3

Issues related to mitigation in the long-term context

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Table of Contents

EXECUTIVE SUMMARY

This chapter documents baseline and stabilization scenarios in the literature since the publication 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 during the past five years. Of special relevance is how ranges published for driving forces and emissions in the newer literature compare with those used in the TAR, SRES and pre-SRES scenarios. This chapter focuses particularly on the scenarios that stabilize atmospheric concentrations of greenhouse gases (GHGs). The multi-gas stabilization scenarios represent a significant change in the new literature compared to the TAR, which focused mostly on carbon dioxide (CO_2) emissions. They also explore lower levels and a wider range of stabilization than in the TAR.

The foremost finding from the comparison of the SRES and new scenarios in the literature is that the ranges of main driving forces and emissions have not changed very much *(high agreement, much evidence)*. Overall, the emission ranges from scenarios without climate policy reported before and after the SRES have not changed appreciably. Some changes are noted for population and economic growth assumptions. Population scenarios from major demographic institutions are lower than they were at the time of the SRES, but so far they have not been fully implemented in the emissions scenarios in the literature. All other factors being equal, lower population projections are likely to result in lower emissions. However, in the scenarios that used lower projections, changes in other drivers of emissions have offset their impact. Regional medium-term (2030) economic projections for some developing country regions are currently lower than the highest scenarios used in the SRES. Otherwise, economic growth perspectives have not changed much, even though they are among the most intensely debated aspects of the SRES scenarios. In terms of emissions, the most noticeable changes occurred for projections of SO_x and NO_x emissions. As short-term trends have moved down, the range of projections for both is currently lower than the range published before the SRES. A small number of new scenarios have begun to explore emission pathways for black and organic carbon.

Baseline land-related CO_2 and non-CO_2 GHG emissions remain significant, with continued but slowing land conversion and increased use of high-emitting agricultural intensification practices due to rising global food demand and shifts in dietary preferences towards meat consumption. The post-SRES scenarios suggest a degree of agreement that the decline in annual land-use change carbon emissions will, over time, be less dramatic (slower) than those suggested by many of the SRES scenarios. Global long-term land-use scenarios are scarce in numbers but growing, with the majority of the new literature since the SRES contributing new forestry and biomass scenarios. However, the explicit modelling of land-use in long-term global scenarios is still relatively immature, with significant opportunities for improvement.

In the debate on the use of exchange rates, market exchange rates (MER) or purchasing power parities (PPP), evidence from the limited number of new PPP-based studies indicates that the choice of metric for gross domestic product (GDP), MER or PPP, does not appreciably affect the projected emissions, when metrics are used consistently. The differences, if any, are small compared to the uncertainties caused by assumptions on other parameters, e.g. technological change *(high agreement, much evidence)*.

The numerical expression of GDP clearly depends on conversion measures; thus GDP expressed in PPP will deviate from GDP expressed in MER, more so for developing countries. The choice of conversion factor (MER or PPP) depends on the type of analysis or comparison being undertaken. However, when it comes to calculating emissions (or other physical measures, such as energy), the choice between MER-based or PPP-based representations of GDP should not matter, since emission intensities will change (in a compensating manner) when the GDP numbers change. Thus, if a consistent set of metrics is employed, the choice of MER or PPP should not appreciably affect the final emission levels *(high agreement, medium evidence)*. This supports the SRES in the sense that the use of MER or PPP does not, in itself, lead to significantly different emission projections outside the range of the literature *(high agreement, much evidence)*. In the case of the SRES, the emissions trajectories were the same whether economic activities in the four scenario families were measured in MER or PPP.

Some studies find differences in emission levels between using PPP-based and MER-based estimates. These results critically depend on, among other things, convergence assumptions *(high agreement, medium evidence)*. 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 and saving decisions are the main drivers of growth in the models. 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 potentials. Different results can also be due to inconsistencies in adjusting the metrics of energy efficiency improvement when moving from MER-based to PPP-based calculations.

There is a clear and strong correlation between the CO_2-equivalent concentrations (or radiative forcing) of the published studies and the CO_2-only concentrations by 2100, because CO_2 is the most important contributor to radiative forcing. Based on this relationship, to facilitate scenario comparison and assessment, stabilization scenarios (both multi-gas and CO_2-only studies) have been grouped in this chapter into different categories that vary in the stringency of the targets, from low to high radiative forcing, CO_2-equivalent concentrations and CO_2-only concentrations by 2100, respectively.

Essentially, any specific concentration or radiative forcing target, from the lowest to the highest, requires emissions to eventually fall to very low levels as the removal processes of the ocean and terrestrial systems saturate. For low to medium targets, this would need to occur during this century, but higher stabilization targets can push back the timing of such reductions to beyond 2100. However, to reach a given stabilization target, emissions must ultimately be reduced well below current levels. For achievement of the very low stabilization targets from many high baseline scenarios, negative net emissions are required towards the end of the century. Mitigation efforts over the next two or three decades will have a large impact on opportunities to achieve lower stabilization levels *(high agreement, much evidence)*.

The timing of emission reductions depends on the stringency of the stabilization target. Lowest stabilization targets require an earlier peak of CO_2 and CO_2-equivalent emissions. In the majority of the scenarios in the most stringent stabilization category (a stabilization level below 490 ppmv CO_2-equivalent), emissions are required to decline before 2015 and are further reduced to less than 50% of today's emissions by 2050. For somewhat higher stabilization levels (e.g. below 590 ppmv CO_2-equivalent) global emissions in the scenarios generally peak around 2010–2030, followed by a return to 2000 levels, on average around 2040. For high stabilization levels (e.g. below 710 ppmv CO_2-equivalent) the median emissions peak around 2040 *(high agreement, much evidence)*.

Long-term stabilization scenarios highlight the importance of technology improvements, advanced technologies, learning-by-doing, and induced technological change, both for achieving the stabilization targets and cost reduction *(high agreement, much evidence)*. While the technology improvement and use of advanced 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 scenarios show different technology dynamics and ways in which technologies are deployed, while maintaining the key role of technology in achieving stabilization and cost reduction.

Decarbonization trends are persistent in the majority of intervention and non-intervention scenarios *(high agreement, much evidence)*. The medians of scenario sets indicate decarbonization rates of around 0.9 (pre-TAR) and 0.6 (post-TAR) compared to historical rates of about 0.3% per year. Improvements of carbon intensity of energy supply and the whole economic need to be much faster than in the past for the low stabilization levels. On the upper end of the range, decarbonization rates of up to 2.5% per year are observed in more stringent stabilization scenarios, where complete transition away from carbon-intensive fuels is considered.

The scenarios that report quantitative results with drastic CO_2 reduction targets of 60–80% in 2050 (compared to today's emission levels) require increased rates of energy intensity and carbon intensity improvement by 2–3 times their historical levels. This is found to require different sets of mitigation options across regions, with varying shares of nuclear energy, carbon capture and storage (CCS), hydrogen, and biomass.

The costs of stabilization crucially depend on the choice of the baseline, related technological change and resulting baseline emissions; stabilization target and level; and the portfolio of technologies considered *(high agreement, much evidence)*. Additional factors include assumptions with regard to the use of flexible instruments and with respect to revenue recycling. Some literature identifies low-cost technology clusters that allow for endogenous technological learning with uncertainty. This suggests that a decarbonized economy may not cost any more than a carbon-intensive one, if technological learning is taken into account.

