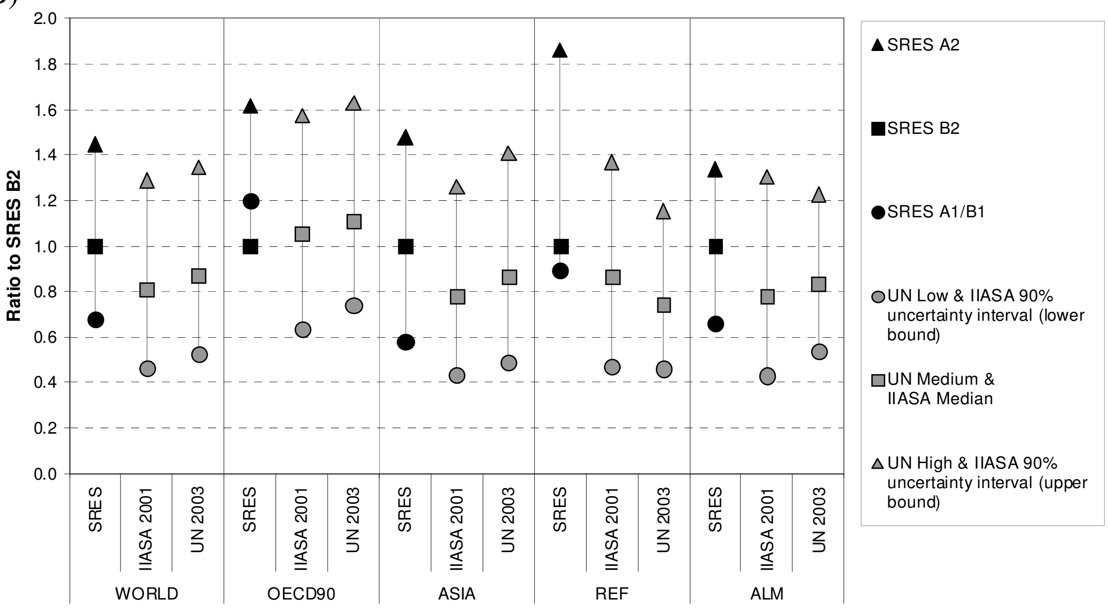


Figure 3.2: *Population size worldwide and for four SRES macro regions, relative to the population size in the SRES B2 projection for (a) 2050 and (b) 2100. Source: van Vuuren and O'Neill, in press, based on data from (Nakicenovic, 2000;Lutz et al., 2001;UN, 2003, 2005;US.BoC, 2005;WorldBank, 2005)*

IIASA (2001) and the UN (2004) are the only major demographic institutions that have produced updated projections for the world that extend to 2100. These are shown in comparison to the SRES assumptions in Figure 3.2B. Patterns are qualitatively similar to those found for 2050, but larger in magnitude. For example, the most recent central projections for global population are 1.4 to 2.0 billion (13 to 19 per cent) lower than the medium population scenario of 10.4 billion used in the SRES B2 scenarios. Similar changes are visible for the outer ends of the range. As was the case with the outlook for 2050, the long-term changes at the global level are driven by the developing country regions (Asia and ALM), with the changes particularly large in China, the Middle East and North Africa, and Sub-Saharan Africa.

Figure 3.2 compares population projections used in emissions scenarios published since TAR to those used in emissions scenarios that appeared in or before TAR. Interestingly, the range of population projections used since TAR has not changed substantially, despite the downward trend in new population projections in the demographic literature. Ninety per cent of the population scenarios in both the pre- and post-TAR distributions fall between a global population of 7 and 15 billion in 2100. In other words, most emissions scenarios in the literature have not incorporated the latest demographic literature yet. O'Neill *et al*. (2001) show that downward revisions in population projections are likely to lead to lower emissions, even when accounting for potential indirect effects on economic growth. This effect cannot be discerned in post-TAR emissions scenarios, however, because studies using new demographic projections have also updated other important drivers of emissions, obscuring the effect of demographic changes (see later in this chapter).

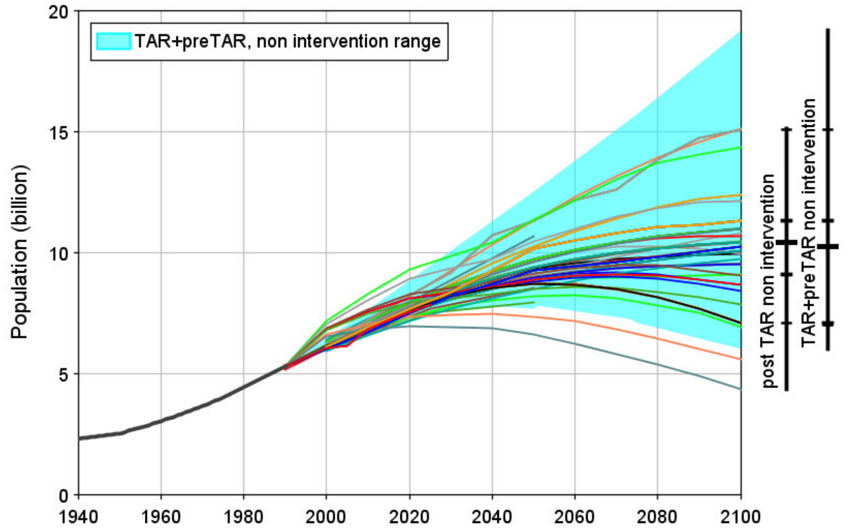


Figure 3.3: *Comparison of population assumptions in post-TAR emissions scenarios with those used in previous scenarios. Blue shaded areas spans range of 132 population scenarios used in TAR or pre-TAR emissions scenarios; individual curves show population assumptions in 85 emissions scenarios in the literature since 2001. Two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios by 2100. The horizontal bars indicate the 5th, 25th, 50th, 75th and the 95th percentiles of the distributions. Data source: Nakicenovic et al., 2006*

Although the range of projected population sizes has shifted down, this does not necessarily imply that the previous population assumptions (including SRES) are no longer useful. Most of the SRES scenarios still fall within the plausible range of population outcomes according to more recent literature (see Figure 3.3). However, the high end of the SRES population range now falls above the range of recent projections from IIASA and the UN. This is a particular problem for population projections in East Asia, the Middle East, North Africa and the Former Soviet Union, where the differences are large enough to strain credibility (van Vuuren and O'Neill, in press). In addition, the population assumptions in SRES and in more recent emissions scenarios do not cover well the low end of the current range of population projections. A small number of new population projections judged to be consistent with SRES storylines have been developed (Gruebler *et al*., in press; Fisher *et al*., in press; Hilderink, 2004).

3.2.1.2 Economic development

Economic activity is a dominant driver of energy demand and thus of emissions of greenhouse gases. Economic activities take many forms, from extraction of various raw materials, through manufacturing of physical goods, to provision and use of a broad range of services. Each of these activities requires input of energy and leads to emissions of a broad range of substances, including greenhouse gases (GHGs). In models, in analysis and certainly for reporting purposes, the activities need to be aggregated. Aggregation is generally done by converting activities into monetary units through the use of a set of observed market prices. For long-term scenarios, economic growth is usually reported in the form of growth of gross domestic product (GDP) or gross national product (GNP). To get a meaningful comparison over time of the real size of economic activities, changes in price levels must be taken into account and corrected for by reporting activities in constant prices taken from a base year. One way of reducing the effects of differences in base year employed in different studies is to report only growth rates in activity levels. Therefore, in the rest of this section the focus will be on growth rates rather than on absolute numbers.

Another difficulty arises in comparing economic data or aggregating across nations or world regions and particularly how to convert from one monetary unit to another. There are two main alternatives: using the observed market exchange rate (MER) in a fixed year, or using a purchasing power parity (PPP) index (see Box 3.1).

Box 3.1
For international comparisons, GDP data must be converted into a common unit. The conversion can be based on observed market exchange rates (MER) or purchasing power parity estimates (PPP), in which a correction is made for differences in price levels among countries. PPP is currently considered to be the better alternative if data are used for welfare or income comparisons across regions. PPP exchange rates are derived through a process of equalizing the purchasing power of different currencies by eliminating differences in price levels for various goods. Usually, market exchange rates under value the purchasing power of currencies in developing countries, see Figure 3.4.

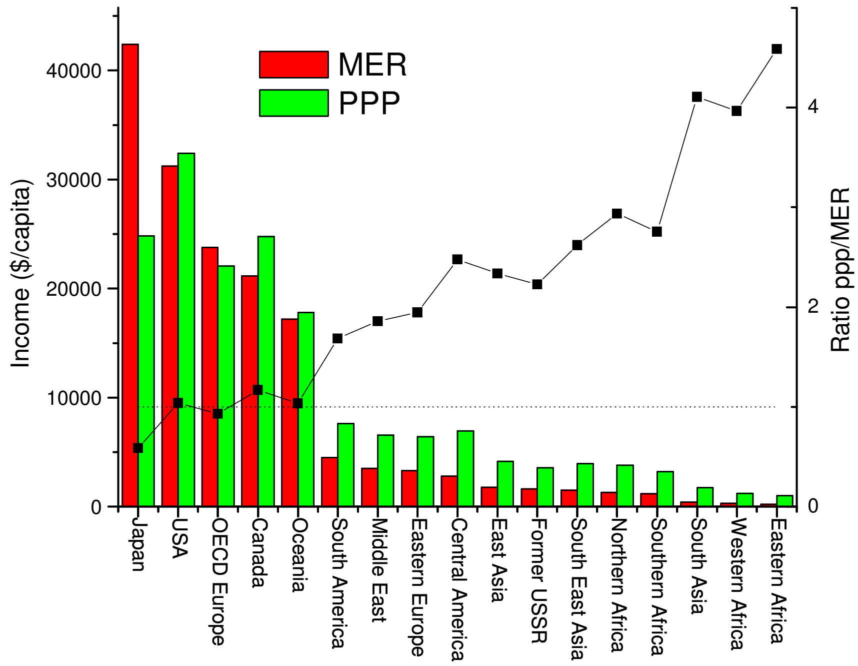


Figure 3.4: *Regional GDP per person expressed in MER and PPP on the basis of World Bank data aggregated to 17 global regions. The left y-axis and columns compare absolute data, while the right y-axis and line graph compare the ratio between PPP and MER data. Source: van Vuuren and Alfsen (2006)*

Clearly, derivation of PPP exchange rates requires analysis of a relatively large amount of data. This makes it impractical to derive PPP rates for every year. Hence, methods have been devised to derive PPP rates for new years on the basis of price indices. Unfortunately, there is currently no single method or price index favoured for doing this, resulting in different sets of PPP rates (e.g. from the OECD, Eurostat, World Bank and Penn World Tables) although the differences tend to be small. Furthermore, scenarios expressed in PPP are relatively few. This creates some practical difficulties in reporting economic scenarios based on PPP exchange rates and is one reason why economic scenario data are generally reported on the basis of MER - although for some models PPP values are also given.

GDP trajectories in the large majority of scenarios in the literature are calibrated in MER. A few dozen scenarios exist in the literature that use PPP exchange rates, but most of them are shorter-term, generally running out to 2030.

3.2.1.3 GDP growth rates in the new literature compared to SRES

Many of the long-term economic projections in the literature have been specifically developed for climate related scenario work. Figure 3.5 compares the income range of the 195 scenarios from the pre-TAR and TAR literature with the 121 new scenarios developed post-TAR. While there is a considerable overlap in the GDP numbers published, perhaps the most interesting difference is that the median of the new scenarios is about the half of the median in the pre-TAR scenario literature. The data suggest that the upper as well as the lower bounds of the range of economic growth has remained unchanged in the current projections. It should be noted, however, that this is mainly due to a small group of particularly very high growth scenarios.

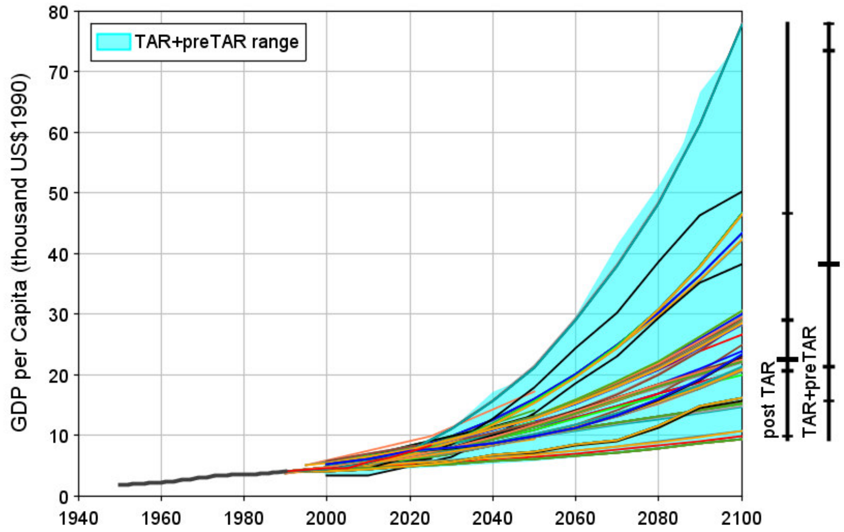


Figure 3.5: *More recent scenarios in the literature since the publication of TAR (post TAR) do not extend to the highest GDP growth rates in the TAR and pre TAR literature, but extend marginally below the lowest level. The median of the new scenarios is about the half of the median of the in the pre-SRES and TAR scenario literature. Two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios by 2100. The horizontal bars indicate the 5th, 25th, 50th, 75th and the 95th percentiles of the distributions*

A comparison of some recent short-term GDP projections and the SRES scenarios is illustrated in Figure 3.6 (see also Van Vuuren and O'Neill - in press). The SRES scenarios project a very wide range of global economic growth rates from 1.0 per cent (A2) to 3.1 per cent (A1) to 2030, both based on MER. This range is somewhat wider than the range covered by the DOE (2005) high and low scenarios (1.2 to 2.5 per cent). The central projections of DOE, IEA and the World Bank all contain growth rates of around 1.5 to 1.9 per cent, thus occurring in the middle of the range of the SRES scenarios, near the B2 trajectory. Other medium term energy scenarios are also reported to have growth rates in this range (IEA, 2004).

For the OECD and Eastern Europe and Central Asia (Reforming economic, REF) regions, the correspondence between SRES outcomes and recent scenarios is relatively good, although the SRES GDP growth rates are somewhat conservative. In the ASIA region, the SRES range and its median value are just above that in recent studies. The differences between the SRES outcomes and more recent projections are largest in the ALM region covering Africa, Latin America and the Middle East. Here, the A1 and B1 scenarios clearly lie above the upper end of the range of current projections (4 to 5 per cent), while A2 and B2 fall near the centre of the range (1.4 to 1.7 per cent). The recent short-term projections reported here expect current barriers to economic growth in these regions to slow growth, at least until 2015.

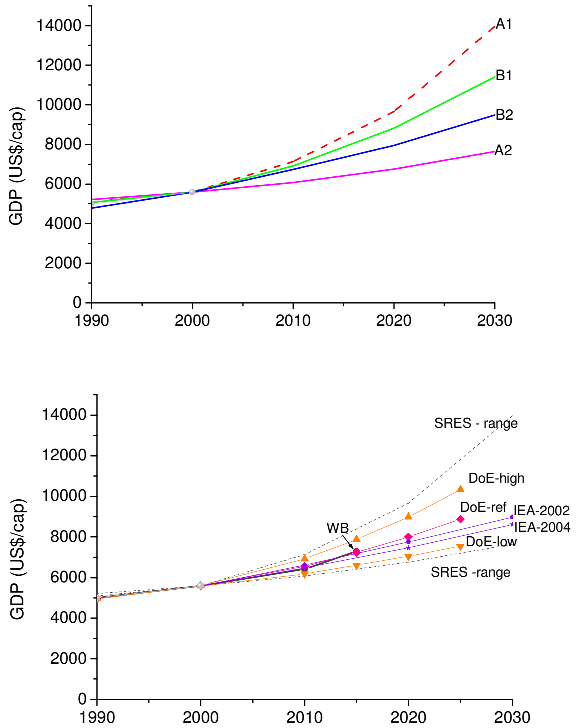


Figure 3.6: *Comparison of global GDP growth in the SRES scenarios and more recent projections. SRES = (Nakicenovic et al., 2000), WB = World Bank (WorldBank, 2004), DoE = assumptions used by US.Department of Energy (US.DoE, 2004a), IEA assumptions used by IEA (IEA, 2002;IEA, 2004)*

3.2.1.4 The use of MER in emissions scenarios modeling

Recently, the uses of MER-based economic projections in SRES have been criticized (Castles and Henderson, 2003a,b; Henderson, 2004[3]). The vast majority of scenarios published in the literature use MER based projections. Some exceptions exist such as recent scenarios with the MERGE model Manne and Richels, 2003) or shorter term scenarios going to 2030 including the G-Cubed model (McKibbin *et. al,* 2004 a,b), the IEA World Energy Outlook (WEO, 2005) and the POLES model used by the European Commission (2003a). The main criticism of the MER based models is that the GDP for world regions covered in the models are derived using market exchange rates (MER) and were not corrected with respect to purchasing power parities (PPP) in most of the model runs. The consequence is that the economic activity levels in non-OECD countries generally appear to be lower than they actually are when measured in PPP units. In addition, the high growth SRES scenarios (A1 and B1 families) assume that regions tend to conditionally converge in terms of relative per person income across regions (see Section 3.1.4). The use of MER and the assumption of conditional convergence combined leads to overstated economic growth in the poorer regions, and accordingly excessive growth in energy demand and emission levels, according to the critics. A team of SRES researchers responded to this criticism, indicating that in their view, the use of MER or PPP data does not in itself lead to different emission projections outside the range of the literature, and that the use of PPP data in most of the models was at the time and still is infeasible due to lack of existing data and projections (Nakicenovic *et al*., 2003, Grübler *et al*., 2004). Also a growing

[3] Note that the literature sources are not peer reviewed.

number other researchers have indicated their different opinions on this issue or explored it in a more quantitative sense (e.g. Nordhaus, 2006; Tol, 2006; Manne and Richels, 2003; McKibben *et al*., 2004a,b; Holtsmark and Alfsen, 2004a,b; and van Vuuren and Alfsen, 2006).

There are at least two strands to this debate. On the one hand there is the question of whether economic projections based on MER are appropriate, and thus whether the economic growth rates reported in the SRES and other MER based scenarios are reasonable and robust. On the other hand, there is the question of whether the choice of PPP is appropriate as regions develop and global trade further shrinks the importance of the informal sector while most goods and services, and in particular energy, trade shift toward MER exchange rates

On the question of whether PPP or MER should be employed in economic scenarios, the debate at the moment seems to be fully open - with both theoretic and pragmatic considerations playing a role. Nordhaus (2005) recommends, for principle and practical reasons, that economic growth scenarios should be constructed by using regional or national accounting MER based figures (including growth rates) for each region, but using PPP exchange rates for aggregating regions updated over time by use of a superlative price index. Others (e.g. van Vuuren and Alfsen, 2006) argue that the use of MER data in long-term modelling is preferable as data are available, and international trade within the models are based on MER. The real economic consequences of the choice of conversion rates will obviously depend on how the scenarios are constructed as well as on the type of model used for quantifying the scenarios. In some of the short-term scenarios (with a horizon to 2030) a bottom up approach is taken where assumptions about productivity growth and investment/saving decisions are the main drivers of growth in the models (e.g. McKibbin *et. al*, 2004a,b). In long-term scenario models, a top down approach is more commonly used where the actual growth rates are more directly prescribed based on convergence or other assumptions about long-term growth potential.

When it comes to emission projections, it is not as likely that the choice of exchange rate will have a substantial effect. The reason is that the choice of metric for economic activity also clearly will influence the numerical values of the emission coefficients. If a consistent set of metrics is employed, it is difficult to see why the choice of metric should affect the final emission level substantially, unless the share of the non-tradable sector of the economy is very different in PPP based scenarios compared to MER based scenarios.

Manne and Richels (2003) and McKibben *et al*. (2004a,b) in their modelling work find some differences in emission levels between using PPP and MER based estimates, as a result of counteracting influences in their models. Detailed analysis of their work shows that these results critically depend on, among other things, the combination of convergence assumptions and Grübler (2006). Holtsmark and Alfsen (2004a,b) showed that in their simple model consistent replacement of the metric (PPP for MER) - for income levels as well as for underlying technology relationships - leads to a full cancellation of the impact of choice of metric on projected emission levels. While using PPP values might give rise to lower economic growth rates for developing countries under the convergence assumption - it will also have an impact on the relationship between income and demand for energy with lower economic growth leading to slower improvements in energy intensities. On the basis of these studies, it seems likely that using PPP based values instead of MER based values in scenarios with similar basic driving forces would only mildly change results in terms of physical parameters, such as energy use or greenhouse gas emissions measured in physical units.

The debate clearly shows the need for modelers to be more transparent in explaining conversion factors as well as taking care in determining exogenous factors used for their economic and emission scenarios.

3.2.1.5 Energy use

Future evolution of energy systems is a fundamental determinant of GHG emissions. Energy demand growth is in most of the models a function of driving forces such as demography and the level and nature of human activities such as mobility, information processing and manufacturing. In addition, the type of energy consumed is also important. While Chapters 4 through 11 report on medium terms projection for different parts of the energy system, long-term energy projections published since TAR are reported here. Figure 3.7 compares the range of the 196 pre-SRES scenarios with 342 new, post-SRES, long-term energy scenarios in the literature. The ranges are comparable, with very small changes on the lower and upper bounds. It is interesting to note that the median is now somewhat lower. In general, the energy growth observed in the newer scenarios does not deviate significantly from the previous ranges as reported in the SRES report. However, most of the scenarios reported here have not adapted the lower population levels discussed in 3.2.1.1.

In general, the same situation exist for underlying trends as represented by change in energy intensity (GJ/$) and change in the carbon factor of the energy system (CO_2/GJ) as shown in Figure 3.11. In all scenarios, energy intensity improves significantly across the century - with a mean annual intensity improvement of 1.1 per cent. The 90 per cent range of the annual average intensity improvement is between 0.5 and 1.9 per cent (which is fairly consistent with historic variation in this factor). This range in fact implies a difference in total energy consumption in 2100 of a factor 183 per cent - indicating the importance of the uncertainty associated with this factor. The carbon factor is more constant in scenarios without climate policy. The mean annual improvement rate is 0.4 per cent, while the uncertainty range is again relatively large (-0.1 to 1.7 per cent). On the high end of this range scenarios are found that assume that energy technologies without CO_2 emissions become competitive without climate policy as a result of increasing fossil fuel prices and rapid technology progress for carbon free technologies. Scenarios with a low carbon factor improvement coincide with scenarios with a large fossil fuel base, less resistance to coal consumption or lower technology development rates for fossil free energy technologies. Although not shown here, several scenario studies report that compared to previous projection coal has been assigned larger market shares as a result as revised estimates of oil and gas reserves.

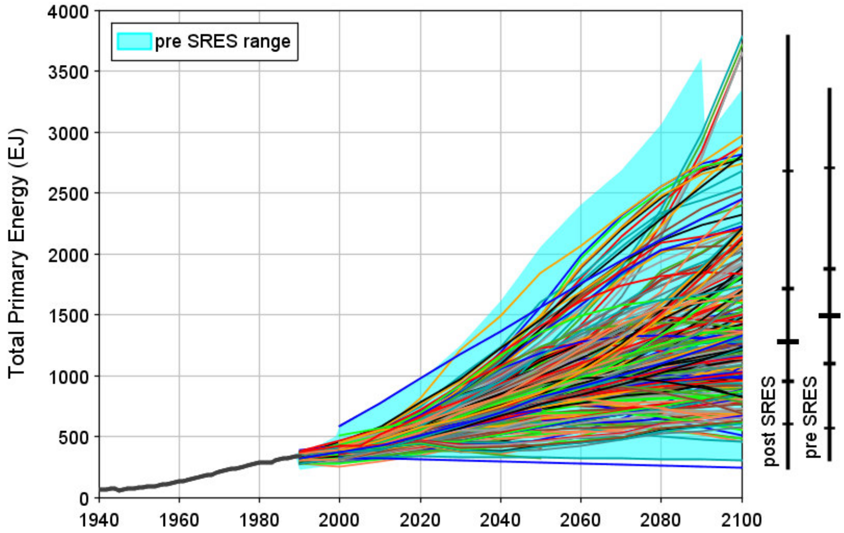


Figure 3.7: *Comparison of 196 pre-SRES energy scenarios in the literature compared with the 342 more recent, post-SRES scenarios. The ranges are comparable, with very small changes on the lower and upper bounds. Two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios by 2100. The horizontal bars indicate the 5th, 25th, 50th, 75th and the 95th percentiles of the distributions*

3.2.1.6 Land use change and land use management

Understanding land-use and land cover changes is crucial to understanding climate change. Even if land activities are not considered as subject to mitigation policy, the impact of land use change on emissions, sequestration, and albedo plays an important role in radiative forcing. Figure 3.8 portrays these relationships.

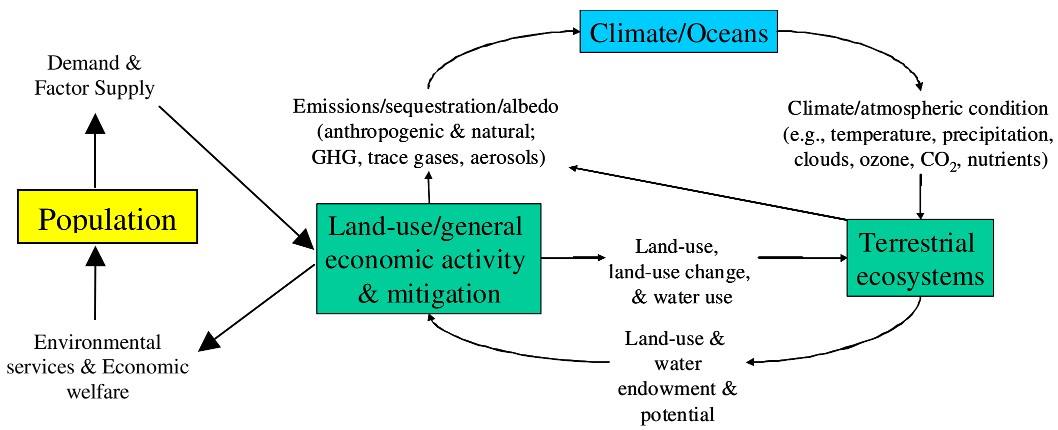


Figure 3.8: *Land in long term climate modeling*

Over the past several centuries, human intervention has markedly changed land surface characteristics, in particular through large scale land conversion for cultivation (Vitousek *et al*., 1997). Land cover changes have an impact on atmospheric composition and climate via two mechanisms: biogeophysical and biogeochemical. Biogeophysical mechanisms include the effects of changes in surface roughness, transpiration, and albedo that over the past millennium are thought to have had a global cooling effect (Brovkin *et al*., 1999). Biogeochemical effects result from direct emissions of CO_2 into the atmosphere from deforestation. Cumulative emissions from historical land cover conversion for the period 1920–1992 have been estimated to be between 56.2 and 90.8 Pg C (McGuire *et al*., 2001), and as much as 156 Pg C for the entire industrial period 1850–2000, roughly a third of total anthropogenic carbon emissions over this period (Houghton, 2003). In addition, land management activities (e.g., cropland fertilization and water management, manure management and forest rotation lengths) also affect land based emissions of CO_2 and non-CO_2 GHGs, where agricultural land management activities are responsible for approximately 52 per cent of global atmospheric inputs of methane (CH_4) and agricultural soils are responsible for 84 per cent of global nitrous oxide emissions (N_20), for a net contribution from non-CO_2 GHGs of approximately 14 per cent of all anthropogenic greenhouse gas emissions (USEPA, 2006a).

Until recently, projected changes in land use were not explicitly represented in carbon cycle studies. The first studies of the effects of future land use changes on the global carbon cycle employed trend extrapolations (Cramer *et al*., 2004), extreme assumptions about future land use (House *et al*., 2002), or derived trends of land use change from the SRES story lines (Levy *et al*., 2004). However, recent studies have shown that land use (e.g., Gitz and Ciais, 2004) and feedbacks in the society-biosphere-atmosphere system (e.g., Strengers *et al*., 2004) must be considered for realistic estimates of the future development of the carbon cycle; thereby motivating the explicit modelling of land use drivers in integrated assessment frameworks.

In general, land use drivers influence either the demand for land based products and services (e.g., food, timber, bio-energy crops, and ecosystem services) or land use production possibilities and opportunity costs (e.g., yield improving technologies, temperature and precipitation changes, and CO_2 fertilization). Non-market values — both use and non-use such as environmental services and species existence values respectively — will also shape land use outcomes.

Food demand is a dominant land use driver, and population growth and economic growth are the most significant food demand drivers through per person consumption. Total world food consumption (kcal) is expected to increase by greater than 50 per cent by 2030 (Bruinsma, 2003). Moreover, economic growth is expected to generate significant structural change in consumption patterns, with diets shifting to include more livestock products and fewer staples such as roots and tubers. As a result, per person meat consumption is expected to show a strong global increase, on the order of 25 per cent by 2030, with faster growth in developing and transitional countries of more than 40 and 30 per cent, respectively (Bruinsma, 2003; Cassman *et al*., 2003). The Millennium Ecosystem Assessment (MA) scenarios projected that global average meat consumption would increase from 36 kg/person in 1997 to 41 – 70 kg/person by 2050, with corresponding increases in overall food and livestock feed demands (Millennium Ecosystem Assessment, 2005). Additional cropland is expected to be required to support these projected increases in demand. Beyond 2050, food demands are expected to level off with population.

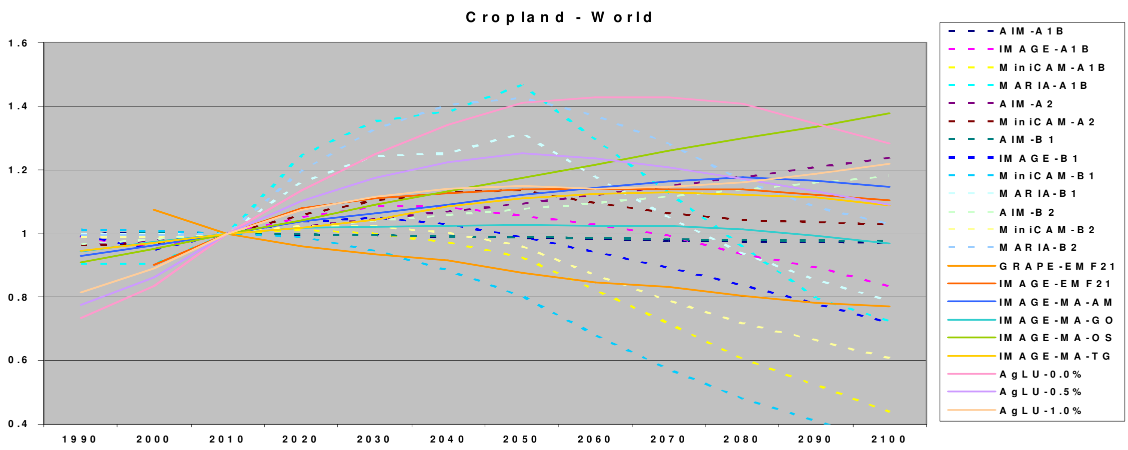
Technological change is also a critical driver of land use, and a critical assumption in land use projections. For example, Sands and Leimbach (2003) suggest that globally 800 million hectares of cropland expansion could be avoided with a 1.0 per cent annual growth in crop yields. Alternatively, the MA scenarios implement a more complex representation of yield growth projections that, in addition to autonomous technological change, reflect the changes in production practices, public investment, technology transfer, environmental degradation, and climate change. The net effect is positive but declining productivity growth over time for some commodities due in large part to diminishing marginal technical productivity gains and environmental degradation. In both studies, increasing (decreasing) net productivity per hectare results in reduced (increased) cropland demand.

In general, technological change assumptions in long term land use projections are not readily available. As an important driver, in the future more emphasis needs to be placed on transparency and understanding of technological change assumptions.

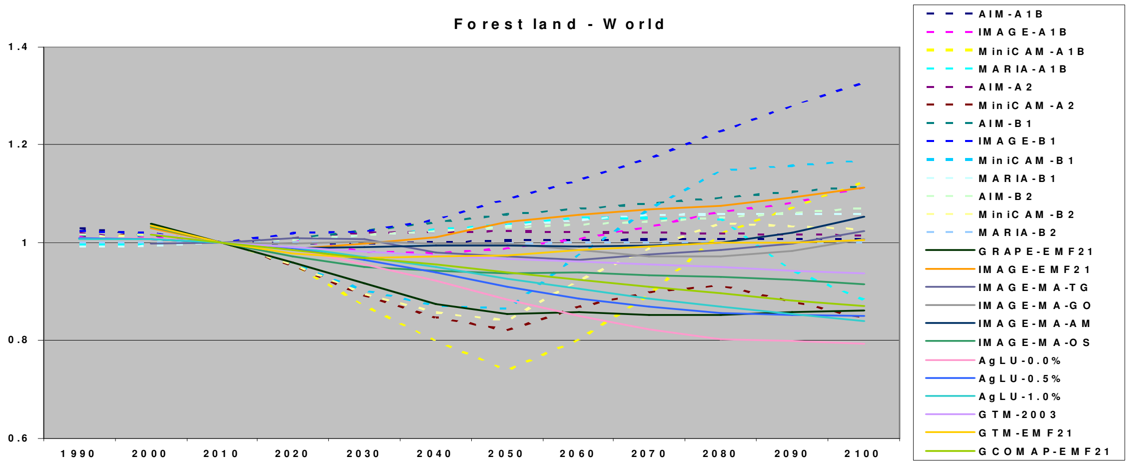
Also important to land use projections are potential changes in climate. For instance, rising temperatures and CO_2 fertilization may improve regional crop yields in the near term, thereby reducing pressure for additional cropland and resulting in increased afforestation. However, modeling the beneficial impacts of CO_2 fertilization is not as straightforward as once thought. Recent results suggest: lower crop productivity improvements in the field than shown previously with lab results (e.g., Ainsworth and Long, 2005); likely increases in tropospheric ozone and smog associated with higher temperatures that will depress plant growth and partially offset CO_2 fertilization; expected increases in the variability of annual yields; CO_2 effects favouring C3 over C4 crops while temperature increases favour C4 over C3 crops; potential decreased nutritional content in plants subjected to CO_2 fertilization and increased frequency of temperature extremes; and increases in forest disturbance frequency and intensity (in general, see WGII report, Chapter 5). Long term projections need to consider these issues as well as examine the potential limitations or saturation points of plant responses. However, to date, long term scenarios from integrated assessment models are only just beginning to represent climate feedbacks on terrestrial ecosystems, much less fully account for the many effects. Transparency in future implementations will be important.

Only a few global studies have focused on long term (century) land use projections. The most comprehensive studies, in terms of sector and land type coverage, are SRES (Nakicenovic *et al*., 2000), the SRES implementation with the IMAGE model (Strengers *et al*., 2004), the scenarios from the Global Scenarios Group (Raskin *et al*., 2002), UNEP's Global Environment Outlook (UNEP, 2002), the Millennium Ecosystem Assessment (2005), and some of the EMF-21 Study models (Kurosawa, in press; van Vuuren *et al*., in press-a; Rao and Riahi, in press; Jakeman and Fisher, in press; Riahi *et al*., in press; van Vuuren *et al*., in press-b). Recent sector specific economic studies have also contributed global land use projections for climate analysis, especially for forestry (Sands and Leimbach, 2003; Sohngen and Mendelsohn, 2003; Sohngen and Mendelsohn, in press; Sathaye *et al*., in press; Sohngen and Sedjo, in press). In general, the post SRES scenarios have projected increasing global cropland area, smaller forest land area, and mixed results for changes in global grassland (Figure 3.9). Unlike the SRES land use scenarios that span a broader range while representing diverse storylines, the post-SRES scenarios from improved modelling illustrate greater convergence across models on projected land use change.

(A)



(B)



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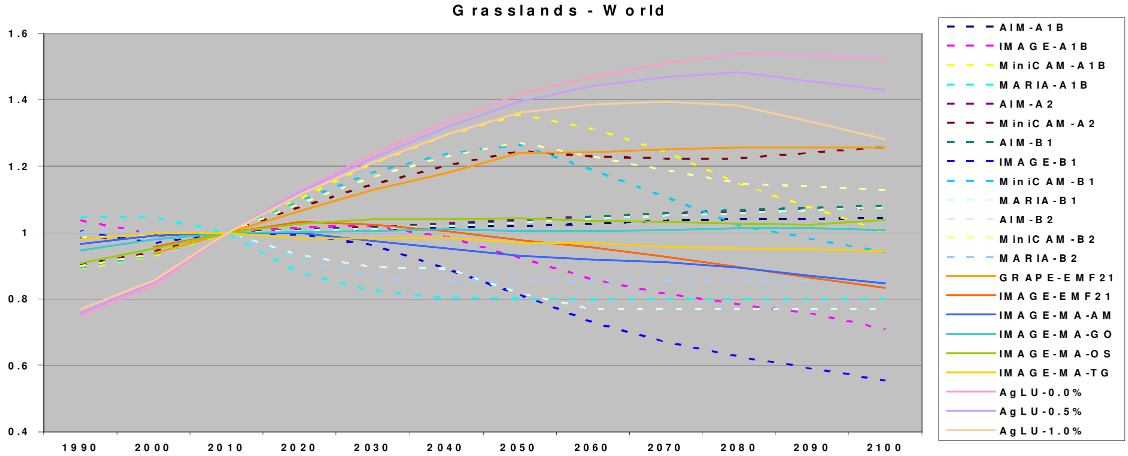


Notes:
IMAGE-EMF21 = van Vuuren *et al.* (in press-a) scenario from EMF-21 Study; IMAGE-MA-xx = Millennium Ecosystem Assessment (2005) scenarios from the IMAGE model for four storylines (GO = Global Orchestration, OS = Order from Strength, AM = Adaptive Mosaic, TG = TechnoGarden); AgLU-x.x% = Sands and Leimbach (2003) scenarios with x.x% annual growth in crop yield; GTM-2003 = Sohngen and Mendelsohn (2003) global forest scenario; GTM-EMF21 = Sohngen and Sedjo (in press) global forest scenario from EMF-21 Study; GCOMAP-EMF21 = Sathaye *et al.* (in press) global forest scenario from EMF-21 Study; GRAPE-EMF21 = Kurosawa (in press) scenario from EMF-21 Study

Figure 3.9: *Global cropland (a), forest land (b) and grassland (c) projections (2010 = 1; SRES scenarios denoted with dashed lines, post-SRES scenarios denoted with solid lines)*

Most post-SRES global scenarios project significant changes in agricultural land caused primarily by changes in food demand and the structure of supply as moderated by international trade. Scenarios with larger amounts of land used for agriculture result from assumptions about higher population growth rates, higher food demands, and lower rates of technological improvement that generate negligible increases in crop yields. Combined, these effects are projected to lead to a sizeable expansion (up to 40 per cent) of agricultural land between 1995 and 2100 (Figure 3.9). Conversely, lower population growth and food demand, and more rapid technological change, are projected to result in lower demand for agricultural land (as much as 20 per cent less global agricultural acreage by the end of the century). In the near-term, all scenarios suggest an increase in agricultural acreage to meet projected increases in food demands over the next few decades. The global forest scenarios largely mirror the agricultural scenarios; thereby, illustrating both the positive and negative aspects of some existing global land modelling. Most of the long-term scenarios assume that forest trends are driven almost exclusively by cropland expansion or contraction, and only deal superficially with driving forces such as global trade in agricultural and forest products and conservation demands. However, global integrated assessment and computable general equilibrium scenario models in general are beginning to more directly and realistically model the competing driving forces of land use/cover change.

Without incentives or technological innovation, biomass crops are currently not projected to assume a large share of global business as usual land cover - no more than about 4 per cent by 2100. However, this conclusion is based on lower oil prices than observed in 2006.

3.2.2 Emissions

The span of CO_2 emissions across baseline scenarios in the literature is still large, with 2100 emissions ranging from 2.7 to around 36 GtC. The possible interpretations of this large range for future emissions in scenarios are many. The most important is that the uncertainty as to how the main driving forces, such as population growth, economic development, and energy production, conversion and end use, might unfold during the century as shown above. The most significant change in the range of emissions is that the highest scenarios of more than 40 GtC are no longer represented in the newer literature. Total emissions of 40 GtC corresponds to approximately the 95th percentile of the scenarios published before TAR.

3.2.2.1 CO_2 emissions from energy and industry

This category of emissions encompasses CO_2 emissions from burning fossil fuels, and industrial emissions from cement production and sometimes feedstocks[4]. Figure 3.10 compares the range of the pre-TAR and TAR baseline scenarios with the post-TAR baseline scenarios. The figure shows that the scenario range has remained almost the same since the TAR. There seems to have been an upward shift on the high end, but careful consideration of the data shows that this is caused by only 4 scenarios and the change is therefore not significant. The majority of scenarios, both pre- and post-TAR indicate an increase of emissions across most of the century, resulting in a range of 2100 emissions of 10 to 21 GtC CO_2 emissions from energy and industry. Also the range of emissions depicted by the SRES scenarios is consistent with the range of other emission scenarios reported in the literature; both in the short and long-term (see Van Vuuren and O'Neill, in press).

[4] It should be noted, however, that there sometimes are large ambiguities on what is actually included in emissions scenarios reported in the literature. Some of the CO_2 emissions paths included in the ranges may therefore also include non-energy emissions such as those form land-use changes. However, since non-energy-related emissions are low compared to energy-related ones, their impact on the results of the scenario comparisons is nevertheless expected to be negligible.

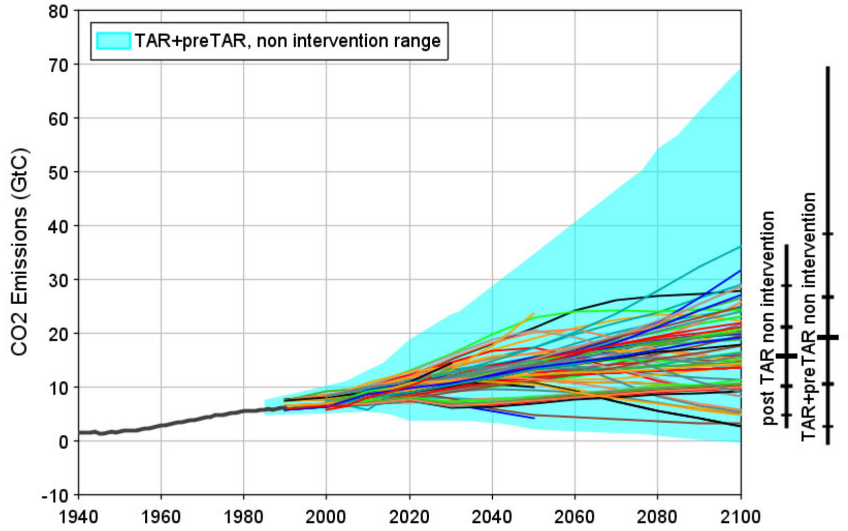


Figure 3.10: *Comparison of the TAR and pre-TAR energy-related and industrial CO_2 emissions scenarios in the literature with the post-TAR, scenarios. Two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios by 2100 (Nakicenovic et al. 2006)*

Several reasons may contribute to the fact that emissions have not declined in spite of somewhat lower projections for population and GDP. An important one is that the lower demographic projections are only recently being integrated into emission scenario literature. Second, indirect impacts in the models are likely to offset part of the direct impacts. For instance, lower energy demand leads to lower fossil fuel depletion, thus allowing for a higher share of fossil fuels in the total energy mix over a longer period of time. Finally, in recent years there has been increasing attention to the interpretation of fossil fuel reserves reported in the literature. Some models may have decreased oil and gas use in this context, leading to higher coal use (and thus higher emissions).

Analysis of scenario literature using the Kaya identity, shows that almost all baseline scenarios indicate a continuous decline of the primary energy intensity (E/GDP), while the change in the carbon factor (C/E) is much slower - or even stable (see Figure 3.11 and section 3.2.1.3). In other words, in the absence of climate policy, structural change and energy efficiency improvement do contribute to lower emissions, but changes in the energy mix have a much smaller (or even zero) contribution. This conclusion is true for both the pre- and post-TAR scenario literature. One change seems to have happened, which is that the low range of carbon factor scenarios (thus those with a very rapid decline of this factor) is not present in the current literature.