There are different metrics for reporting costs of emission reductions, although most models report them in macro-economic indicators, particularly GDP losses. For stabilization at 4–5 W/m^2 (or ~ 590–710 ppmv CO_2-equivalent) macro-economic costs range from -1 to 2% of GDP below baseline in 2050. For a more stringent target of 3.5–4.0 W/m^2 (~ 535–590 ppmv CO_2-equivalent) the costs range from slightly negative to 4% GDP loss *(high agreement, much evidence)*. GDP losses in the lowest stabilization scenarios in the literature (445-535 ppmv CO_2-equivalent) are generally below 5.5% by 2050, however the number of studies are relatively limited and are developed from predominantly low baselines *(high agreement, medium evidence)*.

Multi-gas emission-reduction scenarios are able to meet climate targets at substantially lower costs compared to CO_2-only strategies (for the same targets, *high agreement, much evidence*). Inclusion of non-CO_2 gases provides a more diversified approach that offers greater flexibility in the timing of the reduction programme.

Including land-use mitigation options as abatement strategies provides greater flexibility and cost-effectiveness for achieving stabilization *(high agreement, medium evidence)*. Even if land activities are not considered as mitigation alternatives by policy, consideration of land (land-use and land cover) is crucial in climate stabilization for its significant atmospheric inputs and withdrawals (emissions, sequestration, and albedo). Recent stabilization studies indicate that land-use mitigation options could provide 15–40% of total cumulative abatement over the century. Agriculture and forestry mitigation options are projected to be cost-effective abatement strategies across the entire century. In some scenarios, increased commercial biomass energy (solid and liquid fuel) is a significant abatement strategy, providing 5–30% of cumulative abatement and potentially 1–15% of total primary energy over the century.

Decision-making concerning the appropriate level of mitigation in a cost-benefit context is an iterative risk-management process that considers investment in mitigation and adaptation, co-benefits of undertaking climate change decisions and the damages due to climate change. It is intertwined with development decisions and pathways. Cost-benefit analysis tries to quantify climate change damages in monetary terms as the social cost of carbon (SCC) or time-discounted damages. Due to considerable uncertainties and difficulties in quantifying non-market damages, it is difficult to estimate SCC with confidence. Results depend on a large number of normative and empirical assumptions that are not known with any certainty. SCC estimates in the literature vary by three orders of magnitude. Often they are likely to be understated and will increase a few percent per year (i.e. 2.4% for carbon-only and 2–4% for the social costs of other greenhouse gases (IPCC, 2007b, Chapter 20). SCC estimates for 2030 range between 8 and 189 US$/tCO$_2$-equivalent (IPCC, 2007b, Chapter 20), which compares to carbon prices between 1 to 24 US$/tCO$_2$-equivalent for mitigations scenarios stabilizing between 485-570 ppmv CO$_2$-equivalent) and 31 to 121 US$/tCO$_2$-equivalent for scenarios stabilizing between 440-485 ppmv CO$_2$-equivalent, respectively *(high agreement, limited evidence).*

For any given stabilization pathway, a higher climate sensitivity raises the probability of exceeding temperature thresholds for key vulnerabilities *(high agreement, much evidence)*. For example, policymakers may want to use the highest values of climate sensitivity (i.e. 4.5°C) within the 'likely' range of 2–4.5°C set out by IPCC (2007a, Chapter 10) to guide decisions, which would mean that achieving a target of 2°C (above the pre-industrial level), at equilibrium, is already outside the range of scenarios considered in this chapter, whilst a target of 3°C (above the pre-industrial level) would imply stringent mitigation scenarios, with emissions peaking within 10 years. Using the 'best estimate' assumption of climate sensitivity, the most stringent scenarios (stabilizing at 445–490 ppmv CO$_2$-equivalent) could limit global mean temperature increases to 2–2.4°C above the pre-industrial level, at equilibrium, requiring emissions to peak before 2015 and to be around 50% of current levels by 2050. Scenarios stabilizing at 535–590 ppmv CO$_2$-equivalent could limit the increase to 2.8–3.2°C above the pre-industrial level and those at 590–710 CO$_2$-equivalent to 3.2–4°C, requiring emissions to peak within the next 25 and 55 years, respectively *(high agreement, medium evidence).*

Decisions to delay emission reductions seriously constrain opportunities to achieve low stabilization targets (e.g. stabilizing concentrations from 445–535 ppmv CO$_2$-equivalent), and raise the risk of progressively more severe climate change impacts and key vulnerabilities occurring.

The risk of climate feedbacks is generally not included in the above analysis. Feedbacks between the carbon cycle and climate change affect the required mitigation for a particular stabilization level of atmospheric CO$_2$ concentration. These feedbacks are expected to increase the fraction of anthropogenic emissions that remains in the atmosphere as the climate system warms. Therefore, the emission reductions to meet a particular stabilization level reported in the mitigation studies assessed here might be underestimated.

Short-term mitigation and adaptation decisions are related to long-term climate goals *(high agreement, much evidence)*. A risk management or 'hedging' approach can assist policymakers to advance mitigation decisions in the absence of a long-term target and in the face of considerable uncertainties relating to the cost of mitigation, the efficacy of adaptation and the negative impacts of climate change. The extent and the timing of the desirable hedging strategy will depend on the stakes, the odds and societies' attitudes to risks, for example with respect to risks of abrupt change in geo-physical systems and other key vulnerabilities. A variety of integrated assessment approaches exist to assess mitigation benefits in the context of policy decisions relating to such long-term climate goals. There will be ample opportunity for learning and mid-course corrections as new information becomes available. However, actions in the short term will largely determine what future climate change impacts can be avoided. Hence, analysis of short-term decisions should not be decoupled from analysis that considers long-term climate change outcomes *(high agreement, much evidence).*

3.1 Emissions scenarios

The evolution of future greenhouse gas emissions and their underlying driving forces is highly uncertain, as reflected in the wide range of future emissions pathways across (more than 750) emission scenarios in the literature. This chapter assesses this literature, focusing especially on new multi-gas baseline scenarios produced since the publication of the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic *et al*., 2000) and on new multi-gas mitigation scenarios in the literature since the publication of the IPCC Third Assessment Report (TAR, Working Group III, Chapter 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, grouped as A1, A2, B1 and B2, at the time of their publication in 2000. Of special relevance in this review is the question of how representative the SRES ranges of driving forces and emission levels are of the newer scenarios in the literature, and how representative the TAR stabilization levels and mitigation options are compared with the new multi-gas stabilization scenarios. Other important aspects of this review include methodological, data and other advances since the time the SRES scenarios were developed.

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 baseline scenario assumptions, but rather on 'modeller's choice' scenarios. Thus, further uncertainties have been introduced due 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, notably due to the Kyoto Protocol entering into force, and other climate-related policies that are being implemented in many parts of the world.

Another difficulty in straightforward comparisons is that the information and documentation of the scenarios in the literature varies considerably.

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).

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.
- To provide input to negotiations of possible agreements to reduce GHG emissions.

Scenario definitions in the literature differ depending on the purpose of the scenarios and how they were developed. 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 change or prices). 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 and Sanderson, 2001) and CO_2 emissions (Webster *et al*., 2002, 2003; 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). 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; and Carpenter *et al*., 2005).

3.1.1.2 Narrative storylines and modelling

The literature based on narrative storylines that describe futures is 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 and 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, 1985b; Schwartz, 1991; Shell, 2005).

Catastrophic futures feature prominently in the narrative scenarios literature. They typically involve large-scale environmental or economic collapse, 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 where cases provide emissions pathways.