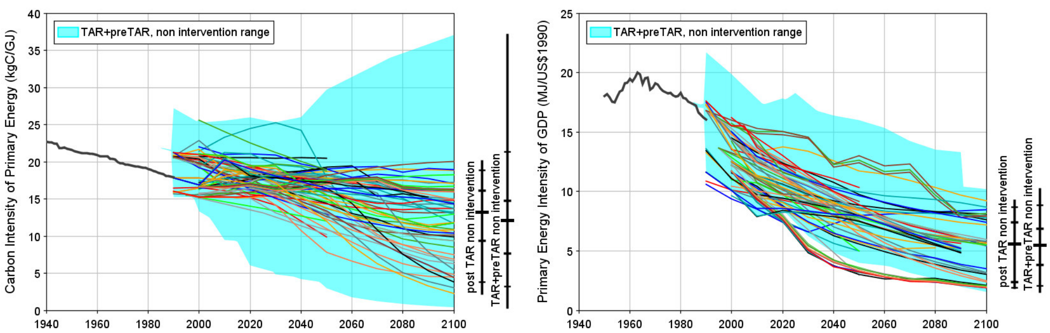


Figure 3.11: *Development of carbon intensity of energy (left) and primary energy intensity of GDP (right). Historical development and projections reported for and after the Third Assessment Report. The blue colored range illustrates the range of 193 carbon intensity and 152 energy intensity - pre 2001 non-intervention scenarios. Source: Nakićenović et al. 2006*

Baseline or reference emissions projections generally come from 3 types of studies: 1) studies meant to represent a 'best-guess' of what might happen if present days trends and behaviour continues; 2) studies with multiple baseline scenarios under comprehensively different assumptions (storylines); and 3) studies based on a probabilistic approach. In literature since TAR, some discussion of the purpose of these approaches has occurred (see Schneider, 2001; Grübler *et al.*, 2002 and Webster *et al.*, 2002). In Figure 3.10 (left panel) a comparison of the outcomes of some prominent examples of these approaches is made by comparing the outcome of baselines scenarios reported in the set of EMF-21 scenarios, representing the "best-guess" approach, to the outcomes of the SRES scenarios, representing the storyline approach. In the right panel the SRES range is compared to the probabilistic approach (see Webster *et al.*, 2002; Richels *et al.*, 2004 for the probability studies).

The figure shows that the (unintentional) uncertainty range drawn up by the range of different models participating in the EMF-21 study is somewhat smaller than those of the second two categories. Uncertainty here mainly originates from different modelling approaches and from modeller's insights into 'the mostly likely values' for driving forces. The two probabilistic studies and SRES explicitly assume more radical developments, but the number of studies involved is smaller. This leads to the low end of scenarios for the second category with very specific assumptions on development that may lead to low greenhouse gas emissions. The range of scenarios in the probabilistic studies tends to be between these extremes. Overall, the three different approaches seem to lead to consistent results, confirming the range of emissions reported in Figure 3.12 and confirming the emission range of scenarios used for TAR.

In conclusion, when surveying the emission scenario literature since the last IPCC assessment, the range reported there, by and large, is still representative of the available literature. However, by most measures the range of the newer scenarios is somewhat narrower; they tend to be characterised by lower population projections than A1 and A2 from the SRES scenarios, lower developing country economic growth rates than B1, and lower carbon and/or energy intensities.

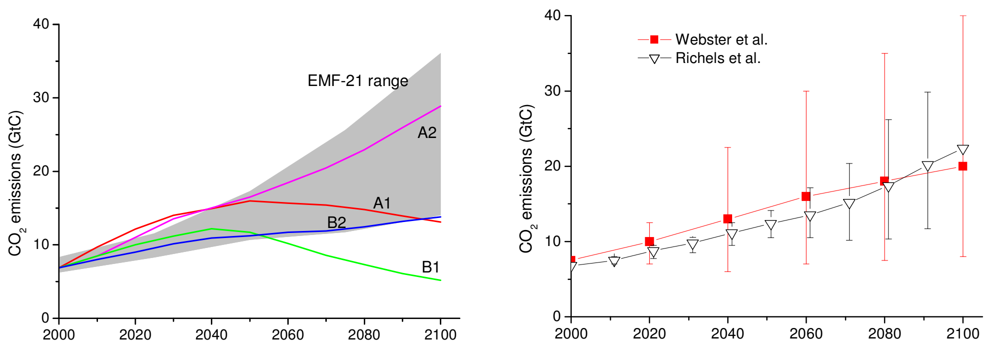
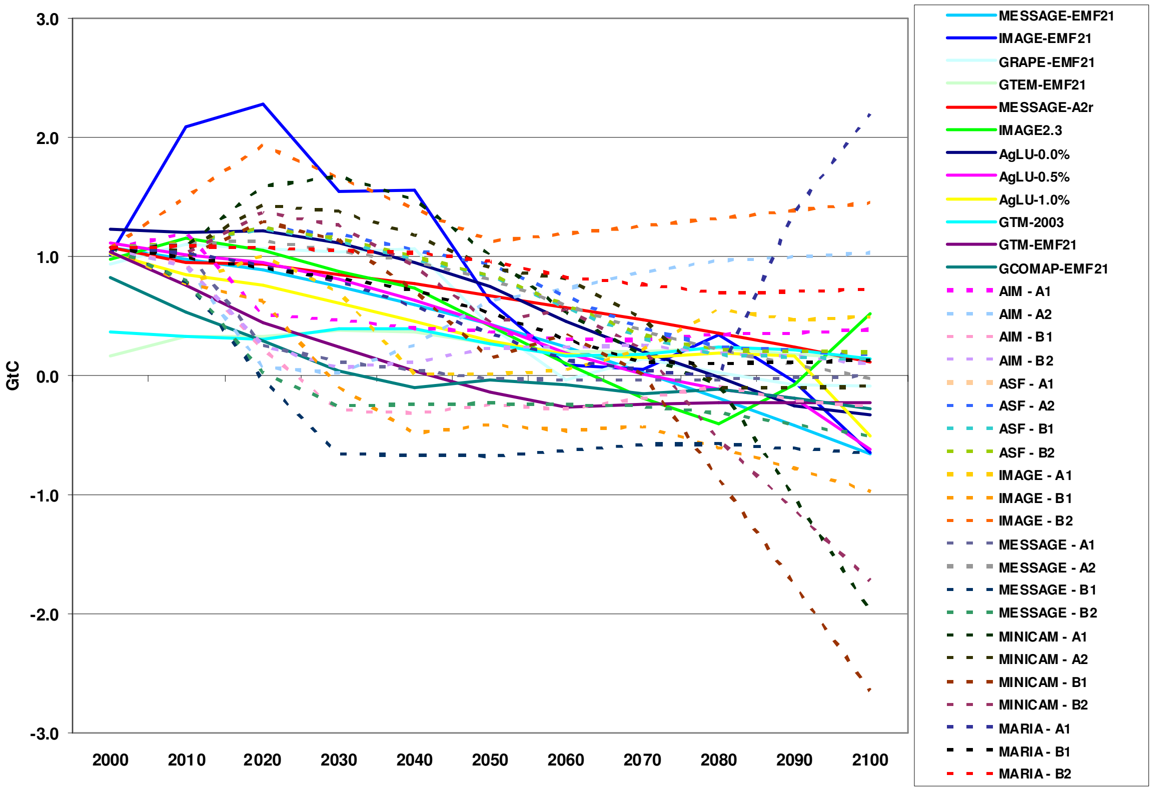


Figure 3.12: *Comparison of different long-term scenario studies for CO_2 emissions: IPCC SRES, 'EMF-21 range' (grey area) indicating the range of the lowest and highest reported values in the EMF-21 study (Weyant et al., 2006). Webster et al. (2002) and Richels et al. (2004) indicating the mean (markers) and 95% intervals of the reported ranges of these studies (for the latter, the 95% interval of the combined range for optimistic and pessimistic technology is shown)*

3.2.2.2 Anthropogenic land emissions and sequestration

Some of the first global integrated assessment scenario analyses to account for land use related emissions were the IS92 scenario set (Legett *et al*., 1992) and the SRES scenarios (Nakicenovic *et al*., 2000). However, out of the six SRES models, only four dealt with land use specifically (MiniCAM: Edmonds *et al*., 1996; MARIA: Mori and Takahashi, 1999; IMAGE 2.1: Alcamo *et al*., 1998; and AIM: Kainuma *et al*., 2003), of which MiniCAM and MARIA used more simplified land use modules. ASF (Lashof and Tirpak, 1990) also simulated land use emissions, however without a specific land use module. MESSAGE incorporated land use results from the AIM model to derive land use emissions (IPCC, 2000). Although SRES was a seminal contribution to scenario development, the treatment of land use emissions was not the focus of this assessment; and, therefore, neither was the modelling of land use drivers, land management alternatives, and the many emissions sources, sinks, and GHGs associated with land.

While some recent assessments, like the Third Global Environment Outlook of UNEP (UNEP, 2002) and the Millennium Ecosystem Assessment (MA, 2005), have evaluated land based environmental outcomes (global environment and ecosystem goods and services respectively), the Energy Modelling Forum's 21st Study (EMF-21) was the first large scale exercise with a special focus on land as a climate issue. In EMF-21, the integrated assessment models incorporated non-CO_2 greenhouse gases, like those from agriculture, and carbon sequestration in managed terrestrial ecosystems (Kurosawa, in press; van Vuuren *et al*., in press-a; Rao and Riahi, in press; Jakeman and Fisher, in press). A few additional papers have subsequently improved upon their EMF-21 work (Riahi *et al*., in press; van Vuuren *et al*., in press-b). In general, the land use change carbon emissions scenarios since SRES project high global annual net releases of carbon in the near future that decline over time, leading to net sequestration by the end of the century in some scenarios (see Figure 3.13). The clustering of the non-harmonized post-SRES scenarios in Figure 3.13 suggests a degree of expert agreement that the decline in annual land use change carbon emissions over time will be less dramatic (slower) than suggested by many of the SRES scenarios. Many of the post-SRES scenarios project a decrease in net deforestation pressure over time as population growth slows and crop and livestock productivity increase; and, despite continued projected loss of forest area in some scenarios (Figure 3.9), carbon uptake from afforestation and reforestation could result in net sequestration.



Notes:
1) MESSAGE-EMF21 = Rao and Riahi (in press) scenario from EMF-21 Study; GTEM-EMF21 = Jakeman and Fisher (in press) scenario from EMF-21 Study; MESSAGE-A2r = Riahi *et al*. (forthcomingin press) scenario with revised SRES-A2 baseline; IMAGE 2.3 = van Vuuren *et al*. (forthcomingin press-b2006) scenario; see Figure 3.9 notes for additional scenario references
The IMAGE 2.3 emissions include N_2O and CH4 carbon equivalent emissions.

Figure 3.13: *Baseline land-use change and forestry carbon emissions (solid lines denote post-SRES scenarios, dashed lines denote SRES scenarios)*

There also seems to be a consensus in recent non-CO_2 GHG emissions baseline scenarios that CH_4 and N_2O emissions will increase until the end of this century, potentially doubling in some baselines (see Table 3.1; Kurosawa, in press; van Vuuren *et al*., in press-a; Rao and Riahi, in press; Jakeman and Fisher, in press; Riahi *et al*., in press; van Vuuren *et al*., in press-b).

Table 3.1: *Baseline global agricultural non-CO_2 greenhouse gas emissions from various long-term stabilization scenarios (GtCeq)*

Scenario	Agricultural emissions sources represented	CH4					N2O				
		2000	2020	2050	2070	2100	2000	2020	2050	2070	2100
GTEM-EMF21	Fossil fuel combustion, livestock and fertiliser, paddy rice	0.1699	0.2346	0.3484			0.1386	0.1844	0.2588		
MESSAGE-EMF21	Enteric, manure, paddy rice, soil n2o	0.7023	0.9339	1.6511	1.6368	1.3787	0.7009	0.9495	1.2684	1.0328	0.6320
IMAGE-EMF21	Soil processes, paddy rice, fertilizer use, livestock, manure and biomass & agricultural waste burning	1.3160	1.7630	1.9930	2.0490	2.0450	0.6020	0.8080	0.9090	0.9430	0.9530
GRAPE-EMF21	Enteric, manure, paddy rice, fertlized soils, biomass combustion	0.7068	0.7236	0.7782	0.7693	0.7540	0.7596	0.9033	1.0465	1.0714	1.1073
MESSAGE-A2r	Enteric, manure, paddy rice, soil n2o	0.7027	0.9348	1.3032	1.5057	1.7927	0.7009	0.9495	1.1906	1.3015	1.4248
IMAGE 2.3	Soil processes, paddy rice, fertilizer use, livestock, manure and biomass & agricultural waste burning	0.8470	1.0153	1.1417	1.1965	1.2252	0.5484	0.6706	0.7922	0.8361	0.8379

Notes: SAR GWPs used to compute carbon equivalent emissions. The GTEM-EMF21 scenario goes to 2050.

As noted in Section 3.2.1.4, climate change feedbacks could have significant influence on long-term land use and, to date, are not fully represented in long-term modelling of land scenarios. Similarly, climate feedbacks can also affect land-based emissions. For instance, rising temperatures and CO_2 fertilization can influence the amount of carbon that can be sequestered by land and may also lead to increased afforestation due to higher crop yields. Climate feedbacks in the carbon cycle could be extremely important. For instance, Leemans *et al*. (2002) showed that CO_2 fertilization and soil respiration could be as important as the socio-economic drivers in determining the land use emissions range.

In addition, new insights suggest that there may be other potentially important climate feedbacks in the carbon-climate system currently not accounted for in integrated assessment scenarios that may naturally reduce terrestrial carbon sequestration-soil drying and forest dieback (Cox *et al*., 2000). However, these studies, as well as studies that try to capture changes in climate due to land use change (Sitch *et al*., 2005) have thus far not been able to provide definitive guidance. A modelling system that integrates land use change scenarios in a fully coupled dynamic climate-carbon system is required in the future for such an assessment.

3.2.2.3 Non-CO_2 greenhouse gas emissions

The emissions scenario chapter in TAR (Morita *et al*., 2001) recommended that future research should include greenhouse gases (GHGs) other than CO_2 into new scenarios work. The reason was that at that time, certainly regarding mitigation, most of the scenarios literature was still primarily focused on CO_2 emissions. Nevertheless, some multigas scenario work existed, including the SRES baseline scenarios, but also some other modeling efforts (Manne and Richels 2000, Babiker *et al*. 2001, Tol 1999). The most important other GHGs or non-CO_2 gases include: methane (CH_4), nitrous oxide (N_2O), and a group of fluorinated compounds (HFCs, PFCs, and SF_6). Since the TAR, the number of modeling groups producing long-term emission scenario of non-CO_2 gases has dramatically increased. As a result the quantity and quality of non-CO_2 emissions scenarios has improve appreciably.

Unlike CO_2 where the main emissions related sectors are few, i.e., energy, industry, and land use, non-CO_2 emissions originate from a larger and more diverse set of economic sectors. See Table 3.2 for a list of major GHG emitting sectors and their corresponding emissions estimated for 2000. To make the non-CO_2 emissions comparable to those of CO_2, the common practice is to compare and aggregate emissions by using global warming potentials (GWPs).

Table 3.2: *Global GHG Emissions for 2000 (MtCe)*

Sectors	Sub-sectors	CO2	Methane	N2O	F-gases
	Coal	2,218	123		
ENERGY	Nat Gas	1,309	244		
6843	Petroleum Syst	2,857	17		
60%	Stationary/Mobile Sources		16	61	
	LUCF (net)	2,081			
LUCF	Soils			711	
AGRICULTURE	Biomass		134	51	
3691	Enteric Fermentation		476		
32%	Manure Management		61	56	
	Rice		177		
	Cement	226			
	Adipic & Nitric Acid Prd			43	
INDUSTRY	HFCs				26
408	PFCs				29
4%	SF6				15
	Substitution of ODS				52
WASTE	Landfills		213		
388	Wastewater		154	22	
3%	Other		3	3	
TOTAL GHG	11,378	8,691	1,618	947	122
		76%	14%	8%	1%

Sources: de la Chesnaye et al, 2006.

The most important work on non-CO_2 GHG emissions scenarios has been done in the context of EMF 21. The EMF 21 study updated the capability of long-term integrated assessment models for modeling non-CO_2 GHG emissions. The results of the study are illustrated in Figure 3.14.

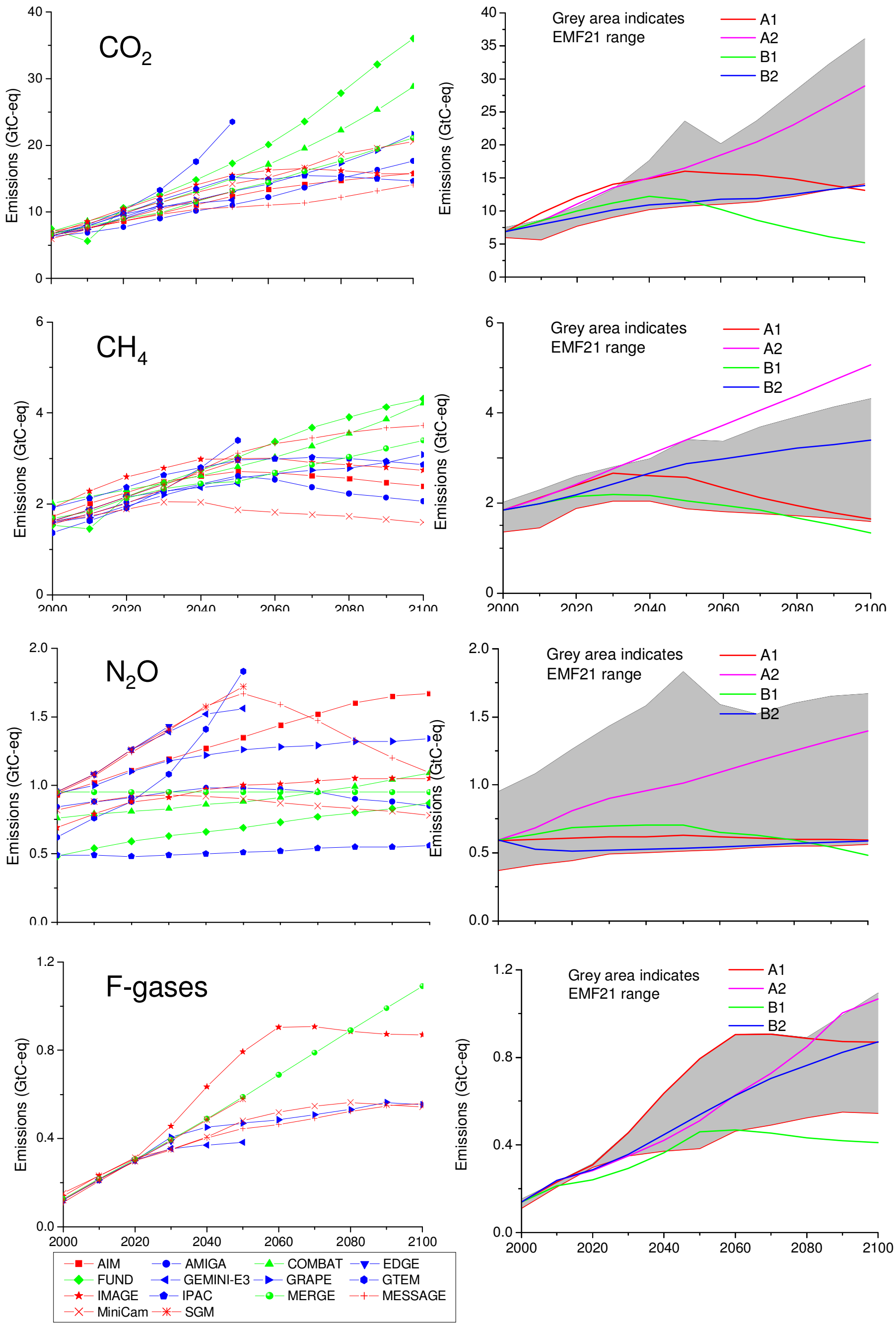


Figure 3.14: *Development of baseline emission in the EMF-21 scenarios (left) and comparison between EMF21 and SRES scenarios (right)*

Evaluating the long-term projections of anthropogenic methane emissions from the EMF 21 data show a significant range in the estimates[5]. The differences in model results for methane emissions start with a range between 1.37 to 2.01 GtCe (average of 1.67 GtCe) for 2000, grow to a range between 1.87 to 3.82 GtCe (average of 2.84 GtCe) for 2050, and continue to a range between 1.59 to 4.67 GtCe (average of 3.19 GtCe) for 2100. For further evaluation, emissions from SRES are compared to the EMF 21 range and show that for methane emissions, the two data sets are fairly

[5] In the EMF21 study, reference case scenarios were considered to be 'modelers choice' where harmonization of input parameters and exogenous assumptions was not sought.

consistent. The ranges, however, are caused by different uncertainties. The methane emission differences in SRES are due to the different storylines. The differences in the EMF 21 reference cases are due mainly to changes in the economic activity level projected in key sectors by each of the models. This could include, for example, increased agriculture production or increased supply of natural gas and below ground coal in the energy sector. In addition, different modeling groups employed various methods of representing methane emissions in their models and also made different assumptions as to how specific methane emission factors for each economic sector change over time. Finally, it should be noted that the degree to which agricultural activities are represented in the models differs substantially. For example, some models represent all agricultural output as one large commodity, 'agriculture,' while others have considerable disaggregation. More disaggregated models can define emissions factors in a more specific way. Interestingly, the latter group of models tend to find slower emissions growth rates (see van Vuuren *et al.*, 2005).

The range of long-term projections of anthropogenic nitrous oxide emissions is wider for methane in the EMF 21 data. Here the differences in emission projections start with a range between 0.49 to 0.95 GtCe (average of 0.81 GtCe) for 2000, grow to a range between 0.51 to 1.83 GtCe (average of 1.22 GtCe) for 2050, and continues to a range between 0.56 to 3.14 GtCe (average of 1.22 GtCe) for 2100. Note that for N_2O, base year emissions of the different models differ substantially. Two factors may contribute to this. First of all, different definitions exist of what should be regarded as human-induced and natural emissions in the case of N_2O emissions from soils. Second, some models may not have included all emission sources. The same argument on the cause of future differences as mentioned under methane also applies here.

The last group of non-CO_2 gases are fluorinated compounds which including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). The global total emissions of these gases are estimated at 122 MtCe or slightly over 1 per cent of all GHG for 2000. While the emissions of some fluorinated compounds are projected to decrease, many are expected to grow substantially because of the rapid growth rate of some emitting industries (e.g., semiconductor manufacture and magnesium production and processing), and the replacement of ozone depleting substances (ODSs) with HFCs. Long-term projections of these fluorinated GHGs are generated by a fewer number of models but still show a wide range in the results over the century. The range of emissions in 2000 is quite small. For 2050, this grows to a range between 0.44 to 0.79 GtCe (average of 0.57 GtCe), and widens to a range between 0.54 to 1.36 GtCe (average of 0.83 GtCe) for 2100. The range of the SRES results compared to the EMF 21 results is about the same.

Overall, since SRES the level of information on non-CO_2 emissions has increased substantially. The range of projections, however, is still more-or-less the same. This range indicates that the emissions of non-CO_2 GHGs as a group are projected to increase, but somewhat less rapidly than CO_2 emissions. The main reason is that the most important sources of CH_4 and NO_x are agricultural activities - which grow at a less rapid rate than energy use (the main source of CO_2 emissions).

3.2.2.4 Scenarios for Air Pollutants and Other Radiative Substances

Sulfur Dioxide Emissions Scenarios

Sulfur emissions are relevant for climate change modelling as they contribute to the formation of aerosols, which affect precipitation patterns and, taken together, reduce radiative forcing. Sulfur emissions also contribute to regional and local air pollution. Historically, global sulfur dioxide emissions have grown approximately in parallel with the increase in fossil fuel use (Smith *et al.*, 2001 and 2004; Stern, 2005). Since about the late 1970s, however, the growth in emissions has slowed considerably (Grübler, 2002). Implementation of emissions controls, a shift to lower sulfur fuels in most industrialized countries, and the economic transition process in Eastern Europe and the Former Soviet Union have contributed to the lowering of global sulfur emissions (Smith *et al.*, 2001). Conversely, with accelerated economic development, the growth of sulfur emissions in many parts of Asia has been fast in recent decades, albeit growth rates have declined considerably recently (Streets *et al.*, 2000; Stern 2005; Cofala *et al.* 2006; Smith *et al.*, 2004). A review of the recent literature indicates that there is some uncertainty concerning present global anthropogenic sulphur emissions, with estimates for the year 2000 between 55.2 MtS (Stern, 2005), 57.5 MtS (Cofala *et al.* 2006) and 62 MtS (Smith *et al.*, 2004).[6]

Many empirical studies have explored the relationship between sulfur emissions and related drivers, such as economic development (Grübler, 1998, and Smith *et al.*, 2004). The main driving factors that have been identified are increasing income, changes in the energy mix, and a greater focus on air pollution abatement (as a consequence of increasing affluence). Together, these factors may result in an inverted U-shaped pattern of SO_2 emissions, where emissions increase at early stages of industrialization, peak and then fall at higher levels of income, following a Kuznets curve (World Bank, 1992). This general trend is also apparent in most of the recent emissions scenarios in the literature.

Over time, new scenarios have generally produced lower SO_2 emissions projections. A comprehensive comparison of SRES and more recent sulphur emissions scenarios is given in Van Vuuren and O'Neill (in press). Figure 3.15 illustrates that the resulting[7] spread of sulphur emissions over the medium term (up to the year 2050) is predominantly due to the varying assumptions about the timing of future emissions control, particularly in developing countries. Scenarios at the lower bound assume the rapid introduction of sulphur control technologies on a global scale, and hence, a reversal of historical trends and declining emissions in the initial years of the scenario. Conversely, the upper bound of emissions are characterized by a rapid increase over the next decades, primarily driven by increasing use of coal and oil at relatively low levels of sulfur control (SRES A1 and A2).

The comparison shows that overall, the SRES scenarios are fairly consistent with recent projections concerning the long-term uncertainty range (Smith *et al.*, 2004; see Figure 3.15). However, the emissions peak over the short-term of some high emissions scenarios in SRES lie above the upper bound estimates of the recent scenarios. There are two main reasons for this difference. First, recent sulfur inventories for the year 2000 have shifted downward. Second, and perhaps more importantly, new information on present and planned sulfur legislation in some developing countries, such as India (Carmichael *et al.*, 2002) and China (Streets *et al.*, 2001) has become available. Anticipating this change in legislation, recent scenarios project sulfur emissions to peak earlier and at lower levels compared to SRES. Also the lower bound projections of the recent literature have shifted downward slightly compared to SRES.

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6 Note that the Cofala *et al.* inventory does not include emissions from biomass burning, international shipping and aircrafts. In order to enhance comparability between the inventories, emissions from these sources (6 MtS globally) have been added to the original Cofala *et al.* values.

7 The Amann (2002) projections were replaced by the recently updated IIASA-RAINS projection from Cofala *et al.* (2005) forthcoming

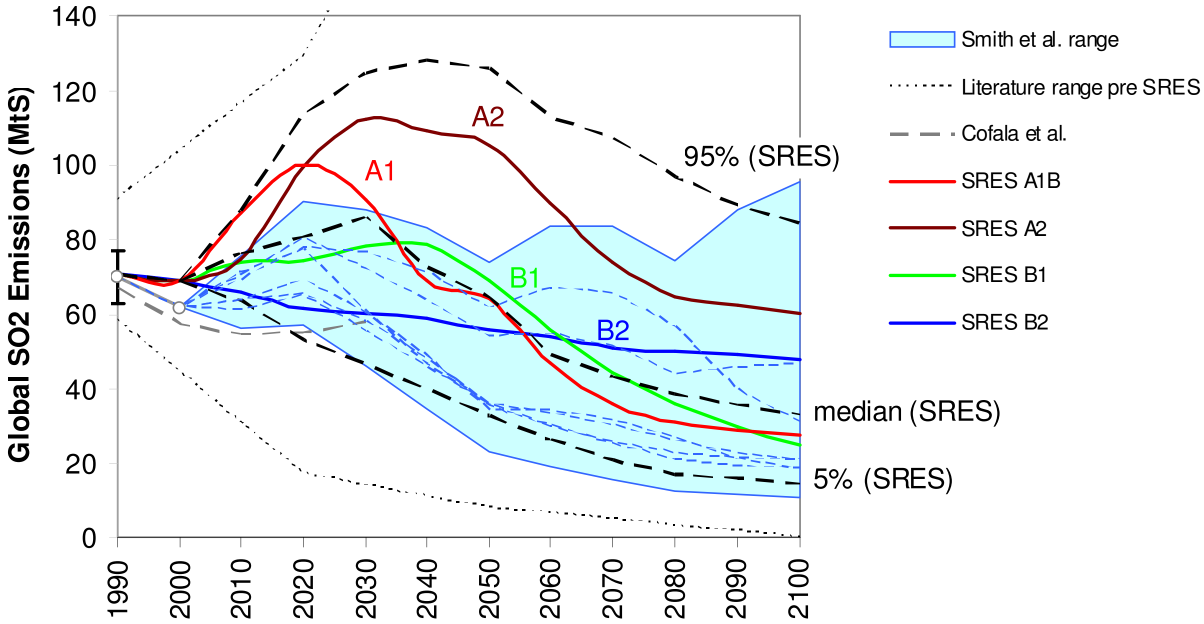


Figure 3.15: *Sulfur dioxide emissions scenarios. Thick colored lines depict the four SRES marker scenarios and the black dashed lines show the median, 5th and 95th percentile of the frequency distribution for the full ensemble of all 40 SRES scenarios. The blue area (and the thin dashed lines in blue) illustrates individual scenarios and the range of the Smith et al. (2004). Dotted lines give the minimum and maximum of sulfur emissions scenarios developed pre SRES (Source: Gruebler, 1998)*

NO_x Emissions Scenarios

The most important sources of NO_x emissions are fossil fuel combustion and industrial processes, which combined with other sources like natural and anthropogenic soil release, biomass burning, lightning, and atmospheric processes, amount to around 25 MtN per year. Considerably uncertainties exist particularly around the natural sources (Prather *et al.*, 1995; Olivier *et al.*, 1998, Olivier and Berdowski, 2001, Cofala *et al.* (2006). Fossil fuel combustion in the electric power and transport sectors is the largest source of $NO_{x,}$ with emissions largely being related to the combustion practice. In recent years, emissions from fossil fuel use in North America and Europe are either constant or declining. In most parts of Asia and other developing parts of the world, however, emissions have been increasing, mainly due to the growing transport sector (van Aardenne, 1999; Cofala *et al.* 2006, Smith, 2005; WBCSD, 2004). However in the longer term, most studies project that NO_x emissions in developing countries will saturate and eventually decline following the trend in the developed world. The pace of this trend is however uncertain. Emissions are projected to peak in the developing world as early as 2015 (WBCSD, 2004 focusing on the transport sector) and in worst cases around the end of this century (see the high emissions projection of Smith, 2005).

There have been very few global scenarios for NO_x emissions since the earlier IS92 scenarios and SRES. An important characteristic of these (baseline) scenarios is that they consider air pollution legislation (in the absence of any climate policy). Some scenarios, such as those by Bouwman and van Vuuren (1999) and Collins *et al.* (1999) often use IS92a as a ‘loose’ baseline, with new abatement policies added. Many scenarios report rising NO_x emissions up to the 2020s (Figure 3.16), with the lower bound given by the short-term Cofala *et al.* (2006) reference scenario, projecting emissions to stay at about present levels for the next two to three decades. In the most recent longer term scenarios (Smith, 2005), NO_x emissions range between 32 and 47 MtN by 2020, which corresponds to an increase in emissions of about 6 to 50 per cent compared to 2000. The long-term spread is considerably larger, ranging from 9 to 74 MtN by 2100 (see Figure 3.16). A comparison of global NO_x emissions in the SRES scenarios with the Smith (2005) and Cofala *et al.* projections is given in Figure 3.16. The majority of the SRES scenarios (70 per cent) lie within the range of the new Smith (2005) scenarios. It is apparent from the illustration, however, that the upper and lower bounds of the range of the recent projections has shifted downward compared to SRES.

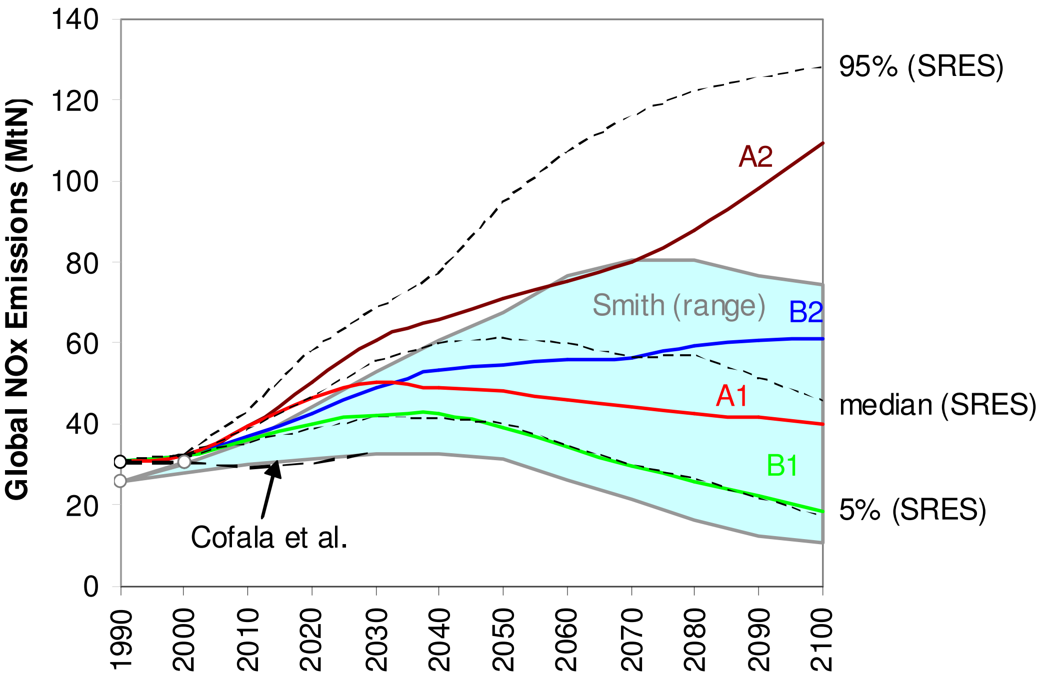


Figure 3.16: *NO_x emissions scenarios. Thick colored lines depict the four SRES marker scenarios and the black dashed lines show the median, 5th and 95th percentile of the frequency distribution for the full ensemble of all 40 SRES scenarios. The blue area illustrates the range of the recent Smith (2005) projections*

Emissions Scenarios for Black and Organic Carbon

Black and Organic Carbon emissions (BC and OC) are mainly formed by incomplete combustion processes as well as from gaseous precursors (Penner *et al*., 1993; Gray & Cass 1998). The main sources of BC and OC emissions include fossil fuel combustion in industry, power generation, traffic and residential sectors as well as biomass and agriculture waste burning. Natural sources like forest fires and savannah burning are other major contributors. There has recently been some research suggesting that BC may be a contributor to global warming (Hansen *et al*. 2000; Andrae 2001; Jacobson 2001, Ramaswamy *et al*., 2001). However the uncertainty concerning the effects of BC and OC on the change in radiative forcing and hence global warming is still high (see Jacobson, 2001 and Penner *et al*., 2003).

Currently, BC and OC emissions have been poorly represented in economic and systems engineering models due to unavailability of data. For example, in IPCC's Third Assessment Report, BC and OC estimates were developed by using CO emissions (IPCC, 2001). Recently, some detailed global and regional emission inventories of BC and OC have become available (e.g. Cooke *et al*., 1999; Bond *et al*. 2004; Kupiainen and Klimont, 2004). However, considerable uncertainty still exists in the inventories (Table 3.3), mainly due to the variety in combustion techniques for different fuels as well as measurement techniques. In order to represent these uncertainties, some studies like Bond *et al*. (2004) provide high, low and 'best-guess' values.

Table 3.3: *Emission Inventories for Black and Organic Carbon*

Source	**Year**	**Black carbon**	**Organic carbon**
Penner *et al*., 1993	1980	12,610	-
Cooke & Wilson 1996	1984	7,970*	-
Cooke *et al*., 1999	1984	5,100*	7,000*
Bond *et al*. (using Cooke *et al*., 1999 efs)	1996	9,122	26,936
Bond *et al*., 2004	1996	4,626(3,132-10,048)	8,856 (5,141-17,419)
Liousse, Guillaume *et al*.		10,200	
RAINS	1995	5,000	12,848

The development in the inventories has resulted in the possibility of estimating future BC and OC emissions. Streets *et al*. (2004) use the fuel use information and technological change in the SRES scenarios to develop estimates of BC and OC emissions from both contained combustion as well as natural sources for all the SRES scenarios until 2050. Rao *et al*. (2005) and Smith *et al*. (2006) estimate BC and OC emissions until 2100 for two IPCC SRES scenarios, with an assumption of increasing affluence leading to an additional premium on local air quality. Liousse *et al*. (2005) use IPCC SRES scenarios and apply static emission factors to obtain corresponding BC and OC emissions.

Figure 3.17 suggests that technological development is an important factor in the magnitude of future BC and OC emissions. Liousse *et al*. (2005) neglects the effects of technological change leading to much higher emission estimates as compared to Streets *et al*. (2004), Rao *et al*. (2005) and Smith *et al*. (2006). In addition, Rao *et al*. (2005), also account for current and proposed environmental legislation that have synergies for BC and OC emissions, especially in the transportation sector. In general, as seen in Figure 3.17, Liousse *et al*. (2005) can be considered to represent an outer bound on emission estimates as it neglects effects of technological change while the other studies that include such dynamics show more agreement in future emission estimates. This suggests the necessity for comprehensive technology rich frameworks that capture structural and technological change in the energy system in order to obtain future BC and OC emission pathways.

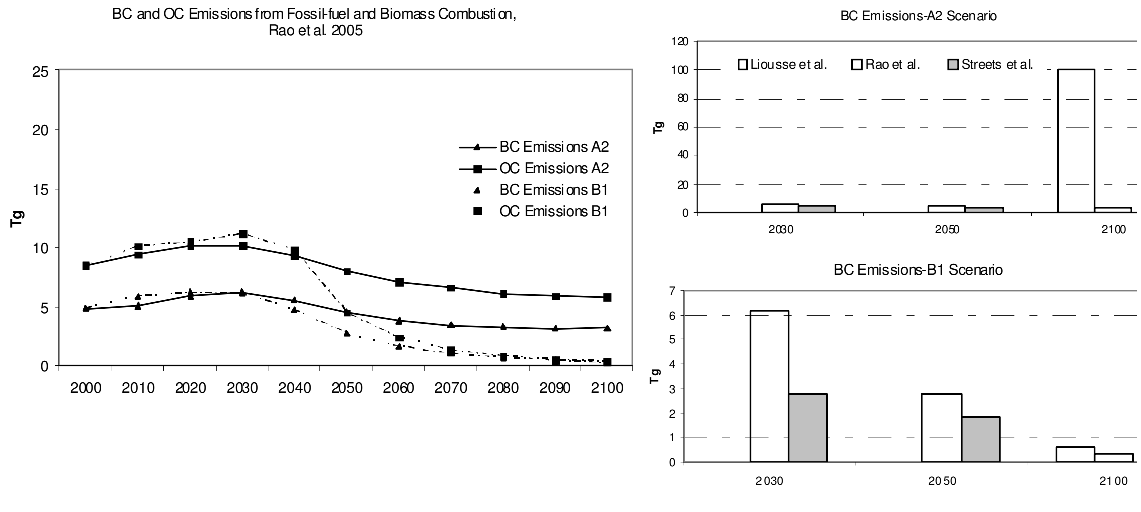


Figure 3.17: *BC/OC Emission Estimates Scenarios from Different Studies*

Both Streets *et al.* (2004) and Rao *et al.* (2005) show a general decline in BC and OC emissions in developed countries as well as regions such as East Asia (including China). In other developing regions like Africa and South Asia, slower technology penetration rates lead to much lower emission reductions. There is a large decline in emissions from the residential sector in the developing countries, due to the gradual replacement of traditional fuels and technologies with more efficient ones. Transport related emissions in both industrialized and developing countries decline in the long-term due to stringent regulations, technology improvements and fuel switching.

An important feature of the recent scenario literature is the long-term decline in BC/OC emissions intensities per unit of energy use (or economic activity). The majority of the above studies thus indicate that the long-term BC and OC emissions might be decoupled from the trajectory of CO_2 emissions. In aggregate, technological change and environmental legislation both contribute to the long-term decline in BC/OC emissions, a trend that is apparent even in the most carbon intensive scenarios with significant increases of CO_2 emissions over the course of the century.

3.3 Mitigation scenarios

3.3.1 Introduction

The scenario database that was updated for AR4 (Hanaoka *et al.*, 2006; Nakicenovic *et al.*, 2006) includes 324 mitigation scenarios that describe global emission trends over the next century. Of these, 151 were developed after the TAR. The recent mitigation scenario literature is discussed and compared with the TAR mitigation scenarios in this section. Short-term scenarios with a regional or national focus are discussed in Section 3.3.5.

3.3.2 Definition of a stabilization target

Mitigation scenarios explore how certain climate or emissions targets can be achieved (mostly vis-à-vis a baseline scenario). The actual climate target that is chosen in scenario analysis is a crucial issue. In response to UNFCCC's call for a 'stabilization of greenhouse gas concentrations at a level that prevents dangerous anthropogenic interference,' most, but not all, mitigation studies have focused their efforts on generating GHG concentration stabilization scenarios. However, several other climate targets may be chosen (see e.g. Richels *et al*., 2004; Van Vuuren *et al*., 2005; Morlot *et al*., 2005). In general, selecting a climate policy target early in the cause-effect chain of human activities to climate change impacts, such as emissions stabilization, increases the certainty of achieving required reduction measures, while increasing the uncertainty on climate change impacts (see Figure 3.18 and Table 3.4). Selecting a climate target further down the cause-effect chain (e.g. temperature change, or even avoided climate impacts) provides for greater specification of a desired climate target, but decreases certainty on required emission reductions.

A commonly used target in mitigation literature is stabilization of the concentration of CO_2 in the atmosphere. If more than one GHG is studied, a useful alternative is to formulate a GHG concentration target in terms of radiative forcing, thereby weighting the concentrations of the different gases by their radiative properties. The advantage of radiative forcing targets over temperature targets is that the calculation of radiative forcing does not depend on climate sensitivity. The disadvantage is that a wide range of temperature impacts are possible for each radiative forcing level. Temperature targets, on the other hand, have the important advantage of being more directly linked to climate change impacts.

Another approach is to calculate risks or probability of exceeding particular values of global annual mean temperature rise since pre-industrial times looking across various stabilization or radiative forcing targets. For example, den Elzen and Meinhausen (2005) used two probability density functions of climate sensitivity (Wigley & Raper 2001, Murphy *et al.* 2004) in the MAGICC climate model to estimate relationships between the probability of achieving climate targets and required emission reductions. Similarly Hare and Meinshausen (2005) draw on a wider range of probability distributions for climate sensitivity and emission scenarios. Studies by Richels *et al*. (2004), Yohe *et al*. (2004), den Elzen *et al*. (2006), Keppo *et al*. (in press), Kypreos (in press) have used a similar probabilistic concept in an economic context. The studies analyse the relationship between mitigation costs and the increase in probability of meeting specific temperature targets.

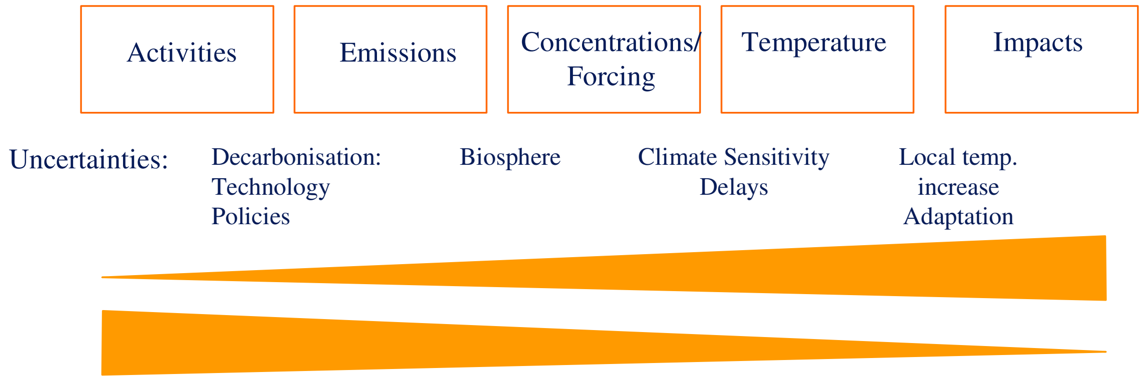


Figure 3.18: *Simple representation of the cause-effect chain of climate change. Choice of policy target within the chain has consequences for uncertainty*

Table 3.4: *Advantages and disadvantages of using different stabalisation targets*

Target	Advantages	Disadvantages
Concentrations of different greenhouse gasses	Can be translated relatively easily into emission profiles (reducing uncertainty on costs)	Does not allow for substitution among gasses (thus loosing the opportunities of cost reduction of what flexibility)
Radiative forcing	Relatively easy translation to emission targets (thus not including climate sensivity in costs calculations)	Does allow for full flexibility in substitution among gasses; Connects well to earlier work on CO_2 stabilisation; Allows for easy connection to work with GCMs/Climate models Can be expressed in terms of CO_2-equivalent concentration target (if preferred for communication with policy-makers)
Global mean temperature	Metric is also used to organize impact literature; and as has shown to be a reasonably proxy for impacts	Large uncertainty on required emissions reduction (as result of the uncertainty in climate sensitivity) and thus costs
Impacts	Direct link to objective of climate polices	Very large uncertainties in required emission reductions and costs
Emissions	Lower uncertainty on costs	Very large uncertainty on global mean temperature increase and impacts Either needs a different metric to allow for aggregating different gasses (e.g. GWPs) or forfeits opportunity of substitution
Costs	No uncertainty on costs	Very large uncertainty on global mean temperature increase and impacts

The choice of different targets is relevant because it leads to different uncertainty ranges and to different strategies and outcomes. Also, stabilization of one type of target, such as temperature, does not imply stabilization of other possible targets, such as radiative forcing, concentrations or emissions. The most cost-effective way to stabilize temperature is not radiative forcing stabilization; but rather to peak radiative forcing at a certain concentration, and then decrease with additional emissions reductions so as to avoid (delayed) further warming and stabilize global mean temperature (see Meinshausen, 2006; Khesqi *et al*., 2005; den Elzen *et al*., 2006).

In addition to stabilization targets, targets also can be defined to limit the rate of temperature change. While such targets have the advantage of providing a link to impacts related to the rate of climate change, strategies to achieve them may be more sensitive to uncertainties and thus, require careful planning. Rate of temperature change targets, for instance, may be difficult to achieve in the short-term even using multi-gas approaches (Swart *et al*., 1998; Manne and Richels, in press; van Vuuren *et al*., in press).

Following recent developments in mitigation assessment literature, this chapter concentrates on comparing abatement actions to achieve given radiative forcing. However, temperature stabilization targets are also discussed.

3.3.3 How to define substitution among gases

In a multi-gas studies, a method is needed to compare different greenhouse gases with different atmospheric lifetimes and different radiative properties. Ideally, the method would allow for substitution between gases (in order to achieve cost reductions) but ensure equivalence in climate impact. Fuglestvedt *at al*. (2003) provide a comprehensive overview of the different methods that have been proposed, and the advantages and disadvantages of using them. One of these methods, CO_2-equivalent emissions based on Global Warming Potentials (GW_p), has been adopted by current climate policies, such as the Kyoto Protocol and the United States climate policy (White-House, 2002). Despite the continuing scientific debate on the use of GWPs (that is, they are not based on economic considerations and use an arbitrary time horizon) the concept is regarded as convenient and, to date, no alternative measure has attained comparable status. The discussion on substitution metrics is linked to the discussion on climate policy targets in the previous section. As long as the target of climate policies is not defined (in terms of which aspects of climate change are important or the level or timing) then it is difficult to evaluate GW_p as an emission metric.

Nevertheless, other methods have been analyzed. Useful overviews of the mitigation and economic implication of substitution metrics are provided by Godal (2003) and Bradford (2001). Models that use intertemporal optimization can avoid the use of GWPs based on a chosen climate target. Manne and Richels (2001) showed that GWPs as the basis of substitution did not lead to the cost-optimal path for the long-term targets analyzed (minimizing welfare losses under an exogenously set forcing ceiling while accounting for life times and forcing strength of various gasses). In particular, reducing methane early had no benefit for reaching the long-term target given its short life time in the atmosphere. Some models in the recent EMF-21 study validated this result (see Weyant and de la Chesnaye, in press). Figure 3.19 shows the projected EMF-21 CO_2, CH_4, N_2O, and F-gas reductions across models stabilizing radiative forcing at 4.5 W/m^2. Most of the EMF-21 models based substitution between gases on GWPs. However, three models substituted gases on the basis of intertemporal optimization. While for most of the gasses, there are no systematic differences between the results from the two groups, for methane and some F-gasses (not shown), there are clear differences. These differences are the result of very different lifetimes of these gases than that of CO_2. For models using GWPs, the reduction of CH_4 emissions in the first three decades is substantial. The models that do not use GWPs, do not substantially reduce CH_4 until the end of the time horizon. Shortlived gasses (like CH_4) have a low contribution in reductions in these models, while the opposite is the case for gases with much longer lifetimes than CO_2. Using GWPs implies that, despite its short lifetime, CH_4 reductions become a cost-effective near term abatement strategy (Van Vuuren *et al*., 2006). It should be noted that if a short-term climate target is selected (e.g. rate of temperature change) then intertemporal optimization models would favour early methane reductions.

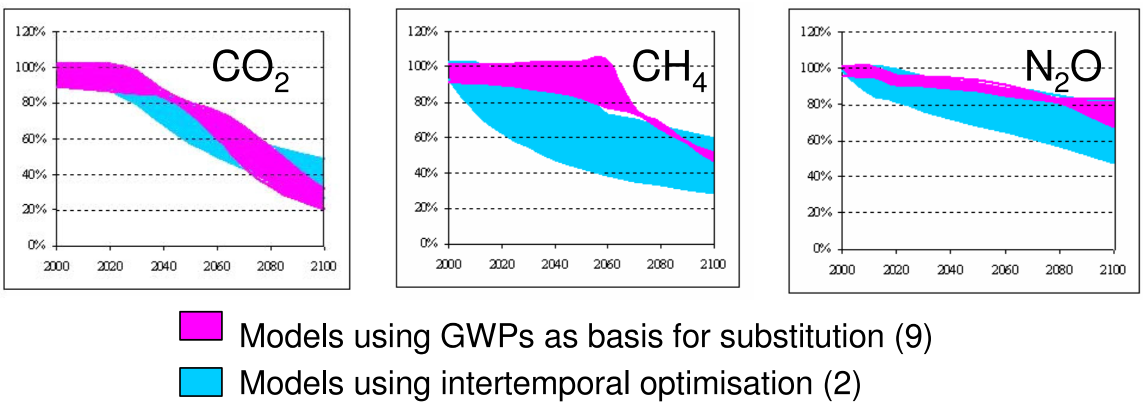


***Figure 3.19:** Reduction of emissions in the stabilization strategies aiming for stabilization at 4.5 W/m^2 (multigas strategies). Range (standard deviation) for models using GWPs (purple) versus those not using them (blue). For the first group, all 9 reporting long-term models were used. For the second category, results of 2 of the 3 reporting models were used (the other model shows the same pattern with respect to the distribution among gasses but has a far higher overall reduction rate and as such an outlier)*

While GWPs do not necessarily lead to the most cost effective stabilization solution (depending on the long-term target), they can be a practical choice: an exchange metric is needed to facilitate emissions trading between gasses for example if that is the chosen policy instrument. Having a metric broadens the set of abatement alternatives, creating the potential opportunity for cost savings through 'what flexibility' (i.e. substitution among gases) in reduction strategies. Therefore, it is appropriate to ask what are the costs of using GWPs versus not using them; and, whether other 'real world' metrics exist that could perform better. O'Neill (2003) and Johansson *et al*. (2005) have argued that the disadvantages of GWPs are likely to be outweighed by the advantages by showing that the cost difference between a multi-gas strategy and a CO_2-only strategy is much larger than the difference between a GW_p-based multi-gas strategy and a cost-optimal strategy. Aaheim *et al*. (2005) found that the cost of using GWPs compared with optimal weights depends on the ambition of climate policies. GWPs have the advantage of not needing a particular target (e.g., long-term stabilization). Postponing the early CH_4 reductions of the GW_p-based strategy (as is suggested by intertemporal optimization) leads to much greater increases of temperature in the 2000-2020 period. The reason is that the alternative, increased reduction of CO_2 from the energy sector, leads to changes in energy consumption that also reduce sulphur emissions and the cooling associated with sulphur based aerosols.

3.3.4 Emission pathways

The focus on this chapter is on emission scenarios, i.e. studies that specify the emissions of greenhouse gasses over time based on an explicit description of underlying activities and technologies. In addition, a set of literature exists that constructs more hypothetical pathways that specify emission pathways over time as a function of long-term (stabilization) targets. This type of study often focuses on specific questions with respect to the consequences of timing (in terms of environmental impacts) or overall reduction rates. In the past, these studies often focused on CO_2-only (e.g. the emission pathways developed by Wigley *et al*., 1996). A specific issue raised in the literature on emission pathways has been the issue of a temporary overshoot. Meinshausen (2006) showed that for low concentration targets (i.e. below 3 W/m^2/ 450 ppm CO_2-eq) overshoot is inevitable given the feasible maximum rate of reduction (e.g. 50 ppm). Wigley (2003) argued that his overshoot profiles may give important economic benefits. The overshoot profiles in his study are actually characterized by a large overshoot (e.g. 100 ppm). In response, O'Neill and Openheimer (2004) showed that the associated incremental warming of these profiles may significantly increase the risks of exceeding critical climate thresholds to which ecosystems are known to be able to adapt. Others studied emission pathways that lead to less extreme concentration overshoots that may provide a sensible compromise between these two results. For instance, the 'peaking strategies' chosen by Den Elzen *et al*. (2006) show that it is possible, to increase the likelihood of meeting the long-term temperature target, or to reach targets with a similar likelihood at lower costs. Similar arguments for analysis of overshoot strategies are made by Khesqi *et al*. (2005). At the moment, the majority of scenario literature still focusses on issues related to long-term stabilization. Just a few notable studies have explicitely exlored the implication of peaking or overshoot strategies. The consideration of interim targets, including the economic implication of overshoot or peaking strategies, thus remain an important field for future research. Such studies would be important for a better understanding of the implications of short-term action for achieving long-term climate targets.

3.3.5 Long-term stabilization scenarios

A large number of studies focusing on climate stabilization have been published since TAR. Several model comparison projects contributed to the new literature, including the Energy Modelling Forum's EMF19 (Weyant, 2004) and EMF21 studies (Weyant and De la Chesnaye, in press) that focused on technology change and multigas studies respectively, the IMCP (International Model Comparison Project) that focused on technological change (Ederhofer *et al*., 2006), and other modelling work (USCCSP, in press).

Comparison of mitigation scenarios is more complicated now than at the time of the TAR. There are three important reasons that contribute to this:

- At the time of TAR, most mitigation literature concentrated on CO_2 emissions from energy and industry. Now, part of the modelling community has expended their analysis to include non-CO_2 gases, while others have continued to focus solely on CO_2. Similarly, most scenario analysis in the past focused on the stabilization of CO_2 concentrations. As discussed in the previous section, multigas mitigation scenarios use different targets (often radiative forcing, but sometimes also temperature).
- Some recent studies developed scenarios that do not stabilize radiative forcing (or temperature) - but show a peak before the end of the modelling time horizon (in most cases 2100).
- At the time of TAR, many studies used the SRES scenarios as baselines for their mitigation analyses. These studies thus were based on a set of comprehensive and comparable set of assumptions. Now, there is a range of underlying assumptions.

It should also be noted that another categorization of scenarios exists: scenarios that aim at stabilization of climate change (with respect to atmospheric concentrations, radiative forcing, or temperature change), versus other mitigation scenarios that generally explore the implications of climate mitigation and policies, but without the ultimate goal of climate stabilization. Obviously, studying different scenario groups (based on analytic differences) independently provides a less useful basis for assessment of the literature as a whole. In this section, some metrics are introduced to group the CO_2-only and multigas scenarios so that they are reasonably comparable. In Figure 3.20 the reported CO_2 concentrations in 2100 are plotted against the 2100 radiative forcing (relative to pre-industrial times) for a subset of the available multi-gas studies for which those metrics are readily available.

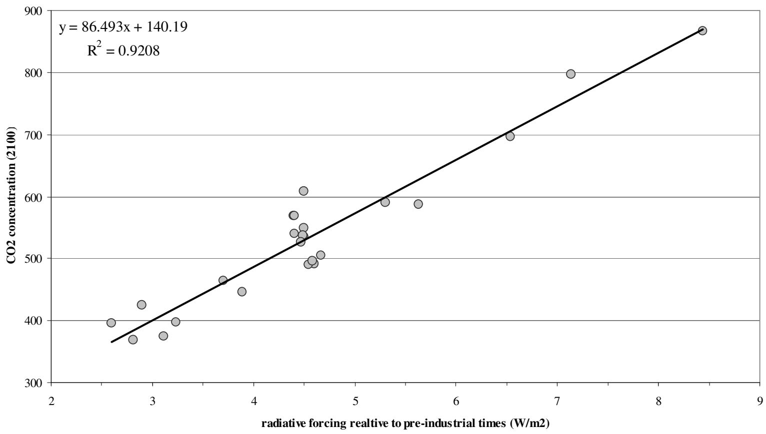


Figure 3.20: *Relationship of radiative forcing vis-à-vis CO_2 concentration for the year 2100 (25 multigas stabilization scenarios for alternative stabilisation targets)*

Figure 3.20 shows a clear relationship between the change in radiative forcing and the CO_2 concentration level by 2100. This can be explained by the fact that CO_2 forms by far the most important contributor to radiative forcing - and subsequently, a reduction in radiative forcing needs to coincide with a reduction in CO_2 concentration. The correlation between the two indicators is relatively strong. Nevertheless, some spread across the scenarios is caused by several factors, including differences in the rate of abatement among alternative gases, differences in specific forcing values for GHGs and other radiative gases (in particular aerosols), and differences in the atmospheric chemistry and carbon cycle models that are used. On the basis of this relationship, available mitigation literature has been classified into 5 different classes that vary in the stringency of the climate targets. The most stringent group include those scenarios that aim to stabilize radiative forcing below 3.25 W/m^2. This group also includes all CO_2-only scenarios that stabilise CO_2 concentrations below 420 ppm. The least stringent group of mitigation scenarios, in contrast, have a radiative forcing in 2100 above 6 W/m^2 - associated with CO_2 concentrations above 660 ppm. Three intermediate groups have been defined as well. By far the most studied group of scenarios are those that aim to stabilize radiative forcing at 4 to 5 W/m^2 or 490 to 570 ppm CO_2 (see Table 3.5 below). The classification of scenarios, as given in Table 3.5, permits the comparison of multigas and CO_2-only stabilization scenarios according to groups of scenarios with comparable level of mitigation stringency. Thus the sequel of this section uses these categories (A to E) for analyzing the underlying dynamics of stabilization scenarios as a function of the stabilization target.

Table 3.5: *Groups of mitigation scenarios for ranges of stabilization targets and alternative stabilization metrics. Groups of stabilization targets were defined using the relationship in Figure 3.20*

Category	Additional Radiative forcing	CO_2 concentration	CO_2 - eq. concentration	Global mean temperature increase above pre-industrial equilibrium, using best guess climate sensitivity [1,2]	No. of scenarios
	W/m^2	ppmv	ppmv	Celsius	
A	< 3.25	< 420	<510	1.3-2.6	16
B	3.25 - 4	420 - 490	510-590	2.6-3.3	9
C	4 - 5	490 - 570	590-710	3.3-4.1	83
D	5 - 6	570 - 660	710-860	4.1-4.9	6
E	> 6	> 660	<860	4.9-5.5	3
Total					117

[1] Note that global mean temperature at equilibrium is different from expected global mean temperatures in 2100 due to the inertia of the climate system

[2] These equilibrium temperatures follow from the equivalent CO_2 concentration value and the simplified expression for equilibrium temperatures as used in WG I, Chapter 10, section 10.7.2

3.3.5.1 Emission reductions and timing

Figure 3.21 shows the projected CO_2 emissions associated with the new mitigation scenarios. In addition, the figure depicts the range of the TAR stabilization scenarios (Morita *et al.*, 2001), comprised of more than 80 scenarios that are stabilizing atmospheric CO_2 between 450 and 750 ppmv.

Independent of the stabilization level, scenarios show that the scale of the emissions reductions required relative to the reference scenario increases over time (see also USCCSP, in press). Essentially, any specific concentration or radiative forcing target requires emissions to fall very low as the removal processes of the ocean and terrestrial systems saturate. Higher stabilization targets do push back the timing of this ultimate result beyond 2100. However, to reach given stabilization targets there is no way to avoid the need to ultimately reduce emissions to below current levels, even to almost zero (IPCC 2001).

An increasing body of literature is assessing the attainability of very low targets of 350 ppmv CO_2 and below (e.g., Azar *et al.*, 2005; van Vuuren *et al.*, in press, Riahi *et al.*, in press) (group A). An important characteristic of the new stabilization scenarios (black lines in Figure 3.21) is thus that they extend beyond the lower boundary of the range of TAR stabilization scenarios of 450 ppmv CO_2 (see upper left panel of Figure 3.21). The attainability of such low targets is shown to depend on 1) using a wide range of different reduction options and 2) the technology ‘readiness’ of advanced technologies. Most scenario studies indicate that carbon capture and storage in combination with fossil fuels and biomass energy conversion processes could contribute significantly to attaining such low targets. If biomass is grown sustainably, the use of CCS in combination with biomass may lead to negative emissions (Williams 1998, Obersteiner *et al.* 2000, IPCC 2005). Rao and Riahi (in press), Azar *et al.* (in press) and Van Vuuren *et al.* (in press) all find that while negative emissions technologies might be essential for achieving very stringent targets (350 ppmv and below), their importance diminishes at higher stabilization levels (>450 ppmv CO_2).

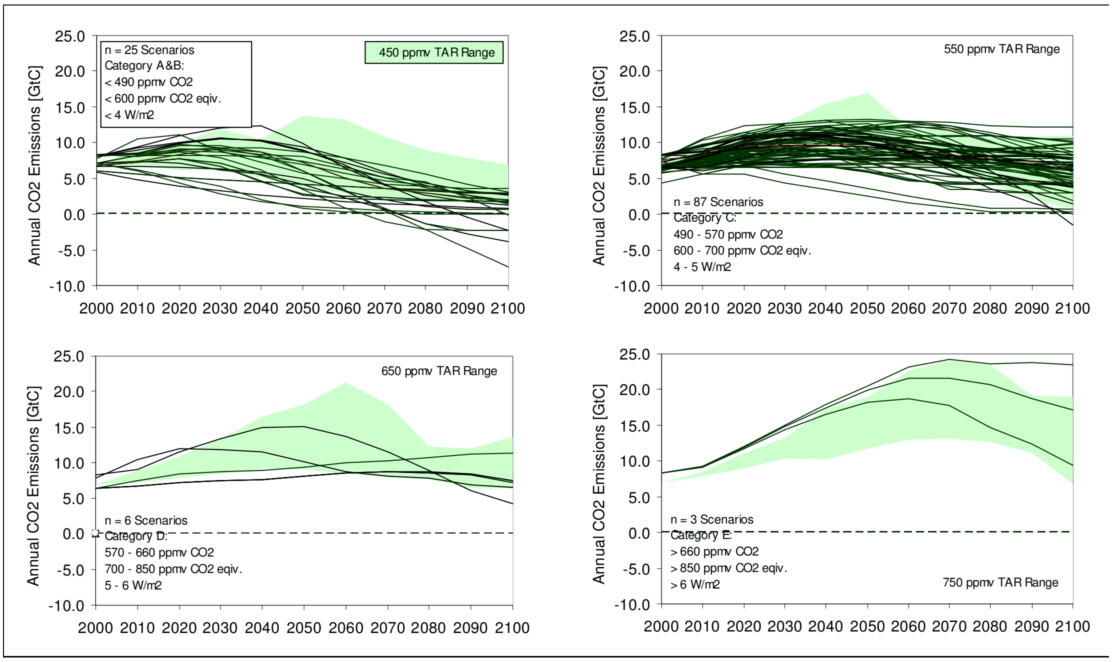


Figure 3.21: *Emissions pathways of mitigation scenarios for alternative groups of stabilization targets (Category A to E, see Table 3.5). Black lines give the projected CO_2 emissions for the recent mitigation scenarios developed post TAR (Source: Nakicenovic et al., 2006, and Kainuma et al., 2006 -. Green shaded areas depict the range of more than 80 TAR stabilization scenarios (Morita et al., 2001)*

The emission range for the scenarios with intermediate targets between 4 to 5 W/m^2 (scenarios in category C) is fully consistent with the range of the 550 ppm CO_2 scenarios in TAR. Emissions in this category tend to show peak emissions around 2050 - with emissions in 2100 similar or slightly below emissions today. Although less rapid and forceful reductions are required, studies focussing on this stabilization category find that a wide portfolio of reduction measures would be needed to achieve such emission pathways in a cost effective way.

Relatively few new scenarios have been published for the higher stabilization targets (category D & E). The emission profiles of these scenarios are found to be consistent with the emissions ranges as published in the Third Assessment Report. The two highest categories of stabilization scenario overlap with low-medium category baseline scenarios (see Section 3.2) - which partly explains the small number of scenarios published.

Obviously, there is a relatively strong relationship between the cumulative CO_2 emissions in the 2000-2100 period and the stringency of climate targets (see Figure 3.22). The uncertainties associated with individual stabilization levels (shown by the different percentiles) are primarily due to alternative model parameterization of the carbon cycle and partly by differences in emissions pathways (delayed reduction pathways can allow for somewhat higher cumulative emissions). In general, scenarios aiming for targets below 3.25 W/m^2 require cumulative CO_2 emissions around 400 GtC (range of 300-750 GtC). The cumulative emissions increase for subsequently less stringent targets. The middle category (4-5 W/m^2) requires emissions to be in the order of 900 GtC (range of 600-1050 GtC). The highest category (>6W/m^2) exhibit emissions on average around 1300 GtC (range of 1000 - 1800 GtC).

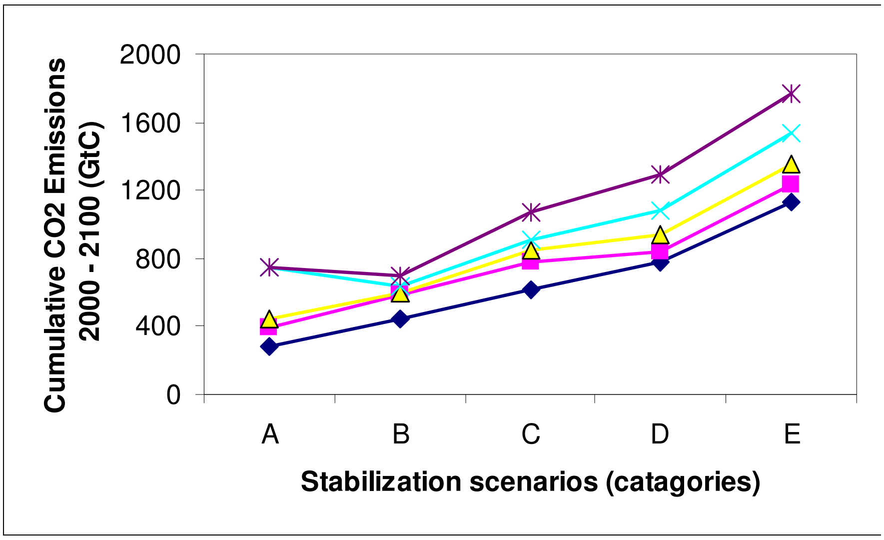


Figure 3.22: *Relationship between the scenario's cumulative carbon dioxide emissions (2000-2100) and the stabilization target (categories A to E of Table 3.5). The lines give the 5th, 25th, median, 75th and 95th percentile of the full scenario distribution. (data source: Nakicenovic et al., 2006, and Kainuma et al., 2006)*

Also the timing of emission reductions is coupled to the stringency of the climate target. Timing of climate policy has been an important topic in scenario literature. While some studies argue for early action for smooth transitions and stimulating technology development (e.g. Ha-Doung, 1996; Azar and Dowlatibadi, 1999; Van Vuuren and de Vries, 2001), others emphasize delayed response to benefit from better technology and higher CO_2 fertilization rates from natural systems at later points in time (e.g. Wigley *et al*., 1996) (see also Tol, 2000). These arguments imply that the literature of scenarios studies can draw up a range of reduction targets in specific years for the same stabilization target. Nevertheless, stringent targets require an earlier peak of CO_2 emissions, while also emissions need to be reduced more rapidly afterwards (Figure 3.23). In the most stringent group (< 3.25 W/m^2) available scenarios on average stabilize emissions around 2020 (ranging up to 2030). Such a trajectory would require a comprehensive global mitigation effort including a further tightening of existing climate policies in Annex I countries, and simultaneous emission mitigation in developing countries, where most of the increase in emissions is expected in the coming decades. For the medium group (4-5 W/m^2) the peak of global emissions generally occurs around 2040; followed by a return to 2000 levels around 2080. For targets above 5 W/m^2, the median emissions peak around 2040 to 2050. The figure also indicates that the uncertainty range is relatively small for the more stringent targets (< 3.25 W/m^2), indicating the reduced flexibility of the emissions path and the requirement for early mitigation. The uncertainty is however broader for the less stringent categories. Recent literature that focuses on overshoot profiles indicate that these ranges are likely to be even wider still(e.g. Wigley, 2004).

A small number of studies have analyzed the timing of when emissions would have to peak to achieve long-term stabilization. The literature ranges presented here are fairly consistent with results presented in Den Elzen *et al.*, forthcoming. Compared to the WRE emission profiles (Wigley *et al.* 1996), however, the current literature, in general, indicates a delay in the timing of when the peak of emissions would occur. For instance, for 450 ppmv CO_2 (category B) the WRE profiles indicated a peak in emissions around 2010 (instead of 2020 for recent sceanios); for 550 ppmv CO_2 the WRE indicated a peak around 2025 (instead of 2040 for the current scenarios).

The right-hand panel of Figure 3.23 illustrates the time at which CO_2 emissions will have to return to present levels. For stringent stabilization targets (below 4 W/m^2; category A and B) emissions return to present levels on average before the middle of this century, i.e., about one to two decades after the year that emissions peak. For more modest stabilization levels emissions return to present values with a considerable delay. In most of the scenarios of the highest stabilization category (above 6 W/m^2; category D) emissions could stay above present levels throughout the century.

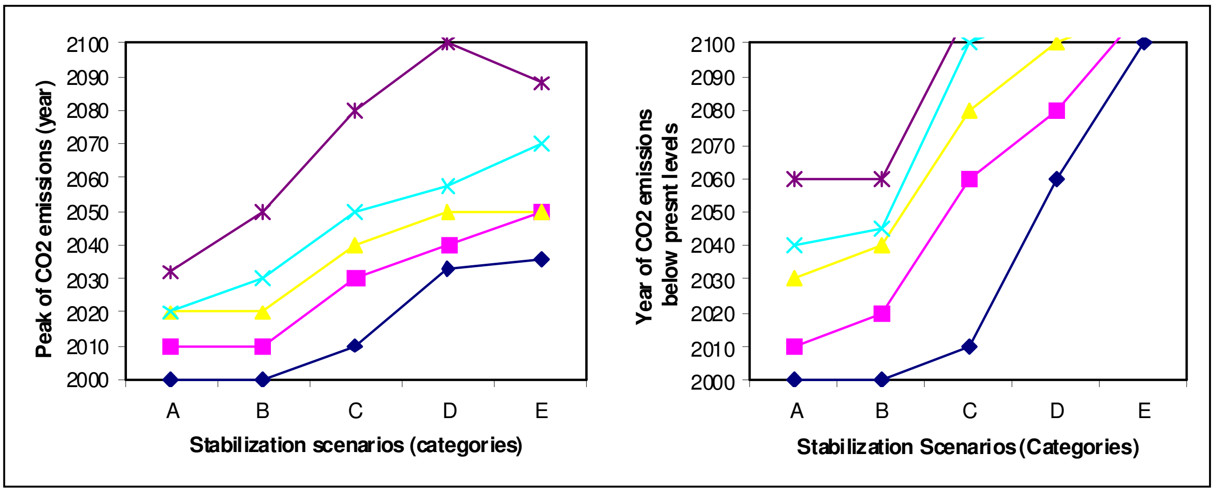


Figure 3.23: *Relationship between the stringency of the stabilization target (category A to E) and 1) the time at which CO_2 emissions have to peak (left-hand panel), and 2) the year at which emissions return to present (2000) levels. The lines show the 5th, 25th, median, 75th, and 95th percentile of the full scenario distribution (data source: Nakicenovic et al., 2006, and Kainuma et al., 2006)*

The absolute level of the required emissions reduction does not only depend on the stabilization target, but also on the baseline emissions (see Hourcade and Shukla, 2001). This is clearly shown in the right-hand panel of Figure 3.24, which gives the relationship between the cumulative baseline emissions and the cumulative emissions reductions (by 2100) that are needed for achieving stabilization at alternative levels of stringency (categories A to E). The figure also shows the wide spread in baseline emissions within each reduction category. The widest spread of baseline emissions is found for the medium mitigation category (4-5 W/m^2), which contains the largest number of scenarios (and widest range of different approaches). Note also the pronounced difference in this relationship for 2030 (left-hand panel in Figure 3.24) as compared to the long-term trend (2100, left-hand panel in Figure 3.24).

Apart from differences in carbon cycle modelling, scenarios with high baseline emissions require a higher reduction rate to reach the same reduction target: this implies that the different reduction categories need to show up as diagonals in Figure 3.24. As shown in the figure, this is indeed the case for the long-term (by 2100), with the most stringent scenarios (category A) showing on the lower right side and the least stringent scenarios (category E) on the upper right. This is also the case for the 'category averages' (see large triangles in Figure 3.24). As indicated in the figure, a scenario with high baseline emissions may require much deeper emission reduction to reach a medium stabilization target than a scenario with low baseline emissions to reach the most stringent targets.

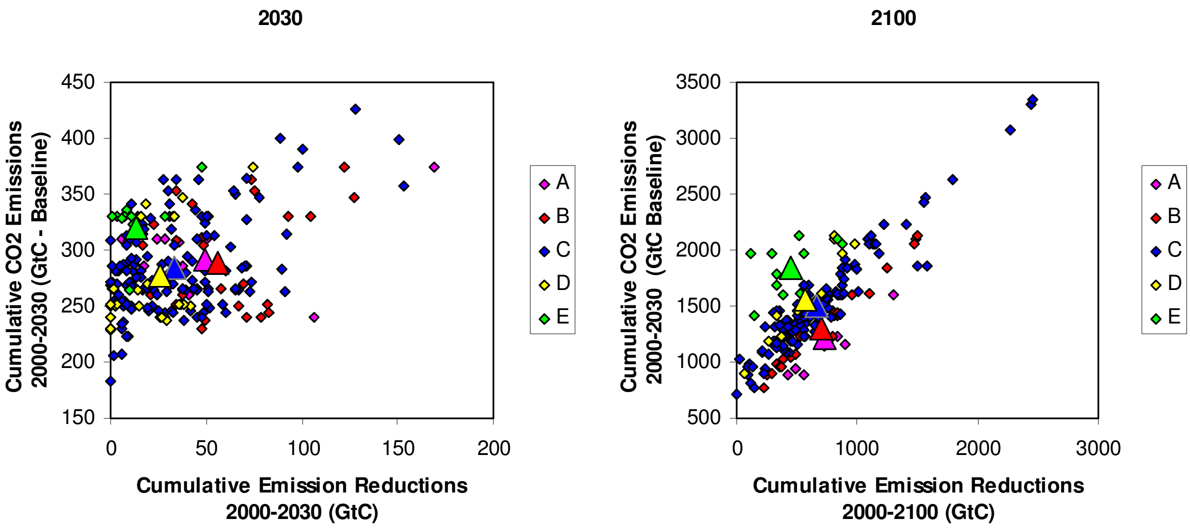


Figure 3.24: *Relationship between required cumulative emissions reduction and carbon emissions in the baseline by 2030 (left-hand panel) and 2100 (right-hand panel). Coloured rectangles denote individual scenarios for alternative stabilization targets (categories A to E). The large triangles indicate the averages for each category (data source: Nakicenovic et al., 2006, and Kainuma et al., 2006)*

The median of stabilization scenarios suggests an increase in required emissions reductions over the course of the century from about 200 GtC to around 1200 GtC if the target is tightened from about 6 to below 3.25 W/m^2 (for an 'average' baseline with a cumulative emission of 1600 GtC). These central values are, surrounded by significant uncertainty. Interestingly, Figure 3.24 also shows that (for the studies included) the mitigation scenarios with very stringent targets are developed from baseline scenarios that cover a similar wide spread in emissions as the scenarios with less stringent targets (with the exception of the middle group that covers a wider range).

The similar plot is also presented for 2030 (left-hand side). While the averages of the different stabilization categories are aligned in a similar way as discussed for 2100 (reductions are larger for category A&B than for category E); the uncertainty ranges here are very large. The general tendency of increasing emissions reductions for higher baseline emissions is evidently shown also for 2030, but the clear cut distinction between the cumulative reductions needed for alternative targets is not visible any more. This implies that, while there is relatively strong agreement across the scenarios with respect to the cumulative amount of long-term reductions necessary to achieve a specific target, there is less agreement with respect to the timing of the mitigation and the associated emissions pathway.

Finally, the averages across the scenarios in the literature indicate that going from 2030 to 2100 the reduction effort increases from around 10-60 GtC to 450-700 GtC. For an average baseline of around 290 GtC of cumulative emissions by 2030, reductions to get to the most stringent stabilization category (A) are thus about 20 per cent or 60 GtC; for 2100 this means that for baselines of about 1200 GtC cumulative emissions, reductions need to be around 60 per cent or 700 GtC to achieve stabilization at category A. As indicated by Figure 3.24 it is important to take account of the uncertainty surrounding these "average" values.

3.3.5.2 GHG abatement measures

The abatement of GHG emissions can be achieved through a wide portfolio of measures in the energy, industry, agricultural and forest sectors, the principal sources of emissions and thus global warming (see also Edmonds *et al*., 2004; Pacala and Socolow, 2004; Metz and van Vuuren, 2006). Measures for reducing CO_2 emissions range from structural changes in the energy system and replacement of carbon-intensive fossil fuels by cleaner alternatives (such as a switch from coal to natural gas, or the enhanced use of nuclear and renewable energy) to demand-side measures geared toward energy conservation and efficiency improvements. In addition, the capturing of carbon during energy conversion processes with subsequent storage in geological formations or the ocean (CCS) provide an "add-on" "end of pipe" approach for the decarbonization of hydrocarbon fuels allowing for example the continued use of fossil fuels with low CO_2 emissions to the atmosphere. Another important option for CO_2 emission reduction encompasses the enhancement of forest sinks through afforestation, reforestation activities and avoided deforestation.

In the energy sector the above mentioned options can be grouped into two principal measures for achieving CO_2 reductions: 1) improving the efficiency of energy use (or measures geared toward energy conservation); and 2) reducing the emissions per unit of energy consumption. The latter comprises the aggregated effect of structural changes in the energy systems and the application of CCS. To explore the importance of these two strategies, a response index has been calculated (based on the full set of stabilization scenarios from the database). This index is equal to the ratio of the reductions achieved by energy efficiency over those achieved by carbon factor improvements.

The response index for the stabilization scenarios are illustrated in Figure 3.25. Similar to Morita and Robinson (2001) it is found that the mitigation response to reduce CO_2 emissions would shift over time from initially focusing on energy intensity reductions in the beginning of the 21^{st} century to more carbon factor reduction in the latter half of the century (Figure 3.25). The amount of reductions coming from carbon factor improvement is more important for the most stringent scenarios. The main reason is that the impact of energy intensity reduction would be saturated toward the end of the 21^{st} century, and the use of low-carbon or carbon-free energy sources would become relatively much more important. This result is also confirmed in model comparison studies (Weyant, 2004; Ederhofer *et al*., 2006)

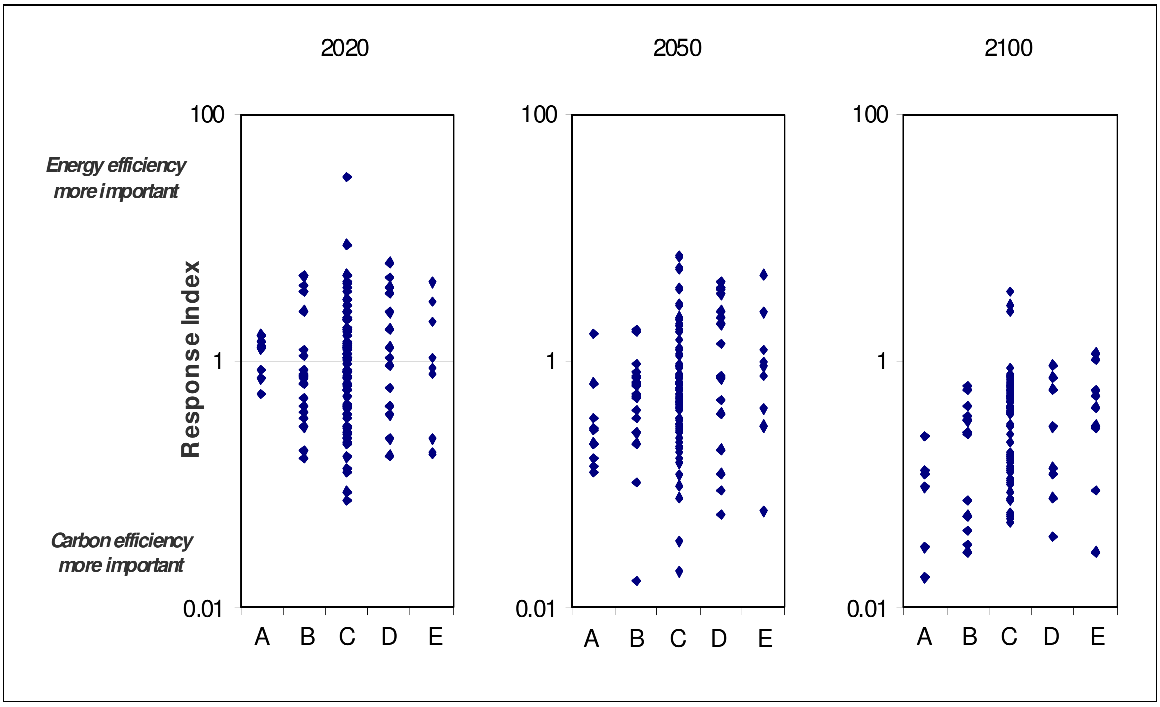


Figure 3.25: *Response index to assess priority setting in energy intensity reduction (more than 1.0) or in carbon intensity reduction (less than 1.0) for all stabilization scenarios in the literature database (Nakicenovic et al., 2006, and Kainuma et al., 2006). The panels give the development of the index for the years 2020, 2050, and 2100*

In addition to measures for reducing CO_2 a number of relatively cheap options for non-CO_2 gases exist. A number of recent studies (Tol, 2003; Hyman *et al*., 2003; Sarofim *et al*., 2005; de la Chesnaye *et al*. 2005; van Vuuren *et al* 2005 and in press; Riahi *et al*., in press) emphasize the important role of these gases for the cost-effectiveness of emissions reductions (for details see Section 3.3.5.4)

Figure 3.26 illustrates the relative contribution of measures for achieving climate stabilization from three main sources: 1) CO_2 from energy and industry; 2) CO_2 from land-use change; and 3) the full basket of non-CO_2 emissions from all relevant sources. The left-hand panel compares the contribution of these measures for achieving stabilization at an intermediate target of 4.5 W/m^2 for a wide range of baseline scenarios and alternative models. The right-hand panel thus illustrates the baseline and model uncertainty for the portfolio of emissions reductions given a specific long-term target. The right-hand panel, in contrast, gives the sensitivity of the contribution of individual measures for a range of stabilization targets (between 2.6 and 5.3 W/m^2 by 2100). The figure builds on scenarios from three selected modelling frameworks (IMAGE, MiniCAM, and MESSAGE) for which information for alternative targets were available.

As shown by Figure 3.26, an important conclusion across all stabilization levels and baseline scenarios is the central role of emissions reductions in the energy and industry sectors. All stabilization studies are consistent in that (independent of the baseline or target uncertainty) more than 65 per cent of total emissions reduction would occur in this sector. Thus the primary focus of any cost effective mitigation strategy has to target the full basket of energy-related and industrial sources of CO_2. The non-CO_2 gases and land-use related emissions are seen to contribute together up to 35 per cent of total emissions reductions. As noted further above, however, the majority of recent studies indicate the relative importance of the latter two sectors for the cost-effectiveness of integrated multigas GHG abatement strategies (see also Section 3.3.5.4 on CO_2-only versus multigas mitigation and 3.3.5.5 on land use).

The strongest divergence across the scenarios concerns the contribution of landuse related mitigation. The results range from negative contributions of landuse change to potential emissions savings of more than 300 GtC over the course of the century (Figure 3.26). The primary reason for this is the large uncertainty with respect to future competition for land between dedicated bio-energy plantations and potential gains from carbon savings in terrestrial sinks. Some scenarios, for example, project massive expansion of dedicated bio-energy plantations, leading to an increase of emissions due to net deforestation (compared to the baseline).

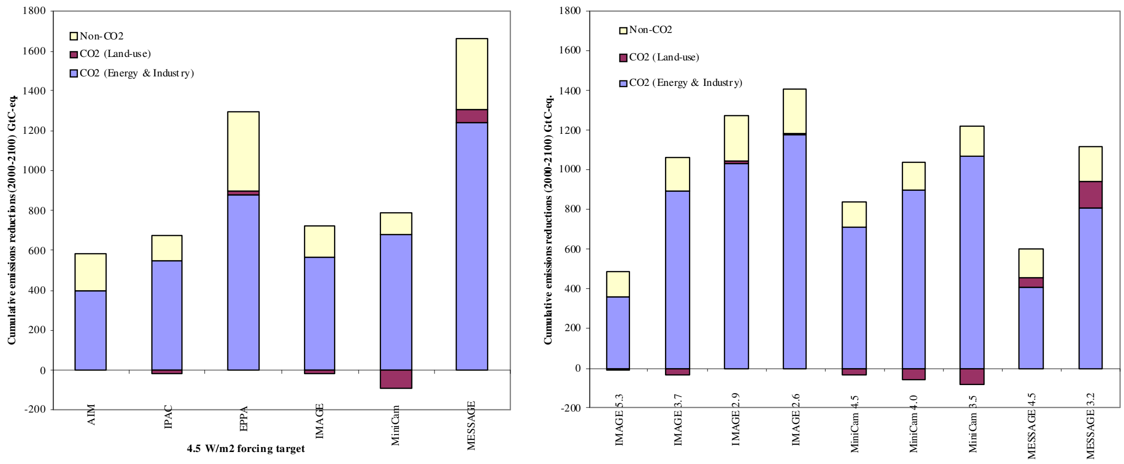


Figure 3.26: *Cumulative contribution of alternative measures by source (2000-2100): 1) CO_2 from energy and industry, 2) CO_2 from land-use change, and 3) the full basket of non-CO_2 emissions from all relevant sources. Left-hand panel illustrates model and baseline scenario uncertainty for an intermediate stabilization target of 4.5 W/m^2. Right-hand panel denotes alternative stabilization targets (2.6 to 5.3 W/m^2). Data source: (EMF-21, Smith et al., in press; Van Vuuren et al., in press; Riahi et al., in press)*

An illustrative example for the further breakdown of mitigation options for reducing GHG emissions, including alternative measures in the principal energy and industry sector is shown in Figure 3.27. For the comparison stabilization scenarios for a range of targets (about 3 to 4.5 W/m^2) based on two illustrative models (IMAGE and MESSAGE) for which sufficient data were available have been selected. With respect to the baselines, the two models share comparable assumptions with regard to the main emissions drivers, including economic and population change based on updated versions of the B2 SRES scenario family (Van Vuuren *et al.*, 2006, and Riahi *et al.*, in press). The models, however, differ significantly with respect to other assumptions and their own interpretation of the storyline with respect to particularly technological change, long-term abatement potentials, as well as model methodology and structure.

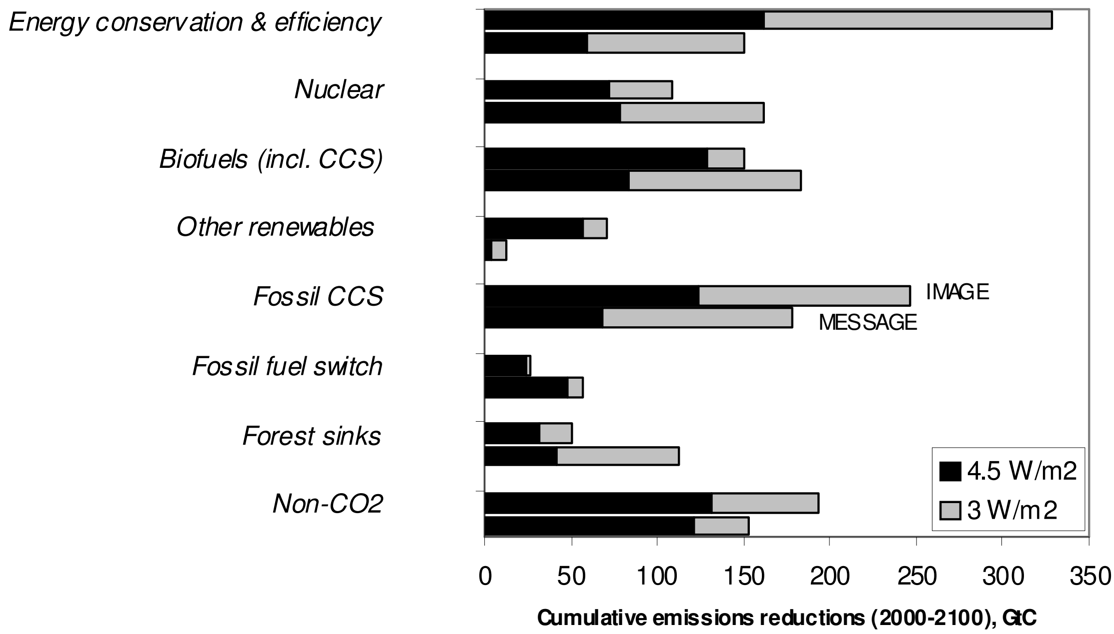


Figure 3.27: *Cumulative emissions reductions for alternative mitigation measures (2000-2100). The figure shows scenarios from two illustrative models (IMAGE and (MESSAGE) aiming at the stabilization of radiative forcing for 3 and 4.5 W/m^2 repectively. Black bars denote reductions for a target of 4.5 W/m^2 and grey bars the additional reductions to achieve 3 W/m^2. Data source: Van Vuuren et al., 2006, and Riahi et al., 2006*

Figure 3.27 illustrates the importance of a wide portfolio of reduction measures, with most of the measures showing contributions of more than 50 GtC over the course of the century (in at least one of the two modeling frameworks). The numbers should be seen as indicative because of the limited set of just two models. The strong agreement between the two models with respect to the large potential of energy conservation, biomass, carbon capture and storage, nuclear and non-CO_2 gases nevertheless indicates the importance of these measures as part of the mitigation portfolio. Also illustrated in Figure 3.27 is the increase of emissions reductions that become necessary when the target moves from 4.5 to about 3 W/m^2. Most of the mitigation options increase their contribution significantly by up to a factor of more than two.