3.1.1.3 Global futures scenarios

Global futures scenarios are deeply rooted in the long history of narrative scenarios (Carpenter *et al*., 2005; UNEP, 2002). 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, 1985a, 1985b; Schwartz, 1991).

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; 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, starting from 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 scenarios

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 emissions reduction, but often do not quantify the benefits of reduced impacts from climate change. Stabilization scenarios are mitigation scenarios that aim at a pre-specified GHG reduction pathway, leading to stabilization of GHG concentrations in the atmosphere.

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 (CO_2-eq) stabilization scenarios), or maximum allowable changes in temperature or sea level.
- 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 (SD) 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 a sustainability transition that lead to generally low GHG emissions, even though the scenarios do not include policies or measures explicitly directed at emissions mitigation.

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 window' 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 multi-gas 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

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[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 'Barbarization' (Gallopin *et al*., 1997) and 'A Passive Mean World' (Glenn and Gordon, 1997).

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 include 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 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 significant 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. A simple mimicking by developing countries of the development paradigm established by industrialized countries could lead to a very large increase in global GHG emissions (see Chapter 2). It may be noted, however, that energy/GDP elasticities in industrialized countries have first increased in successive stages of industrialization, with acceleration during the 1950s and 1960s, but have fallen sharply since then, due to factors such as relative growth of services in GDP share, technical progress induced by higher oil prices and energy conservation efforts.

In developing countries, where a major part of the infrastructure necessary 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 industrial policies directed towards rural development and integrated urban, regional, and transportation planning, thereby avoiding urban sprawl and facilitating more efficient transportation and energy systems. The main issue 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 technical possibilities for less energy-intensive development patterns in the long run, leading to low carbon futures in southern countries that are compatible with national objectives (see e.g. La Rovere and Americano, 2002). Section 12.2 of Chapter 12 develops this argument further.

On the other hand, the barriers to such development pathways should not be underestimated, going from financial constraints to cultural behaviours in industrialized and 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 concerning 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 include labour force and its productivity projections. Labour force utilization depends on factors such as the number of working-age people, the level of 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 improvements in labour quality (capacity building) and the pace of technical change associated with building up the capital-output ratio and the quality of capital.

The literature examining production functions shows 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), suggests that 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 (Abramovitz, 1986; Baumol, 1986), using a standard neoclassical economic growth setup following Solow (1956), found evidence of convergence only between the richest countries. Other research efforts documented 'conditional convergence' – meaning that countries appeared to reach their own steady states at a fairly uniform rate of 2% 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, thus confirming past trends. Total factor productivity (TFP) levels and convergence for the evolution of income distribution are also important. Expected catch-up, and even overtaking per-person incomes, as well as changes in leaders in the world distribution of income, are among some of the findings in this literature. Quah (1993, 1996) found that the world is moving towards a bimodal income distribution. Some recent assessments demonstrate divergence, not convergence (World Bank, 2002; Halloy and Lockwood, 2005; UNSD, 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. Social inertia (as referred to in Chapter 2, see Section 2.2.3) also contributes to delay convergence. Therefore only limited catch-up can be factored in baseline 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 accelerate the adoption of new technologies and create incentives for human capital formation and thus accelerate convergence (Martins and Nicoletti, 2005). Nelson and Fagerberg, arguing within an evolutionary paradigm, have different perspectives on the convergence issue (Fagerberg, 1995; Fagerberg and Godinho, 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 above discussion provides the economic background for the range of assumptions on the long-term convergence of income between developing and developed countries (measured by GDP per person) found in the scenario literature. The annual rate of income convergence between 11 world regions in the SRES scenarios falls within the range of less than 0.5% in the A2 scenario family to less than 2% in A1 (both in PPP and MER metrics). The highest rate of income convergence in the SRES is similar to the observed convergence, during the period 1950–1990, of 90 regions in Europe (Barro and Sala-i-Martin 1997). However, Grübler *et al*. (2006) note that extending convergence analysis to national or sub-national level would suggest that income disparities are 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. An important finding from the sensitivity analysis performed is that less convergence generally yields higher emissions (Grübler *et al*., 2004). In B2, an income ratio (between 11 world regions, in market exchange rates) of seven 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 in the same direction were also obtained for A2. This can be explained by slower TFP growth, slower capital turnover, and less ‘technological congruence’, leading to slower adoption of low-emission technologies in developing countries. On the other hand, as climate stabilization scenarios require global application of climate policies and convergence in the adoption of low-emission technologies, they are less compatible with low economic convergence scenarios.

3.1.5 Development pathways and GHG emissions

In the long run, the links between economic development and GHG emissions depend not only on the growth rate (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 an assumed overall rate of economic growth (Jung *et al*., 2000; see also examples discussed in Section 12.2 of Chapter 12).

- Structural changes in the production system, namely the role of high or low energy-intensive industries and services.
- Technological patterns in sectors such as energy, transportation, building, waste, agriculture and forestry – the treatment of technology in economic models has received considerable attention 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 encompassing both human settlements and urban structures in a given territory, and its 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 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 (e.g. per person income) or through more disaggregated economic parameters, such as the structure of expenses devoted to a given need (e.g. 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 socio-economic 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 important, but the outcome in terms of GHG emissions will also depend on dynamic links between technology, consumption patterns, transportation and urban infrastructure, urban planning, and rural-urban distribution of the population (see also Chapters 2 and 11 for more extensive discussions of some of these issues).

3.1.6 Institutional frameworks

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.
3. Processes for effective interventions (e.g. the mix of market and regulatory processes).

Institutional structures vary considerably across nations, even those 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). Other relevant developments may include greater use of market mechanisms and institutions to enhance global cooperation and more effectively manage global environmental issues (see also Chapter 12).

A weak institutional structure basically explains why an economy can be in a position that is significantly below the theoretically efficient production frontier, with several economists terming it as a 'missing link' in the production function (Meier, 2001). Furthermore, weak institutions also cause frictions in economic exchange processes, resulting in high transaction costs.

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 will generally 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, etc.), introducing 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 (see Chapter 2 and Halsnaes, 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 (Halsnaes, 2002, see also Chapters 2 and 12).

In today's 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, causing accelerated urbanization in the process. 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.
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 shape institutions and the way in which they function. Social norms of ownership and distribution have a vital influence on the structure of production and consumption, as well as the quality and extent of the 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, such as education, are amenable to interventions. Barring some negative features, such as segregation, 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).

While institutional arrangements are sometimes described as part of storylines, scenario specifications generally do not include explicit assumptions about them. The role of institutions in the implementation of development choices and its implications to climate change mitigation are discussed further in Section 12.2 of Chapter 12.

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, as well as technological and institutional change. An often-used identity to describe changes in some of these factors is based on the IPAT identity (Impact = Population x Affluence x Technology – see Holdren, 2000; Ehrlich and Holdren, 1971) and in emissions modelling is often called the 'Kaya identity' (see Section 3.2.1.4 and Yamaji *et al*., 1991). These two relationships state 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 800 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 and Lee, 1998) and made available through the Internet. Systematic reviews of the baseline and mitigation scenarios were reported in the SRES (Nakicenovic *et al*., 2000) and the 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.

3.2.1.1 Population projections

Current population projections reflect less global population growth than was expected at the time the 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.

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, 2006). This global result is driven primarily 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 show lower than expected fertility rates, 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 International Institute for Applied Systems Analysis (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 rates that are quite high relative to other industrialized countries.