3.3.5.3 Stabilization costs

Different models use different metrics to report the direct costs of emission reductions. Users of top-down general equilibrium models tend to report GDP losses, while system-engineering partial equilibrium model users report the increase of energy system costs or abatement costs. A common cost indicator is the marginal cost/price of emissions reduction measured in \$/tC or \$/tCO_2.

Figure 3.28 shows the GDP losses for stabilization scenarios in the literature as a function of cumulative emissions reductions for the short and long-term (2030 and 2100). As illustrated, GDP losses tend to generally increase with the level of mitigation. The relationship is however relatively weak and overshadowed by large uncertainties. Note in particular the logarithmic scale for GDP-losses, showing almost two orders of magnitude difference in the loss in GDP at comparable levels of emissions reductions. To a large extent the differences can be explained by the spread of alternative assumptions for long-term productivity change, possible substitution between costs factors, recycling of revenues, baselines and technologies covered (see e.g. Weyant, 2000; Barker *et al*. 2002). Uncertainties concerning these factors are smaller over the short-term, which explains the somewhat stronger congruence of results for 2030 (left-hand panel of Figure 3.28). Nevertheless, short-term costs estimates are also so uncertain that it is hardly possible to map out consistent messages for mitigation-induced costs on the basis of comparisons of the results from conceptually and structurally very diverse models. At the same time, a number of recent individual modelling studies that have published costs as a function of multi-climate targets emphasize the increase in costs for more stringent targets, both for macro-economic costs measures as well as abatement costs (e.g. Richels *et al*., 2004; Sarofim *et al*., 2005; Van Vuuren *et al*., in press-a; Van Vuuren *et al*., in press-b, Azar *et al*., in press, Tol, in press; Bollen *et al*., 2005, Riahi *et al*., in press). Some exceptions exists for models that assume that baseline results are far from a low cost solution - and climate policies may in fact help in getting to such a solution (e.g. by improving international relationships or by creating new markets for climate friendly products and technologies (Barker *et al*., 2006). The lack of a clear relationship in Figure 3.28 between the stringency of the climate target and the macro-economic costs is also a result of the fact that studies using more optimistic technology assumptions and/or lower baseline emissions often examine more stringent stabilization targets than those assuming less favourable conditions for mitigation (which simply cannot reach these targets). As more technology-optimistic models also lead to lower costs, an overview of all available literature tends to hide the relationship that is reported in the individual studies.

Therefore, the relationship between targets and costs can also be shown on the basis of more limited (and possibly more structured) comparisons. Figure 3.29 shows GDP losses and the net present value of 2000-2100 abatement costs based on a selection of studies, i.e. only those reporting costs for a wide range of stabilization targets. In Figure 3.29 costs for different stabilization targets are reported. Colour codes are also used to identify different types of baselines in the figure. In most cases there is a very clear relationship illustrating that costs generally increase with the stringency of the target. For 2050, GDP losses in the studies covered in Figure 3.29 are below 1 per cent for the target categories D and E. For categories A-C costs are on average higher, and show a wide range. For instance, for category C costs vary from a 1 per cent GDP increase (gain) to a 5 per cent loss. The average costs tend to centre around 1 per cent. For category B, the range is even wider (-4 to 10 per cent). Taking out the two extremes, this range is substantially reduced to 0-5 per cent or around 2 per cent on average. For the studies that also uses different baselines (in addition to multiple stabilization levels), Figure 3.29 shows that high emission baselines (e.g. A1 and A2) lead to higher costs. The uncertainty range across the models, however, is at least of a similar magnitude.

The results for the net present value of abatement costs show a similar picture - although trends come out more clearly (given the fact that abatement costs only capture direct costs, this cost estimate is by definition more certain). The values range from nearly zero to 40 trillion US$. The highest level corresponds to around 2-3 per cent of the NPV of global GDP over the same period. Two models (IMAGE and MESSAGE) examined the influence of both the stabilization level and baseline emissions. These studies report a clear influence of both factors - with costs for category step being of similar order of magnitude as the differences across baselines. The cost differences between these two models are smaller than those caused by the baseline and stabilization target. Abatement costs calculated by GET and MiniCam are comparable (although they widen the range). An estimate of abatement costs across all EMF-21 models (based on marginal prices and reduction rates) gives an even wider range - although the relationship with stabilization levels can still be regarded as robust. Typical numbers for category C are around 2-5 trillion US$ for stabilisation from baselines with medium emission levels (or smaller than 0.3 per cent of the NPV of GDP). For category B this is 2-20 trillion (or up to 1 per cent of the NPV of GDP). The results of these studies published since TAR can be regarded as consistent with the numbers presented in TAR, although the new studies extend results to substantially lower stabilization levels.

Although the absolute level of macro-economic costs differ considerably across scenarios, there is stronger agreement across models concerning the dynamics of change with respect to certain assumptions. For example, the stabilization scenarios of the multi-model comparison project (IMCP: Edenhofer *et al*., 2006) indicate the importance of induced technological change as a driver of significant reductions in the long-term costs of climate mitigation.

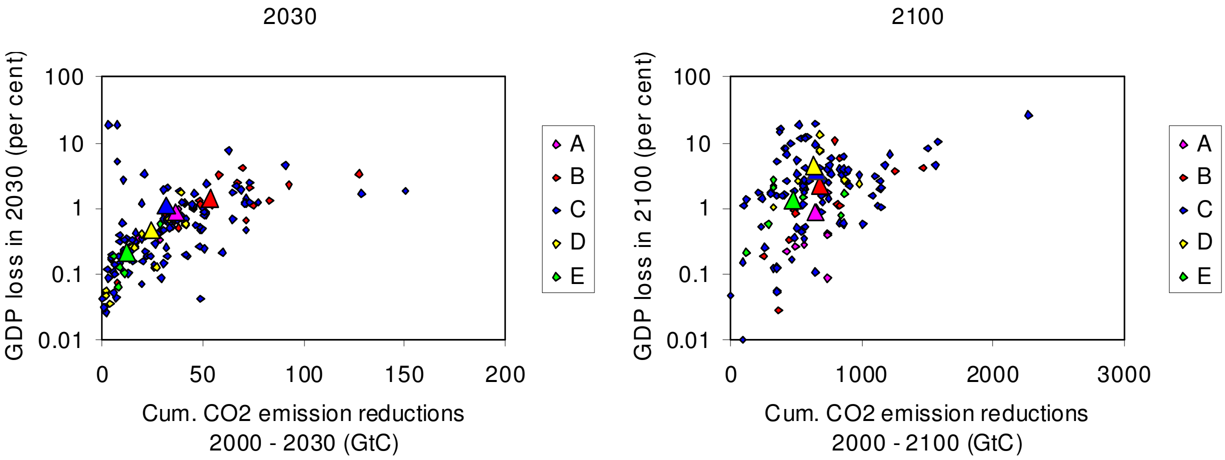
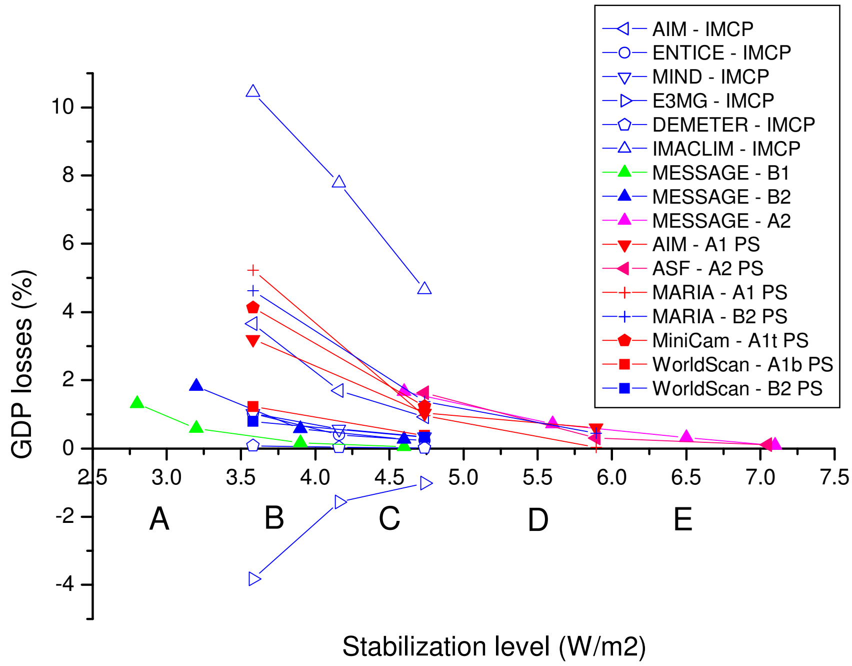


Figure 3.28: *Relationship between cumulative emissions reductions and GDP loss by 2030 (left-hand panel) and 2100 (right-hand panel). Data source: Nakicenovic et al., 2006, and Kainuma et al., 2006. Coloured rectangles denote individual scenarios for alternative stabilization targets (categories A to E). The large triangles indicate the averages for each category. Data source: Nakicenovic et al., 2006, and Kainuma et al., 2006*

a) Selected studies reporting GDP losses



b) Selected studies reporting abatement costs

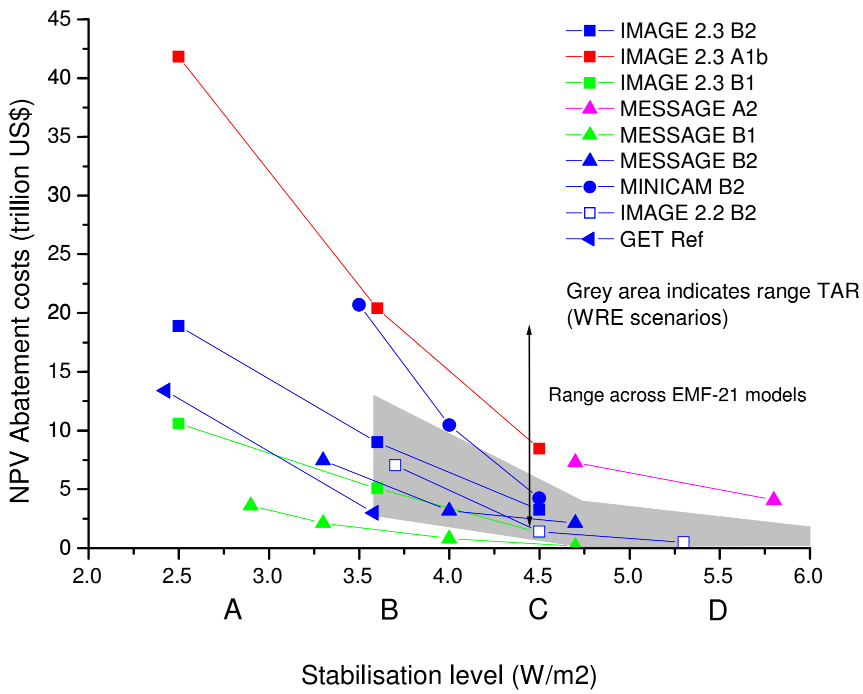


Figure 3.29: *Selected of studies that report GDP losses (a) or abatement costs (b) as a function of the stabilization level. For GDP, reduction in 2050 is reported. For abatement costs, the Net Present Value of abatement costs in the 2000-2100 period are reported using a 5% discount rate. The range of EMF-21 models instead is indicated based on a proxy of abatement costs by multiplying the marginal price and reduction rates*

Finally, it needs to be added that some new literature is now analysing the costs of reaching temperature targets by means of strategies that peak radiative forcing, instead of aiming for stabilization. Den Elzen *et al*. (2006) show that significant cost reductions can be achieved in this way - both for stringent and less stringent targets.

3.3.5.4 The role of non-CO_2 GHGs

Since about 1999, more and more attention has been paid to incorporating non-CO_2 gases into climate mitigation and stabilization analyses. As a result, there is now a body of literature (see de la Chesnaye *et al*. 2005, van Vuuren *et al*. 2005, Weyant and de la Chesnaye 2005) showing that: (1) there are greater and more diverse emitting sectors for non-CO_2 GHG than for CO_2; and (2) mitigation costs for these sectors can be lower than for energy-related CO_2 sectors. These two factors, taken together, lead to a larger portfolio of mitigation options for an economy. When all these options are employed in a multigas mitigation policy, there is a significant potential for reduced costs, for a given climate policy objective, versus the same policy when CO_2 is the only GHG directly mitigated. These cost savings can be especially important where carbon dioxide is not the dominant gas, on a percentage basis, for a particular economic sector and even for a particular region.

For non-CO_2 gases, a number of parallel numerical experiments have been carried out by the Energy Modeling Forum (EMF-21, Weyant and de la Chesnaye 2005). Even though it can be argued that abatement cost curves for these gases used in these experiments still rely on a few preliminary studies, the conclusion that acting on these gases presents the potential of very significantly cutting costs of meeting various emissions reduction targets at various points in time is robust. The most critical questions, from a policy point of view, are related to how to compare the relative contribution of these gases in climate forcing. They are indeed characterized by very different residence times in the atmosphere. Criticisms of the use of GWPs are well established but there is currently no consensus about alternatives that can be easily used in optimal control models to study when it would be optimal to abate these gases. This technical difficulty explains why no study has been published so far in a stochastic optimal control framework in a way similar to studies on CO_2 or on biological carbon sequestration. Theoretical analysis suggests however two important conclusions: (1) if the pace of warming in future decades is viewed as a binding constraint (in a cost-efficiency framework) or as causing significant damages, then abating short-lived gases such as CH_4, over the short run, would have a high social value - it would slowdown global warming and gain some time for displaying low cost carbon saving technologies; and (2) if global warming in future decades is viewed as less critical than possible high climate risks beyond given, currently unknown, concentration thresholds, then it would be economically more efficient to trigger abatements of short lived gases only after the resolution of information about these risks in order to facilitate the switching toward very tight concentration constraints.

Further research is needed, to scrutinize more in depth this trade-off, considering that all these gases are emitted by sectors very heterogeneous in terms of economic dynamics and technical inertia. Given the recent work by the economic community to incorporate non-CO_2 gases into analysis of potential GHG mitigation and associated costs, this section looks at the recent EMF - 21 study for assessment of non-CO_2 mitigation. This was done by setting the modelling target of stabilizing radiative forcing at 4.5 W/m^2 compared to pre-industrial levels. Therefore, greenhouse gas emissions in the different models need to be reduced substantially in comparison to each model reference emission scenario. There were two cases or strategy employed to achieve the mitigation target: (1) directly mitigate CO_2 emissions from the energy sector (with some indirect reduction in non-CO_2 gases); and (2) mitigate all available GHG in costs-effective approaches using full 'what' flexibility.

In the CO_2-only mitigation cases the most significant mitigation is from CO_2 emissions that are reduced by about 75 per cent in 2100 compared to baseline. At the same time, there are some emission reductions in CH_4 and N_2O as systemic changes in the energy system, induced by putting a price on carbon, also reduces these emissions. Emissions of CH_4 are reduced by about 20 per cent and N_2O by about 10 per cent. These changes are illustrated in Figure 3.30.

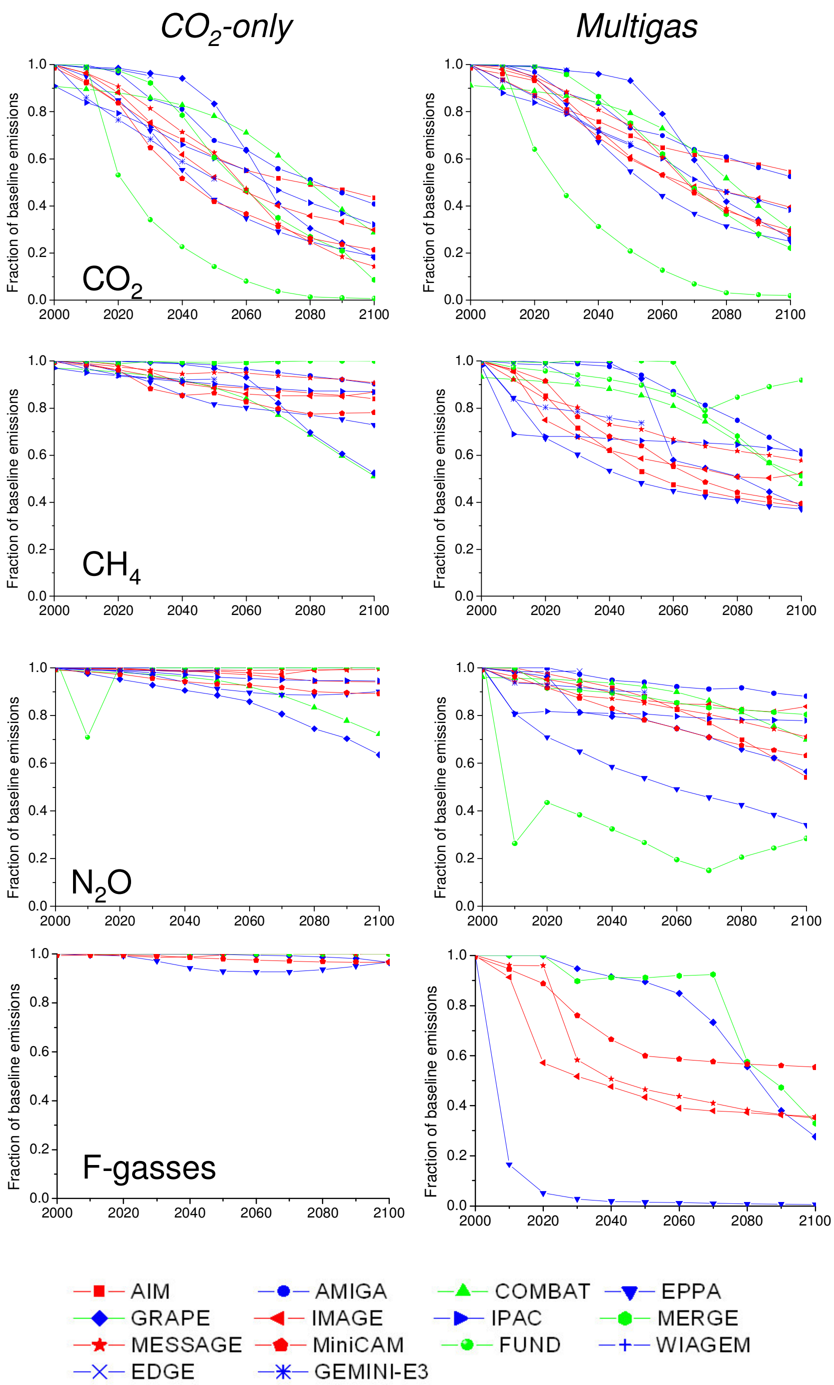


Figure 3.30: *Reduction of emissions in the CO_2-only versus multi-gas strategies*

In the second multigas mitigation scenario, an appreciable percentage of the emission reductions occur through reductions of non-CO_2 gases, which then results in smaller required reductions of CO_2. The emission reduction for CO_2 in 2100 drops (on average) as a result from 75 per cent to 67 per cent. This percentage is still rather high, caused by the large share of CO_2 in total emissions (on average, 60 per cent in 2100) and partly due to exhaustion of reduction options for the of non-CO_2 gases. The reductions of CH_4 across the different models averages around 50 per cent, with remaining emissions coming from sources for which no reduction options were identified, such as CH_4 emissions from enteric fermentation. For N_2O, the increased reduction in the multi-gas strategy is not as large as for CH_4 (almost 40 per cent). The main reason is that the identified potential for emission reductions for the main sources of N_2O emissions, fertilizer use and animal manure, is still limited. Finally, for the fluorinated gases, high reduction rates (about 75 per cent) are found across the different models.

Although the contributions of different gases change sharply over time, there is a considerable spread among the different models. This also can be seen in Figure 3.30. Many models project relatively early reductions of both CH_4 and the fluorinated gases under the multi-gas case. However, the subset of models that does not use GWPs as the substitution metric for the relative contributions of the different gases to the overall target, but does assume inter-temporal optimization in minimizing abatement costs, do not start to reduce CH_4 emissions substantially until the end of the period. The reason for this result is that in aiming at the long-term target, it is less cost effective to engage in early CH_4 emission reductions because CH4 has a short atmospheric life-time (about eleven years). In other words, since the benefits to reducing radiative forcing in the atmosphere are more immediately felt with CH_4 mitigation, these models ‘wait’ to reduce these emissions as the target approaches. In their calculations, there is not much benefit in reducing CH_4 early in the simulation.

The increased flexibility of a multigas mitigation strategy is seen to have significant implications for the costs of stabilization across all models participating in the EMF-21. These scenarios concur that multigas mitigation is significantly cheaper than CO_2-only. The potential reductions of the marginal abatement cost ranges in the majority of the studies between 30 to 85 per cent (See Figure 3.31).

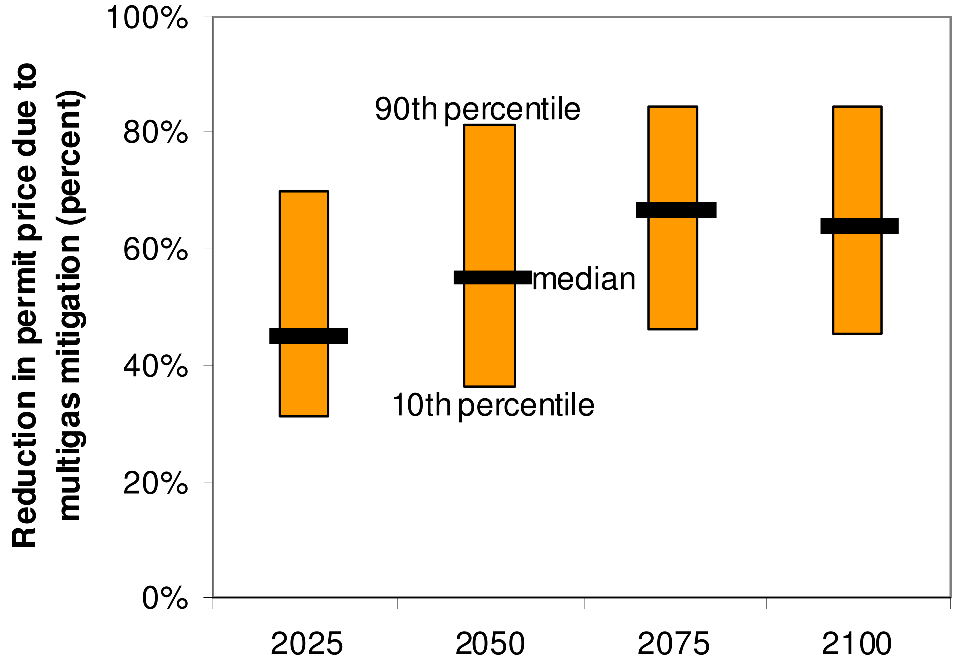


Figure 3.31: *Reduction in marginal carbon abatement cost (percent) in multigas stabilization scenarios compared to CO_2 only cases. Ranges correspond to alternative scenarios for a stabilization target of 4.5 W/m^2. Data source: Weyant and de la Chesnaye, 2005*

Finally, the EMF-21 research also showed that for some sources of non-CO_2 gases, the identified reduction potential is still very limited (e.g. most agricultural sources for N_2O emissions). In particular for long-term scenarios (and more stringent targets) identifying how this potential may develop in time is a crucial research question. Attempts to estimate the maximum feasible reductions (and the development of potential over time) have been made in van Vuuren *et al.*, in press.

3.3.5.5 Land use

Changes in land use practices are regarded as an important component of long-term strategies to mitigate climate change. Modifications to land use activities can reduce emissions of both CO_2 and non-CO_2 gases (CH_4 and N_2O), increase sequestration of atmospheric CO_2 into plant biomass and soils, and produce biomass fuel substitutes for fossil fuels (see Chapters 8, 9, and 4 of this volume for discussions of detailed land related mitigation alternatives). Available information before TAR suggested that land has the technical potential to sequester up to an additional 87 billion tonnes C (GtC) by 2050 in global forests alone (Watson *et al.*, 1995; Watson *et al.*, 2000; IPCC, 2001). In addition, current technologies are capable of substantially reducing CH_4 and N_2O emissions from agriculture (DeAngelo *et al.*, in press; USEPA, 2006b). A number of global biomass energy potential assessments have also been conducted (see Berndes *et al.* (2003) for an overview). Most of the assessments are done with large regional spatial resolutions (exceptions are Fischer and Schrattenholzer, 2001; Sorensen, 1999; and Hoogwijk *et al.*, 2005). These studies provide important characterizations of technical potential that informs analyses that identify cost-effective mitigation strategies, such as stabilization studies. Hoogwijk *et al.* (2005), for example, estimated the potential of abandoned agricultural lands for providing biomass for primary energy demand and identified the technical biomass supply limits of this land type (e.g., under the SRES A2 scenario, abandoned agricultural lands could provide for only 20 per cent of the total energy demand).

The explicit modeling of land based climate change mitigation in long-term global scenarios is relatively new and rapidly developing. As a result, assessment of the long-term role of global land based mitigation was not formally addressed by SRES, the Special Report on Land use, Land-use Change, and Forestry (Watson *et al*., 2000), or the TAR. This section assesses the modeling of land in long-term climate stabilization and the relationship to detailed global forestry mitigation estimates from partial equilibrium sectoral models that model 100-year carbon price trajectories.

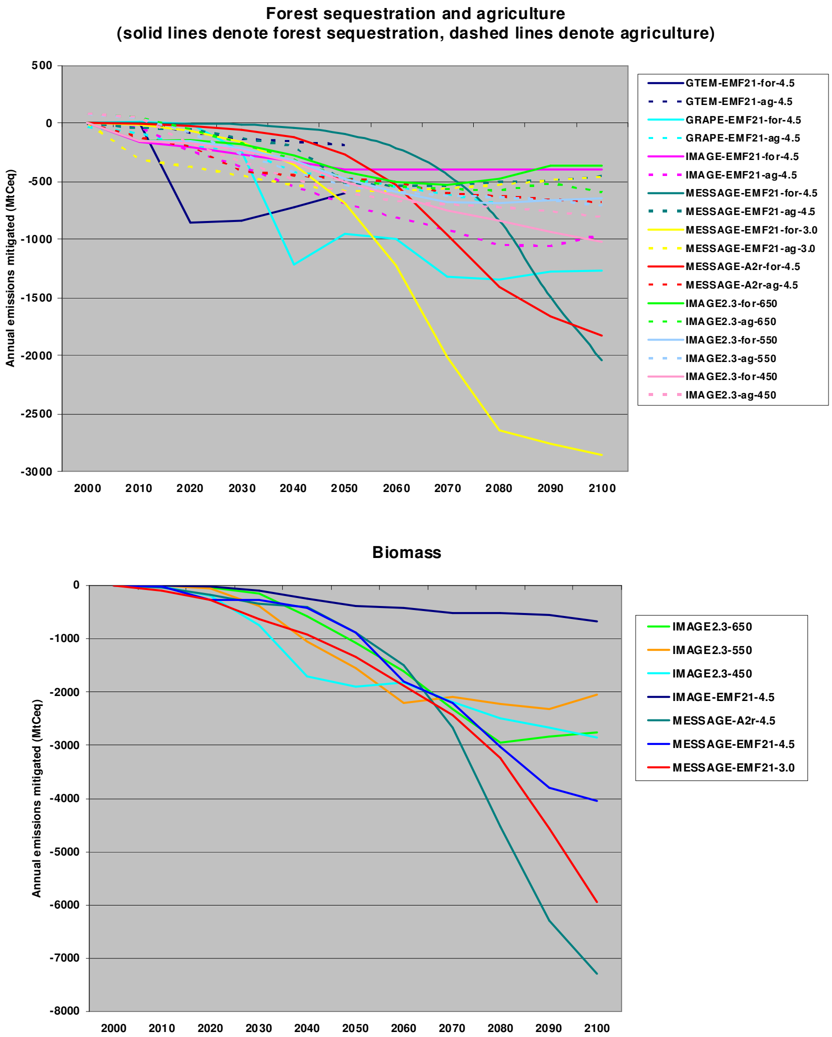
Development of, among other things, global sectoral land mitigation models and bottom-up agricultural mitigation costs has facilitated the formal incorporation of land mitigation in long-term integrated assessment of climate change stabilization strategies (see Table 3.6). Sands and Leimbach (2003) were one of the first to explicitly explore land based mitigation in stabilization, suggesting that the total cost of stabilization could be reduced by including land strategies in the set of eligible mitigation options (energy crops in this case). The Energy Modelling Forum Study-21 (EMF-21) was the first coordinated stabilization modeling effort to include an explicit evaluation of the relative role of land in stabilization. Building on their EMF-21 efforts, some modeling teams have also generated even more recent stabilization scenarios with additional revisions in land modeling. The studies listed in Table 3.6 are conspicuously different in the specifics of their land modelling. Differences in the types of land considered, emissions sources (also see Table 3.1), and mitigation alternatives and implementation imply different opportunities and opportunity costs for land related mitigation; and, therefore, different outcomes.

Table 3.6: *Global long-term land mitigation scenarios modeling overview*

Source	Modeling type	Climate policies	Land-based GHG abatement	Land types modeled
Climate stabilization policy scenarios (2100 stabilization relative to pre-industrial times unless otherwise indicated)				
Sands and Leimbach (2003)	Dynamic iteration between land, economic, and climate models	WBGU (max temperature change of 2 degrees C, max temp change rate of 0.2 degrees C/decade) - energy CO2 mitigation scenarios without non-CO2 reductions and with exogenous non-CO2 reduction	Energy, including bioenergy crops	Managed forest, crop land, pastur unmanaged forest
Kurosawa (in press)	Integrated assessment model	Stabilize radiative forcing at 4.5 W/m2	Agriculture (MACs), forestry (Kurasawa, 2004), biomass (endogenous)	Forest, cropland, grassland
van Vuuren et al. (in press-a)	Integrated assessment model	Stabilize radiative forcing at 4.5 W/m2. Additional stabilization targets also ran (3.7 and 5.3 W/m2). Detailed land mitigation data only available for 4.5 W/m2 scenario.	Agriculture (MACs), afforestation (MACs), biomass primarily for liquid fuels (MACs)	Food crops (e.g., cereals, rice, mai pulses, roots & tubers, oil crops), bio crops, grass & fodder, forest (11 typ 6 other land cover types
Rao and Riahi (in press)	Integrated assessment model	Stabilize radiative forcing at 4.5 and 3.0 W/m2	Agriculture (MACs), forestry (iterated with Sohngen and Sedjo (in press) model for core scenarios; sink and biomass supply curves from DIMA model for sensitivity scenarios), and biomass/geologic sequestration option (endogenous)	Not explicitly modeled for core scena forest, cropland, and forest biomass modeled for sensitivity scenarios
Jakeman and Fisher (in press)	Computable general equilibrium model	Stabilize radiative forcing at 3.6 W/m2 for 2050 (based on 4.5 W/m2 2100 target)	Agriculture (endogenous), forestry (MACs)	Not explicitly modeled
Riahi et al. (in press)	Integrated assessment model	Stabilize radiative forcing at 4.5 W/m2. Numerous additional stabilization targets with alternative baselines. Detailed land mitigation data only available for 4.5 W/m2 scenario.	Agriculture (MACs and AEZ/BLS for crop residue biomass potential), forestry (DIMA sink and biomass supply curves)	Forest, arable land, forest biomass la and urban land
van Vuuren et al. (in press-b)	Integrated assessment model	Stabilize CO2eq concentrations at 650, 550, and 450 ppm.	Agriculture (MACs), afforestation (IMAGE model based MACs), biomass solid & liquid fuels (TIMER energy model MACs)	Food crops (e.g., cereals, rice, mai pulses, roots & tubers, oil crops), bio crops, grass & fodder, forest (11 typ 6 other land cover types
Carbon price policy scenarios(2000 US$ per tonne C)				
Sohngen and Mendelsohn (2003)	Dynamic iteration between partial equilibrium global forestry and energy dynamic optimization models	2 forest carbon price paths: $7.14 (2010) - $61.34 (2100) $21.80 (2010) - $187.54 (2100)	Afforestation, timber harvest rotation length, forest management intensity	Forests - managed and unmanage unique regional forests
Sands and Leimbach (2003)	Partial equilibrium global land-use recursive dynamic model	2 biomass carbon price paths: $31 (2005) - $123 (2050), then constant to 2095; $62 (2005) - $246 (2050), then constant to 2095	Biomass energy crop production	Managed forest, crop land, pastur unmanaged forest
Sathaye et al. (in press)	Partial equilibrium global forestry dynamic optimization model	6 forest carbon price paths: $5 (2010); rising at 5% per year $10 (2010); rising at 5% per year $10 (2010); rising at 3% per year $20 (2010); rising at 3% per year $100 (2010); remaining constant over time. $75 (2010); rising by $5 per year through 2050.	Forestation (short and long rotation), avoided deforestation	Forests, wastelands
Sohngen and Sedjo (in press)	Partial equilibrium global forestry dynamic optimization model (updated from Sohngen and Mendelsohn, 2003)	Same as Sathaye et al. (in press)	Afforestation, timber harvest rotation length, forest management intensity	Forests - managed and unmanage unique regional forests
Sohngen and Mendelsohn (in press)	Partial equilibrium global forestry dynamic optimization model (updated from Sohngen and Mendelsohn, 2003)	Sohngen and Mendelsohn (2003) price paths	Afforestation, timber harvest rotation length, forest management intensity	Forests - managed and unmanage unique regional forests

Four of the modelling teams in the EMF-21 study directly explored the question of the cost-effectiveness of including land based mitigation in stabilization solutions and found that including these options (both non-CO_2 and CO_2) provided greater flexibility and was cost-effective for stabilizing radiative forcing at 4.5 W/m^2 by 2100 compared to pre-industrialized times (Kurosawa, in press; van Vuuren *et al.*, in press-a; Rao and Riahi, in press; Jakeman and Fisher, in press). Jakeman and Fisher, for example, found that including land-use change and forestry mitigation options reduced the emissions reduction burden on all other emissions sources such that the projected decline in global real GDP associated with achieving stabilisation was reduced to 2.3 per cent at 2050 (US$3.6 trillion in 2003 dollars), versus losses of around 7.1 per cent (US$11.2 trillion) and 3.3 per cent (US$5.2 trillion) for the CO_2-only and multi-gas scenarios respectively. Unfortunately, none of the EMF-21 papers isolated the GDP effects associated with biomass fuel substitution or agricultural non-CO_2 abatement. However, given agriculture's small estimated share of total abatement, the GDP savings associated with agricultural non-CO_2 abatement could be expected to be modest overall, though potentially strategically significant to the dynamics of mitigation portfolios. Biomass, on the other hand, may have a substantial abatement role and therefore a large effect of the total mitigation cost of stabilisation. Both of these mitigation opportunities are discussed further below.

Figure 3.32 presents the projected mitigation from forestry, agriculture, and biomass for the EMF-21 4.5 W/m^2 stabilisation scenarios, as well as additional scenarios produced by the MESSAGE and IMAGE models-a 3.0 W/m^2 scenario from Rao and Riahi (in press), a 4.5 W/m^2 scenario from Riahi *et al*. (in press), and 650, 550, and 450 CO_2 equivalent stabilisation scenarios from van Vuuren *et al*. (in press-b) (see Rose *et al*., forthcoming, for a synthesis). Table 3.7 illustrates the relative importance of forestry, agriculture, and biomass in achieving the stabilization targets. While there are clearly different land based mitigation pathways being taken by the models (Figure 3.32) in generating cumulative reductions of 12-124 GtCeq from 2000 to 2100, some general observations can be made. First, energy and industry (excluding biomass) assume approximately 60-80 per cent of the stabilization responsibility over the century. However, forestry, agriculture, and biomass are called upon to provide significant mitigation contributions on the order of 8-43 per cent over the century, with absolute emissions reductions increasing over time and biomass providing most of the cumulative land based mitigation. It is interesting to note that, Sohngen and Mendelsohn (2003) projected forest sequestration could account for a third of total abatement over the century. What is interesting is that the study used a cost-benefit framework, vs. the cost-effectiveness frameworks of the stabilisation studies discussed in this section, that equated global economy-wide marginal climate change mitigation benefits and costs to explicitly exploring the role of global forest sequestration.. Sohngen and Mendelsohn also found that more substantial savings from forest sequestration were realized during the last half of the century.



Source: Rose *et al*. (forthcoming)
Notes: See Figures 3.9 and 3.13 notes for scenario references.

Figure 3.32: *Forest sequestration, agricultural, and biomass emissions reductions from baselines associated with various 2100 stabilisation targets (Note: y-axis' have different ranges)*

Table 3.7: *Global land-based mitigation's share of total emissions reductions for various 2100 stabilisation targets*

		IMAGE-EMF21					MESSAGE-EMF21*					GRAPE-EMF21					MESSAGE-A2r			
Mitigation source		2020	2050	2100	2000-2050	2000-2100	2020	2050	2100	2000-2050	2000-2100	2020	2050	2100	2000-2050	2000-2100	2020	2050	2100	2000-205
Non-land	All GHGs	70%	81%	83%	77%	81%	54%	53%	63%	60%	57%	66%	35%	90%	32%	81%	84%	87%	72%	86%
Forest	CO2	13%	5%	4%	8%	5%	0%	3%	11%	2%	9%	1%	53%	7%	55%	14%	1%	2%	5%	2%
Agriculture	CH4	15%	8%	8%	10%	8%	5%	14%	2%	10%	5%	-4%	1%	1%	12%	2%	4%	3%	2%	4%
	N2O	1%	1%	1%	1%	1%	2%	2%	0%	2%	1%	37%	12%	2%	0%	4%	4%	1%	0%	2%
Biomass	Fuel substitution	na	na	na	na	na	38%	26%	4%	24%	17%	na	na	na	na	na	6%	5%	7%	5%
	Energy with CCS (BECS)	na	na	na	na	na	0%	2%	19%	2%	11%	nm	nm	nm	nm	nm	0%	2%	14%	1%
	Total	1%	5%	5%	4%	5%	38%	28%	23%	25%	28%	na	na	na	na	na	7%	7%	21%	6%
Land totals	%	30%	19%	17%	23%	19%	46%	47%	37%	40%	43%	34%	65%	10%	68%	19%	16%	13%	28%	14%
	GtCeq	-0.5	-1.5	-2.0	-32.4	-124.3	-0.3	-1.5	-6.5	-2.9	-25.4	0.0	-1.2	-2.0	-3.0	-11.9	-0.4	-1.6	-9.8	-3.9

		650 CO2eq. ppm					550 CO2eq. ppm					450 CO2eq. ppm					3.0 W/m2			
		IMAGE2.3					IMAGE2.3					IMAGE2.3					MESSAGE-EMF21			
Mitigation source		2020	2050	2100	2000-2050	2000-2100	2020	2050	2100	2000-2050	2000-2100	2020	2050	2100	2000-2050	2000-2100	2020	2050	2100	2000-205
Non-land	All GHGs	78%	71%	76%	74%	73%	79%	76%	82%	76%	79%	81%	78%	78%	78%	79%	70%	69%	61%	69%
Forest	CO2	14%	6%	2%	8%	4%	11%	5%	3%	6%	4%	6%	4%	5%	4%	4%	3%	8%	12%	6%
Agriculture	CH4	1%	5%	3%	3%	3%	2%	3%	3%	3%	3%	4%	3%	3%	3%	3%	12%	6%	2%	8%
	N2O	4%	2%	1%	3%	2%	4%	2%	1%	2%	1%	3%	2%	1%	2%	1%	4%	1%	0%	3%
Biomass	Fuel substitution	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	11%	13%	1%	13%
	Energy with CCS (BECS)	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	1%	3%	24%	2%
	Total	3%	16%	18%	12%	18%	4%	15%	11%	13%	13%	7%	14%	14%	14%	13%	12%	16%	25%	15%
Land totals	%	19%	13%	6%	14%	9%	16%	10%	7%	11%	8%	13%	8%	9%	9%	8%	30%	31%	39%	31%
	GtCeq	-0.2	-2.0	-3.7	-6.7	-40.8	-0.3	-2.6	-3.4	-9.6	-44.3	-0.5	-3.0	-4.7	-13.2	-51.9	-0.7	-2.6	-9.3	-6.8

Source: Rose et al. (forthcoming)
Notes:
** Results based on the 4.5 W/m2 MESSAGE scenario from the sensitivity analysis of Rao and Riahi (in press).*
The GTEM scenarios ran through 2050 and the GTEM land mitigation totals include fossil fuel co2 emissions reductions in agriculture. The GRAPE model projected an increase in CH4 emissions in 2020.
nm = not modeled, na = data not available

The potential timing of land-based mitigation varies across stabilization scenarios. Agriculture and forestry mitigation options are thought to be cost effective near term abatement strategies, and many of the stabilization scenarios presented support that perspective, with these options contributing as much as 60 per cent and 65 per cent of mitigation in 2020 and 2050 respectively. However, while some scenarios project that forest sequestration will have its largest relative mitigation role in the initial decades, other scenarios suggest that the role of forest sequestration will peak in the middle of the century and continue to contribute a substantial share through 2100. In general, the overall mitigation role of non-CO_2 agricultural abatement of rice and livestock methane (enteric and manure) and soil nitrous oxide is projected to be modest throughout the time horizon, with some suggestion of increased importance in early decades. Land results from Rao and Riahi (in press) also find that a more aggressive stabilization policy might require shifting additional mitigation responsibility to agriculture early in the century and forestry later in the century. This pattern is not evident in the results from van Vuuren *et al*. (in press-b).

Some of the recent studies suggest that biomass could be essential to stabilization, especially as a negative emissions strategy that combines biomass with CO_2 capture and storage (CCS, capture of combustion CO_2 emissions for sequestration in geologic formations)-e.g, Rao and Riahi, in press; Riahi *et al*., in press; van Vuuren *et al*., in press-b; as well as developing scenario exercises, such as those from the US Climate Change Science Program, USCCSP, forthcoming). Across scenarios, absolute emissions reductions from biomass are projected to grow slowly in the first half of the decade and then rapidly in the second half as new biomass processing and mitigation technologies become available. Figure 3.32 suggests biomass mitigation of up to 2 GtC in 2050 and 2 to 7 GtC in 2100. Modeled demands for biomass include electric power and end use sectors (transportation, buildings, industry, and non energy uses). Without CCS, electric power is projected to dominate biomass demand in the initial decades and, in general, with less stringent stabilization targets. Later in the decade and for more stringent targets, transportation is projected to dominate biomass use. When biomass is combined with CCS, biomass mitigation shifts to the power sector to take advantage of the net negative emissions from the combined abatement option. However, further research is merited to more fully characterize biomass' long-term mitigation potential, especially in terms of the opportunity costs of land and utilization alternatives, infrastructure possibilities, geologic formation characterisation, biomass supply requirements, cost estimates (collection, transportation, and processing), conversion technologies, land area requirements and constraints, and ecosystem externalities. In particular, present studies are relatively poor in representing land competition with food supply and timber production, which has a significant influence on the economic potential of bio-energy crops (an exception is Sands and Leimbach, 2003).

A brief comparison of land related results from 4.5 W/m^2 scenarios of Rao and Riahi, who use a SRES B2 reference, and Riahi *et al*., who use, among other things, a revised SRES A2 reference (see Grübler *et al*., in press), illustrates the importance of constraints on biomass potential as well as baselines in general and their potential influence on projected land outcomes. With greater population growth, food demand, and greater reliance on coal, more emissions are generated in the revised A2 reference and, therefore, more mitigation is required from the conventional technologies characteristic of A2. Biomass GHG mitigation is also greater (Figure 3.32). However, biomass is not able to maintain its relative role, slipping from 28 per cent to 14 per cent of total mitigation over the century. This result illustrates the limits-both ecological and economic-to biomass mitigation (see also Figure 3.27).

Terrestrial mitigation projections are expected to be regionally unique, while still linked across time and space by changes in global physical and economic forces. Rao and Riahi (in press) provide a glimpse into the possible regional role of land mitigation when reconciled with a full set of mitigation alternatives in identifying the most cost effective mitigation portfolios without any consideration of who might actually pay for mitigation. Rao and Riahi discuss the different potential role of agricultural mitigation (not inclusive of bioenergy crops) across industrialized and developing country groups, finding that: (a) agriculture is expected to be a larger share of the developing countries' mitigation portfolio at 7 per cent in 2020, 12 per cent in 2050, and 6 per cent in 2100 versus 1, 4 and 1 per cent respectively for industrialized countries; and (b) developing countries are likely to assume responsibility for the large majority of the agricultural mitigation (72 per cent in 2020, 81 per cent in 2050, and 82 per cent in 2100). Some regional forest mitigation results are discussed below.

Integrated assessment models have relied on detailed sectoral models or engineering studies to model the costs of forest and agricultural mitigation respectively. One of three approaches can be used to integrate land mitigation costs into climate CGE and integrated assessment models: (1) input exogenous abatement/sequestration cost schedules (e.g., Kurosawa used schedules from DeAngelo *et al*., in press; Criqui *et al*., in press, used curves from the Agripol global agricultural model; Jakeman and Fisher, in press, used sequestration curves from the global forestry model of Sohngen and Sedjo, in press); (2) iterate with land sector models (e.g., Sands and Leimbach, 2003; Sohngen and Mendelsohn, 2003; Rao and Riahi, in press); or (3) employ internally endogenized responses. The third option requires that land input use be explicitly modelled, therefore, until recently, most models could only entertain the first or second of these options. Endogenizing mitigation with the second or third option requires different strategies and presents unique challenges for forestry, agriculture, and biomass. While forestry mitigation strategies are not novel, modelling forest investment behaviour requires dynamic optimization modelling capable of considering future markets (vs. recursive modelling). For agriculture, modelling of the detailed mitigation actions and technologies represented in agricultural abatement schedules requires the use of techniques like those employed for modelling non- CO_2 GHG mitigation for energy and industry sectors (Hyman *et al*., 2003). Finally, biomass production is a relatively new economic sector that lacks historical data, which makes model calibration more difficult.

With many of the integrated assessment models calling on the services of sectoral models, it is natural to ask what long-term mitigation do the sectoral land economic models project? The sectoral models use exogenous carbon price paths to simulate different climate policies and assumptions, where the starting point and rate of increase are determined by factors such as the aggressiveness of the abatement policy, abatement option and cost assumptions, and the social discount rate (Sohngen and Sedjo, in press). Figure 3.33 plots the carbon price paths inferred from many of the stabilisation scenarios discussed in this subsection (solid lines). These are the carbon equivalent price trajectories that would have produced mitigation results identical to that produced for stabilization. Figure 3.33 also plots the carbon price paths from recent global sectoral mitigation studies (dashed lines; Sohngen and Sedjo, in press; Sathaye *et al*., in press; Sands and Leimbach, 2003). Sohngen and Sedjo and Sathaye *et al*. consider forest carbon price paths with forest lands, while Sands & Leimbach evaluate biomass carbon price paths and explicitly model economic competition between alternative global land uses.

Stabilization (e.g., EMF-21, discussed above) and optimal (Sohngen and Mendelsohn, 2003) climate abatement policies suggest that carbon prices will rise over time. Table 3.8 compares the forest mitigation outcomes from stabilization and sectoral scenarios that have similar carbon price trajectories. Rising carbon prices will provide incentives for additional forest area, longer rotations, and more intensive management to increase carbon storage. Table 3.8 shows that the vast majority of forest mitigation is projected to occur in the second half of the century, with tropical regions in most cases assuming a larger share of global forest sequestration/mitigation than temperate regions. Lower initial carbon prices can shift early period mitigation to the temperate regions since, at that time, carbon incentives are inadequate for arresting deforestation. The sectoral models project that tropical forest mitigation activities are expected to be heavily dominated by land use change activities (reduced deforestation and afforestation), while land management activities (increasing inputs, changing rotation length, adjusting age or species composition) are expected to be the slightly dominant strategies in temperate regions. The sectoral models, in particular, Sohngen and Sedjo, suggest substantially more mitigation in the second half of the century. A number of factors are likely to be contributing to this deviation from the integrated assessment model results. First and foremost, is that Sohngen and Sedjo explicitly model future markets, which none of the integrated assessment models are currently capable of doing. Therefore, a low carbon price that is expected to increase rapidly results in a postponement of additional sequestration actions in Sohngen and Sedjo until the price (benefit) of sequestration is greater. Endogenously modeling forest biophysical and economic dynamics will be a significant future challenge for integrated assessment models. Conversely, the integrated assessment models may be producing a somewhat more muted forest sequestration response given their explicit consideration of available mitigation alternatives across sectors and regions, and, in some cases, land use alternatives.

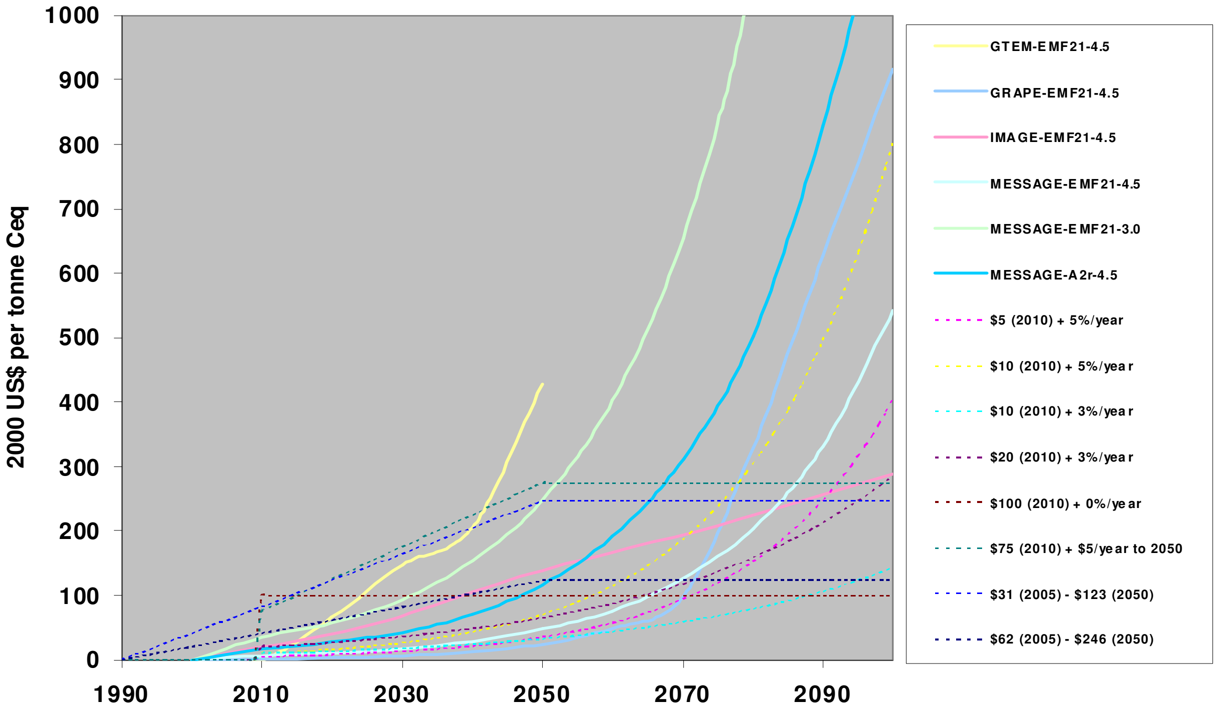


Figure 3.33: *Stabilisation and hypothetical carbon price paths (stabilisation denoted with solid lines, hypothetical denoted with dashed lines)*

Table 3.8: *Cumulative forest carbon gained above baseline by 2020, 2050 and 2100 from long term global forestry and stabilisation scenarios (GtC)*

$10 (2010) + 5% per year				
		2020	**2050**	**2100**
Sathaye et al. (in press)	World	na	24.9	96.5
	Temperate	na	6.9	32.4
	Tropics	na	15.0	66.0
Sohngen and Sedjo (in press)	World	0.0	6.2	146.6
original baseline	Temperate	0.9	2.2	56.7
	Tropics	-0.9	4.0	89.9
Sohngen and Sedjo (in press)	World	0.4	4.1	132.9
accelerated deforestation baseline	Temperate	0.3	3.3	58.0
	Tropics	0.2	0.8	75.0
Stabilisation at 4.5 W/m2 by 2100				
		2020	**2050**	**2100**
GRAPE-EMF21	World	-0.2	19.2	79.6
	Temperate	0.0	2.7	12.3
	Tropics	-0.1	16.5	67.3
IMAGE-EMF21	World	2.4	11.3	31.1
	Temperate	2.1	9.1	24.8
	Tropics	0.3	2.2	6.3
MESSAGE-EMF21*	World	0.0	0.9	41.6
	Temperate	0.0	0.0	6.4
	Tropics	0.0	0.9	35.2

Source: Stabilisation data assembled from Rose et al. (forthcoming)
Notes:
** Results based on the 4.5 W/m2 MESSAGE scenario from the sensitivity analysis of Rao and Riahi (in press).*
Tropics: Central America, South America, Sub-Saharan Africa, South Asia, Southeast Asia
Temperate: North America, Western and Central Europe, Former Soviet Union, East Asia, Oceania, Japan
na = data not available

There are a number of other important outcomes from changes in land that should be tracked and reported in order to properly evaluate long-term land mitigation. Of particular importance to climate stabilization are the albedo implications of land use change, which can offset emissions reducing land use change, as well as the potential climate driven changes in forest disturbance frequency and intensity that could affect the effectiveness of forest mitigation strategies. Non-climate implications may also need to be considered. As shown in the Millennium Ecosystem Assessment (2005), land use has implications for social welfare (e.g., food security, clean water access), environmental services (e.g., water quality, soil retention), and economic welfare (e.g., output prices and production).

A number of relevant key baseline land modelling challenges have already been discussed in Sections 3.2.1.3 and 3.2.2.2. Central to future long-term land mitigation modelling are improvements in the dynamic modelling of regional land use and land use competition and mitigation cost estimates. The total cost of any land based mitigation strategy should include the opportunity costs of land, which are dynamic and regionally unique functions of changing regional bio-physical and economic circumstances. Other important issues include evaluation of key baseline input sensitivities and narrowing the range of acceptable values (e.g., crop productivity in Sands and Leimbach, 2003; land supply and harvesting costs in Sohngen and Mendelsohn, in press), and improvements in mitigation cost estimates for agriculture to address uncertainties due to the novel and detailed mitigation technologies represented and land heterogeneity, which imply data limitations and uncertainty about adoption and marginal responses.

In summary, recent stabilization studies have found that including landuse mitigation options (both non-CO_2 and CO_2) provides greater flexibility and cost-effectiveness. Even if land activities are not considered as mitigation alternatives by policy, landuse is crucial in climate stabilization for its significant atmospheric inputs and withdrawals (emissions, sequestration, and albedo), as well as its susceptibility to changes in the atmospheric condition. The explicit modeling of land based climate change mitigation in long-term global scenarios is relatively new and rapidly developing. Forestry, agriculture, and biomass are called upon to provide significant mitigation contributions in recent stabilisation scenarios. In some scenarios, biomass (energy and liquid fuel) is essential to stabilisation, especially as a negative emissions strategy that combines biomass energy with CO_2 capture and storage, where biomass potential is defined by key factors, in particular oil prices, food demand, and conversion capacity. Agriculture and forestry mitigation options are projected to be cost effective near term abatement strategies in some stabilization scenarios, but not all. Global forestry models project greater additional forest sequestration than found in stabilization scenarios, a result attributable in part to differences in the modelling of forest dynamics and general economic feedbacks. Despite recent model development, there are still significant opportunities for improving baseline and mitigation land use scenarios.

3.3.5.6 Air Pollutants, including co-benefits

Quantitative analysis on a global scale for the implications of climate mitigation for air pollutants such as SO_2, NO_x, CO, VOC, BC and OC, are relatively scarce. Many of these gases have local and regional impacts on human health and the ecosystem. Information on these gases is also missing in the most recent scenario database (Nakicenovic, *et al.* 2006; Hanaoka *et al.* 2006), which was used in the previous sections to analyze scenario ranges for GHGs.

Air pollutants and greenhouse gases are often emitted by the same sources, and changes in the activity of these sources affect both types of emissions. Previous studies have focused on purely ancillary benefits to air pollution that accrue from a climate mitigation objective but recently there is a focus on integrating air quality and climate concerns, thus analyzing the co-benefits of such policies. Several recent reviews have summarized the issues related to such benefits (OECD 2000, OECD 2003). They cover absolute air pollutant emission reductions, monetary value of reduced pollution, the climatic impacts of such reductions and the improved health effects due to reduced pollution.

The magnitude of such benefits largely depends on the assumptions on future policies and technological change in the baseline against which they are measured, as discussed in Morgensten (2000). For example, Smith *et al.* (2005) and Rao *et al.* (2005) assume an overall growth in environmental awareness with increased affluence in the baseline scenario and thus reduced air pollution even in absence of any climate policies. As seen in Rao *et al.* (2005) inclusion of current and future legislation for local pollution in the baseline scenario can imply a significant decline in such emissions and thus affect the available potential for additional climate policy related benefits. The pace of this trend differs significantly across pollutants and baseline scenarios and may or may not have an obvious effect on greenhouse gases. An added aspect of ancillary benefit measurement is the representation of technological options. Some emissions control technologies reduce both air pollutants and greenhouse gases, like selective catalytic reduction (SCR) on gas boilers that reduces not only NO_x, but also N_2O, CO and CH_4 (IPCC, 1997), But there are also examples where, at least in principle, emission control technologies aimed at a certain pollutant could increase emissions of other pollutants. For example, the substitution of more fuel-efficient diesel engines for gasoline engines might lead to higher PM/black carbon emissions (Kupiainen and Klimont 2004). Thus estimating co-benefits of climate mitigation should include adequate sectoral representation of emission sources, a wide range of substitution possibilities, assumptions on technological change and a clear representation of current environmental legislation.

Only a few studies have explored the longer term ancillary benefits of climate policies. Alcamo *et al.* (2002) assess in detail the linkages between regional air pollution and climate change in Europe over the period 1990-2100 and suggest that the overlap areas of regional air pollution and climate change may be considerable after 2050. However, Mayerhofer *et al.* (2002) suggest that air pollution policies in Europe will play a greater role in air pollutant reductions than climate policy after 2050. Smith and Wigley (in press) suggest that there will be a slight reduction in global sulfur aerosols as a result of long-term multigas climate stabilization. Rao *et al.* (2005) and Smith and Wigley (in press) find that climate policies can reduce cumulative BC and OC emissions by providing the impetus for adoption of cleaner fuels and advanced technologies. In addition, the inclusion of co-benefits for air pollution can have significant impacts on the cost effectiveness of both the climate policy and air pollution policy under consideration. Van Harmelen *et al.* (2002) find that to comply with agreed upon or future policies to reduce regional air pollution in Europe, mitigation costs are implied, but these are reduced by 50-70 per cent for SO_2 and around 50 per cent for NO_x when combined with GHG policies.

The different spatial and temporal scale of greenhouse gases and air pollutants is a major difficulty in evaluating ancillary benefits. Swart *et al.* (2004) stress the need for new analytical bridges between these different spatial and temporal scales. Rypdal (2005) suggests the possibility of including some local pollutants like CO and VOCs in global climate agreement with others like NO_x and aerosols being regulated by regional agreements. Another difficulty in calculating the ancillary benefits is the large uncertainty associated with the climate effect of reduced air pollutant emissions. Some air pollutants like sulphate and carbonaceous aerosols exert radiative forcing and thus global warming. For example, Smith and Wigley (in press) find that the attendant reduced aerosol cooling from sulphates can more than offset the reduction in warming that accrues from reduced GHGs. On the other hand, air pollutants such as NO_x, CO and VOC act as indirect greenhouse gases having an influence for example via their impact on OH radicals and therefore the lifetime of direct greenhouse gases (e.g., methane and HFC). Further, the climatic effects of some pollutants like BC and OC aerosols remain unclear.

While there has been a lot of recent research in estimating co-benefits of joint GHG and air pollution policies, most current studies do not have a comprehensive treatment of co-benefits in terms of reduction costs and the related health and climate impacts in the long-term, thus indicating the need for more research in this area.

3.3.5.7 Regional and national mitigation scenarios and costs

3.3.6 Characteristics of regional and national mitigation scenarios

Table 3.9 summarizes a selection of national mitigation scenarios. There are broadly two types of national scenarios with focus on climate mitigation. First, there are scenarios that study mitigation options and related costs under a given national emissions cap and trade regime. Second, there are national scenarios that focus on the evaluation of climate mitigation measures and policies in the absence of specific emissions targets. The former type of analysis has been mainly undertaken in the studies in the EU and Japan. The latter type has been explored in the United States, Canada and Japan. In addition, there is also an increasing body of literature, mainly in developing countries, which analyses national GHG emissions in the context of their domestic concerns such as energy security and environmental co-benefits. Many of these analyses do not explicitly address emissions mitigation. In contrast to global studies, regional scenario analyses have focused on shorter time horizons typically up to between 2030 and 2050.

A number of scenario studies have been conducted for various countries within Europe. These studies explore a wide range of emission caps, taking into account local circumstances and potentials for technology implementation. Many of these studies have used specific burden sharing allocation schemes, like the contraction and convergence (C&C) approach for calculating the allocation of worldwide emissions to estimate national emissions ceilings. The United Kingdom's Energy White Paper (DTI, 2003) examined measures to achieve a 60 per cent reduction in CO_2 emissions as compared to the current level by 2050. Several studies have explored renewable energy options, for example, the possibilities of expanding the share of renewable energy and the resulting prospects for establishing clean hydrogen production from renewable energy sources in Germany (Deutscher Bundestag, 2002; Fischedick and Nitsch, 2002; Fischedick *et al.*, 2005). A European study, the COOL project (Tuinstra, 2002) has explored the possibilities of reducing emissions in the Netherlands by 80 per cent in 2050 compared to 1990 levels. In France, the Inter Ministerial Task Force on Climate Change (MIES, 2004) has examined mitigation options that could lead to significant reductions in per person emissions intensity. Savolainen *et al.* (2003) and Lehtila *et al.* (2005) have conducted a series of scenario analyses in order to assess technological potentials in Finland for a number of options, including wind power, electricity saving possibilities in household and office appliances, and emission abatement of fluorinated GHGs.

Scenario studies in the United States have explored the implications of climate mitigation for energy security (Hanson *et al.*, 2004). For example, Mintzer *et al.* (2003) developed a set of scenarios describing three divergent paths for US energy supply and use from 2000 through 2035. These scenarios were used for the identification of key technologies, important energy policy decisions, and strategic investment choices that may enhance energy security, environmental protection, and economic development.

A wide range of scenario studies have also been conducted to estimate the potential emissions reductions and the associated costs for Japan. For example, Masui *et al.* (2006) developed a set of scenarios that explore the implications of severe emissions cut backs between 60 and 80 per cent CO_2 by 2050 (compared to 1990). Another important study by Akimoto *et al.* (2004) evaluates the possibilities of introducing the carbon capture and storage (CCS) option and its economic implications for Japan.

National scenarios pertaining to developing countries such as China and India mainly analyze future emission trajectories under various scenarios that include considerations like economic growth, technology development, structure changes, globalization of world markets, and impacts of mitigation options. Unlike the scenarios developed for the European countries, most of the developing country scenarios do not specify limits on emissions (van Vuuren *et al.*, 2003; Jiang and Hu, 2005). Chen (2005) shows that structural change can be a more important contributor than technology efficiency improvement for CO_2 reduction.

***Table 3.9:** List of national scenarios*

	Author/Agency	Model	Time Horizon	Target Variables	Base year	Target of Reduction
U.S.A.	Hanson et al. (2004)	AMIGA[1]	2000-2050	-	2000	(about 44% in 2050)
Canada	Natural Resource Canada[NRCan] (2000)	N.A.	2000-2050	GHG emission	2000	(53% in 2050)
India	Nair et al. (2003)	Integrated modeling framework [1,3]	1995-2100	cumulative CO2 emission		550 ppm, 650ppm
	Shukla et al. (2005)	ERB[2]	1990-2095	CO2 emission		550 ppm
	Garg et al. (2003)	MARKAL[3], AIM/Enduse[3]	2000-2035	cumulative CO2 emission		7% from reference by 2035
China	Wenying Chen (2005)	MARKAL-MACRO[2,3]	2000-2050	CO2 emission	reference	5%-45% in 2050
	van Vuuren et al. (2003)	IMAGE/TIMER [2,4]	1995-2050	GHG emission	1995	-
	Jiang et al. (2003)	IPAC-emission[2,3]	1990-2100	GHG emission	1990	-
Netherlands	COOL (2002)		1990-2050	GHG emission	1990	80% in 2050
Germany	Deutscher Bundestag (2002)	WI[4], IER	2000-2050	CO2 emission	1990	80% in 2050
UK	Department of Trade and Industry[DTI] (2003)	MARKAL[3]	2000-2050	CO2 emission	2000	45%, 60%, 70% in 2050
Sweden	Ministry of the Environment (2003)	N.A.	2000-2050	GHG emission	1990	4.5tCO2eq / capita (about 50% in 2050)
France	Interministerial Task Force on Climate Change[MIES]	N.A.	2000-2050	CO2 emission	2000	0.5 tC/cap (70% in 2050)
Japan	Ministry of the Environment (2005)	AIM/Material[1] MENOCO[4]	2000-2050	CO2 emission	1990	60-80% in 2050
	Ministry of Economy, Trade and Industry (2005)	GRAPE[3]	2000-2100	CO2/GDP	2000	1/3 in 2050 1/10 in 2100
	Masui et al. (2005)	AIM/Material[1]	2000-2050	CO2 emission	1990	74% in 2050
	Akimoto (2004)	Optimization model[3]	2000-2050	CO2 emission	2000	0.5% / yr (21% in 2050)
	Japan Atomic Industrial Forum [JAIF] (2005)	MARKAL[3]	2000-2050	CO2 emission	2010 (1990)	40% in 2050

1: CGE type top-down model, 2: other type top-down model, 3: bottom-up technology model with optimization, 4: bottom-up technology model without optimization.

The scenario construction for India pays specific attention to developing country dynamics underlying the multiple socio-economic transitions during the century, including demographic transitions. Other issues addressed are the relationship between GHG emissions and local pollutants (Garg *et al.,* 2003) and potential shifts away from coal intensive baselines to the use of natural gas and renewables (Nair *et al*., 2003). Shukla *et al.* (2006) discuss the Indian GHG emissions pathways constructed along the lines of global SRES scenarios and examine socio-economic and technological transitions that would underlie the different non-intervention scenarios, besides assessing how a global stabilization target such as 550 ppmv would further influence these transitions.

There are several country scenarios that consider drastic reduction of CO_2 emissions. In one study rates of improvement of energy intensity and carbon intensity increase by about two to three times their historical levels in the scenarios with a 60-80 per cent reduction of CO_2 in 2050 are contemplated (Kawase *et al.*, 2006).

Table 3.10 summarizes scenarios with more than 40 per cent CO_2 reductions from 2000 to 2050 in several developed countries. In addition, some Chinese scenarios have also been included that report drastic reductions compared with the reference case. Physical indicators of the Chinese economy indicate that in most sectors efficiency is below the OECD average, thus providing a greater scope for improvement. (Jiang *et al.*, 2003; Masui *et al.*, 2006; Akimoto *et al.*, 2004; JAIF, 2004; Hanson *et al.*, 2004; DTI, 2003; Radanne , 2004; Deutscher Bundestag, 2003; NRCan, 2000; Treffersa *et al.*, 2005; Tuinstra *et al.*, 2002; Van Vuuren *et al.*, 2003). It should be noted that comparison of energy intensity of the Chinese economy on the basis of market exchanges rates to OECD averages suggests even larger differences, but this is very misleading given the differences in purchasing power (PPP corrected energy intensity data gives a somewhat better basis for comparison but still suffers from uncertainty about data and different economic structures).

Table 3.10: *Developed countries scenarios with more than 40% reduction as compared to 2000 emissions, and some Chinese scenarios: CO_2 emission changes from 2000 to 2050; Energy intensity and carbon intensity in 2000, and changes from 2000 up to 2050*

Country	CO_2 emission change [%] (2000-2050) ◆: BaU scenarios ○: Intevention scenarios +: Drastic reduction scenarios (more than 40%)	Intensities in 2000		Annual change in energy intensity and carbon intensity		
		Energy intensity [toe /1000 95$]	Carbon intensity [ton CO_2 /ktoe]	Annual change in energy intensity (2000-2050)	Annual change in carbon intensity (including CCS) (2000-2050)	Share of CCS in carbon intensity reduction (2000-2050)
China	59.5 … 377.8	0.97	2.61	-4.02 … -2.47	-1.04 … -0.33	0
Japan	-74.2 … 33.9	0.09	2.26	-2.82 … -0.82	-1.87 … -0.73	0; 36.9 … 58.14
Germany	-76.0 … -15.9	0.13	2.43	-2.83 … -1.41	-2.73 … -1.28	0; 78.3 … 84.2
France	-69.8 … 38.8	0.15	1.46	-2.26 … -1.33	-2.65 … -1.75	0; 61.4 … 100
UK	-69.9 … -11.3	0.18	2.26	-3.05 … -2.52	-2.39 … -0.61	4.10 … 79.9
USA	-46.2 … 65.7	0.26	2.47	-2.70 … -2.20	-1.29 … -0.54	38.8 … 65.5

Each country's scenarios report a wide range of improvement in energy intensity and carbon intensity. The maximum annual energy intensity improvement across countries ranges from 2.26 per cent (France) to 4.02 per cent (China). The maximum annual carbon intensity improvement varies from 1.04 per cent (China) to 2.73 per cent (Germany).

In the countries with low energy intensity levels in 2000 such as Japan, Germany and France, drastic CO_2 reductions are achieved by carbon intensity improvement means such as shifting to natural gas in the United Kingdom, renewable energy in the Netherlands, and CCS in certain scenarios in France, Germany and the United Kingdom. France has a scenario where CCS accounts for 100 per cent of carbon intensity improvement. Most the scenarios with drastic CO_2 reductions for the United States and the United Kingdom assume the introduction of CCS.

Figure 3.34 shows the change in energy mix corresponding to the scenarios considered in Table 3.10. Most of the scenarios assume lower usage of coal. The UK scenario assumes a shift to gas up to 58.9 per cent. Nuclear use in France is assumed to be 65 per cent. In the Netherlands scenario, the contribution of renewables is the highest at 77.3 per cent. In various Japanese scenarios, the share of nuclear energy ranges from 0 to 40 per cent and that of renewables from 0 to 60 per cent. In Chinese scenarios, the share of nuclear is about 4 per cent and that of renewables is about 10 per cent. The share of coal ranges from 35 to 62 per cent.

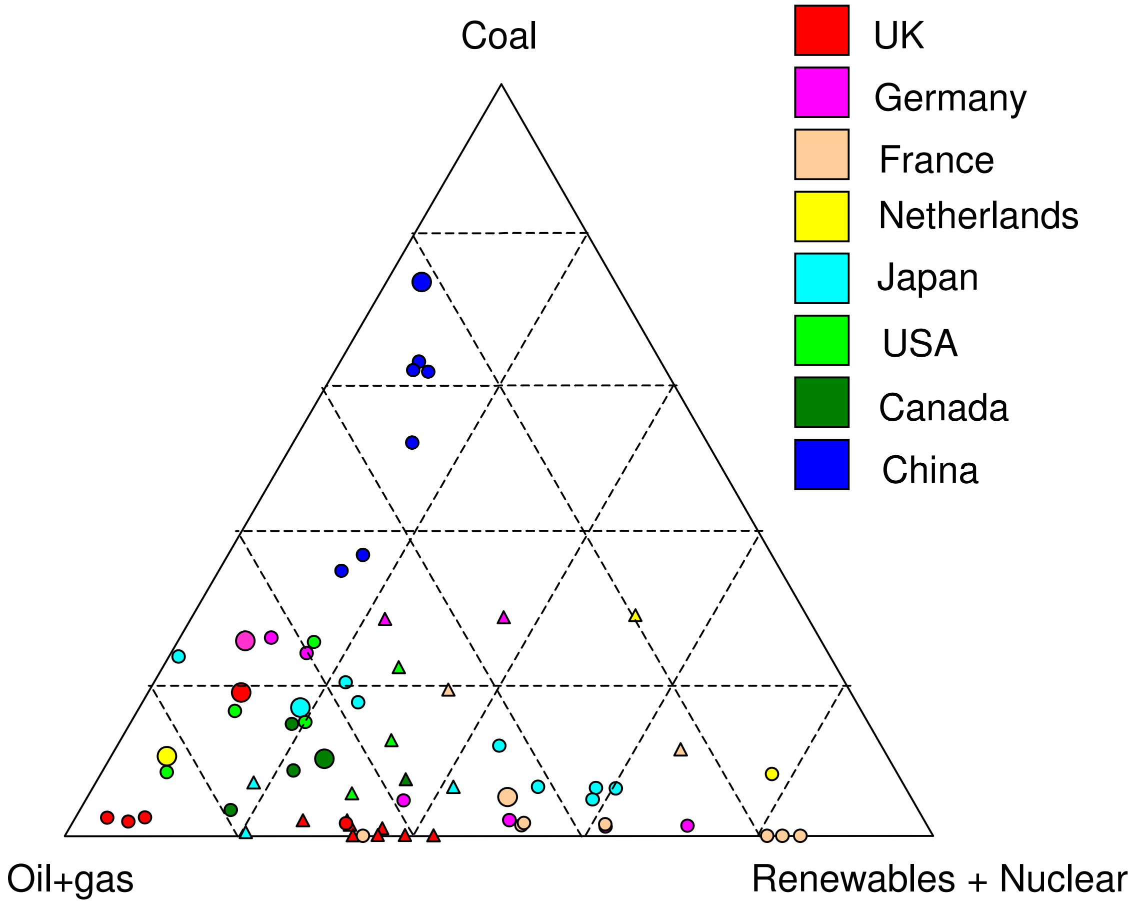


Figure 3.34: *Share of energy resources in 2000 and 2050. Large circle symbols indicate the values in 2000. Small circles and triangles indicate the values in 2050. The triangle symbols indicate the scenarios that has CCS contribution with greater than 5% in the total reduction of* CO_2 *emissions*

3.3.6.1 Costs of mitigation in regional and country scenarios

TAR (IPCC, 2001) shows the incremental cost of reducing a tonne of carbon in 2010 in developed regions such as the United States, OECD-Europe, Japan, and CANS (Canada, Australia, and New Zealand). TAR reports a wide range of carbon taxes across different countries, from about 50 to about 1000 in 1990 US$/tC.

Figure 3.35 shows the relationship between carbon tax and the CO_2 mitigation rate from the baseline in 2050 in some major countries such as the United States, Japan, EU-15, India, China, Former Soviet Union (FSU) and Eastern Europe taken from the literatures since TAR. In the range of carbon tax 50 to 250 US$2000/tC, the amount of carbon reduction varies widely across scenarios and countries. For example, with a low carbon tax rate in the range of 50 to 100 US$2000/t-C, some scenarios show low CO_2 reduction from baseline, such as in Japan and EU-15. On the other hand, there are some scenarios where high CO_2 reduction is expected with a low carbon tax rate not only in China and India but also in the United States. However, with a high carbon tax in the range of 250 to 500 US$2000/t-C, more CO_2 reduction is expected in China and India, whereas relatively lower reductions are projected in developed countries such as the United States, Japan and EU-15.

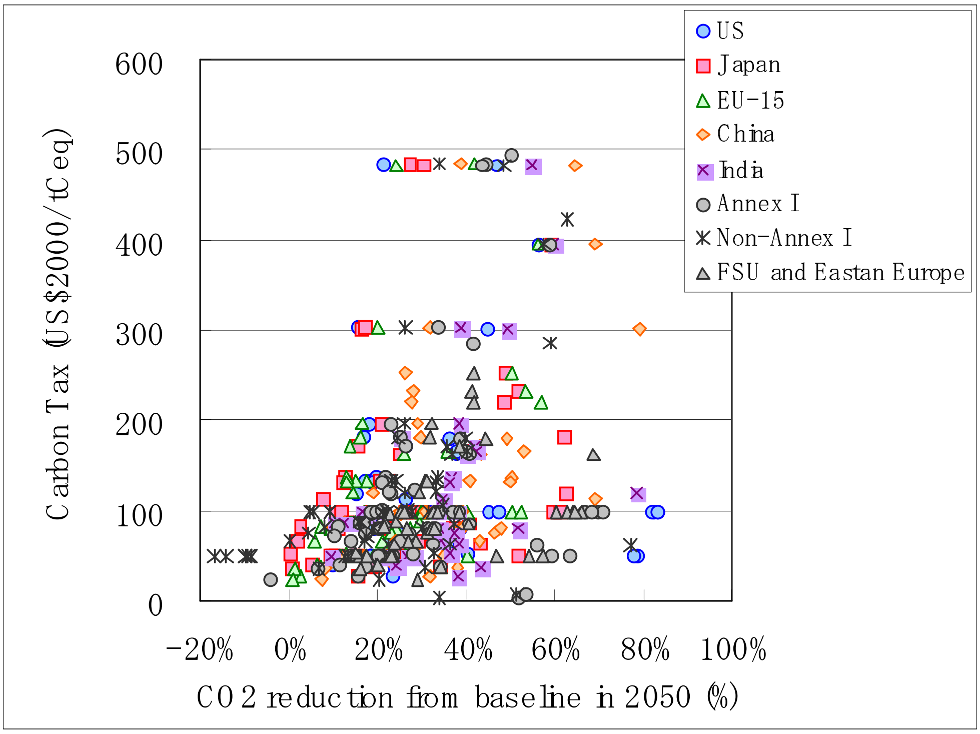


Figure 3.35: *Relation between carbon tax and CO_2 reduction from baseline in 2050 in selected countries taken from the literature published since TAR*

In some non-Annex I countries CO_2 emissions may increase as a consequence of mitigation in Annex I countries due to carbon leakage. There is a case in which CO_2 emissions in Annex I countries increase in mitigation scenarios because of emissions trading. However, most scenarios indicate a reduction of emissions in both Annex I and on-Annex I countries.

3.4 Role of technologies in long-term mitigation and stabilization: research, development, deployment, diffusion and transfer

Technology is among the central driving forces of GHG emissions. It is one of the main determinants of economic development, consumption patterns and thus human well-being. At the same time, technology and technological change offer the main possibilities for reducing future emissions and achieving the eventual stabilization of atmospheric concentrations (see Ch. 2, Section 2.9.1.2).

The ways in which technology reduces future GHG emissions in long-term emission scenarios include:

- Improving technology efficiencies and thereby reducing emissions per unit service (output). These measures are enhanced when complemented by energy conservation and rational use of energy;
- Replacing carbon intensive sources of energy by less intensive ones, such as switching from coal to natural gas. These measures can also be complemented by efficiency improvements (e.g.

combined natural gas power plants are more efficient than modern coal power plants) thereby further reducing emissions;

- Introducing carbon capture and storage to abate uncontrolled emissions. This option could be applied at some time in the future in conjunction with essentially all electricity generation technologies, many other energy conversion technologies and energy-intensive processes using fossil energy sources as well as biomass (in which case it corresponds to net carbon removal from the atmosphere);
- Introducing carbon free renewable energy sources ranging from a larger role of hydro and wind power, photovoltaics and solar thermal power plants, modern biomass (that can be carbon neutral resulting in zero net carbon emissions) and other advanced renewable technologies;
- Enhancing the role of nuclear power as another carbon free source of energy. This would require a further increase of the nuclear share in global energy, dependent on the development of 'inherently' safe reactors and fuel cycles, resolution of the technical issues associated with long-term storage of fissile materials and improvement of national and international non-proliferation.
- New technology configurations and systems, e.g. hydrogen as a carbon free carrier to complement electricity, fuel cells, new storage technologies, and long distance electricity transmission. These can complement other technologies, in particular giving them leverage on the transportation technologies.
- Reducing GHG and CO_2 emissions from agriculture and land use in general critically depends on diffusion of new technologies and practices toward less fertilizer intensive production and improvement of tillage and livestock management.

Virtually all scenarios assume that technological and structural changes occur during this century leading to relative reduction of emissions compared to the hypothetical case of attempting to 'keep' emissions intensities of GDP and structure the same as today (see Ch. 2, Section 2.9.1.3). Figure 3.36 shows such a hypothetical range of cumulative emissions under the assumption of 'freezing' technology and structural change in all scenarios at current levels, but letting populations change and economies develop as assumed in the original scenarios (Nakicenovic *et al*., 2005). To show this, the energy intensity of GDP and the carbon intensity of energy are kept constant. The bars in the figure indicate the central tendencies of the scenarios in the literature by giving the cumulative emissions ranges between the 25^{th} and the 75^{th} percentile of the scenarios in the scenario database.[8] The hypothetical cumulative emissions (without technology and structural change) range from 2427 (25^{th} percentile) to 3133 (75^{th} percentile) with a median of 2804 GtC by 2100.

The next bar in Figure 3.36 shows cumulative emissions by keeping carbon intensity of energy constant while allowing energy intensity of GDP to evolve as originally specified in the underlying scenarios. This in itself reduces the cumulative emissions substantively, by more than 40 to almost 50 per cent (75^{th} and 25^{th} percentiles, respectively). Thus, structural economic changes and more efficient use of energy lead to significant reductions of energy requirements across the scenarios as incorporated in the baselines indicating that the baseline already includes vigorous carbon saving. In other words, this means that many new technologies and changes that lead to lower relative emissions are assumed in the baseline and means that any mitigation measures and policies need to go beyond these baseline assumptions.

The next bar in Figure 3.36 also allows carbon intensities of energy to change as originally assumed in the underlying scenarios. Again, the baseline assumptions lead to further and substantial

[8] The outliers, above the 75^{th} and below the 25^{th} percentile are discussed in more detail in the subsequent sections.

reductions of cumulative emissions, by some 13 to more than 20 per cent (25th and 75th percentile, respectively), *or less than half of emissions*, as compared to the case of no improvement of energy or carbon intensities. This results in the original cumulative emissions as specified by reference scenarios in the literature, from 1085 (25th percentile) to 1460 (75th percentile) with a median of 1268 GtC by 2100. It should be noted that this range is for the 25th to the 75th percentile only. In contrast, the full range of cumulative emissions across 56 scenarios in the database is from 566 to 1974 GtC.[9]

The next and final step is to compare the cumulative emissions across baseline scenarios with those in the mitigation and stabilization variants of the same scenarios. Figure 3.36 shows in the last bar yet another significant reduction of future cumulative emissions from 728 to 1032 (corresponding to the 25th to the 75th percentile of the full scenario range) with a median of 847 GtC by 2100. This corresponds to about 70 per cent emissions reduction across mitigation scenarios compared to the hypothetical case of no changes in energy and carbon intensities and still a large, or about a 30 per cent reduction compared to the respective baseline scenarios.[10]

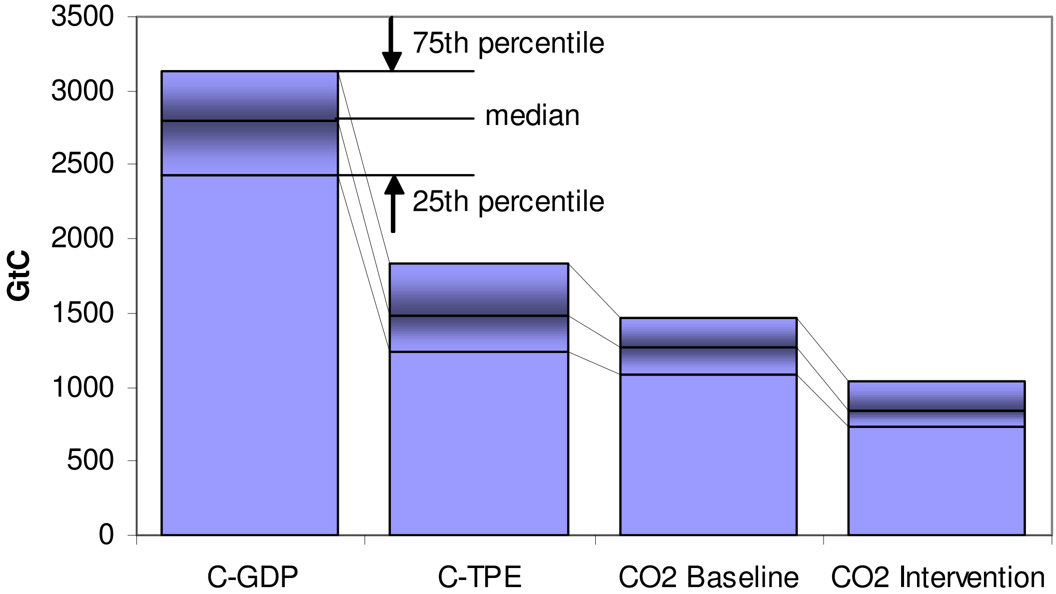


***Figure 3.36**: Median, 25th and 75th percentile of global cumulative carbon emissions by 2100 in the scenarios developed since 2001: The range labeled C-GDP refers to hypothetical futures without improvement in energy and carbon intensities in the scenarios, the range labeled C_TPE keeps only carbon intensity of energy constant while energy intensity of GDP is the same as originally assumed in scenarios, the range labeled CO_2 baseline are the 39 baseline scenarios in the database, while the region labeled CO_2 intervention includes 140 mitigation and/or stabilization scenarios. Source: After Nakicenovic et al. (2005)*

This illustrates the importance of technology and structural changes both in reference and mitigation scenarios across the literature. However, this is a very aggregated illustration across all scenarios and different mitigation levels for cumulative emissions. Thus, it is useful to also give a more

[9] The cumulative emissions range represents a huge increase compared to the historical experience. Cumulative global emissions were about 300 GtC from the 1860s to today, a very small fraction indeed of future expected emissions across the scenarios.

[10] In comparison, the full range of cumulative emissions from mitigation and stabilization scenarios in the database is from 214 to 1853 GtC.

specific illustrative example. Figure 3.37 gives such an illustration by showing the importance of technological change assumptions in both reference and mitigation scenarios for a 550 ppmv concentration target based on four SRES scenarios. Such analyses are increasingly becoming available commissioned by national governments. For instance, Placet *et al*. (2004) provide a detailed study of possible technology development pathways under climate stabilization for the US government Climate Change Technology Program. To illustrate the importance of technological change, actual projected scenario values in the original SRES no-climate policy scenarios are compared to a hypothetical case with frozen 1990 structures and technologies for both energy supply and end-use. The difference (denoted by a grey shaded area in Figure 3.37) illustrates the impact of technological change leading to improved efficiency and "decarbonization" in energy systems, already incorporated into the baseline emission scenario.

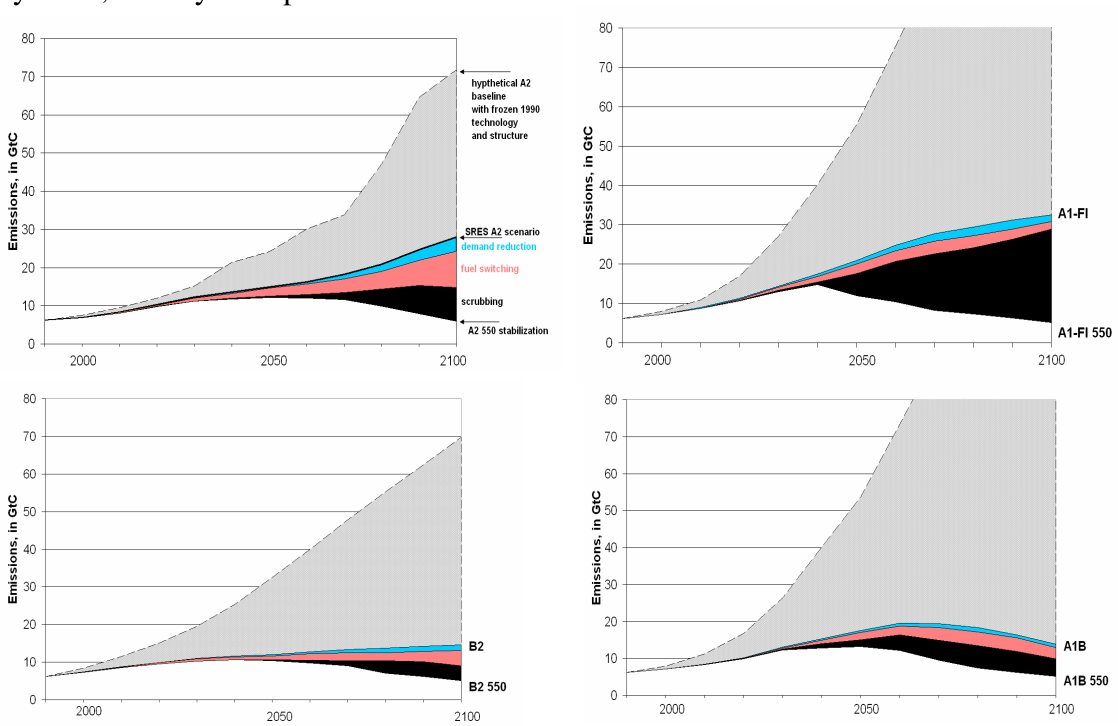


Figure 3.37: *Impact of technology on global carbon emissions in reference and climate mitigation scenarios. Global carbon emissions (GtC) in four scenarios developed within the IPCC SRES and TAR (A2, B2 top and bottom of left panel; A1FI and A1B top and bottom of right panel). Grey shaded area indicated the difference in emissions between the original no-climate policy reference scenario compared with a hypothetical scenario assuming frozen 1990 energy efficiency and technology, illustrating the impact of technological change incorporated already into the reference scenario. Color shaded areas show the impact of various additional technology options deployed in imposing a 550 ppmv CO_2 stabilization constraint on the respective reference scenario including energy conservation (blue), substitution of high-carbon by low- or zero-carbon technologies (orange), as well as carbon capture and sequestration (black). Of particular interest are the two A1 scenarios shown on the right hand side of the panel that share identical (low) population and (high) economic growth assumptions making thus differences in technology assumptions more directly comparable. Source: Adapted from SRES (2000), TAR (2001), Riahi and Roehrl (2001), and Edmonds (2004)*

The impacts of technological options leading to emission reductions is illustrated by color shaded areas in Figure 3.37 regrouped into three categories: demand reductions (e.g. through deployment of more efficient end-use technologies such as lighting or vehicles), fuel switching (substitution of high GHG emitting technologies by low- or zero-emitting technologies such as renewables or nuclear), and finally, CO_2 capture and storage technologies. The mix in the mitigative technology portfolio required to reduce emissions from the reference scenario level to that consistent with the illustrative 550 ppmv stabilization target varies as a function of the baseline scenario underlying the model calculations (shown in Figure 3.37) as well with the degree of stringency of the stabilization target adopted (not shown in Figure 3.37). An interesting finding from a large number of modelling studies is that scenarios with higher degrees of technology diversification (e.g. scenario A1B in Figure 3.37) also lead to a higher degree of flexibility with respect of meeting alternative climate (e.g. stabilization) targets and generally also to lower overall costs compared to less diversified technology scenarios. This illustrative example also confirms the conclusion reached in Section 3.3 above that was based on a broader scenario literature.