Lutz *et al*. (2004), UN (2004) and Fisher *et al*. (2006) have produced updated projections for the world that extend to 2100. The most recent central projections for global population are 1.4–2.0 billion (13–19%) lower than the medium population scenario of 10.4 billion used in the SRES B2 scenarios. 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.

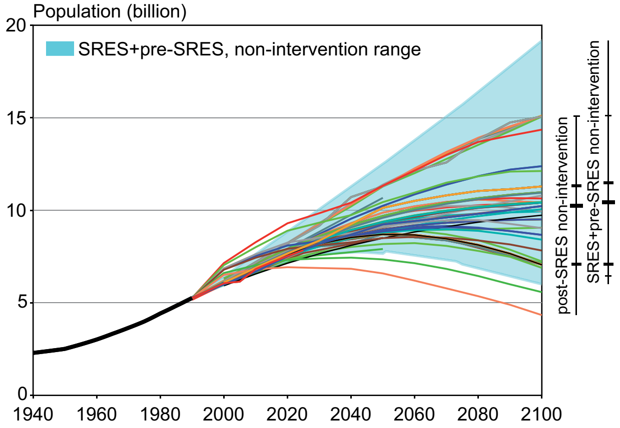

Figure 3.1: *Comparison of population assumptions in post-SRES emissions scenarios with those used in previous scenarios. Blue shaded areas span the range of 84 population scenarios used in SRES or pre-SRES emissions scenarios; individual curves show population assumptions in 117 emissions scenarios in the literature since 2000. The 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: After Nakicenovic et al., 2006.

Most of the SRES scenarios still fall within the plausible range of population outcomes, according to more recent literature (see Figure 3.1). 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, 2006). In addition, the population assumptions in SRES and the vast majority of more recent emissions scenarios do not cover the low end of the current range of population projections well. New scenario exercises will need to take the lower population projections into account. All other factors being equal, lower population projections are likely to result in lower emissions. However, a small number of recent studies that have used updated and lower population projections (Carpenter *et al*., 2005; Van Vuuren *et al*., 2007; Riahi *et al*., 2006) indicate that changes in other drivers of emissions might partly offset the impact of lower population assumptions, thus leading to no significant changes in emissions.

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[2] It should be noted that the sources of scenario data vary. For some scenarios the data comes directly from the modelling teams. In other cases it has been assembled from the literature or from other scenario comparison exercises such as EMF-19, EMF-21, and IMCP. For this assessment the scenario databases from Nakicenovic *et al.* (2006) and Hanaoka *et al*. (2006) were updated with the most recent information. The scenarios published before the year 2000 were retrieved from the database during SRES and TAR. The databases from Nakicenovic *et al*. (2006) and Hanaoka *et al.* (2006) can be accessed on the following websites: http://iiasa.ac.at/Research/TNT/WEB/scenario_database.html and www-cger.nies.go.jp/scenario.

3.2.1.2 Economic development

Economic activity is a dominant driver of energy demand and thus of greenhouse gas emissions. This activity is usually reported as gross domestic product (GDP), often measured in per-person (per-capita) terms. To derive meaningful comparisons over time, changes in price levels must be taken into account and corrected by reporting activities as constant prices taken from a base year. One way of reducing the effects of different base years employed across various studies is to report real growth rates for changes in economic output. Therefore, the focus below is on real growth rates rather than on absolute numbers.

Given that countries and regions use particular currencies, another difficulty arises in aggregating and comparing economic output across countries and world regions. There are two main approaches: using an observed market exchange rate (MER) in a fixed year or using a purchasing power parity rate (PPP) (see Box 3.1). GDP trajectories in the large majority of long-term scenarios in the literature are calibrated in MER. A few dozen scenarios exist that use PPP exchange rates, but most of them are shorter-term, generally running until the year 2030.

3.2.1.3 GDP growth rates in the new literature

Many of the long-term economic projections in the literature have been specifically developed for climate-related scenario work. Figure 3.2 compares the global GDP range of 153 baseline scenarios from the pre-SRES and SRES literature with 130 new scenarios developed since SRES (post-SRES). There is a considerable overlap in the GDP numbers published, with a slight downward shift of the median in the new scenarios (by about 7%) compared to the median in the pre-SRES scenario literature. The data suggests no appreciable change in the distribution of GDP projections.

A comparison of some recent shorter-term global GDP projections using the SRES scenarios is illustrated in Figure 3.3. The SRES scenarios project a very wide range of global economic per-person growth rates from 1% (A2) to 3.1% (A1) to 2030, both based on MER. This range is somewhat wider than that covered by the USDOE (2004) high and low scenarios (1.2–2.5%). The central projections of USDOE, IEA and the World Bank all contain growth rates of around 1.5–1.9%, thus occurring in the middle of the range of the SRES scenarios. Other medium-term energy scenarios are also reported to have growth rates in this range (IEA, 2004).

Regionally, for the OECD, Eastern Europe and Central Asia (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 of 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%–5%), while A2 and B2 fall near the centre of the range (1.4–1.7%). The recent short-term projections reported here contain an assumption that current barriers to economic growth in these regions will slow growth, at least until 2015.

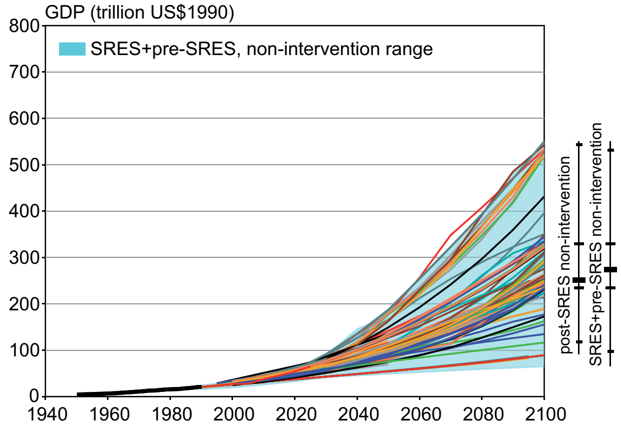

Figure 3.2: *Comparison of GDP projections in post-SRES emissions scenarios with those used in previous scenarios. The median of the new scenarios is about 7% below the median of the pre-SRES and SRES scenario literature. The two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios by 2100. The horizontal bars indicate the 5th, 25th, 50th, 75th and the 95th percentiles of the distributions.*

3.2.1.4 The use of MER in economic and emissions scenarios modelling

The uses of MER-based economic projections in SRES have recently been criticized (Castles and Henderson, 2003a, 2003b; Henderson, 2005). The vast majority of scenarios published in the literature use MER-based economic projections. Some exceptions exist, for example, MESSAGE in SRES, and more recent scenarios using the MERGE model (Manne and Richels, 2003), along with shorter term scenarios to 2030, including the G-Cubed model (McKibbin *et al*., 2004a, 2004b), the International Energy Outlook (USDOE, 2004), the IEA World Energy Outlook (IEA, 2004) and the POLES model used by the European Commission (2003). The main criticism of the MER-based models is that GDP data for world regions are not corrected with respect to purchasing power parities (PPP) in most of the model runs. The implied 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). According to the critics, the use of MER, together with the assumption of conditional convergence, lead to overstated economic growth in the poorer regions and excessive growth in energy demand and emission levels.