This brief assessment of the role of technology across scenarios indicates that there is a significant technological change and diffusion of new and advanced technologies already assumed in the baselines and additional technological change 'induced' through various policies and measures in the mitigation scenarios. The newer literature on induced technological change assessed in the previous sections along with other scenarios (e.g., Grübler, Nakicenovic and Nordhaus, 2002 and Köhler *et al.,* 2006, see also Ch. 11) also affirms this conclusion.

3.4.1 Carbon free energy and Decarbonization

3.4.1.1 Decarbonization Trends

Decarbonization denotes the declining average carbon intensity of primary energy over time (see Kanoh, 1992). Although the decarbonization of the world's energy system is comparatively slow (0.3 per cent per year), the trend has persisted throughout the past two centuries (Nakicenovic, 1996). The overall tendency toward lower carbon intensities is due to the continuous replacement of fuels with high carbon content by those with low carbon content; however, intensities are currently increasing in some developing regions. In short to medium term scenarios such a declining tendency for carbon intensity may not be as discernable as across the longer term literature, e.g. in World Energy Outlook 2004 (IEA, 2004), the reference scenario to 2030 does show the replacement of gas for other fossil fuels as well as cleaner fuels due to limited growth of nuclear and bioenergy.

Another effect contributing toward reduction of carbon intensity of the economy is the declining energy requirements per unit GDP, or energy intensity of GDP. Globally, energy intensity has been declining more rapidly than carbon intensity of energy (0.9 per cent per year) during the past two centuries (Nakicenovic, 1996). Consequently, carbon intensity of GDP declined globally at about 1.2 per cent per year.

The carbon intensity of energy and energy intensities of GDP were shown in Section 3.2 of this chapter, Figure 3.11, for the full scenario sample in the scenario database compared to the newer (developed after 2001) non-intervention scenarios. AS in Sections 3.2 and 3.3, the range of the scenarios in the literature until 2001 is compared with recent projections from scenarios developed after 2001 (Nakicenovic *et al*., 2005). Figure 3.38 compares the decarbonization trends (energy and GDP) of post-2001 scenarios with the earlier literature, Figure 3.39 shows the same comparisons for non-intervention scenarios and Figure 3.40 for the intervention and stabilization scenarios.

The majority of the scenarios in the literature portray a similar and persistent decarbonization trend as observed in the past. In particular, the medians of the scenario sets indicate energy decarbonization rates of about 0.9 (pre-2001 literature median) and 0.6 (post-2001 median) per cent per year which is a significantly more rapid decrease compared to the historical rates of about 0.3 per cent per year. Decarbonization of GDP is also more rapid with about 2.5 per cent per year (for both pre and post-2001 literature medians) compared to the historical rates of about 1.2 per cent per year. As expected, the intervention and stabilization scenarios have significantly higher decarbonization rates and the post-2001 scenarios include a few with significantly more rapid decarbonization of energy extending even into the negative range. This means that toward the end of the century these more extreme decarbonization scenarios foresee net carbon removal from the atmosphere, e.g. through carbon capture and storage in conjunction with large shares of biomass energy. Such developments represent a radical paradigm shift compared to the current and more near term energy systems, implying significant and radical technological changes.

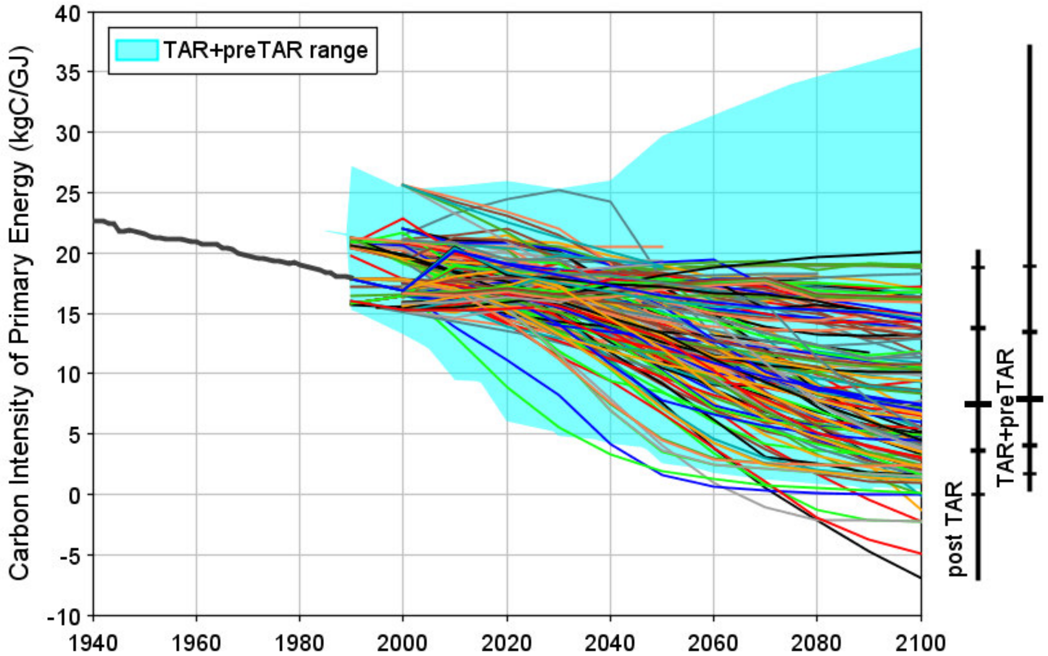


Figure 3.38a: *Carbon Intensity of Primary Energy: Historical development and 203 projections for intervention and non-intervention scenarios developed after 2001. The gray range illustrates the range of 356 pre 2001 scenarios. Adapted from Nakicenovic et al.,(2005); Historical data: Nakicenovic (1996)*

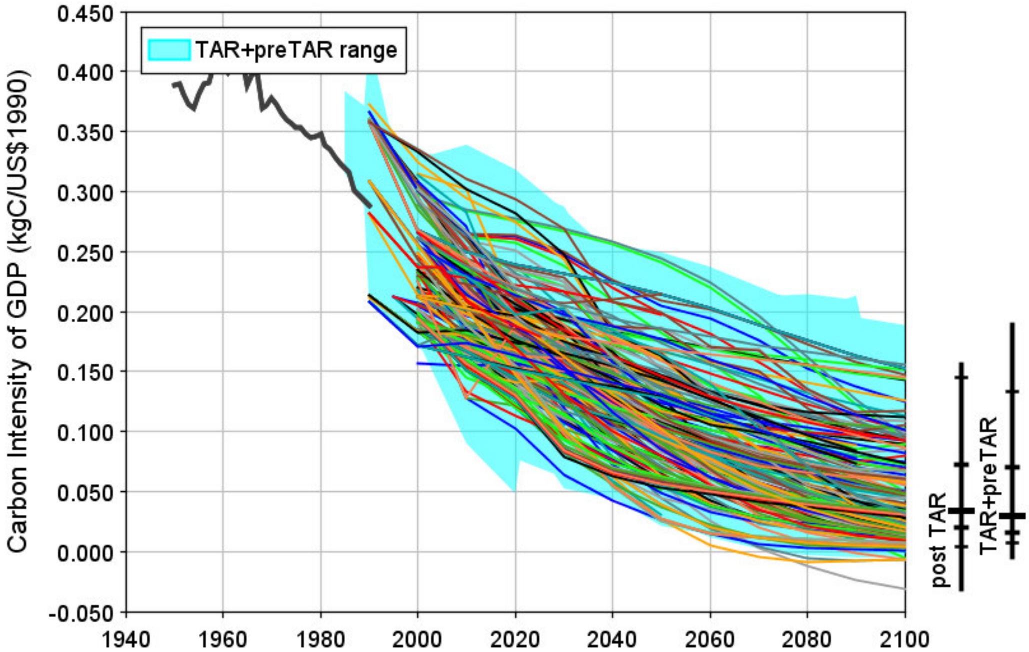


Figure. 3.38b: *Carbon Intensity of GDP: Historical development and 220 projections for intervention and non-intervention scenarios developed after 2001. The gray range illustrates the range of 335 pre 2001 scenarios. Adapted from Nakicenovic et al.,(2005); Historical data: Nakicenovic (1996)*

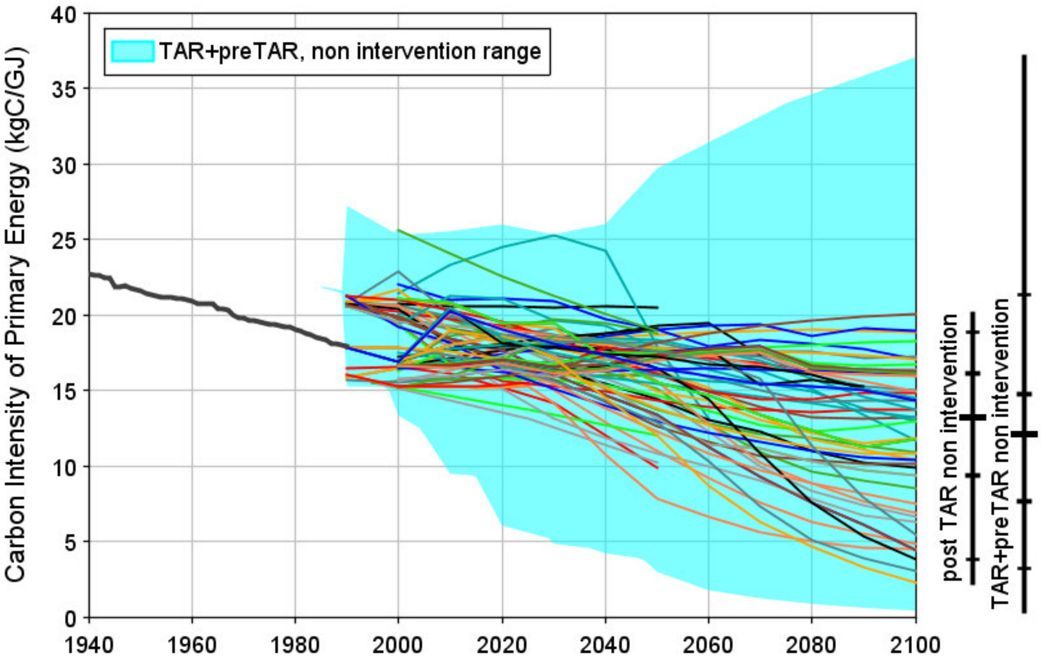


Figure 3.39a: *Carbon Intensity of Primary Energy: Historical development and 74 projections for non-intervention scenarios developed after 2001. The gray range illustrates the range of 193 pre 2001 non-intervention scenarios. Adapted from Nakicenovic et al.,(2005); Historical data: Nakićenović (1996)*

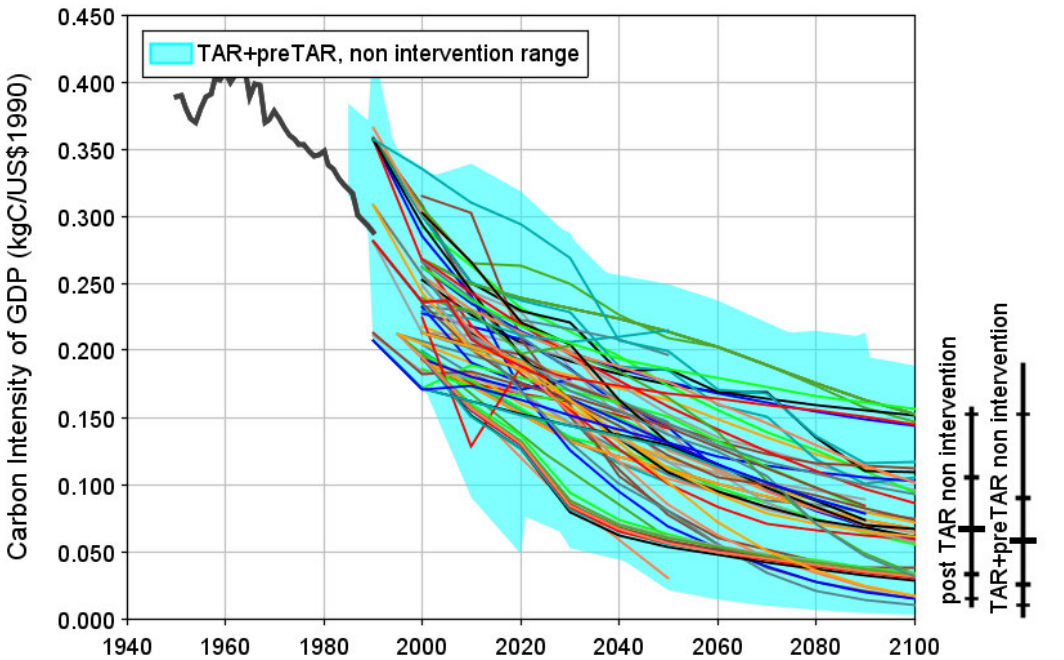


Figure 3.39b: *Carbon Intensity of GDP: Historical development and 76 projections for non-intervention scenarios developed after 2001. The gray range illustrates the range of 180 pre 2001 non-intervention scenarios. Adapted from Nakicenovic et al.,(2005); Historical data: Nakićenović (1996)*

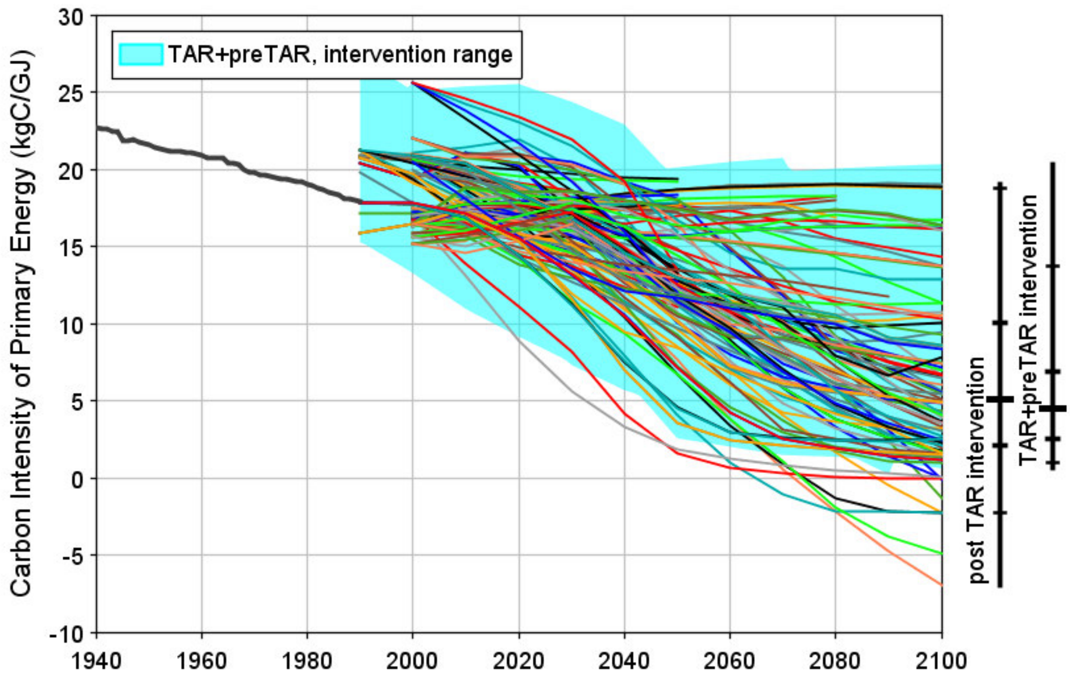


Figure 3.40a: *Carbon Intensity of Primary Energy: Historical development and 129 projections for intervention scenarios developed after 2001. The gray range illustrates the range of 163 pre 2001 intervention scenarios. Adapted from Nakicenovic et al.,(2005); Historical data: Nakicenovic (1996)*

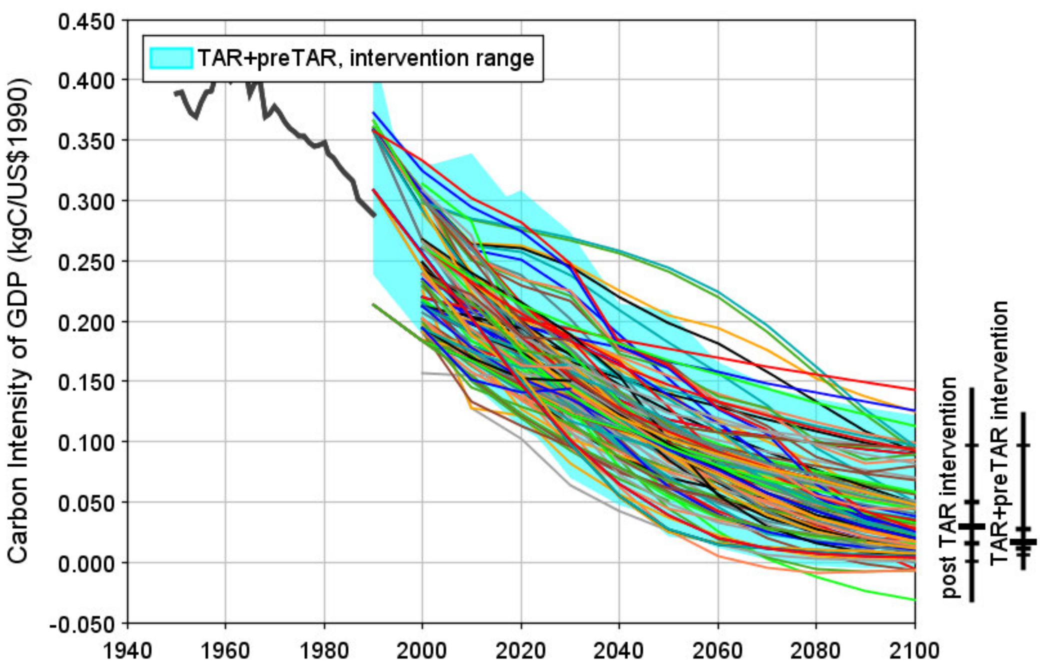


***Figure 3.40b**: Carbon Intensity of GDP: Historical development and 144 projections for intervention scenarios developed after 2001. The gray range illustrates the range of 155 pre 2001 intervention scenarios. Adapted from Nakicenovic et al., (2005); Historical data: Nakicenovic (1996)*

In contrast, the scenarios that are most intensive in use of fossil fuels lead to practically no reduction in carbon intensity of energy, while all scenarios portray decarbonization of GDP. For example, the upper bound of the recent scenarios developed after 2001 depict slightly increasing (about 0.3 per cent per year) carbon intensities of energy (A2 reference scenario, Mori, 2003, see Figure 3.10 comparing carbon emissions across scenarios in the literature presented in Section 3.2). Most notably, a few scenarios developed before 2001 follow an opposite path compared to other scenarios: decarbonization of primary energy with decreasing energy efficiency until 2040, followed by rapidly increasing ratios of CO_2 per unit of primary energy after 2040-in other words, re-carbonization. These scenarios lie in the long-term well above the range spanned by the new scenarios, indicating a shift towards more rapid CO_2 intensity improvements in the recent literature (Nakicenovic *et al*., 2005). In contrast, there are just a very few scenarios in the post 2100 literature that envisage increases in carbon intensity of energy.

The highest rates of decarbonization of energy (up to 2.5 per cent per year for the recent scenarios) are from scenarios that include a complete transition in the energy system away from carbon intensive fossil fuels. Clearly, the majority of these scenarios are intervention scenarios, although also some non-intervention scenarios show drastic reductions in CO_2 intensities due to reasons other than climate policies (e.g., the combination of sustainable development policies and technology push measures to promote renewable hydrogen systems, Barreto *et al*., 2003). The relatively fast decarbonization rate of intervention scenarios is also illustrated by the median of the post 2001 intervention scenarios, which depict an average rate of improvement 1.1 per cent per year over the course of the century, compared to just 0.3 per cent for the non-intervention scenarios. Note, nevertheless, that the modest increase in carbon intensity of energy improvements in the intervention scenarios above the 75 percentile of the distribution of the recent scenarios (Figure

3.40). The vast majority of these scenarios represent sensitivity analysis; have climate policies for mitigation of non-CO_2 greenhouse gas emissions (methane emissions policies: Reilly *et al.*, forthcoming); or have comparatively modest CO_2 reductions measures, like the implementation of a relatively minor carbon tax of $10/tC (about $2.7/t$CO_2$) over the course of the century (e.g., Kurosawa, 2004). Although these scenarios are categorized according to our definition as intervention scenarios, they do not necessarily lead to the stabilization of atmospheric CO_2 concentrations.

3.4.1.2 Key factors for carbon free energy and decarbonization development

All of the technological options, assumed to contribute toward further decarbonization and reduction of future GHG emissions, require further research and development (R&D) to improve their technical performance, reduce costs and achieve social acceptability. In addition, deployment of carbon saving technologies needs to be applied at ever larger scales to benefit from potentials of technological learning that can result in further improved costs and economic characteristics of new technologies. Most importantly, appropriate institutional and policy inducements are required to enhance widespread diffusion and transfer of these technologies.

The full replacement of dominant technologies in the energy systems is generally a long process. In the past, the major energy technology transitions have lasted more than half a century such as the transition from coal as the dominant energy sources in the world some 80 years ago to dominance of crude oil during the 1970s. Achieving such a transition in the future toward lower GHG intensities is one of the major technological challenges addressed in mitigation and stabilization scenarios.

Figures 3.41 and 3.42 show the ranges of energy technology deployment across scenarios by 2030 and 2100 for baseline (non-intervention) and intervention (including stabilization) scenarios, respectively. In general, the deployment of energy technologies in general and of new technologies in particular is significant indeed, even through the 2030 period, but especially by 2100. The deployment ranges should be compared with the current total global primary energy requirements of some 440 EJ in 2000. Coal, oil and gas reach median deployment levels ranging from some 150 to 250 EJ by 2030. The variation is significantly higher by 2100 but even medians reach levels of close to 600 EJ for coal in reference scenarios and thereby exceeding by a half the current deployment of all primary energy technologies in the world. Deployment of nuclear and biomass is comparatively lower in the range of about 50 to 100 EJ by 2030 and up to ten times as much by 2100. This all indicates that radical technological changes occur across the range of scenarios.

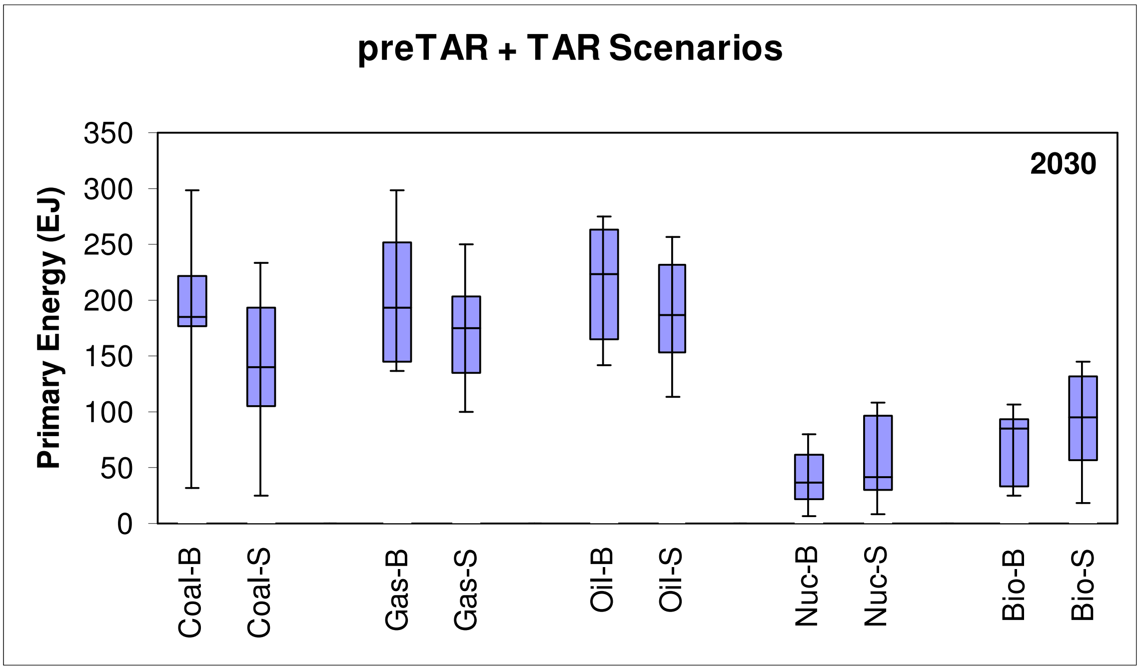


Figure 3.41a: *Deployment of primary energy technologies across pre-2001 scenarios by 2030: Left "error" bars show baseline (non-intervention) scenarios and right ones intervention and stabilization scenarios. Shown the full ranges of the distributions (full vertical line with two extreme tic marks), the 25th and 75th percentiles (gray area) and the median (middle tic mark)*

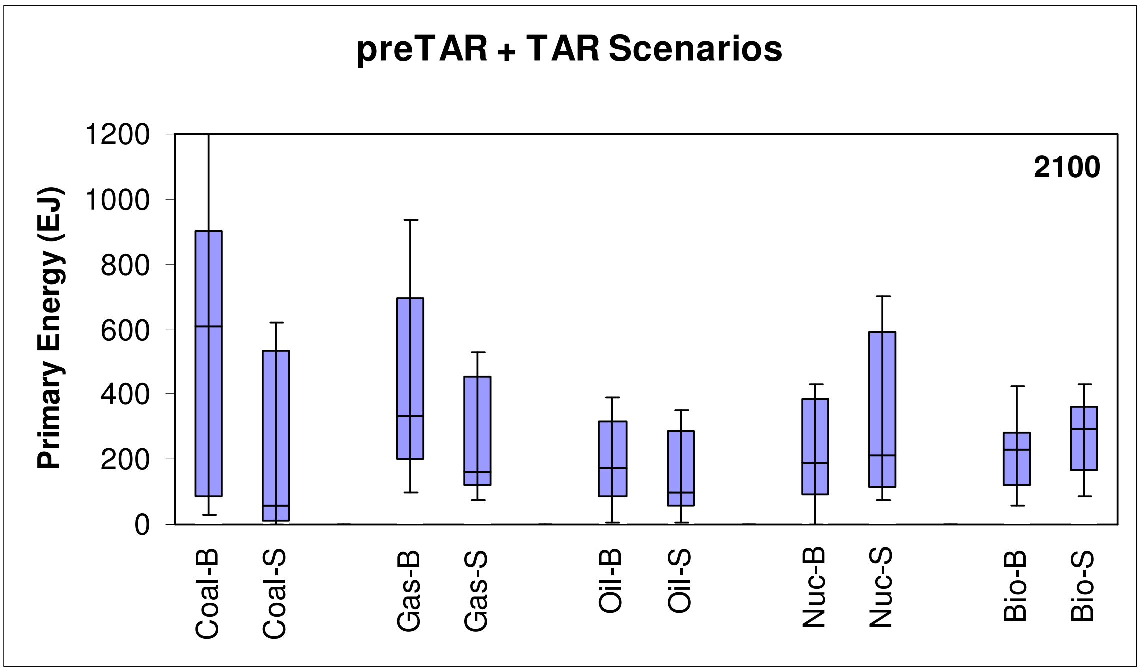


Figure 3.41b: *Deployment of primary energy technologies across pre-2001 scenarios by 2100: Left "error" bars show baseline (non-intervention) scenarios and right ones intervention and stabilization scenarios. Shown the full ranges of the distributions (full vertical line with two extreme tic marks), the 25th and 75th percentiles (gray area) and the median (middle tic mark)*

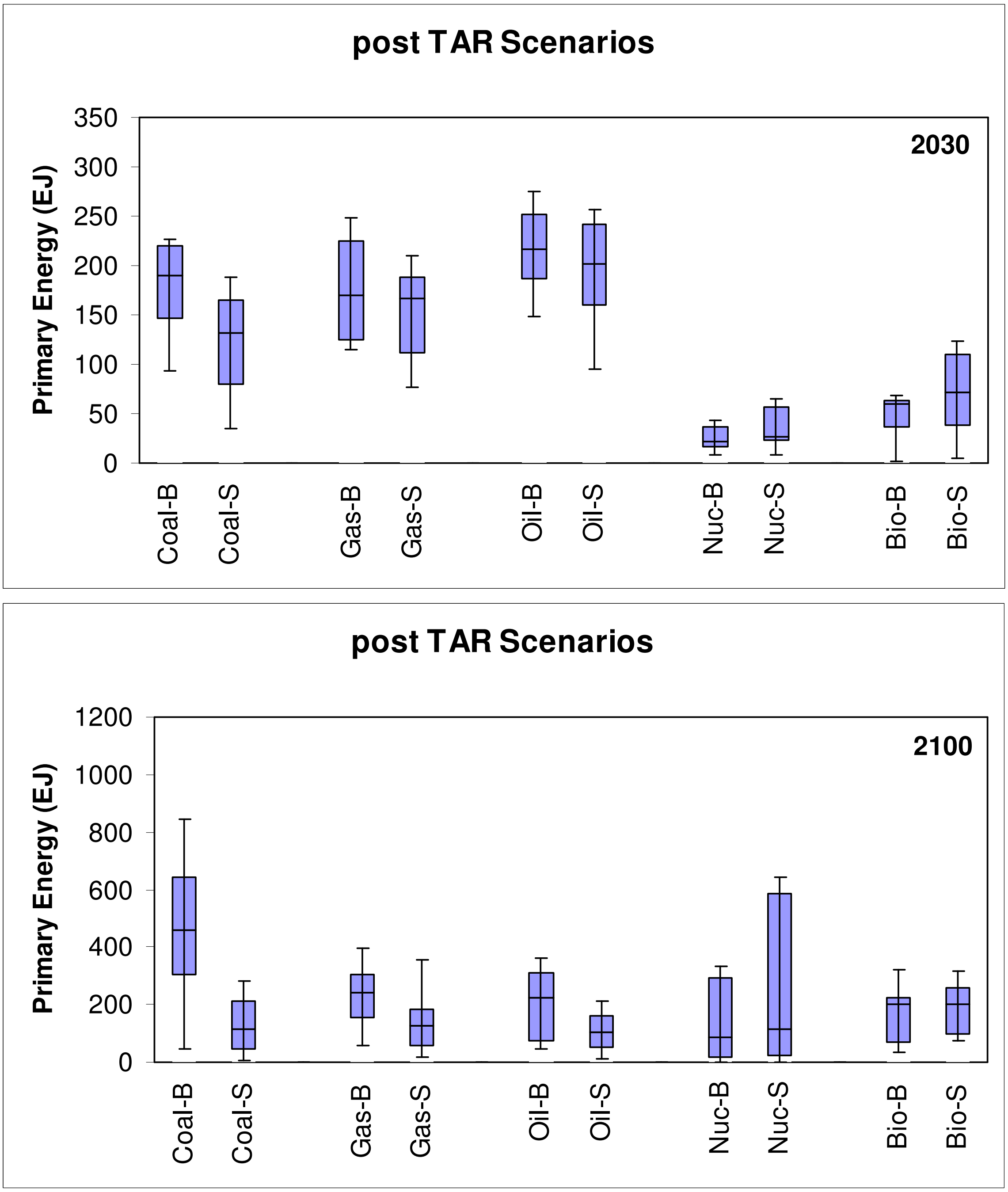


Figure 3.42b: *Deployment of primary energy technologies across post-2001 scenarios by 2100: Left "error" bars show baseline (non-intervention) scenarios and right ones intervention and stabilization scenarios. Shown the full ranges of the distributions (full vertical line with two extreme tic marks), the 25th and 75th percentiles (gray area) and the median (middle tic mark)*

The deployment ranges are large for each of the technologies but do not differ all that much comparing the pre-2001 with post-2001 scenarios over both time periods, up to 2030 and 2100. Thus while technology deployments are large in the mean and variance, the patterns have changed little in the new compared with the older scenarios. What is really significant in both sets of literatures is the radically different structure and portfolio of technologies between baseline and stabilization scenarios. Mitigation generally means significantly less coal, somewhat less natural gas and consistently more nuclear and biomass, two zero-carbon primary energy sources. What cannot be seen from this comparison, due to the lack of data and information about the scenarios, is the extent to which carbon capture and storage are deployed in mitigation scenarios. However, it is very likely that most of the coal and much of the natural gas deployment across stabilization scenarios occurs in conjunction with carbon capture and storage. The overall conclusion is that mitigation and stabilization in emissions scenarios have a significant inducement on diffusion rates of carbon saving and zero-carbon energy technologies.

3.4.2 RD&D and investment patterns

As mentioned in Ch. 2, the private sector is leading global research and development of technologies that are close to market deployment while public funding is essential for the longer term and basic research. R&D efforts in the energy area especially important for GHG emissions reduction.

Accelerating the availability of advanced and new technologies will be central to greatly reducing CO_2 emissions from energy and other sources. Innovation in energy technology will be integral to meeting the objective of emission reduction. Investment and incentives will be needed for all components of the innovation system - research and development (R&D), demonstration, market introduction and its feedback to development, flows of information and knowledge, and the scientific research that could lead to new technological advances.

Thus, sufficient investment will be required to ensure the best technologies are brought to market in a timely manner. These investments and the resulting deployment of new technologies provide an economic value. Model calculations enable economists to quantify the value of improved technologies as illustrated for two technologies in Figure 3.43.

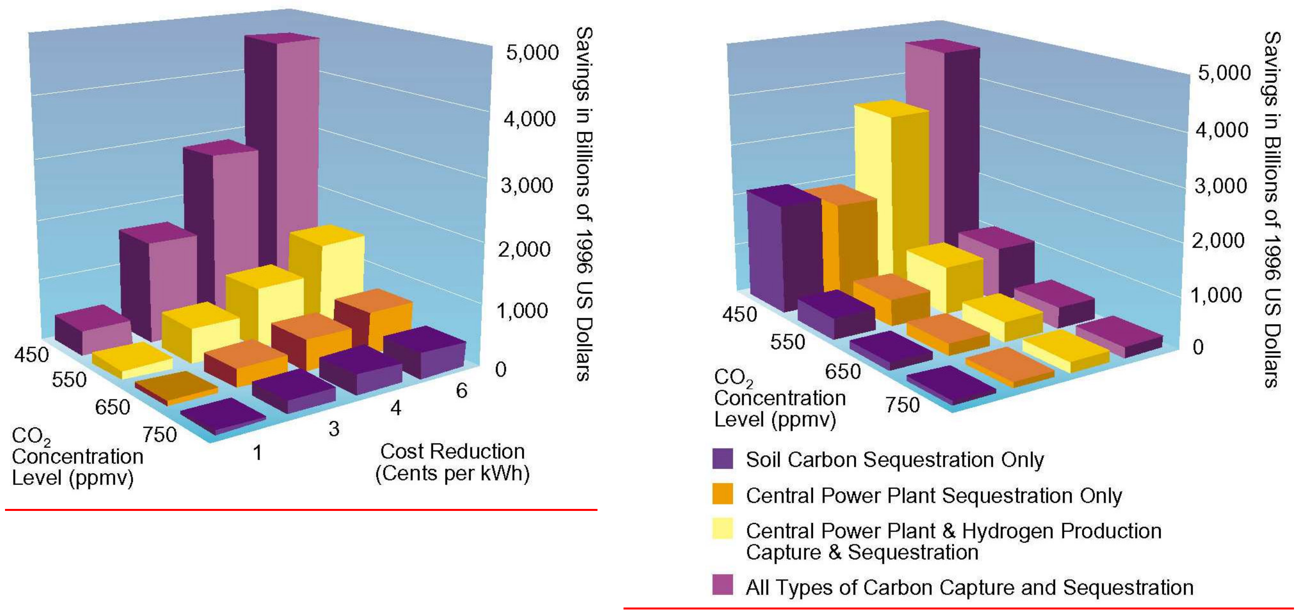


Figure 3.43: *The value of improved technology. Modelling studies enable to calculate the economic value of technology improvements that increase particularly drastically with increasing stringency of stabilization targets (750, 650, 500, and 450 ppmv respectively) imposed upon a reference scenario (modelling after the IS92a scenario in this particular modelling study). Detailed model representation of technological interdependencies and competition and substitution is needed for a comprehensive assessment of the economic value of technology improvements. Top panel: cost savings (billions of 1990 US\$) compared to the reference scenario when lowering the costs of solar photovoltaic from a reference value of 9 US cents per kWh (top) by 1, 3, 4, and 6 cents/kWh*

respectively. For instance the value of reducing PV costs from 9 to 3 cents per kWh could amount to up to 1.5 trillion Dollars in an illustrative 550 ppmv stabilization scenario compared to the reference scenario in which costs remain at 9 cents/kWh). Bottom panel: cost savings resulting from availability of an ever larger and diversified portfolio of carbon capture and sequestration technologies. For instance, adding soil carbon sequestration to the portfolio of carbon capture and sequestration technology options (forest-sector measures were not included in the study) reduces costs by 1.1 trillion Dollars in an illustrative 450 ppmv stabilization scenario. Removing all carbon capture sequestration technologies would triple the costs of stabilization for all concentration levels analysed. Source: GTSP

Generally, economic benefits from improved technology increase non-linearly with: a) the distance to current economic characteristics (or the ones assumed to be characteristic of the scenario baseline), b) the stringency of environmental targets, as well as c) the comprehensiveness and diversity of a particular technology portfolio considered in the analysis. Thus, the larger the distance between future technology characteristics compared to current ones, the lower the stabilization target, and the more comprehensive the suite of available technologies (as illustrated by the various CO_2 capture and storage options analyzed in Figure 3.43), the larger will be the economic value of improvements in technology.

These results lend further credence to technology R&D and deployment incentives policies (for example prices[11]) as "hedging" strategies addressing climate change. However, given the current insufficient understanding of the complexity of driving forces underlying technological innovation and cost improvements, cost-benefit or economic "return on investment" calculations have to date not been attempted in the literature, due at least in part to a paucity of empirical technology-specific data on R&D and niche market deployment expenditures and the deep uncertainties involved in linking "inputs" (R&D and market stimulation costs) to "outputs" (technology improvements and cost reductions).

3.4.3 Dynamics and drivers of technological change, barriers (timing of technology deployment, learning)

3.4.3.1 Summary from TAR

IPCC-TAR concluded that reduction of greenhouse gas emissions is highly dependent on both technological innovation and implementation of technologies. The rate of introduction of new technologies, and the drivers for adoption are however different in industrial market economies, economies in transition and developing countries. This is to an extent reflected in global emissions scenarios as they often involve technological change at a level of a dozen or so world regions. This usually involves making more region specific assumptions about future performance, costs and investment needs for new and low carbon technologies.

There are multiple policy approaches to encourage technological innovation and change. Through regulation of energy markets, environmental regulations, energy efficiency standards, financial and other market-based incentives such as energy and emission taxes, governments can induce technology changes and influence the level of innovations. In emissions scenarios, this is reflected

[11] See Newell *et al*., 1999.

in assumptions about policy instruments such as taxes, emissions permits, technology standards, costs and lower and upper bounds on technology diffusion.

3.4.3.2 Dynamics of technology

R&D, technological learning, and spillovers are the three broad categories of drivers of technological change. These are discussed in Ch. 2 Sections 2.9.2.1, 2.9.2.2, and Ch. 11 Section 11.3.4. The main conclusion is that, on the whole, all three of the sources of induced technological change (ITC) play important roles in technological advance.

Technological change is treated largely as an exogenous assumption about costs, market penetration and other technology characteristics in emissions scenarios (Barker *et al*., 2005) with some notable exceptions such as in Gritsevskyi and Nakicenovic (2000). Hourcade and Shukla (2001), in their review of scenarios from top-down general economic models, indicate that technology assumptions play a critical factor affecting the timing and cost of emission abatement in the models. They identify widely differing costs of stabilization at 550 ppmv by 2050 of between 0.2 to 1.75 per cent of GDP, mainly influenced by the size of the emissions in the baseline.

The International Modelling Comparison Project (IMCP) (Edenhofer *et al.*, 2006) compared the treatment relating to technological change in many models covering a wide range of approaches. The economies for technological change were simulated in three groups: effects through R&D expenditures, learning-by-doing (LBD) or specialisation and scale. IMCP finds that ITC reduces costs of stabilization, but in a wide range, depending on the flexibility of the investment decisions and the range of mitigation options in the models. It should be noted, however, that induced technological change is not a "free-lunch" as it requires higher upfront investment and deployment of new technologies in order to achieve cost-reductions thereafter. This can lead to lower overall mitigation costs.

All models indicate that real carbon prices for stabilization targets rise with time in the early years, with some models showing a decline in the optimal price after 2050 due to the accumulated effects of LBD and positive spillovers on economic growth. Another robust result is that ITC can reduce costs when models include low carbon energy sources, such as renewables and nuclear and carbon capture and sequestration, as well as energy efficiency and energy savings. Finally, policy uncertainty is seen as an issue. Long-term and credible abatement targets and policies will reduce some of the uncertainties around the investment decisions and are crucial to the transformation of the energy system.

ITC broadens the scope of technology related policies and usually increases the benefits of early action, which accelerates deployment and cost-reductions of low-carbon technologies (Barker *et al.*, 2006; Sijm, 2004; Gritsevskyi and Nakicenovic, 2000). This is due to the cumulative nature of ITC as treated in the new modelling approaches. Early deployment of costly technologies leads to the benefits of learning and lower costs as diffusion progresses. In contrast, scenarios with exogenous technology assumptions imply waiting for better technologies to arrive in the future, though this too may result in reduced cost of emission reduction (European Commission, 2003).

Other recent work also confirms these findings. For example, Manne and Richels (2004) and Goulder (2004) also found that ITC lowers mitigation costs and that more extensive reductions in GHGs are justified than with exogenous technical change. Nakicenovic and Riahi (2003) noted how the assumption about the availability of future technologies was a strong driver of stabilization costs.

Edmonds *et al*. (2004) studied stabilization at 550 ppmv CO_2 in the SRES B2 world using the MiniCAM model and showed a reduction in costs of a factor of 2.5 in 2100 using a baseline incorporating technical change. Edmonds considers that advanced technology development to be far more important as a driver of emission reductions than carbon taxes. Van Vuuren *et al*. (2004) also concluded that technology development is a key in achieving emission. Weyant (2004) concludes that stabilization will require development on a large scale of new energy technologies and that costs would be reduced if many technologies are developed in parallel and there is early adoption of policies to encourage technology development.

The results from the bottom up and more technology specific modelling approaches give a different perspective. Following the work in particular of IIASA (e.g. Grübler, 1999), models investigating induced technical change emerged during the mid and late 1990s. These models show that ITC can alter results in many ways. In the previous sections of this chapter, it was also illustrated that the baseline choice is crucial in determining the nature (and by implication also cost) of stabilization. However, this influence is itself largely due to the different assumptions made about technological change in the baseline scenarios. Gritsevskyi and Nakicenovic (2000) identified some 53 clusters of least cost technologies allowing for endogenous technological learning with uncertainty. This suggests that a decarbonized economy may not cost any more than a carbon intensive one, if technology learning curves are taken into account. Other key findings are that there is a large diversity across alternative energy technology strategies, a finding that was confirmed in IMCP (Edenhofer *et al*., 2006). These results suggest that it is not possible to choose an 'optimal' direction of energy system development. Modelling reported in TAR (Watson *et al*., 2001) suggests that up to a 5 GtC a year reduction by 2020 (some 50 per cent of baseline projections) might be achieved by current technologies, half of the reduction at no direct cost, the other half at direct costs of less than \$100/tC-equivalent (\$27/tCO_2-eq.).

3.4.3.3 Barriers of Technology transfer, diffusion and deployment for long-term mitigation

A discussion on barriers of development and commercialisation of technologies is carried out in Ch. 2, section 2.9.2.3. Barriers to technology transfer vary according to the specific context from sector to sector and can manifest themselves differently in developed and developing countries, and in economies-in-transition (EITs). These barriers range from a lack of information; insufficient human capabilities; political and economic barriers, such as lack of capital, high transaction costs, lack of full cost pricing, and trade and policy barriers; institutional and structural barriers; lack of understanding of local needs; business limitations, such as risk aversion in financial institutions; institutional limitations, such as insufficient legal protection; and inadequate environmental codes and standards.

One of the most obvious barriers to using innovation to address GHG emissions is the lack of incentives. Economic, regulatory, and social incentives also act as incentives for innovation to find new means of mitigation. Another important type of barrier, which both slows technological change in general and tends to skew it in particular directions, is that posed by 'lock-in'.

3.4.3.4 Dynamics in developing countries and timing of technology deployment

National policies in developing countries necessarily focus on more fundamental priorities of development such as poverty alleviation and providing basic living conditions for their populations and it is unlikely that in the short-term national policies would be driven by environmental concerns. National policies driven by energy security concerns can, however, have strong alignment with climate goals. For the medium to long-term some optimism can certainly be justified. The success of policies that address short-term development concerns will determine the pace at which convergence of the quality of life in the developing and the developed world would occur over the long-term.