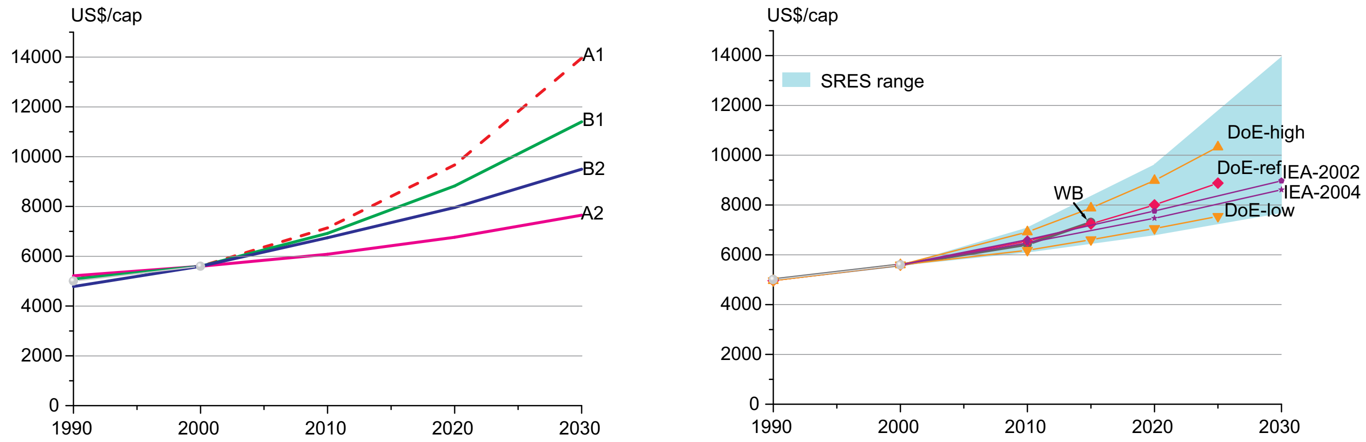

Figure 3.3: *Comparison of global GDP growth per person in the SRES scenarios and more recent projections.*

Notes: SRES = (Nakicenovic *et al*., 2000), WB = World Bank (World Bank, 2004), DoE = assumptions used by US Department of Energy (USDOE, 2004), IEA assumptions used by IEA (IEA, 2002 and 2004); (Van Vuuren and O'Neill, 2006).

A team of SRES researchers responded to this criticism, indicating that the use of MER or PPP data does not in itself lead to different emission projections outside the range of the literature. In addition, they stated that the use of PPP data in most scenarios models was (and still is) infeasible, due to lack of required data in PPP terms, for example price elasticities and social accounting matrices (Nakicenovic *et al*., 2003; Grübler *et al*., 2004). A growing number of other researchers have also indicated different opinions on this issue or explored it in a more quantitative sense (e.g. Dixon and Rimmer, 2005; Nordhaus, 2006b; Manne and Richels, 2003; McKibbin *et al*., 2004a, 2004b; Holtsmark and Alfsen, 2004a, 2004b; Van Vuuren and Alfsen, 2006).

There are at least three strands to this debate. The first is 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. The second is whether the choice of the exchange rate matters when it comes to *emission scenarios*. The third is whether it is possible, or practical, to develop robust scenarios given the sparseness of relevant and required PPP data. While the GDP data are available in PPP, other economic scenario characteristics, such as capital and operational cost of energy facilities, are usually available either in domestic currencies or MER. Full model calibration in PPP for regional and global models is still difficult due to the lack of underlying data. This could be one of the reasons why a vast majority of long-term emissions scenarios continues to be calibrated in MER.

On the question of whether PPP or MER should be employed in economic scenarios, the general recommendations are to use PPP where practical.[3] This is certainly necessary when comparisons of income levels across regions are of concern. On the other hand, models that analyse international trade and include trade as part of their economic projections, are better served by MER data given that trade takes place between countries in actual market prices. Thus, the choice of conversion factor depends on the type of analysis or comparison being undertaken.

For principle and practical reasons, Nordhaus (2005) recommends that economic growth scenarios should be constructed by using regional or national accounting figures (including growth rates) for each region, but using PPP exchange rates for aggregating regions and updating over time by use of a superlative price index. In contrast, Timmer (2005) actually prefers the use of MER data in long-term modelling, as such data are more readily available, and many international relations within the model are based on MER. Others (e.g. Van Vuuren and Alfsen, 2006) also argue that the use of MER data in long-term modelling is often preferable, given that model parameters are usually estimated on MER data and international trade within the models is 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, 2004b). In long-term scenario models, a top-down approach is more commonly used where the actual growth rates are prescribed more directly, based on convergence or other assumptions about long-term growth potentials.

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[3] See, for example, UN (1993), (para 1.38): 'When the objective is to compare the volumes of goods or services produced or consumed per head, data in national currencies must be converted into a common currency by means of purchasing power parities and not exchange rates. It is well known that, in general, neither market nor fixed exchange rates reflect the relative internal purchasing powers of different currencies. When exchange rates are used to convert GDP, or other statistics, into a common currency the prices at which goods and services in high-income countries are valued tend to be higher than in low-income countries, thus exaggerating the differences in real incomes between them. Exchange rate converted data must not, therefore, be interpreted as measures of the relative volumes of goods and services concerned.'

Box 3.1 Market Exchange Rates and Purchasing Power Parity

To aggregate or compare economic output from various countries, GDP data must be converted into a common unit. This conversion can be based on observed market exchange (MER) rates or purchasing power parity (PPP) rates where, in the latter, a correction is made for differences in price levels between countries. The PPP approach is considered to be the better alternative if data is used for welfare or income comparisons across countries or regions. Market exchange rates usually undervalue the purchasing power of currencies in developing countries, see Figure 3.4.

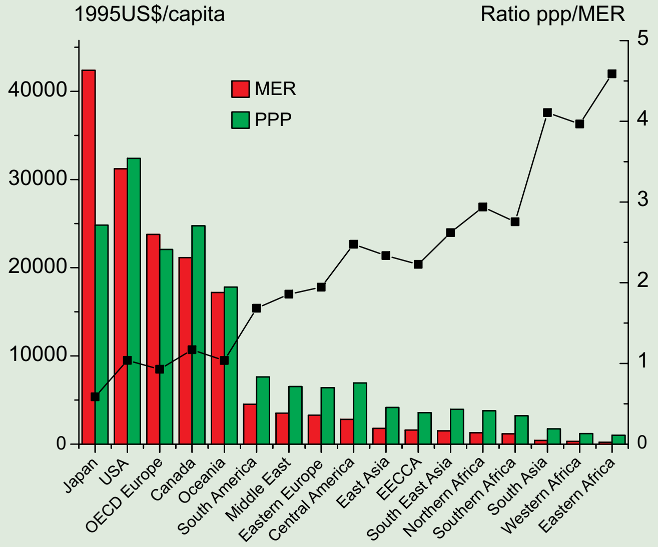

Figure 3.4: *Regional GDP per person, expressed in MER and PPP on the basis of World Bank data aggregated to 17 global regions.*

Note: 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.
EECCA = countries of Eastern Europe, the Caucasus and Central Asia.

Source: Van Vuuren and Alfsen, 2006.

Clearly, deriving PPP exchange rates requires analysis of a relatively large amount of data. 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.

When it comes to emission projections, it is important to note that in a fully disaggregated (by country) multi-sector economic model of the global economy, aggregate index numbers play no role and the choice between PPP and MER conversion of income levels does not arise. However, in an aggregated model with consistent specifications (i.e. where model parameter estimation and model calibrations are all carried out based on consistent use of conversion factors), the effects of the choice of conversion measure on emissions should approximately cancel out. The reason can be illustrated by using the Kaya identity, which decomposes the emissions as follows:

GHG = Population x GDP per person x Emissions per GDP

or: $$GHG = POP \times \left(\frac{GDP}{POP}\right) \times \left(\frac{GHG}{GDP}\right)$$

where GHG stands for greenhouse gas emissions, GDP stands for economic output, and POP stands for population size.[4]

Given this relationship, emission scenarios can be represented, explicitly based on estimates of population development, economic growth, and development of emission intensity.

Population is often projected to grow along a pre-described (exogenous) path, while economic activity and emission intensities are projected based on differing assumptions from scenario to scenario. The economic growth path can be based on historical growth rates, convergence assumptions, or on fundamental growth factors, such as saving and investment behaviour, productivity changes, etc. Similarly, future emission intensities can be projected based on historical experience,

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[4] Other components could be introduced in the identity, such as energy use, without changing the argument.

economic factors, such as labour productivity or other key factors determining structural changes in an economy, or technological development. The numerical expression of GDP clearly depends on conversion measures; thus GDP expressed in PPP will deviate from GDP expressed in MER, particularly for developing countries. However, when it comes to calculating emissions (or other physical measures such as energy), the Kaya identity shows that the choice between MER-based or PPP-based representations of GDP will not matter, since emission intensity will change (in a compensating manner) when the GDP numbers change. While using PPP values necessitates using lower economic growth rates for developing countries under the convergence assumption, it is also necessary to adjust the relationship between income and demand for energy with lower economic growth, leading to slower improvements in energy intensities. Thus, if a consistent set of metrics is employed, the choice of metric should not appreciably affect the final emission level.

In their modelling work, Manne and Richels (2003) and McKibbin *et al.* (2004a, 2004b) find some differences in emission levels between using PPP-based and MER-based estimates. Analysis of their work indicates that these results critically depend on, among other things, the combination of convergence assumptions and the mathematical approximation used between MER-GDP and PPP-GDP. In the Manne and Richels work for instance, autonomous efficiency improvement (AEI) is determined as a percentage of economic growth and estimated on the basis of MER data. In going from MER to PPP, the economic growth rate declines as expected, leading to a decline in the autonomous efficiency improvement. However, it is not clear whether it is realistic not to change the AEI rate when changing conversion measure. On the other hand, Holtsmark and Alfsen (2004a, 2004b), 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.

To summarize: available evidence indicates that the differences between projected emissions using MER exchange rates and PPP exchange rates are small in comparison to the uncertainties represented by the range of scenarios and the likely impacts of other parameters and assumptions made in developing scenarios, for example, technological change. However, the debate clearly shows the need for modellers to be more transparent in explaining conversion factors, as well as taking care in determining exogenous factors used for their economic and emission scenarios.

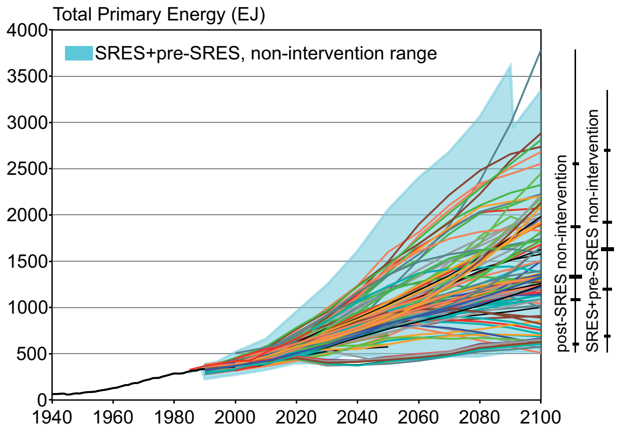

Figure 3.5: *Comparison of 153 SRES and pre-SRES baseline energy scenarios in the literature compared with the 133 more recent, post-SRES scenarios. The ranges are comparable, with small changes on the lower and upper boundaries.*

Note: The 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.

3.2.1.5 Energy use

Future evolution of energy systems is a fundamental determinant of GHG emissions. In most models, energy demand growth is a function of key driving forces such as demographic change and the level and nature of human activities such as mobility, information processing, and industry. The type of energy consumed is also important. While Chapters 4 through 11 report on medium-term projections for different parts of the energy system, long-term energy projections are reported here. Figure 3.5 compares the range of the 153 SRES and pre-SRES scenarios with 133 new, post-SRES, long-term energy scenarios in the literature. The ranges are comparable, with small changes on the lower and upper boundaries, and a shift downwards with respect to the median development. 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 Section 3.2.1.1.

In general, this situation also exists for underlying trends as represented by changes in energy intensity, expressed as gigajoule (GJ)/GDP, and change in the carbon intensity of the energy system (CO_2/GJ) as shown in Figure 3.6. In all scenarios, energy intensity improves significantly across the century – with a mean annual intensity improvement of 1%. The 90% range of the annual average intensity improvement is between 0.5% and 1.9% (which is fairly consistent with historic variation in this factor). Actually, this range implies a difference in total energy consumption in 2100 of more than 300% – indicating the importance of the uncertainty associated with this ratio. The carbon intensity is more constant in scenarios without climate policy. The mean annual long-term improvement rate over the course of the 21st century is 0.4%, while the uncertainty range is again relatively large (from -0.2 to 1.5%). At the high end of this range, some scenarios 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-intensity improvement coincide with scenarios with a

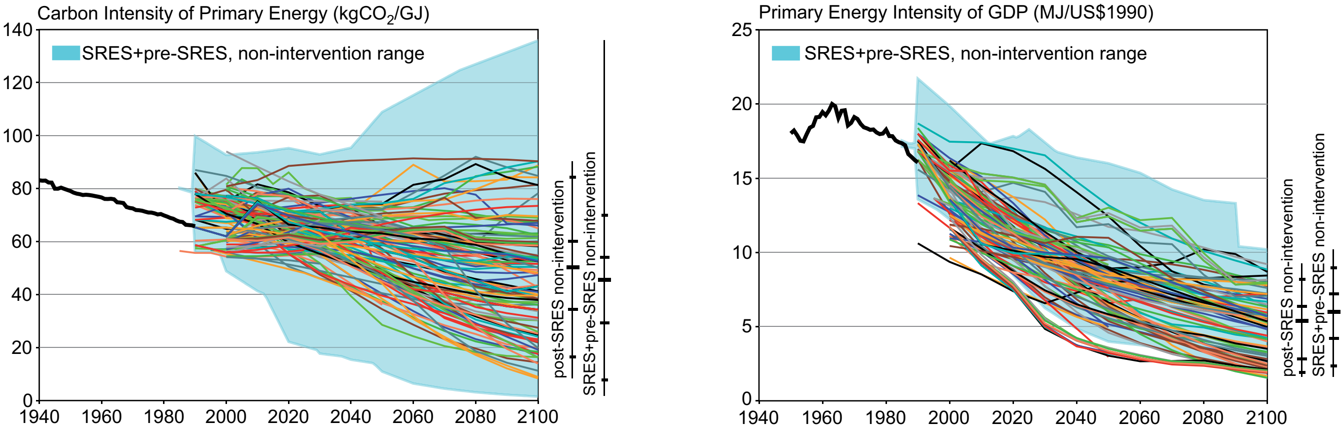

Figure 3.6: *Development of carbon intensity of energy (left) and primary energy intensity of GDP (right). Historical development and projections from SRES and pre-SRES scenarios compared to post-SRES scenarios.*

Note: The blue coloured range illustrates the range of 142 carbon intensity and 114 energy intensity – SRES and pre-SRES non-intervention scenarios.