The process of development results in efficient markets and institutions. But in developing countries, markets and institutions are poorly developed. Nonetheless, development goals for these countries will have to be delivered. The development policies adopted in developing countries are like climate opportunities, as they generate endogenous changes and create path dependence for induced technological change. For long-term scenarios, unfolding of key drivers of technological change in developing countries would depend on three 'changes' that are simultaneous and inseparable within the context of development: (a) exogenous changes such as in technology and behavioural or social; (b) endogenous policies driven by 'development goals'; and (c) the induced change from climate policies. (Shukla *et al*., 2006).

3.5 Interaction between mitigation and adaptation, in the light of climate change impacts and decision making under long run uncertainty

3.5.1 The interaction between levels of mitigation and adaptation

Possible responses to climate change include a portfolio of measures: adaptation - actions that help human and natural systems to adjust to climate change; mitigation - actions that reduce greenhouse gas emissions, or remove greenhouse gases from the atmosphere and thus limit long-term climate change; and, independent of direct response to climate change, technology R&D and institutional innovations that may enhance both the capacity to adapt to and mitigate the effects of climate change in the future (Bosello 2005; Tol 2005a, see also TAR, Hourcade *et al*., 2001. In the search for an appropriate mix of near term actions, there are implicit tradeoffs between the investment in mitigation and in adaptation and the amount of residual climate impacts that society is either prepared to or forced to tolerate (Bosello 2005). Actions on climate change will also be complemented by continued research in areas relevant to climate change such as technology and climate science, which should reduce uncertainties and facilitate future decisions (Richels *et al*. 2004; Caldeira *et al*. 2003; Lempert *et al*. 2004; Yohe *et al*. 2004). Recent assessments of the interactions between these alternative response policies indicate that they are complementary rather than alternatives (Bosello 2005; Nicholls *et al*. 2006 in press). Climate change is partly inevitable in the coming decades, owing to the inertia of the climate system, and most of the benefits of mitigation measures will not be felt until later this century. Adaptation will be necessary even if drastic mitigation is implemented, however, there are limits to adaptation. Thus if climate impacts are to be avoided, mitigation will also be necessary. A combined consideration of the costs and benefits of mitigation vis-à-vis those of adaptation and impacts can provide insights for long-term mitigation strategies, including consideration of the distribution of costs and benefits of each across sectors and regions of the world.

Incomplete understanding of the magnitude and timing of climate change, its likely consequences, and of the effects of response measures, presents a range of difficulties for climate decision makers. Given broad uncertainty, climate change decision-making is not a once-and-for-all event. Rather increasingly it is seen as an iterative process that is likely to take place over decades if not centuries where there will be opportunities for learning and mid-course corrections in light of new information. This suggests a risk management framework as the means to advance climate change decision-making in the light of broad uncertainty (Smith *et al*. 2001, Lempert *et al*. 2004, Keller *et al*. 2006).

The bulk of climate policy assessment to date is devoted to links between mitigation policies and their costs and a wide range of emission and climate scenarios, rather than to adaptation or the interaction between the two. There are a number of reasons for this. First, the focus of the international climate change negotiations has largely been on mitigation (perhaps because attention to adaptation could be viewed as "giving up" on mitigation), even though the importance of adaptation is underlined in Article 4 of the UNFCCC and Article 10 of the Kyoto Protocol (Yamin, Rahman, and Huq 2005; Yamin and Depledge 2004). Second, adaptation is largely understood and undertaken at the local level, often by individual households or farmers, companies or local governments, and is difficult to target through more centralized policies or incentives (Tol, 2005a; Ch 17. & 18, WGII). It is not the primary concern of international policy in part because it is difficult to approach adaptation at this scale. The same argument also complicates the handling of adaptation in global scenarios. Third, it is difficult to make generalizations about the optimal level of adaptation or the ways in which individuals or communities are likely to adapt given the context specific nature of impacts, adaptive capacity and adaptation options (Ch. 17 & 18, WGII; Cash and Moser 2000). Given the uncertainty about future returns at the enterprise level, the potential cost associated with making a poor or irreversible investment can be reduced by delaying an investment decision and waiting for improved information about future climate and therefore project outcomes. Adaptation costs will include the direct opportunity cost of capital as well as the costs associated with committing to an (irreversible) investment while foregoing the option to wait for better information. Uncertainty about climate change will slow down the rate of long-term investment in adaptation strategies (Kokic *et al.* 2005; Kelly, Kolstad, and Mitchell 2005). Third, learning about climate change and adaptation imposes some costs and takes time, which in turn limits the full potential for adaptation to offset climate change damages (Kelly *et al*. 2005). Finally, although the data are improving, and detailed climate and impact assessments at the regional and local scale are available for a few locations (e.g. Hayhoe *et al*. 2004, West and Gawith, 2005), few systematic assessments of adaptation policies and measures exist (Tol, 2005a). Some exceptions can be cited in certain regions, for example in Finland (Carter *et al*. 2005) or in the UK (West and Gawith 2005), and on certain issues (e.g. water basin planning for increased flood risk in some regions in Europe - see UK Environment Agency in press). However, these efforts are limited and recent.

One of the methodological challenges in assessing any economic trade-off among the levels of mitigation and adaptation is valuing and aggregating the damages (impacts) of climate change across differing locations (see 3.5.2). Many authors point to the need for monetized metrics of climate change impacts and their economic consequences in formal policy analysis (Tol *et al.*, 2000; Rothman 2000; Pearce 2003). However increasingly there is recognition that a range of different monetary and physical impact metrics (see Table 3.11) can be used to inform policy decisions (Jacoby 2004; Patwardhan *et al.* 2004; Schneider *et al.* 2000; Corfee-Morlot and Hoehne 2003; Smith *et al.*, 2001, Nicholls *et al*. 2006 in press). Working with an array of monetary and non-monetary indicators of climate impacts, analysts and decision makers are required to make a number of normative judgments in analysis designed to support policy recommendations or decisions. What matters in reporting results is to summarise the normative judgements that are used to construct the estimates and to be capable, using aggregated values, to trace them back to original physical impact data (Azar 1998; Schneider 2004; Schneider *et al.* 2000; Moss and Schneider 2000).

Table 3.11: *Examples of Physical Metrics Used in Climate Change Adapted from Hitz and Smith, 2004*

Natural systems		
Habitats	Change in area extent for wetlands	Nicholls and Lowe 2004
	Shift in area extent by type of ecosystem	Leemans and Eickhout 2004
Plant and animal species	Number of species lost	Thomas 2004
	Shifting range	Parmesan and Yohe, 2003; Root *et al.* 2003
Key ecosystem vulnerabilities or sensitivity of key systems	Coral reefs bleaching events and dieback; adaptive capacity of majority of ecosystems limited	*Hoegh-Guldberg, 1999; O'Neill and Oppenheimer, 2002; Leemans and Eickhout 2004; Hare 2003; Jones 2004*
Ecosystem productivity	Net ecosystem productivity ; net primary productivity; soil C; biomass	Cramer *et al*. 2001
Bio-reserves	Shift in number of ecosystem types within existing bioreserve area	Leemans and Eickhout 2004; White *et al* 1999.
Human systems		
Agriculture	Change in number of people at risk of hunger	Parry *et al.* 1999; Parry *et al*. 2004; Fischer *et al*. 2002
	Change in agricultural production by crop type (e.g. wheat, corn, etc.)	Fischer *et al.* 2002
	Economic losses (or gains) from changes in aggregate crop production (by region and global)	Nordhaus & Boyer 2000; Mendelsohn *et al*. 2000; Schlenker *et al*. 2004; Bosello and Zhang, 2005
Forestry	Change timber yield	
Water	Change in number of people living in countries experiencing water stress (measured by water available per capita per year) or living under water stressed conditions	Arnell 2004; Arnell *et al.*, 2002 Arnell, 1999; Vörösmarty *et al*. 2000
Human health	*Change in number of people at risk of malaria (measured by number of people living in areas where the climate is suitable for transmission of malaria) or death due to malaria*	van Lieshout *et al*, 2004; Dowlatabadi and Tol, 2002
	Change in number of deaths due to heat stress or cold; loss of human life	Tol, 2002a,b; WHO 2002;
	Direct and indirect economic cost of changes in human health, based on mortality and morbidity	Bosello *et al*., 2005
Coastal zones	Change in number of people at risk of flooding in coastal zones (aggregate and distribution)	Nicholls and Lowe 2004; Nicholls *et al*., 1999
	Direct costs (of dryland protection, economic loss of dryland property or wetland) (aggregate or distribution)	Fankhauser, 1995
Socially-contingent impacts	*Number of people subject to migrate as a result of climate change, resource shortage, and resource conflict*	Barnett, 2004

The trade-offs between adaptation and mitigation are intertwined with development pathways. Development pathways determine adaptive and mitigative capacity, as well as sensitivity and vulnerability to climate change (Tol 2005a; Yohe and Tol 2002; Tol and Yohe 2006; Working Goup II, Chapter 20). Some development choices with respect to energy e.g. investments in energy efficiency or distributed energy systems (Epstein and Mills, 2005), may contribute both to adaptation and mitigation (e.g. investment in energy efficiency of buildings may limit human vulnerability to heat waves and reduce energy demand (and emissions) due to air conditioning. Section 3.5.3 below outlines the issues related to integrated assessment and the handling of mitigation and adaptation responses, development and climate damages or impacts in a dynamic context.

3.5.2 Integrated assessment of response strategies[12]

Integrated assessment of long-term mitigation strategies is the main approach to consider the interactions between mitigation and climate change impacts or damages. In some instances these assessment include explicit consideration of adaptation, however in most cases they do not (see below). Discussion here organises the literature into three main categories depending on the way uncertainty is dealt with, the degree of complexity and multi-disciplinary nature of the underlying models, whether impacts are monetized and on the priority given to normative insights on decision making.

Scenario or sensitivity analyses aim to assess and compare mitigation pathways, and in many cases the costs and benefits (either monetized or not), of achieving alternative stabilization targets. Uncertainty analysis is central, thus a sub-category exists as *probabilistic integrated assessment,* which aims to assess the risk of overshooting some climate target (absolute magnitude of GMT rise or rate of climate change) for a set of emissions scenarios or to produce probabilistic climate change projections that quantify the likelihood of a particular outcome. Typical results consist of probability distributions of overshooting a given climate stabilization goal, probabilistic scenarios of climate change, investigations of how a delayed or anticipated global action alters the risks of overshooting or the likelihood of future climate outcomes.

Inverse analyses, such as Safe Landing Analysis and Tolerable Windows Approach, aim to define a corridor of allowable emissions for a given set of avoided or unacceptable impact constraints. These might be a certain magnitude of global mean temperature rise, its rate of change, or sea-level rise, or intolerable mitigation costs (e.g. characterized as maximal yearly decarbonisation rate). The Tolerable Windows Approach differs from the Safe Landing Analysis in that it is based on a more detailed regional integrated model; thus it can specify constraints relating to some categories of sectoral/regional impacts or to mitigation costs. Through sensitivity analyses, inverse approaches provide insights on the influence for short- term decisions of a set of constraints on uncertain parameters over the long-term. They do not prescribe emissions pathways but delineate an allowable emissions corridor given these constraints. In this approach, adaptation is generally not considered explicitly in the analyses however impacts and views about thresholds for what might be considered "dangerous" or unacceptable impacts are explicitly represented as constraints on emissions. Choice of the emissions trajectory is left to decision makers based on their views about boundaries e.g. for (un)acceptable change.

[12] See also Working Group II, Chapter 19 uses a similar structure to review IA literature's treatment of key vulnerabilities and thresholds of change; the focus here is on IA's characterisation of long-term mitigation and interactions with adaptation and avoided impacts.

Optimal control analyses study the optimal pathway for decoupling GHGs emissions and economic growth, assuming the metaphorical "benevolent planner" mandated by cooperative stakeholders. The planner maximizes total welfare (or alternative variables) under given economic, technical and climate constraints. These models incorporate information from economic, climate and impact models in a more compact way than those of the two previous categories by interpreting the most relevant effects in monetary terms. In doing so it loses detailed information that would allow a decision maker to examine more systematically the interaction between uncertainty and the decision. Two basic variations on this approach are: i) a *cost-efficiency analysis* using various forms of climate constraints (concentration ceilings, temperature targets, maximum pace of global warming; and ii) a *cost-benefit analysis* that equates the marginal discounted sums of mitigation costs and climate damages assessed in monetary terms.

A number of issues complicate IA and deserve attention at the outset of this discussion: i) uncertainty related to the scale of assessment (global or local) making it difficult to characterize adaptation; ii) changes in adaptive and mitigative capacity; iii) simplified means of relating damages to temperature or other drives of changes in damages (often referred to as functional forms of damages); and iv) the omission of extremes and abrupt events from IA modelling. A fifth issue concerns treatment of the timing of mitigation and adaptation as well as of impacts (however this is addressed in section 3.6).

Uncertainty increases by an order of magnitude when passing from global to local assessments of climate change, thus the bulk of the effort in IA has been devoted to global scale assessments. Yet local assessments of climate change are a pre-condition for an in-depth examination of adaptation policies. As a result, impact assessments and the damage cost functions used in integrated assessment models often address adaptation in a limited way (Tol 2005a). Failure to consider adaptation may have led to an over estimation of impacts and damage costs in early studies (Tol *et al.* 2000, Callaway 2004, Tol 2005b). On the other hand, the assumption in existing studies that farmers (and other actors) have full information to switch crops and to adapt in an optimal manner (e.g Mendelsohn and Williams 2003) is likely to overestimate the effectiveness of adaptation and underestimate its costs by ignoring the need for learning and transaction costs (Tol *et al.* 2000; Tol 2002b; Kelly *et al.* 2005). Further adaptation assumptions and costs, when included, are almost always included in the damage function rather than separated out. While some regional, sectoral estimates of adaptation benefits and costs exist, the WGII review (see Ch. 17) concludes that cross-sectoral interactions are ignored in the literature and does provide any global estimates looking across all major sectors and regions.

Second, many IA studies *do not adequately account for development* and how it could reduce (or increase) the impacts of climate change and adaptive or mitigative capacity (Yohe and Tol, 2002, Tol 2002b, Tol *et al.* 2004, Rothman 2000, Smith *et al.* 2001, Hitz and Smith 2004). For example, estimates of climate impacts and adaptive capacity depend on assumptions about development, population and demographics, technology and infrastructure, institutional capacity (Tol 2005a, Yohe and Tol 2002). For example, Parry *et al.* (2004) show that there is wide variation in climate impacts on agriculture under different emission and socio-economic development baselines. Tol and Dowlatabadi (2001) demonstrate that, at least in the health sector and when focused on the spread of malaria in Africa, there is significant potential to reduce vulnerability (and thus climate damages) and enhance adaptive capacity by advancing development. They suggest that (over)investment in mitigation might limit funds available for such development which would boost adaptive capacity and thus could further aggravate climate damages, at least in this region and sector (see also Tol 2005a). Tol and Yohe (2006) note that in a global economy there is a trade-off between investment in climate mitigation and in hastening the pace of development (see also Lomborg 2006 and Sachs 2004 on this point). A number of authors are beginning to investigate climate feedbacks on the economy in dynamic macroeconomic modelling frameworks (Kemfert 2002; Bosello and Zhang 2005; Bosello *et al*. 2005). Further, Kemfert and Schumacher (2005) suggest that (over)investment in adaptation required under high levels of climate change could crowd out more productive investments and harm economic development (see also WGII, Ch. 20; WGIII, Ch. 12). This emerging literature underscores the inter-dependence between climate change, economic development, adaptive and mitigative capacity, however studies disagree about the nature of these linkages and patterns in a global context.

Third, the assumed *functional forms for damages* - or how damages vary with climate change - are a key input to IA and significantly influence outcomes yet they remain empirically weak. The consequences of the choice of functional forms are well understood in environmental economics (for example see Ambrosi 2004, Newell and Pizer 2000). In the case of climate analysis the form of the damage function will determine the inter-temporal distribution of damages and therefore the optimal policy response. Since there are few estimates of climate impacts in the literature at a range of temperatures, often damage functions are extrapolated from one or two benchmark estimates - typically a no climate change case, and at doubling of CO_2 concentrations (e.g, Tol 2002b) and extrapolation might be from only two data points. That is, the functional form is derived by assuming zero impacts today and drawing a line or curve to the estimated impacts at some static point in the future (Rothman 2000). Pearce *et al*. (1996) reviewed estimates of climate impacts on the US economy and many functional forms are calibrated using these estimates. An assumption of linearity in a damage function implies greater near term dangers than an assumption of a cubic function (Courtois 2004), which may lead to greater optimal near term emission reductions, and vice versa. Roughgarden and Schneider (1999) reformulated Nordhaus' DICE model to show that with alternative, yet equally plausible, damage functions a significantly more aggressive optimal policy is obtained thus highlighting the importance of taking care in choice of functional form.

Finally, nearly all IA models exclude damages due to increases in extreme weather events, even though there is an emerging literature suggesting that they may add significantly to economic losses from climate changes (Calzadilla, Pauli, and Roson 2006; Hallegatte, Hourcade, and Ambrosi 2006 in press; Hallegatte, Hourcade, and Dumas 2006 in press; Kemfert and Schumacher 2005). Nor do IA studies include "surprise" or abrupt climate change since this cannot currently be modelled with high confidence (Watkiss *et al*. 2005). Abrupt or irreversible events could be triggered in the long-term by policies and behaviours practiced in the near term, though the realization of such impacts could be long delayed. Recently a number of authors have shown that taking the risk of abrupt climate change or climate extremes into account - for example in a cost-benefit or cost-effectiveness framework - implies a need for faster and more stringent mitigation (Keller *et al*. 2005; Schneider and Lane 2004; Yohe, Andronova, and Schlesinger 2004) (also see Section 3.6).

3.5.2.1 Scenario and sensitivity analysis of climate targets

Two prominent examples of integrated assessment models used for scenario analysis are the Asian-Pacific Integrated Model and the IMAGE model (IMAGE-team, 2001; Alcamo *et al*. 1998). The AIM model has recently been used to examine stabilization of CO_2 only at 550 ppm from a reference point of an adapted B2 scenario (Kainuma *et al*. 1999). This work could be used as a basis for a consideration of costs and benefits of climate policies including for instance food risks and health risks (malaria). For the IMAGE model, a particular focus of attention is the simultaneous consideration of land use change and climate change. In several publications, integrated scenarios are used to analyse some of the interactions between these two fields (Leemans *et al*. 2003; Strengers *et al*. 2004; van Vuuren and Bouwman 2005; the Millennium Ecosystem Assessment scenarios as reported in Alcamo *et al*. 2006). This work shows the potential impact of land use change on the carbon cycle (see 3.2 and 3.3) - but can also be used to analyse joint consequences on biodiversity (e.g. Van Vuuren, Sala and Pereira, 2006). Leemans and Eickhout (2004) use the IMAGE model to consider the climate change effects on ecosystems in 2100 for different climate scenarios leading to levels of warming of 1, 2 and 3°C. The model has also been used to assess land use consequences of mitigation strategies, showing the significant land use (and biodiversity) consequences of bioenergy production (Van Vuuren *et al*. 2006). Obviously, these integrated assessment models suffer from limitations. For the IMAGE model, for instance, this includes the biome focus in describing climate impacts on ecosystems and the limited treatment of economic issues in their scenarios.

The scenario approach has also been used to explore the risks of increasing greenhouse gas concentrations. For instance, Meinshausen (2006) integrates each of several probability density functions of climate sensitivity to provide an estimate of the probability that a given stabilized concentration of greenhouse gases will overshoot various thresholds for global mean temperature rise once equilibrium has been reached. Higher stabilization levels lead to higher risks that certain temperature thresholds might be exceeded. Schneider and Mastrandrea (2005) follow a similar methodology to estimate the probability of exceedance of various thresholds that could potentially be considered as dangerous anthropogenic interference (DAI) in the climate system, as well as analysing the differences in the probability of these thresholds under overshoot and non-overshoot stabilisation scenarios. They use a simple model and emphasise that the purpose of the analysis is to demonstrate the validity of the probabilistic approach rather than to produce a quantitative result. Hare and Meinshausen (2005) look at the risk of loss of different animals and plants or other types of regional impacts at different levels of global mean temperature change.

3.5.2.2 Inverse modelling and guardrail analysis

Guardrail analysis uses inverse modelling to identify acceptable emission pathways for a given set of impact or climate change outcomes. Fuessel *et al*. (2001) developed an important tool by using detailed models[13] to estimate regionally specific, non-monetized climate impact response functions (CIRFs) for different sectors (agricultural production, forestry, water runoff and biome changes). This approach avoids metric controversies associated with valuation. Toth *et al*. (2002) use CIRFs to guide a tolerable windows assessment that estimates the existence and shape of necessary emission corridors using different ecological and economic policy objectives. An example of emissions corridors for an illustrative impact threshold that prohibits biome changes of more than 35 per cent worldwide are shown in Figure 3.44. The study provides a means to compare emission corridors that satisfy different criteria for CO_2 only mitigation; mitigation of non-CO_2 gases might be able to achieve greater protection (see section 3.3 for multigas emission pathways). Den Elzen, Meinshausen and Van Vuuren (2006) have recently published a set of corridors that include CO_2 and non-CO_2 gases, estimating both the probabilities of reaching temperature targets and the possible costs of these corridors.

[13] In particular from BIOME1 for ecosystems (Prentice *et al*. 1992) and WaterGAP1.1 (Doll *et al*. 1999), and FAO crop model as adapted in IMAGE2 (Alcamo *et al*. 1998).

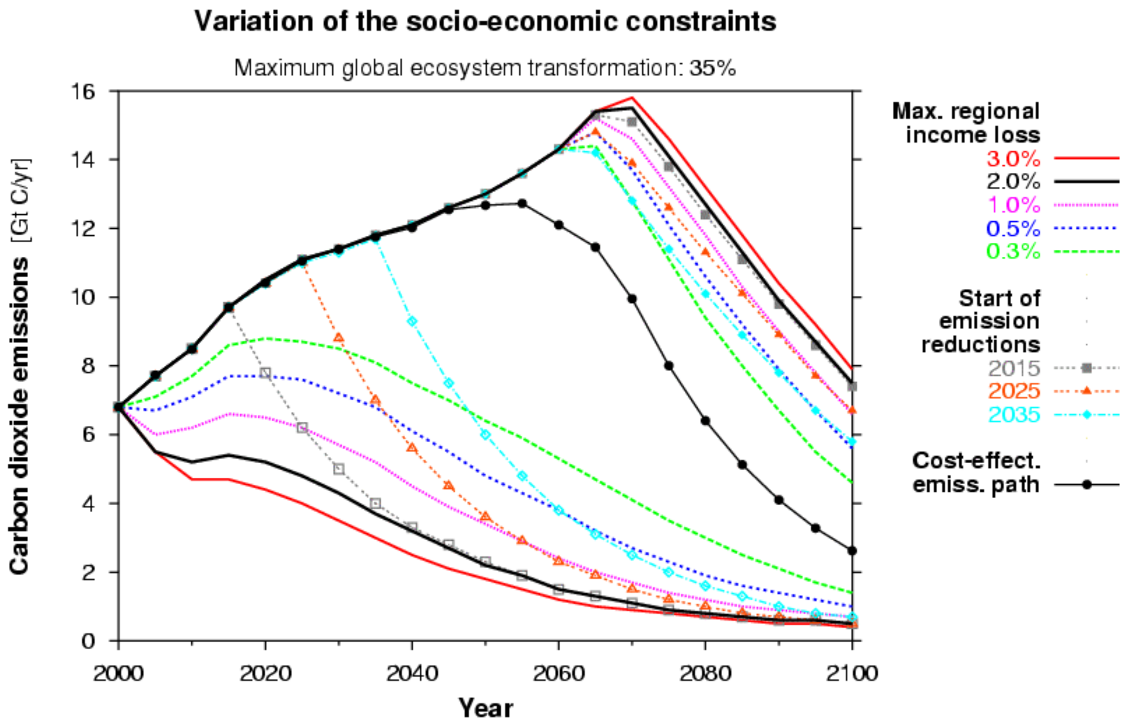


***Figure 3.44:** Admissible corridors for energy-related CO_2 emissions for different levels of regional income loss if at least 65 % of the world's ecosystems are to be preserved under climate change*

The figure shows emission corridors for variations of a regional mitigation cost constraint (from 0.3% to 3% loss of consumption without timing restrictions) and for variations of a timing constraint (from a start date of 2005 to 2035 for a regional mitigation cost constraint of 2%). The diagram shows eight pairs of lines representing emission corridors and one particular emission pathway. The outermost envelope of solid lines indicates the widest emission corridor, i.e. that a wide range of emission trajectories satisfy a 3% loss in consumption and a 65% preservation criterion, if emission reductions begin now. If society would tolerate only lower losses in consumption, the corridor narrows (other solid, dotted and dashed lines) and the maximum possible annual emission rate which is reached during the period decreases. If society delays emission reductions, the corridor also narrows (squares, triangles, diamonds). For comparison, the (middle) line of black dots show the optimal emission reduction path (i.e. that which maximizes global utility) whilst meeting a constraint to preserve 65% of ecosystems. Source: after Toth *et al.* (2002)

An inverse modelling framework can also assess the relationship between emission pathways and abrupt change and two recent studies consider what emission pathways induce (or avoid) THC collapse (Bruckner and Zickfeld 2005, Rahmstorf and Zickfeld 2005). Both studies suggest that without mitigation policy, the risk of exceeding key thresholds within the next few decades for the collapse of the THC is significant. Corfee-Morlot and Höhne (2003) review evidence about the five "areas of concern" highlighted in the TAR, to suggest that only low stabilization targets (e.g. 450ppm CO_2) appear likely to avoid worst case impacts across these numeraires. They show emission corridors to achieve this target concluding that such a target could be virtually out of reach as of 2020 and show how near term mitigation efforts, such as the Kyoto targets, help to keep this long-term policy goal within reach.

3.5.2.3 Optimal control models: cost effectiveness and cost benefit analysis

In cost benefit analyses impacts are monetized and global costs and benefits are "optimized" so that the marginal cost equals the marginal benefit of mitigation. Cost effectiveness analysis, simplifies the challenges in monetization by focusing on costs alone. Given the extremely long time frames over which climate change occurs, key assumptions in either of these analyses are the discount rate and choices about how damages and/or costs are weighted across diverse populations and regions (Pearce 2003, Pittini and Rahman 2004, Tol 2005b, Watkiss *et al*. 2005). Decisions about which values and approaches to use in aggregation are largely normative and thus can be controversial when applied to a global problem such as climate change (Grubb *et al*. 1999).

Nordhaus and Boyer (2000) rely on an integrated model (RICE) and regional impact estimates to characterize global impacts. It is unique among aggregate studies in its attempt to include non-market and potential catastrophic impacts as well as market impacts on a regional basis. Using a willingness-to-pay approach, the model presents aggregate damage curves for regions and by weighted summation, where weights are based either on projected population or regional output in 2100. Global average of damages for a 2.5° warming is 1.5 per cent of world output if weighted by output or 1.9 per cent if weighted by 1995 population. However these impacts vary widely across regions, ranging from benefits of 0.7 per cent of Russian output to net damages of almost 5 per cent in India. For most countries, market impacts are small in comparison to the possibility of potential catastrophic impacts and the large uncertainty associated with these catastrophic impact estimates implies great uncertainty in the overall results. More recently, Nordhaus (2006) uses a detailed (1^o x 1^o) geographic-economic cross-sectional (1990) database to analyse market impacts. Although Nordhaus considers this approach to be experimental and thus results to be preliminary, he suggests previous work may underestimate climate change damages and estimates global average damages for a 3^oC increase in global mean temperature ranging from 0.7 per cent to roughly 3.0 per cent of world output, with variation depending upon the climate scenario (wet or dry) and the approach used to aggregate regional damages.

A number of studies demonstrate that the consideration of abrupt change in cost benefit integrated assessment modelling frameworks changes “optimal” strategies for abatement. Keller *et al*. (2004) and Link and Tol (2004) suggest that significant reductions in anthropogenic greenhouse gas emissions may be an economically efficient investment given even small marginal damages associated with crossing the THC threshold. The same conclusion was found for crossing a hypothetical 2^oC threshold for West Antarctic Ice Sheet (Keller *et al*. 2004). Both Keller *et al*. (2000) and Mastrandrea and Schneider (2001) investigate the impacts of climate damage due to a collapse of THC on “optimal” emissions reductions. Keller *et al*. find that damages from THC collapse of 1per cent of GW_p would justify limiting emissions to avoid such a collapse, while Mastrandea and Schneider (2001) show that use of conventional discounting of 3 per cent and the inclusion of a 10 to 25 per cent increase in damage due to THC shutdown significantly raises optimal carbon taxes (by a factor of four in 2000 and of six in 2100). However, these results are extremely sensitive to the discount rate and time frames for analysis because damages occur far into the future (Mastrandrea and Schneider 2001). Moderate to high discount rates will reduce the net present value of these damages significantly, and will marginalize their impact on mitigation decisions in a cost benefit framework (Ackerman and Finlayson 2006 in press) see also Figures 3.45 and 3.46).

Overall the credibility of cost benefit integrated assessments depends on whether normative assumptions used to construct the inputs (i.e. damage functions) and aggregate outputs are representative of the range of actors covered in the assessments. Azar and Schneider (2001) conclude that cost benefit analysis can justify any emission reduction target, low or high, on the basis of many subjective choices in the analysis (discount rates, treatment of uncertainty) (see also Azar and Lindgren 2003, Howarth 2003; Ingham and Ulph 2004, Mastrandrea and Schneider, 2004). Tol (2001) shows how optimal outcomes vary with views about social justice. Commenting on the use of cost-benefit analyses on a global scale, Jacoby (2004) observes that data are poor and assumptions often controversial, which raises questions about the ability to do credible global assessments of this type without significantly more research in key areas at regional scale (e.g. assessment of vulnerability, adaptive capacity and physical and economic impacts in developing countries). A main challenge concerns monetization of damages.

3.5.2.4 Difficulties in the monetization of damages

Key outputs of optimal control models are estimates of the social costs of carbon (SCC), which is the marginal cost of the emission of one tonne of carbon. Its estimation is strongly dependent on the model formulation and input assumptions with one of the strongest determinants being the discount rate. Hope (2006) presents a quantitative analysis of drivers of SCC based on a review of the wide range of values of SCC found in the literature (Figure 3.45).

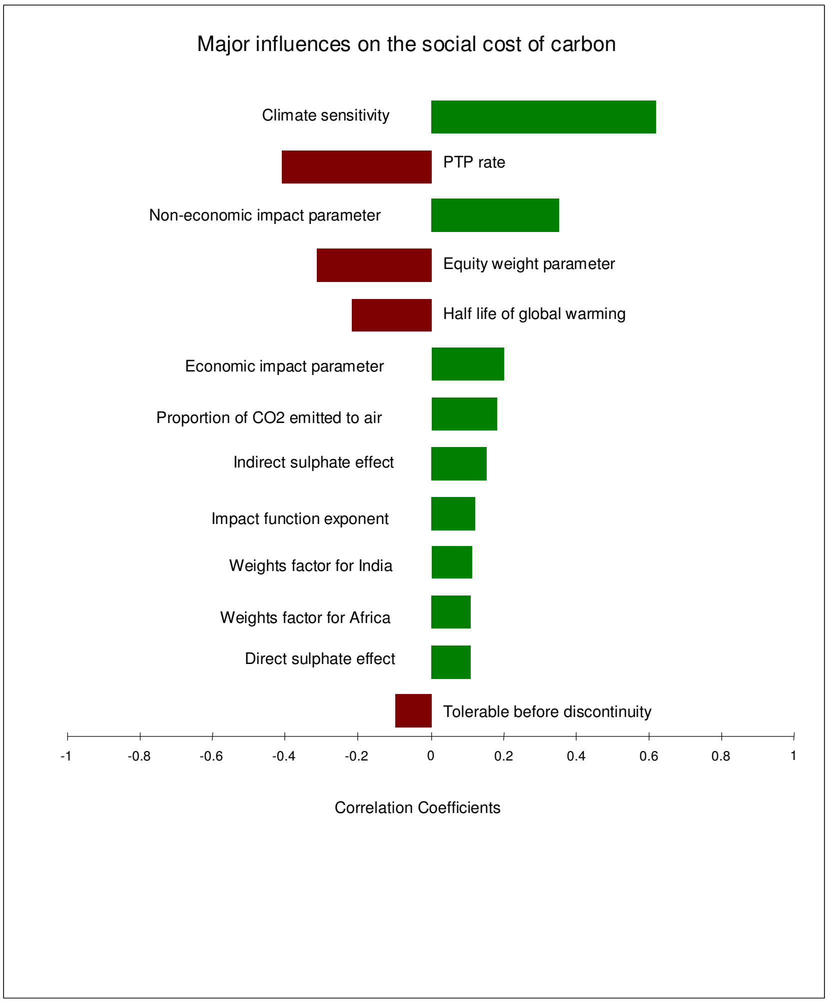


Figure 3.45: *Major influences on the social cost of carbon*
Source: Hope 2006 - Stern Review

Figure 3.46 presents a more general qualitative analysis of the drivers of SCC values (Watkiss *et al*. 2005). As noted above a problem with cost benefit approaches in general (e.g. DICE -Nordhaus 1991; RICE - Nordhaus and Boyer 1999; FUND - Tol 2002a, 2002b; MERGE - Manne, Mendelsohn and Richels 1995) is their aggregation of climate change damages into simplified function based frequently on a single metric for use in an overall cost benefit assessment. This masks diverse regional outcomes (ie. who wins and who loses) by requiring the expression of impacts solely in monetary terms rather than through a range of other metrics.

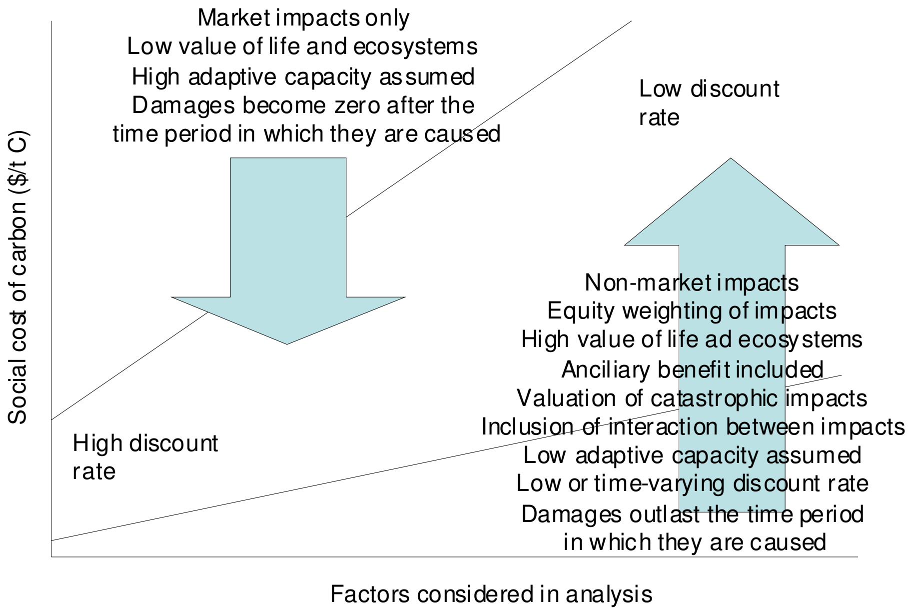


Figure 3.46: *Factors influencing the social cost of carbon (based on Watkiss et al and Downing et al 2005)*

SCC values are higher when non-market impacts, such as degradation of ecosystems, are included rather than only market impacts; when higher values are placed on intangibles such as the value of life and ecosystems; when the potential for low-probability, abrupt, high impact events is considered; when ancillary benefits of climate mitigation policies are included; when interactions between damage in different economic sectors in the same geographical region is considered, and when damages are modelled to outlast the time period in which they are caused. Other key factors include the relative weighting between impacts in different regions of the world.

3.5.3 Risk management approaches: linking emission scenarios to changes in global mean temperature and impacts

Long-term mitigation policy in a risk management framework is informed not only by concern about costs and mitigation options (see 3.3 and 3.4) but also by concern about climate change impacts. Global mean temperature can be used as a key indicator of change that links future emission pathways and mitigation scenarios to climate impacts (see Table 3.12).

Table 3.12: *Ranges of radiative forcing, CO_2 eq. concentrations and temperatures*

Equilibrium Warming with	Probability to stay below equilibrium warming level[15]

Stabilization concentration (CO_2 equivalence)	best-guess climate sensitivity[14]: above pre-industrial	best-guess climate sensitivity[14]: above 1980-2000 average	above pre-industrial / above 1980-2000 average	1.5°C / 1.0°C	2°C / 1.5°C	2.5°C / 2.0°C	3°C / 2.5°C	3.5°C / 3.0°C	4°C / 3.5°C
350 ppm	1.0°C	0.5°C		very likely	very likely	Very likely	Very likely	very likely	Very likely
400 ppm	1.6°C	1.1°C		medium	likely	Very likely	Very likely	very likely	Very likely
450 ppm	2.1°C	1.6°C		unlikely	medium	likely	likely	very likely	Very likely
500 ppm	2.5°C	2.0°C		very unlikely	unlikely	medium	likely	likely	Very likely
550 ppm	3.0°C	2.4°C		very unlikely	unlikely	unlikely	Medium likelihood	likely	likely
600 ppm	3.3°C	2.8°C		very unlikely	very unlikely	unlikely	Medium likelihood	medium likelihood	likely
650 ppm	3.7°C	3.2°C		very unlikely	very unlikely	very unlikely	unlikely	medium likelihood	Medium likelihood
700 ppm	4.0°C	3.5°C		very unlikely	very unlikely	very unlikely	unlikely	medium likelihood	Medium likelihood
750 ppm	4.3°C	3.8°C		very unlikely	very unlikely	very unlikely	unlikely	unlikely	Medium likelihood
800 ppm	4.6°C	4.1°C		very unlikely	very unlikely	very unlikely	unlikely	unlikely	Medium likelihood
850 ppm	4.8°C	4.3°C		very unlikely	very unlikely	very unlikely	Very unlikely	unlikely	unlikely
900 ppm	5.1°C	4.6°C		very unlikely	very unlikely	very unlikely	Very unlikely	unlikely	unlikely
950 ppm	5.3°C	4.8°C		very unlikely	very unlikely	very unlikely	Very unlikely	unlikely	unlikely
1000 ppm	5.5°C	5.0°C		very unlikely	very unlikely	very unlikely	Very unlikely	very unlikely	unlikely

Legend:

very likely	likely	medium likelihood	unlikely	very unlikely
>90%	66%-90%	33%-66%	10%-33%	<10%

3.5.3.1 Linking emission scenarios to change in global mean temperature and key vulnerabilities

Understanding the relationship between mitigation and impacts requires linking emission scenarios to global mean temperature change. Section 3.3.2 relates the mitigation scenario literature to global mean temperature change based on AR4/WGI assessment of the likely range of climate sensitivity. Table 3.5 is derived from WGI (Ch. 10), to highlight in more detail the global mean temperature outcomes associated with different stabilisation targets.

Global mean temperature change is the link between stabilisation targets (in either ppm or W/m^2) and key vulnerabilities. Much of the impacts literature can be organized around global mean temperature change (WGII) and this is used as the central metric for discussing the notion of key vulnerabilities. WGII (Ch. 19) definition of key vulnerabilities takes into account not only predicted impacts but also the ability and potential of different systems to adapt to climate change (WGII, Ch. 19). It (Table 19.2) lists key vulnerabilities between 0 and 2 degrees above 1990 to include reduced

14 Note that global mean temperature at equilibrium is different from expected global mean temperatures in 2100 due to the inertia of the climate system. These equilibrium temperatures follow from the equivalent CO2 concentration value and the simplified expression for equilibrium temperatures (namely dT = (ln(CO2 eq/278ppm))/ln(2))*S, where CO_2 eq is the equivalent concentration level, and S the climate sensitivity - see AR-4 WG1, Chapter 10, section 10.7.2).

15 These probability estimates are derived for illustrative purposes by assuming WG1's estimate of the likely range of climate sensitivity, 2.0°C to 4.5 °C, as being a 80% confidence interval of a lognormal distribution. This translation of a confidence range into a lognormal probability density function (pdf) is equivalent to the applied procedure in e.g. Wigley & Raper (2001), who assumed the IPCC TAR's climate sensitivity estimate of 1.5°C to 4.5°C as being a 90% confidence interval of a lognormal pdf.

low latitude food production, some damages to infrastructure, increases in water stress in dry areas, widespread impacts of drought and forest fires, and loss of up to a quarter of species with half of ecosystems unable to adapt. The table also lists key vulnerabilities between 2 and 4 degrees above 1990 including global declines in food production, rapidly increasing damages to infrastructure, many regions with water stress including regions previously with only mild water stress, large areas of forest threatened with fire, disease or changes to grassland, with biomass loss amplifying warming, and loss of one third of species with two thirds of ecosystems unable to adapt. Table 3.13 highlights examples from the WGII, Chapter 19 discussion of "key vulnerabilities" to demonstrate each of the key systems vulnerable to climate change: geophysical, biological, social, market and extreme events.

Table 3.13: *Examples of key vulnerabilities* avoided *as move lower levels of global annual mean temperature rise relative to 1990 (adapted from WGII, Ch 19) Confidence levels: L= Low, M= Medium, H= High confidence*

GMT range indicating increase relative to 1990	Geophysical systems Example: Greenland ice sheet. (Refer to Table 19.2 WGII for further information, also concerning West Antarctic Ice Sheet and Meridional Overturning Circulation).	Biological systems Example: biodiversity (Refer to Table 19.2 WGII for further information, also concerning ocean systems, forests, rivers & lakes)	Social systems Example: *water* (Refer to Table 19.2 WG II for further information, also concerning coastal resources, health, high mountain communities, indigenous, poor or isolated communities, and cross-border issues).	Market systems Example: *food supply* (Refer to Table 19.2 WGII for further information, also concerning infrastructure and net market impacts)	Extreme Events Example: *fire risk* (Refer to Table 19.2 WGII for further information, also concerning tropical cyclone intensity, flooding, heat and drought).
>4	Complete deglaciation triggered (M-H). Commitment to about 7m sea level rise (H).	Widespread extinctions with additional effects on dependent species and ecosystem services (H).	Many regions severely stressed, requiring extreme adaptations such as out migration (M)	Further declines in global food production compared to those for lower temperatures (M-L)	Conditions expected to be more extreme (H) compared to lower levels of GMT increase
2-4	Widespread to complete deglaciation triggered (H). *Lowers risk of complete deglaciation.*	*Lowers risk of widespread extinctions with additional effects on dependent species and ecosystem services (H).* Loss of one-third of species. About two-thirds of ecosystems cannot adapt (M).	*Limits need for extreme adaptations in many more regions (M).* However many regions presently only mildly stressed experience increased stress (H) including areas fed by snow or glacier melt that lose storage capacity (H).	*Lowers risk of a further decline in global food production associated with higher temperatures (M-L).* Global production peaks and begins to decrease (L).	Frequency and intensity of fires likely to be greater (H) *Lowers risk of more extreme conditions.*
0-2	*Lowers risk of widespread or complete deglaciation (H).* However localized deglaciation will still occur (H).	*Limits risk of species loss from one-third to a quarter of species* (M). *Proportion of ecosystems that cannot adapt reduced from about two-thirds to just below one half* (M).	*Limits risk of adding stress to those regions currently experiencing only mild water stress (H).* However, many regions which are presently stressed reach critical levels, especially in Mediterranean-type climates (H).	*Lowers risk of global net declines in food production projected at higher temperatures (L).* Declines in food production in low latitude regions (L). Potential for increased global production (L).	*Lowers risk of greater and more intense fires in many areas (H)* although still increased fire frequency and intensity in many areas compared to a no-climate-change case, particularly arid and semi-arid areas (H).
Comments	Rate of deglaciation increases with regional warming. Full deglaciation takes several centuries to millennia.	Rapid warming or rainfall changes will exceed natural rates of adaptation. Loss of species is irreversible.	Many adaptations available in low stressed regions such as improved water use efficiency and use of water pricing. More costly adaptations include irrigation and desalinization which have environmental and energy costs.	High adaptive potential, unevenly distributed, realization of potential uncertain	Decreased precipitation will likely increase frequency of fires. In arid climates, fire frequency can increase even with increased precipitation with large enough warming. It can increase biomass, thus resulting in larger fires. Fire fighting capacity can be stepped up,

					but extreme conditions can overwhelm most fire-fighting efforts.

Table 3.12, gives temperatures relative to a pre-industrial and post-industrial reference points showing the post-industrial as 0.5C higher than pre-industrial estimates (see Ch. 10, Working Group I). Stabilization at 450 ppm CO_2 eq. is likely to avoid impacts associated with 2-4 degrees temperature rises above 1990, whereas stabilization at higher levels such as 550 ppm CO_2 equivalent is unlikely to avoid this range of impacts. However, the best guess for temperature rise associated with 450 ppm CO_2 equivalent is 1.6 degrees above 1990 compared with 2.4 degrees for 550 ppm. By contrast, the best guess temperature change associated with stabilization at 550 pm CO_2-eq. is 3 degrees and this would be likely to impose some of the impacts listed for temperature increases of 2 to 4 degrees. For stabilization levels of 650 ppm CO_2-eq, the best guess for temperature increase above 1990 is 3.2 degrees, also implying that many of the impacts listed for 2 to 4 degrees temperature rise above 1990 would be expected to occur. Stabilization at 450 ppm CO_2 equivalent would be likely to limit impacts to those associated with temperature rises of 0-2 degrees above 1990 (Table 19.2, Ch. 19, Working Group II) and avoid those listed as occurring for temperature rise of 2-4 degrees above 1990. Table 3.13, combined with Table 3.12 demonstrates these points.

It is also important to note the risk of exceeding a particular temperature threshold at a given stabilization level depends critically on the shape of the tail of the probability distribution, something that is more strongly influenced by the prior assumptions of the modellers than by observations of the climate system. This suggests that while the risk based analysis shown in Table 3.5 is very informative, one cannot ignore the small, and unquantifiable, probabilities that very large temperature changes might still arise for stabilization of greenhouse gas concentrations even at low levels such as 450 ppm CO_2 eq.

3.5.3.2 Stabilization emission pathways and climate change risks

An important question is how different emission pathways leading to stabilization of concentrations relate to possible policy targets, such as a possible threshold or upper bound for GMT increase (Wigley 2004a, b; Yohe *et al*. 2004, O'Neill and Oppenheimer 2004, Kainuma *et al*. 2004, Meinshausen 2006, Keller *et al*. 2005, Keller *et al*. 2006; Den Elzen *et al*. 2006).[16] In general, for a given target both early action and delayed response emissions profiles can be developed. More recently, overshoot profiles have been added to this. A delayed response could lead to lower (discounted) costs and some additional time to further develop technologies and mitigation strategies but also to higher rates of change for sustained periods of time risk exceeding thresholds for abrupt climate change (Keller *et al*., 2006, Schneider and Lane, 2004). This could challenge the ability for ecosystems to adapt naturally to climate change (e.g. Hare and Meinshausen, 2005) and necessitate rapid adaptation responses in humans systems to more rapidly rising temperatures (e.g. Nicholls and Lowe 2004; see also Working Group II, Chapters 17 and 19). Pathways to a given stabilization target thus affect both mitigation costs, as discussed in sections 3.3 and 3.6, and the benefits of mitigation.

These analyses show that the risks of climate change are affected by the pathway taken toward stabilization (i.e. overshoot pathways, early versus lagged mitigation) as well as by the stabilization target. For example, O'Neill and Oppenheimer (2004) survey a range of approaches and find that

16 Table 3.12 refers to equilibrium temperature rises. Meinshausen (2006) also carried out a probabilistic analysis of transient exceedance of temperature thresholds, for which the probabilities would differ from Table 3.12 and would be emission-pathway dependent as well as stabilization-level dependent.

the transient, pre-equilibrium temperature in 2100 is as much, or more, strongly controlled by the approach to stabilization than by the stabilization target itself. In particular, they find that overshoot pathways can lead to a temperature rise above what would otherwise occur in 2300 (by 0.1 to 0.6 C) and that the rate of temperature change is higher and is sustained longer. Schneider and Mastrandrea (2005) also compared the probability distributions of temperature change induced by specific overshoot and non-overshoot scenarios stabilizing at 500 ppm CO_2 equivalent, based on published probability distributions representing uncertainty in climate sensitivity. They found that, from 2000-2200, the overshoot scenario increased the probability of temporary or sustained exceedance of a threshold of 2ºC above pre-industrial levels by 70 per cent.

Table 3.14 provides an overview of the implications of different stabilization targets for the timing of global emission reductions.

Table 3.14: *Properties of emissions pathways for alternative ranges of CO_2 and CO_2-eq. stabilization targets. All stabilization scenarios in the scenario database (see also sections 3.2 and 3.3; data source Nakicenovic et al., 2006 and Hanaoka et al., 2006)*

Scenario Category	CO2-only concentrations by 2100	CO2-equivalent concentrations by 2100	Year when global emissions peak	Year when global emissions fall below 2000 levels	Change in global emissions in 2050 relative to 2000 levels	Change in global emissions in 2100 relative to 2000 levels
	ppmv	ppmv	year	year	%	%
The 90th precentile range of the stabilisation scenarios in the literature						
A	< 420	<510	2000 - 2040	2000 - 2060	-86 to +18	-161 to -67
B	420 - 490	510-590	2000 - 2050	2000 - 2060	-41 to +33	-91 to -38
C	490 - 570	590-710	2010 - 2080	2010 - dnr	-3 to +73	-85 to +47
D	570 - 660	710-860	2030 - 2100	2060 - dnr	+27 to +116	-24 to +81
E	> 660	>860	2040 - 2090	2100 - dnr	+67 to + 143	-5 to +186

In summary, recent literature demonstrates the usefulness of a risk management approach to assessment of mitigation strategies. Integrated assessment tools facilitate integration of knowledge about climate change risk, mitigation strategies and economic development to explore the trade-offs and interactions between mitigation, adaptation and avoided impact damages. Compared to the TAR, several new issues emerge in this literature with implications for long-term mitigation strategies: more sophisticated, probabilistic representation and a shift in the range of climate sensitivity; a growing understanding of key vulnerabilities, including from abrupt change in geophysical systems, at relatively low levels of climate change (e.g. in the 2-4 C range and possibly in the 0-2 C range); recognition of the broad inter-linkages between climate change and economic development, potentially raising the stakes for "good" decision-making to address the risks of climate change. The recent literature also offers a wider variety of stabilization profiles (rapid change or slow change, delayed or early action) compared to the TAR, making it is possible to identify a number of trade-offs relevant to policy choices. Broad uncertainty inevitably limits what can be said with confidence in quantitative terms but some robust qualitative conclusions can be drawn. While delayed action or overshoot pathways appear to lower mitigation costs, such strategies also raise the risk of triggering impacts at higher levels of climate change for extended periods of time. This raises the question of whether society is a risk-taker or risk-averse in the face of climate change? A risk-taking society might choose to delay action and take the (small) risk of triggering significant and possibly irreversible abrupt change impacts over the long-term. However, if society is risk averse - that is, interested in avoiding downside risk or worst case outcomes - this would suggest a preference for hedging behaviour, or more and earlier mitigation to lower the risk of abrupt climate change (e.g. Yohe *et al*. 2004; Baranzini *et al*. 2003; Keller *et al*., 2006 in press; Ambrosi 2004).

3.6 Linkages between short-term emissions trends and envisaged policies and long-term climate policy targets

For a given vision of the adaptation potential to adverse impacts of climate change, policymakers must determine whether the present emissions trajectory is consistent with the possible range of long-term GHGs stabilization objectives and the sensitivity of various end points to near term decisions. The third assessment report of the IPCC (Chapter 8 on 'costs and ancillary benefits of mitigation' and chapter 10 on 'decision-making frameworks') strongly emphasized differences between the optimal timing of abatement under a 'certainty case', when the ultimate target is known from the outset, and under a 'probabilistic' case, where decision makers account for the fact that the level of a 'dangerous interference' will be progressively revealed and calibrate the policy response accordingly.

In the first approach, the choice of pathway can be seen as a GHG budget problem. A concentration target defines the allowable GHG emissions, and the issue is how to best allocate them between various time horizons. IPCC SAR had demonstrated the reasons why this approach is a misleading oversimplification; it ignores the significant uncertainty regarding long-term objectives, policy makers are not required to make once-and-for-all decisions binding their successors over very long time horizons and there will be ample opportunities for mid-course adjustments over the century in light of new information on climate change and on carbon saving techniques. The choice of abatement path involves balancing the economic risks of rapid abatement now (that premature capital stock retirement will later be proved unnecessary) against the corresponding risks of delay (that more rapid emission reduction will be required later, necessitating premature retirement of a greater proportion of future capital stock) *(SAR, WGIII, SPM).*

A significant amount of material has been produced since SAR and TAR to inform debates about the optimal near term hedging strategy; they upgrade our understanding of the parameters influencing the decisions about the appropriate timing of climate action.

3.6.1 The choice of a near term hedging strategy in the context of long-term climate uncertainty

Models address this timing issue through optimal control procedures that calculate the emissions pathways (and the resulting abatement efforts from a given baseline) in order to maximize total social welfare between now and the very long run. These models are a caricature of an 'act-then-learn' continuous process; they both distort reality but provide very useful insights about it.

First these models describe a metaphor in which a 'benevolent planner' mandated by cooperative stakeholders, attempts to maximize total welfare under given economic, technical and climate constraints. This full cooperation assumption is obviously unrealistic; in real sequential games, players optimize their own moves in response to preceding moves made by other players and the assumption about the degree of cooperative or free riding behaviour is critical; game theory tries to analyse the properties of possible coalitions in crafting and implementing international climate policy (see also Ch. 10 in TAR WGIII). The advantage of the benevolent planner metaphor is that it provides a useful benchmark about what should be the best agreement amongst good faith stakeholders for a given set of beliefs and value judgments.

Second, these models describe a 'decision tree' such as in Figure 3.47. In the parlance of decision analysis, the squares represent points at which decisions are made, the circles represent the reduction of uncertainty and the arrows indicate the wide range of possible decisions and outcomes. The first node summarizes today's investment options - how much should be invested in mitigation, in adaptation, in expanding mitigative and adaptive capacity, or in research to reduce uncertainty? The other nodes represent opportunities to learn and make mid-course corrections (there is no implied meaning to the order of the nodes, nor will uncertainty be fully resolved over time). Learning and decision making are continuous processes but, to disentangle the many determinants of the near term strategy, it is easier to describe it at discrete intervals.

In such sequential decision making approaches, there are two major ways of framing the decision problem. The first way is a cost benefit analysis that employs monetary estimates of the economic and social damages caused by climate change and finds the optimal emissions pathway by equating the marginal discounted sums of mitigation costs and climate damages. The second is a cost effectiveness analysis that uses various forms of climate constraints (concentration ceiling, temperature targets, rate of global warming). This approach is selected by those who refuse money-metric valuation of environmental assets or human life for ethical reasons and those who come to the same conclusion on pragmatic grounds, namely the fact that any such monetization cannot but be non-comprehensive and fragile. In fact, opposition between these two modes of reasoning should not be exacerbated: using a set of environmental constraints is simply a way of considering that, beyond such constraints, the threat of climate change might become unacceptable; in a money-metric valuation approach, the same expectation can be translated through using damage curves with *dangerous* thresholds.

In fact the main serious source of divergence between the two approaches is the discount rate - within a cost effectiveness framework, the 'benefit' of acting, are environmental constraints which are not influenced by discounting; conversely, in a cost-benefit framework, benefits occur later than costs and thus have a lower weighting. The extent of this trade off depends on the level of the discount rate that makes explicit the unavoidable weighting between present and future generations. Without coming back to discussions about the appropriate level of the discount rate (see IPCC SAR and chapter 2 in FAR) understanding how it works matters in this type of approach in order to avoid misplaced debates and understand why its influence on short-term decisions is more complex than often suggested.

First, the discount affects the valuation of the environmental damages relative to consumption but, in models with environmental goods and an aggregate of consumption goods, the marginal utility of consumption decreases as people become richer. The environment becomes a 'superior good' to which future and richer generations give a higher percentage of income and its relative value increases thus offsetting part of the influence of the discount rate Guesnerie (2005) and Tol (1994).

Second, environmental value is affected by the time profile of environmental damages, which is largely determined by the shape of the function deriving damages from cumulated emissions. Lecocq and Hourcade (2003) demonstrate that the steeper the damage function, the lesser the influence of the discount rate on short-term abatement.

Third, pure preference for the present takes place amongst a set of other key economic parameters such as marginal productivity of capital and technical progress. This creates complex links making the overall effect of the discount rate choice ambiguous in many instances. For example, high growth scenarios imply optimistic assumptions on the marginal productivity of capital leading to high discount rates; but if such scenarios are run under the assumption of damage thresholds, these thresholds are crossed sooner than in low growth scenarios, which may make early action necessary.

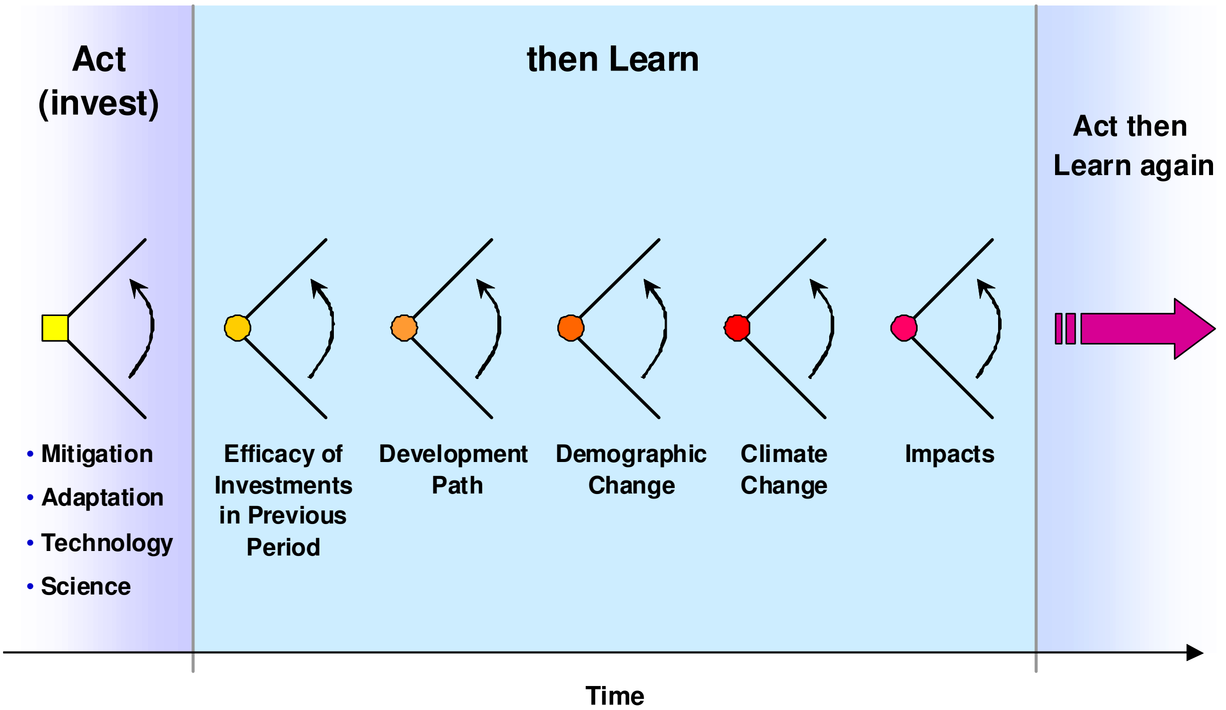


Figure 3.6-1: *The Sequential Nature of the Climate Policy Process*

Fourth, the discount rate plays a role amongst two other valuation parameters, the subjective distribution of probabilities about damages and the risk premium - the amount that society is willing to pay to avoid risk. For example, if it is assumed that there is a likelihood of substantial harm, abatement costs are low, and society is highly risk averse, then an aggressive abatement policy would be optimal. Conversely, if it is assumed that the likelihood of great harm is small, abatement costs are high, and society is less risk averse, then a less aggressive abatement policy will be optimal. As uncertainty is resolved over time, the level of abatement may be adjusted.

This section reviews recent results which, in this framework, provide information with respect to technical parameters that are critical to the timing of mitigation action.

3.6.2 Factors affecting timing of climate policy actions

For a given discount rate and risk premiums, factors affecting the timing of policy action include the level of concentration or temperature targets, the effect of technical and socio-economic system dynamics on short-term mitigation efforts; and the influence of non-CO_2 gases and sequestration options on the time profile of decarbonisation efforts.

3.6.2.1 Influence of concentration or temperature targets in a cost effectiveness framework

Within a cost effectiveness framework, the aim is to minimize the cost of the mix of options needed to remain inside the 'tolerable space'.

Under a Tolerable Windows Approach or a Safe Landing Approach (Alcamo and Kreileman 1996, Swart *et al.* 1998) efforts have been carried out to explore climate policies focusing on global mean temperature. Concentrations ceilings are a poor surrogate for what constitutes dangerous climate change: they by-pass many links from atmospheric chemistry to damages and propagate uncertainty, and they explicitly refer only to long-term climate targets. By contrast, global mean temperature (GMT) is a better and more tangible proxy of climate change impacts (McCarthy *et al.* 2001) that can take into account the rate of climate change, a major determinant of impacts, both for ecosystems and technical systems.

In terms of sequential decision making under uncertainty, using temperature ceilings presents the advantage of dealing explicitly with uncertainty regarding climate sensitivity. The TAR states that '*the equilibrium climate sensitivity was estimated to be between +1.5°C and +4.5°C in the SAR. This range still encompasses the estimates from the current models in active use*' (Houghton *et al.* 2001, chap. IX, p. 561). Wigley and Raper (2001) have proposed an *ad hoc* lognormal distribution, with a 90 per cent confidence range from 1.5°*C* to 4.5°*C*. Since then, significant research has better characterised climate sensitivity and quantified its uncertainty[1 17] but this parameter is hard to constrain and new estimates remain concentrated over the +1.5°*C* +4.5°*C* range with a mean close to +3.5°*C* while not excluding much higher values, admittedly with low probabilities.

- Studies exploring the implications of this uncertainty for decision making (Caldeira *et al*. 2003, Kriegler and Bruckner 2004, Lempert *et al*. 1994, Hammitt *et al*. 1992, Den Elzen and Meinshausen 2005) conclude that the lower the warming threshold and the higher the climate sensitivity (both implying stringent concentrations ceilings), the narrower the global carbon budget.
- A few authors go beyond such sensitivity studies to incorporate not only the consequences of uncertainty about climate sensitivity but also the consequences of revising it given improvements in knowledge. To analyse the trade-off between a costly acceleration of mitigation costs and a (temporary) overshoot of targets and the climate impacts of this overshoot, some form of cost benefit analysis is required. Ambrosi *et al*. (2003) did so through a willingness to pay for not interfering with the climate system. They show that allowing for an overshoot of the ex-ante target significantly decreases the required acceleration of decarbonisation and the peak of abatement costs but does not change drastically the level of abatement prior to the revelation of information.

Furthermore, uncertainty about climate sensitivity magnifies the influence of the rate constraint on short-term decision making, leading to rather stringent policy recommendations for the coming decades. Earlier emissions reductions are found optimal to hedge against eventual high climate sensitivity, which is associated with faster and more intense warming. This result is robust to the choice of discount rate and to beliefs about climate sensitivity. The same authors shows that uncertainty about the rate constraint is even more important for short-term decision making than uncertainty about climate sensitivity or the magnitude of warming. Therefore, research should be aimed at better characterizing early climate change risks with a view to help decision makers in agreeing on a safe guardrail to limit the rate of global warming.

3.6.2.2 Implications of assumptions concerning cost-benefits functions

[17] This is the case either from observations (because historical radiative forcing and ocean heat uptake data are poor) (Andronova et Schlesinger, 2001; Gregory *et al.*, 2002; Knutti *et al.*, 2002, 2003; Frame, 2005) or from atmosphere-ocean global circulation models (because the parameterisations of some key processes such as cloud effects need improving) (Murphy, 2004; Stainforth, 2005).

In the TAR, the pioneer attempts to assess hedging strategies in a cost benefit framework tended to conclude that there was need for only a limited short-term abatement effort. As explained in the preceding section, this result is strongly dependent on the assumptions about the shape of the damage curve, especially with regard to the way it translates non-linear events, singularities and catastrophes - on which cost benefits analyses of climate policies have only recently come to focus.

With damage functions exhibiting smooth and regular damages (such as power functions with integer exponents or polynomial ones), GHG abatement is postponed because, for several decades, the temporal rate of increase in marginal climate change damage remains far lower than the discount rate (which lowers the marginal damages over time). Since most studies are calibrated on a single point, the paradox is that, the higher the exponent (to account for possible catastrophic damages for intense warming) the lower are the damages over the short and medium term, and, consequently, the sum of discounted damages. To factor in costs of major environmental risks triggered by climate change, Nordhaus and Boyer (2000), for instance, increase the scale coefficients of their damage functions without altering their shapes - as a result, their models still recommend low short-term abatement effort.

Such non-linear singularities may stem from large-scale catastrophic events such as slow down of the THC. Recent modelling has shown that including even small probabilities of catastrophic events may substantially alter near term optimal emissions targets and raise the optimal carbon tax (Mastrandea and Schneider 2004, Azar and Lindgren 2003). Azar and Schneider (2001) conclude that cost benefit analysis can justify any emission reduction targets if ‘nasty surprises’ in the climate system are considered. Ingham and Ulph (2004) and Howarth (2003) report similar findings. But these surprises may be caused by other channels than large catastrophic events. For example, they may be triggered by smooth climate changes that exceed a vulnerability threshold (for example, shocks to agricultural systems in developing countries leading to starvation).

Two approaches have been used to scrutinise the impact of such singularities on the timing of action, leading to similar conclusions. Keller *et al.* (2004) explore the combined effects of uncertainty about climate sensitivity and irreversible damage (triggered by a potential ocean thermohaline circulation collapse) to show that significant emissions reductions may be justified to avoid or delay even small damages from an uncertain and irreversible climate change-even when future learning about the system is considered. Together with this general conclusion, they point out the seemingly paradoxical result: if a climate catastrophe seems very likely within a rather near time horizon, it might be considered economically sound to accept its consequences instead of investing in expensive mitigation to avoid the inevitable. Similarly, under a cost effectiveness approach, societies faced with a very tight environmental constraint would prefer a temporary overshoot in emissions in the near term rather than bear the social costs of an exaggerated reduction in emissions as already pointed out by. This result matters because it points to the existence of a window of opportunity for precautionary measures.

Ambrosi *et al.* (2003) focus on the interplay between uncertainty about climate sensitivity and the eventuality of a threshold in climate change damages. They demonstrate that given the uncertainty about climate sensitivity (which brings closer the time when the vulnerability threshold may be exceeded), abrupt damages compared to smooth and regular ones imply early mitigation efforts; meanwhile, there exists a window of opportunity to learn before 2040 the value of climate sensitivity. Furthermore, literature on investment under uncertainty comparing gradual, continuous uncertainty in the global warming process with the possibility of abrupt damages (Dumas and Ha-Duong 2004, Baranzini *et al.* 2003) also justify more early action.

3.6.2.3 Timing of action on non-CO_2 gases and on carbon sequestration and their implications for de-carbonisation pathways

An increasing amount of effort has been devoted since the TAR to analyzing the policy importance of using options other than decarbonisation of the energy system for achieving climate objectives (mitigation of non-CO_2 gases; geological carbon storage; and biological carbon storage or sequestration through vegetation and soil management). These analyses examine the extent to which it is possible to alleviate the constraint impinging on the energy sector over the short to medium term and to facilitate the transition toward low carbon-intensive development patterns. The focus was placed on the optimal timing of non-energy mitigation measures: should these options be used in the short-term to facilitate the energy transition or over longer time horizons as safety-valves as a contingency where 'bad surprises' force an accelerated reduction in net emissions. The optimal use of these options depends on the marginal social value of these actions at a given point in time and throughout the entirety of a long run climate control program - considerations that are not independent of assumptions about climate risks or de-carbonisation policies.

Models used to study hedging strategies represent the carbon cycle in a compact manner as if its behaviour was independent of the time profile of GHG emissions. But a number of contributions have shown that the carbon cycle is sensitive to this time profile (Cox *et al.* 2000, Friedlingstein *et al.* 2001) and deforestation (Gitz and Ciais 2003). In other words, the estimated temperature in 2100 (and the rate of temperature change in this century) is as much, or more, controlled by the pathway to stabilization than by the stabilization target itself (O'Neill and Oppenheimer 2004, Hoegh-Guldberg 1999, Kainuma *et al.* 2004).

Role of biological and geological carbon sequestration

That carbon sequestration lowers the overall cost of reaching emissions targets is unsurprising since this expands the menu of options. It has also been shown that under given circumstances the introduction of carbon capture and sequestration technology can lead indirectly to an expansion of non-fossil fuel electricity generation technologies (Fisher *et al*. 2006). However, research on the potential for carbon capture and geologic sequestration reveals that there is significant uncertainty about these options and their social acceptance.

Ha-Duong and Keith (2003) show that if carbon capture and storage can be achieved with no leakage over time, the option decreases the need for near term precautionary abatement. However, Keller (2004) cautions that under the assumption of leakage from geologic sinks, net damages over long time horizons depends on assumptions regarding the level of decarbonisation achieved using this option.

Concerning the use of biological carbon sequestration to partially substitute for fossil fuel emission mitigation to stabilise atmospheric GHGs concentrations, analysts insist on the asymmetry between carbon emitted by burning fossil energy and carbon emitted (or released) by managing terrestrial ecosystems, because land cover management changes the dynamic properties of the carbon cycle and may even result into significant carbon releases.

Kirschbaum (2003) and Gitz *et al.* (2004) make a distinction between: a) permanent sequestration whose economic potential is restricted by the opportunity cost of land;and b) transitory sequestration which in part bypasses this problem (since land is ultimately reallocated to other uses) but whose social value is lowered by the extra marginal damage caused the release of carbon. The social value of transitory biological sequestration is thus high only under abatement policy in the energy sector that is significant enough to lower future concentrations and may be negative under the opposite assumption. This mechanism has to be accounted for in the study of the optimal timing of deployment of this option.

A significant use of biological sequestration today would place the world on a lower emissions trajectory, while sequestration later may assist in managing an abatement cost peak under circumstances where stringent concentration ceilings and rapid GHG mitigation were required. Kirschbaum (2003) and Gitz *et al.* (2004) find that the social value of transitory biological sequestration is high only under aggressive abatement policy in the energy sector and may be negative under the opposite assumption. Gitz *et al.* (2004) show, in a stochastic optimal control framework, that permanent sequestration (covering up to 100 Mha of plantations in the next two decades, should be used early as a "brake" to lower slightly the optimal rate of abatement in the energy sector but that, such as in Kirschbaum (2003), the bulk of the potential (up to 600 Mha) has to preserved in order to be used later, as a 'safety valve" in case of 'bad news', to cut (by a central estimate of 18 per cent) the peaks of fossil abatement expenditures.

The same conclusion is reached by Read and Lermit (2004) in the specific case when an unacceptable risk of abrupt climate change is revealed by 2020 in the absence of stabilizing CO_2 concentrations at a very low level (e.g., 300 ppm). Massive use of bio-energy with carbon storage (yielding negative carbon emissions) might help to restore pre-industrial CO_2 levels by the middle of the 21st century.

Role of multi-gas mitigation options

A number of parallel numerical experiments have been carried out by the Energy Modelling Forum on the role of multi-gas mitigation. Although it can be argued that abatement cost curves for these gases rely on only a few preliminary empirical studies, the conclusion that mitigation of these gases can significantly cut the costs of meeting various emissions reduction targets at various points in time is robust.

The most critical question, from a policy point of view, is how to compare the relative contribution of these gases to climate forcing. Criticisms of the use of GWPs as an integrating index are well established but there is currently no consensus about alternatives that can be easily used in optimal control models to study optimal timing of abatement of these gases. This technical difficulty explains why no study has been published so far in a stochastic optimal control framework in a similar way to studies on CO_2 or biological carbon sequestration. However, theoretical analysis suggests two important conclusions:

- if the rate of warming in future decades is viewed as a binding constraint (in a cost effectiveness framework) or as causing significant damages, then abating short lived gases such as methane would have a high social value over the short run; it would slow down global warming and allow time for dissemination and uptake of low cost carbon saving technologies; and
- if global warming in future decades is viewed as less critical than possible high climate risks beyond given, currently unknown, concentration thresholds, then it would be economically more efficient to trigger abatements of short lived gases only after the resolution of information about these climate change risks in order to facilitate the switching toward very tight concentration constraints.

3.6.3 Evaluation of short-term mitigation opportunities in long-term stabilization scenarios

For any chosen greenhouse gas stabilization target, near term decisions can be made regarding mitigation opportunities to help maintain a consistent emissions trajectory within a range of long-term stabilization targets. Economy wide modelling of long-term global stabilization targets can help inform near term mitigation choices. This section assesses the most current literature for sectoral emission and mitigation estimates from top down, economywide models. Scenario results from top down models were compared for the year 2030 to evaluate the near term mitigation opportunities in long-term stabilization scenarios. While scenario emission projections vary in resolution and range across models, this assessment illustrates a range of short-term mitigation opportunities for comparable long-term targets. To put these identified mitigation opportunities in context, they will be compared with short-term, bottom up results from Chapters 4 to 11.

For this section, we evaluated a range of scenarios from long-term models (with time horizons beyond 2050) such as AIM, IPAC, IMAGE, GRAPE, MiniCAM, MERGE, MESSAGE, and WIAGEM. Top down models with a short-term time horizon up to 2050, such as POLES and SGM, were also evaluated. Many of the modelling scenarios were an outcome from Stanford University's Energy Modeling Forum Working Group 21, which focused on multigas strategies to address climate change and resulted in the publication of a special issue of the *Energy Journal* (see Weyant and de la Chesnaye, in press). Models that were evaluated in this assessment are listed in Table 3.15.

Table 3.15: *Models Assessed for Mitigation Opportunities in 2030*

Model	Model Type	Solution Concept	Modeling Team and Reference
AIM (Asian-Pacific Integrated Model)	Multi-Sector General Equilibrium	Recursive Dynamic	NIES/Kyoto Univ., Japan Fujino *et al*, in press
GRAPE (Global Relationship Assessment to Protect the Environment)	Aggregate General Equilibrium	Intertemporal Optimization	Institute for Applied Energy, Japan Kurosawa, in press
IMAGE (Integrated Model to Assess The Global Environment)	Market Equilibrium	Recursive Dynamic	Netherlands Env. Assessment Agency van Vuuren *et al*, Energy Journal, in press (IMAGE 2.2) van Vuuren *et al*, Climatic Change, in press (IMAGE 2.3)
IPAC (Integrated Projection Assessments for China)	Multi-Sector General Equilibrium	Recursive Dynamic	Energy Research Institute, China Jiang *et al*, in press
MERGE (Model for Evaluating Regional and Global Effects of GHG Reductions Policies)	Aggregate General Equilibrium	Intertemporal Optimization	EPRI & PNNL/Univ. Maryland, U.S. USCCSP, forthcoming
MESSAGE-MACRO (Model for Energy Supply Strategy Alternatives and Their General Environmental Impact)	Hybrid: Systems Engineering & Market Equilibrium	Intertemporal Optimization	International Institute for Applied Systems Analysis, Austria Rao and Riahi, in press
MiniCam (Mini-Climate Assessment Model)	Market Equilibrium	Recursive Dynamic	PNNL/Univ. Maryland, U.S. Smith and Wigely, in press
SGM (Second Generation Model)	Multi-Sector General Equilibrium	Recursive Dynamic	PNNL/Univ. Maryland and EPA, U.S. Fawcett and Sands, in press
POLES (Prospective Outlook on Long-Term Energy Systems)	Market Equilibrium	Recursive Dynamic	LEPII-EPE & ENERDATA, France Criqui *et al*, 2006
WIAGEM (World Integrated Applied General Equilibrium Model)	Multi-Sector General Equilibrium	Intertemporal Optimization	SPEED, Oldenburg Univ., Germany Kemfert *et al*, in press

For each of these models, the greenhouse gas mitigation emission projections by economic sector in a stabilization target scenario were compared with the projected emissions in the reference case for each model. The projected reduction in greenhouse gas emissions by sector for comparable stabilization targets across the models were then compared for the year 2030. While each model approaches a stabilization target in a different manner, assessing model results for comparable long-term targets informs short-term mitigation decisions by illustrating a range of mitigation opportunities. Across all the models, the long-term target in the stabilization scenarios could be met through the mitigation of multiple greenhouse gases. Most of the scenarios examined across the models do not include carbon capture and storage as a mitigation option, except for the MiniCAM scenario.

Table 3.16 illustrates the global mitigation potential estimates by sector in the year 2030 across a range of scenarios with stabilization targets in the 4 to 5 W/m^2 range. The marginal cost of meeting the potential emission reduction estimates of up to approximately 16,000 $MtCO_2eq$ across all greenhouse gases in the top down model scenarios ranges from less than $\$10/tCO_2eq$ to approximately $\$60/tCO_2eq$. Three important considerations need to be remembered with regard to the reported marginal costs. First, these mitigation scenarios assume complete “what” and “where” flexibility, i.e., there is full substitution among GHGs and reductions take place anywhere in the world as soon as the models begin their analyses. Limiting the degree of flexibility in these mitigation scenarios, e.g., limiting mitigation only to CO_2, removing major countries or regions from undertaking mitigation, or both, will increase marginal costs, all else equal. Second, the marginal costs of realizing these levels of mitigation increase in the time horizon beyond 2030. See Figure 3.33 for an illustration of projected long-term prices. Third, at the economic sector level, emission reduction potential for all greenhouse gases varies significantly across the different model scenarios.

Table 3.16: *Global Emission Reductions in 2030 by Sector for Stabilization Targets of 4-5 W/m*^{2}

Model		IPAC	GRAPE	AIM	MiniCAM	MERGE	IMAGE	MESSAGE	WIAGEM	POLES	SGM
Model Time Horizon		Long-term	Long-term	Long-term	Long-term	Long-term	Long-term	Long-term	Long-term	Short-term	Short-term
Stabilization Target		550 ppmv	4.5 W/m^2 from pre-Industrial	4.5 W/m^2 from pre-Industrial	4.5 W/m^2 from pre-Industrial	4.7 W/m^2 from pre-Industrial	4.5 W/m^2 from pre-Industrial	B2 Scenario, 4.5 W/m^2 from pre-Industrial	2°C from pre-Industrial	550 ppmv	from MiniCAM trajectory
Marginal Cost (2000 U.S. $/tCO2eq)		$14	$2	$29	$12	$15	$18	$9	$9	$57	$21
Reference Emissions 2030 Total All Gases (MtCO_2eq)		55,311	57,030	49,365	54,217	47,243	65,465	57,801	43,100	53,031	53,452
Sector Mitigation Potential in 2030 (Total All Gases MtCO_2eq)	Energy Supply: Electric	6,413	529	5,190	7,346	653	2,400	1,109	6,952	9,459	3,012
	Energy Supply: Non- Electric	579	37	1,083	1,486	412	2,204	517	1,741	2,964	1,660
	Transportation Demand	806	56	487	206	Included in another sector	1,318	276	Included in another sector	467	462[b]
	Buildings Demand	625	389	478	287	Included in another sector	754	531	Included in another sector	983	Included in another sector
	Industry Demand	1,231	Included in another sector	469	1,726	Included in another sector	846	136	Included in another sector	1,879	Included in another sector
	Industry Production	10	276	837	228	1,462[a]	1,133	339	3,593	807	1,631[b]
	Agriculture	-1,012	583	2,000	267		690	584	1,128	-175	4,210
	Forestry	Included in another sector	0	13	0		1,444	40	16	Included in another sector	Included in another sector
	Waste Management	0	4	Included in another sector	340		677	896	Included in another sector	Included in another sector	837
	Global Total	**8,652**	**1,875**	**10,556**	**11,885**	**2,527**	**11,465**	**4,428**	**15,531[d]**	**16,384**	**14,026[c]**
Mitigation as % Reference Emissions		**16%**	**3%**	**21%**	**22%**	**5%**	**18%**	**8%**	**36%**	**31%**	**26%**

[a] MERGE sector mitigation potentials for Industry Production, Agriculture, Forestry and Waste Management are aggregated.
[b] SGM sector mitigation potentials for Transportation Demand and Industry Production are not complete global representation due to varying levels of regional aggregation.
[c] SGM sector mitigation potentials do not sum to global total due to varying levels of regional aggregation.
[d] WIAGEM sector mitigation potentials do not sum to global total due to the breakout of the household and chemical sectors.

In scenarios with lower stabilization targets, higher levels of near term mitigation are required to achieve the target in the long run. Table 3.17 shows mitigation potential and costs for selected model scenarios with lower stabilization targets in the 3-4 W/m^2 range. For these lower target scenarios, the marginal costs range from approximately \$50/tCO_2eq to \$190/tCO_2eq. The mitigation required to meet the targets ranges from approximately 15,000 -24,000 MtCO_2eq.

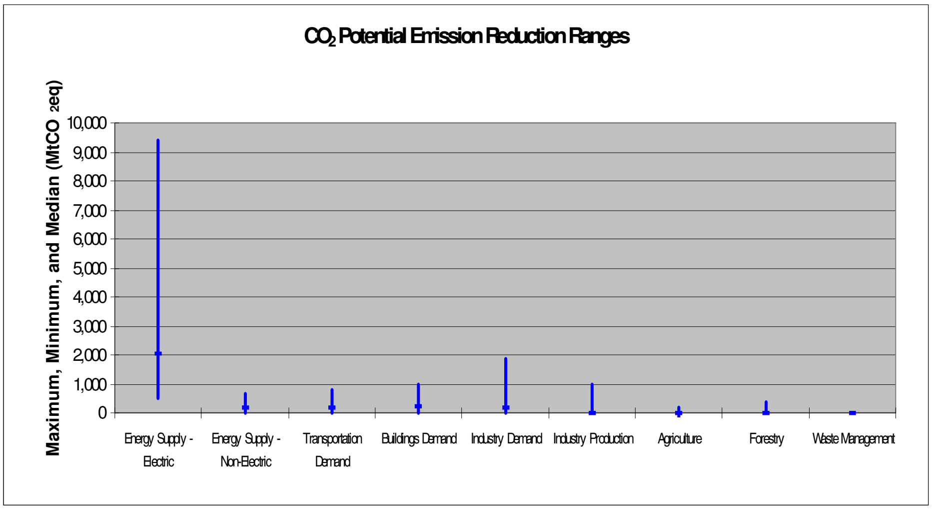
Table 3.17: *Global Emission Reductions in 2030 by Sector for Lower Stabilization Targets*

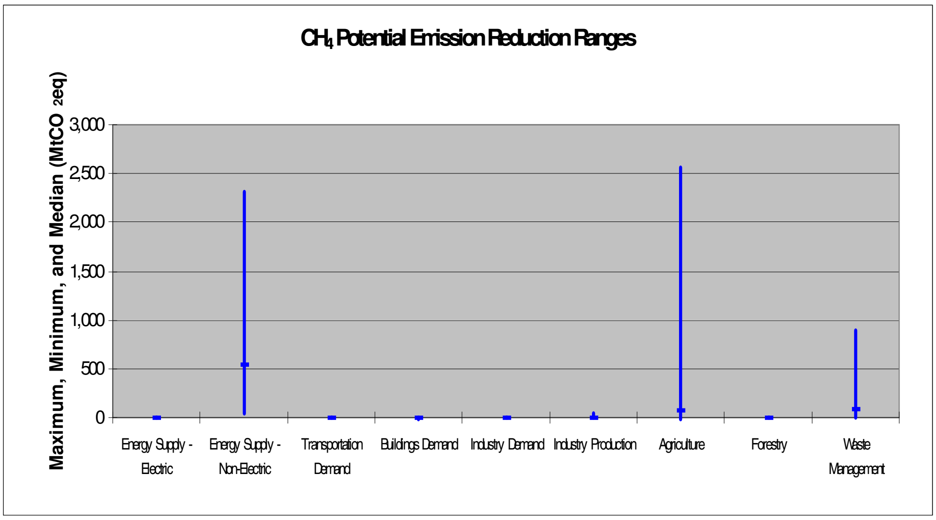
	Model	MiniCAM	MERGE	IMAGE[b]	IMAGE[b]	MESSAGE
	Model Time Horizon	Long-term	Long-term	Long-term	Long-term	Long-term
	Stabilization Target	3.5 W/m^2 from pre-Industrial	3.4 W/m^2 from pre-Industrial	3.7 W/m^2 from pre-Industrial	3.0 W/m^2 from pre-Industrial	B2 Scenario, 3.2 W/m^2 from pre-Industrial
	Marginal Cost (2000 U.S. \$/tCO2 eq)	\$53	\$192	\$48	\$112	\$115
	Reference Case Emissions in 2030 Global Total All Gases (MtCO2 eq)	54,217	47,243	59,735	59,735	57,801
Sector Mitigation Potential in 2030 (Total All Gases MtCO_2eq)	Energy Supply: Electric	11,945	9,533	3,853	8,736	4,296
	Energy Supply: Non-Electric	3,308	3,188	2,252	3,669	2,242
	Transportation Demand	627	Included in another sector	1,491	2,840	2,238
	Buildings Demand	1,372	Included in another sector	522	1,000	1,420
	Industry Demand	5,222	Included in another sector	1,612	3,188	795
	Industry Production	270		1,126	2,024	811
	Agriculture	604	3,580[a]	980	1,208	1,656
	Forestry	0		173	247	604
	Waste Management	768		1,041	1,105	896
	Global Total	**23,848**	**16,302**	**13,039**	**24,018**	**14,959**
	Mitigation as % of Reference Emissions	**44%**	**35%**	**28%**	**40%**	**26%**

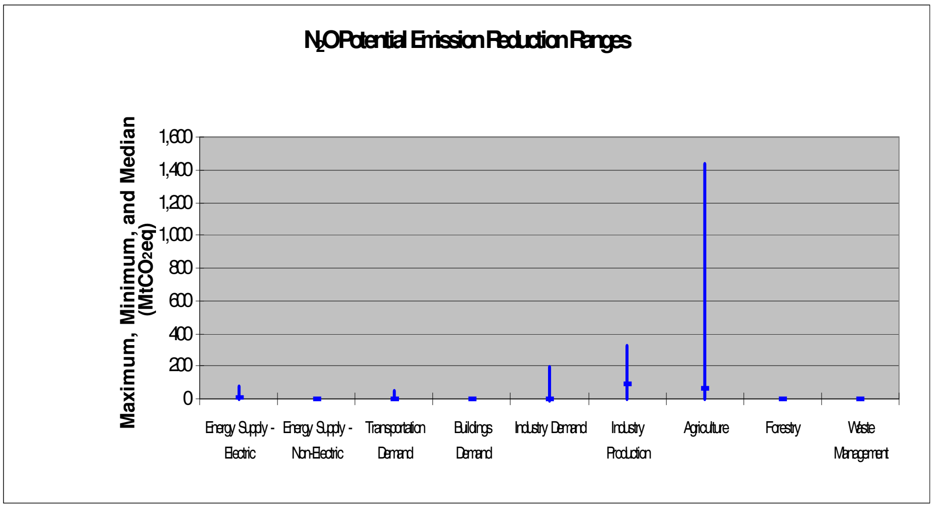
a MERGE sector mitigation potentials for Industry Production, Agriculture, Forestry and Waste Management are aggregated.

b IMAGE scenarios with lower stabilization targets were developed using IMAGE 2.3. IMAGE scenarios shown in Table 3.16 were developed using IMAGE 2.2.

To examine the realizable mitigation opportunities more closely at the sector level, the range of potential mitigation estimates across the various modelling scenarios with stabilization targets in the 4-5 W/m^2 range is illustrated in Figure 3.48. Each of the charts shows the minimum, maximum, and median of mitigation estimates for each greenhouse gas by sector. These potential mitigation ranges highlight sectors on which to focus near term mitigation strategies, consistent with an emission projection path that will meet the stabilization targets. Across all of the models assessed in the 4-5 W/m^2 stabilization target range, the electricity supply sector has the largest potential for near term greenhouse gas mitigation, ranging up to over 9,000 MtCO_2 eq of potential mitigation. Other sectors with relatively high CO_2 mitigation potential include energy demand in the transportation and industry sectors. Mitigation of non-CO_2 greenhouse gases also contributes to the stabilization goals. For methane emission reduction, the largest near term potential mitigation across the model scenarios is in the non-electric energy supply sector (over 2,000 $MtCO_2eq$), the agriculture sector (over 2,500 $MtCO_2eq$), and the waste management sector (nearly 1,000 $MtCO_2eq$). The agriculture sector also has the largest potential for N_2O emission reduction, ranging across the model scenarios up to over 1,400 $MtCO_2eq$. For F Gas emission reduction, mitigation potential in the industry production sector range up to over 800 $MtCO_2eq$.







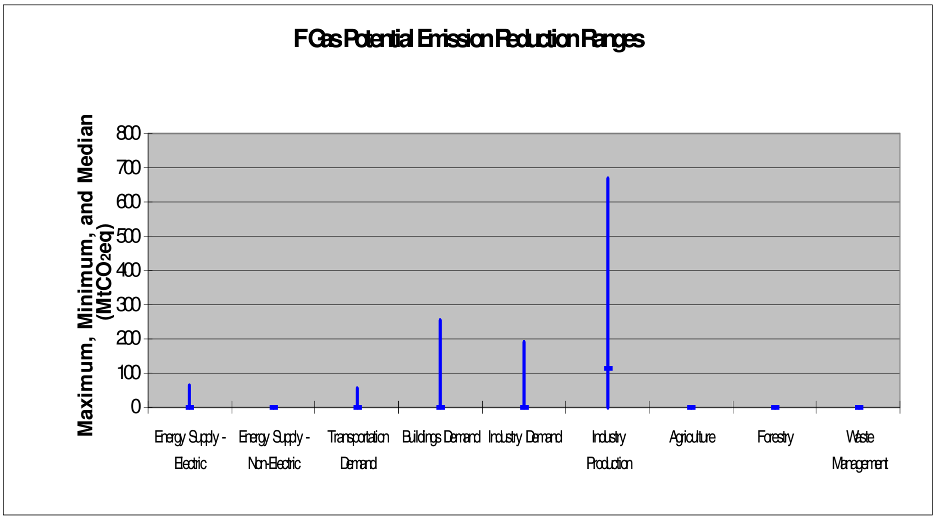


Figure 3.48: *Range of Potential Emission Reduction by Gas for Each Sector*

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