Source: After Nakicenovic et al., 2006.

large fossil fuel base, less resistance to coal consumption or lower technology development rates for fossil-free energy technologies. The long-term historical trend is one of declining carbon intensities. However, since 2000, carbon intensities are increasing slightly, primarily due to the increasing use of coal. Only a few scenarios assume the continuation of the present trend of increasing carbon intensities. One of the reasons for this may be that just a few of the recent scenarios include the effects of high oil prices.

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 and the carbon cycle.

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 206 and 333 Pg CO_2 (McGuire *et al*., 2001), and as much as 572 Pg CO_2 for the entire industrial period 1850–2000, roughly one-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 estimated to be responsible for the majority of global anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. For example, USEPA (2006a) estimated that agricultural activities were responsible for approximately 52% and 84% of global anthropogenic CH_4 or N_2O emissions respectively in the year 2000, with a net contribution from non-CO_2 GHGs of 14% of all anthropogenic greenhouse gas emissions in that year.

Projected changes in land use were not explicitly represented in carbon cycle studies until recently. Previous studies into 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 changes (House *et al*., 2002), or derived trends of land-use change from the SRES storylines (Levy *et al*., 2004). However, recent studies (e.g. Brovkin *et al*., 2006; Matthews *et al*., 2003; Gitz and Ciais, 2004) have shown that land use, as well as feedbacks in the society-biosphere-atmosphere system (e.g. Strengers *et al*., 2004), must be considered in order to achieve realistic estimates of the future development of the carbon cycle; thereby providing further motivation for ongoing development to explicitly model land and land-use drivers in global integrated assessment and climate economic frameworks. For example, in a model comparison study of six climate models of intermediate complexity, Brovkin *et al*. (2006) concluded that land-use changes contributed to a decrease in global mean annual temperature in the range of 0.13–0.25°C, mainly during the 19th century and the first half of the 20th century, which is in line with conclusions from other studies, such as Matthews *et al*. (2003).

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 and economic growth are the most significant food demand drivers through per person consumption. Total world food consumption is expected to increase by over 50% 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, in the order of 25% by 2030, with faster growth in developing and transitional countries of more than 40% and 30%, respectively (Bruinsma, 2003; Cassman *et al*., 2003). The Millennium Ecosystem Assessment (MEA) 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 (Carpenter *et al*., 2005). Additional cropland is expected to be required to support these projected increases in demand. Beyond 2050, food demand is expected to level off with slow-down of population growth.

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% annual growth in crop yields. Similarly, Kurosawa (2006) estimates decreased cropland requirements of 18% by 2050, relative to 2000, with 2% annual growth in global average crop yields. Alternatively, the MEA scenarios implement a more complex representation of yield growth projections that, in addition to autonomous technological change, reflect the changes in production practices, investments, technology transfer, environmental degradation, and climate change. The net effect is positive, but shows declining productivity growth over time for some commodities, due in large part to diminishing marginal technical productivity gains and environmental degradation. In all these studies, increasing (decreasing) net productivity per hectare results in reduced (increased) cropland demand.

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 short term, thereby reducing pressure for additional cropland and resulting in increased afforestation. However, modelling 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 laboratory 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 plants (e.g. wheat, barley, potatoes, rice) over C4 plants (e.g. maize, sugar cane, sorghum, millet) while temperature increases favour C4 over C3 plants; 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. See IPCC (2007b, Chapter 5) for an overall discussion of these issues and this literature. Long-term projections need to consider these issues, as well as examining 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. Current integrated assessment representations only consider CO_2 fertilization and changes in yearly average temperature, if they consider climate change effects at all (e.g. USCCSP, 2006; Van Vuuren *et al*., 2007).

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 the 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 (Carpenter *et al*., 2005), and some of the EMF-21 Study models (Kurosawa, 2006; Van Vuuren *et al*., 2006a; Rao and Riahi, 2006; Jakeman and Fisher, 2006; Riahi *et al*., 2006; Van Vuuren *et al*., 2007). 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, 2007; Sathaye *et al*., 2006; Sohngen and Sedjo, 2006). In general, the post-SRES scenarios, though scarce in number for agricultural land use, have projected increasing global cropland areas, smaller forest-land areas, and mixed results for changes in global grassland (Figure 3.7). Unlike the SRES land-use scenarios that span a broader range while representing diverse storylines, the post-SRES scenarios, for forestry in particular, illustrate greater convergence across models on projected land-use change.

Most post-SRES global scenarios project significant changes in agricultural land caused primarily by regional changes in food demand and production technology. 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%) of agricultural land between 1995 and 2100 (Figure 3.7). 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% less global agricultural acreage by the end of the century). In the short-term, almost all scenarios suggest an increase in cropland acreage and decline in forest land to meet projected increases in food, feed, and livestock grazing demands over the next few decades. Cropland changes range from -18% to +69% by 2050 relative to 2000 (from -123 to +1158 million hectares)

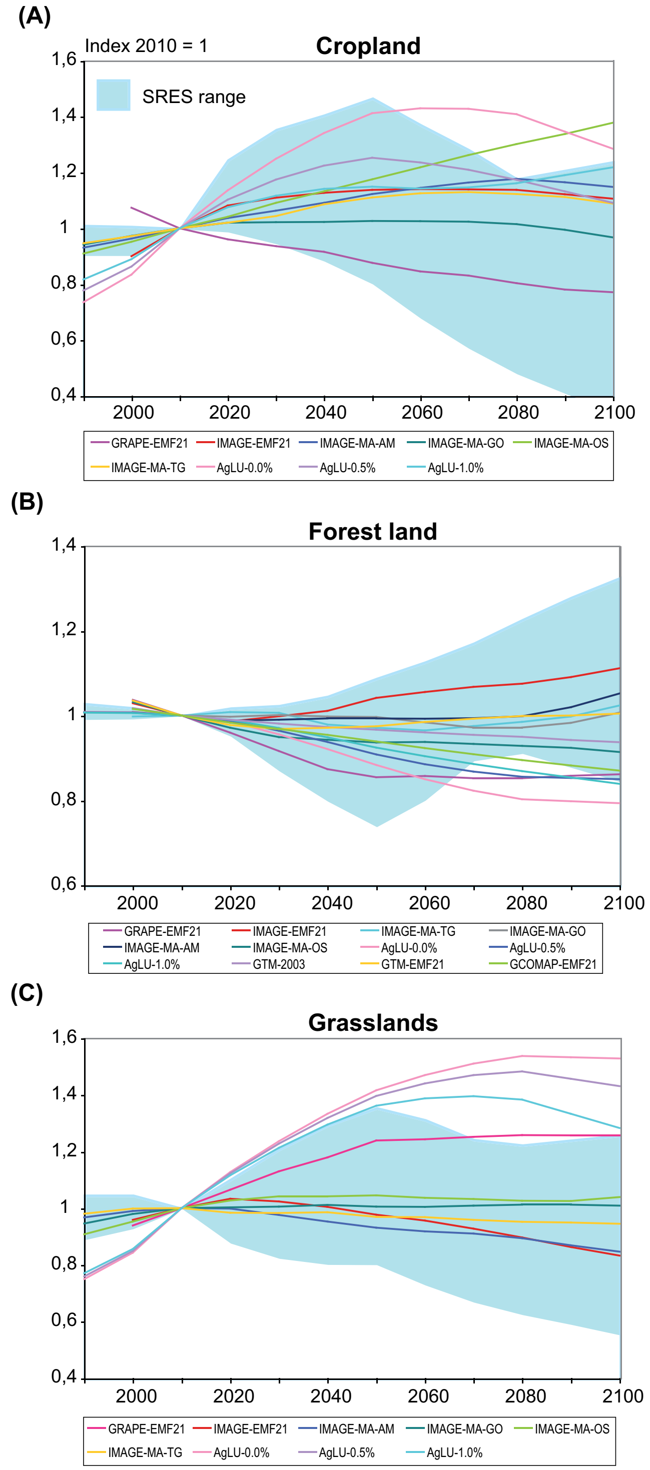

Figure 3.7: *Global cropland (a), forest land (b) and grassland (c) projections.*

Notes: shaded areas indicate SRES scenario ranges, post-SRES scenarios denoted with solid lines. IMAGE-EMF21 = Van Vuuren *et al*. (2006a) scenario from EMF-21 Study; IMAGE-MA-xx = Millennium Ecosystem Assessment (Carpenter *et al*., 2005) scenarios from the IMAGE model for four storylines (GO = Global Orchestration, OS = Order from Strength, AM = Adapting 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 (2006) global forest scenario from EMF-21 Study; GCOMAP-EMF21 = Sathaye *et al*. (2006) global forest scenario from EMF-21 Study; GRAPE-EMF21 = Kurosawa (2006) scenario from EMF-21 Study.

and forest-land changes range from -18% to +3% (from -680 to +94 million hectares) by 2050. The changes in global forest generally 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.

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% by 2100. Until long-run energy price expectations rise (due to a carbon price, economic scarcity, or other force), biomass and other less economical energy supply technologies (some with higher greenhouse gas emission characteristics than biomass), are not expected to assume more significant baseline roles.

3.2.2 Emissions

There is still a large span of CO_2 emissions across baseline scenarios in the literature, with emissions in 2100 ranging from 10 $GtCO_2$ to around 250 $GtCO_2$. The wide range of future emissions is a result of the uncertainties in the main driving forces, such as population growth, economic development, and energy production, conversion, and end use, as described in the previous section.

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.[5] Figure 3.8 compares the range of the pre-SRES and SRES baseline scenarios with the post-SRES baseline scenarios. The figure shows that the scenario range has remained almost the same since the SRES. There seems to have been an upwards shift on the high and low end, but careful consideration of the data shows that this is caused by only very few scenarios and the change is therefore not significant. The median of the recent scenario distribution has shifted downwards slightly, from 75 $GtCO_2$ by 2100 (pre-SRES and SRES) to about 60 $GtCO_2$ (post SRES). The median of the recent literature therefore corresponds roughly to emissions levels of the intermediate SRES-B2 scenarios. The majority of scenarios, both pre-SRES and post-SRES, indicate an increase in emissions across most of the century, resulting in a range of 2100 emissions of 17–135 $GtCO_2$ emissions from energy and industry (90th percentile of the full scenario distribution). Also the range of emissions depicted by the SRES scenarios is consistent with the range of other emission

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[5] It should be noted, however, that there are sometimes considerable 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 from land-use changes.

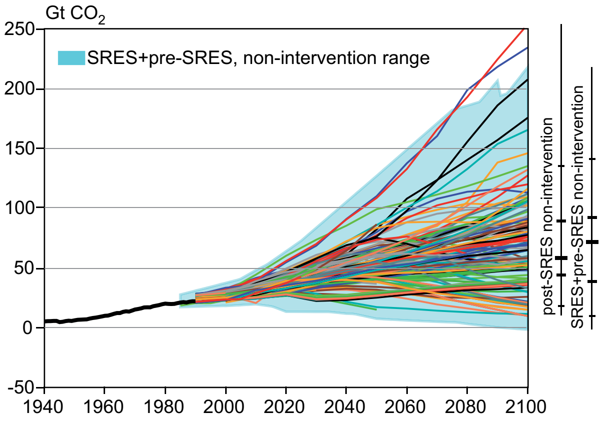

Figure 3.8: *Comparison of the SRES and pre-SRES energy-related and industrial CO_2 emissions scenarios in the literature with the post-SRES scenarios.*

Note: The two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios and indicate the 5th, 25th, 50th, 75th and the 95th percentiles of the distributions by 2100.

Source: After Nakicenovic et al., 2006

scenarios reported in the literature; both in the short and long term (see Van Vuuren and O'Neill, 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 reason 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 pre-SRES and post-SRES baseline scenarios indicate a continuous decline of the primary energy intensity (EJ/GDP), while the change in carbon intensity (CO_2/E) is much slower – or even stable (see Figure 3.6 and Section 3.2.1.5) in the post-SRES scenarios. 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-SRES, SRES, as well as the post-SRES scenario literature.

Baseline or reference emissions projections generally come from three types of studies:

1. Studies meant to represent a 'best-guess' of what might happen if present-day trends and behaviour continue.
2. Studies with multiple baseline scenarios under comprehensively different assumptions (storylines).
3. Studies based on a probabilistic approach.

In literature, since the TAR, there has been some discussion of the purpose of these approaches (see Schneider, 2001; Grübler *et al*., 2002; Webster *et al*., 2002). Figure 3.9 (left panel) shows a comparison of the outcomes of some prominent examples of these approaches 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 range of different models participating in the EMF-21 study is somewhat smaller than those from SRES and the probabilistic approach. The range of EMF-21 scenarios result from different modelling approaches

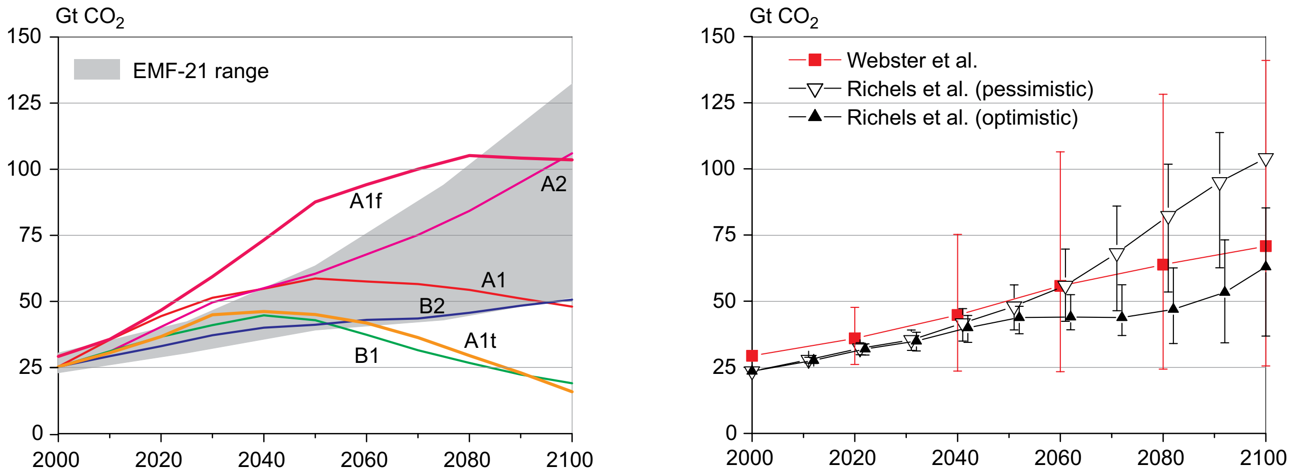

Figure 3.9: *Comparison of various long-term scenario studies for CO_2 emissions. Left panel: IPCC SRES, EMF-21 range (grey area), indicating the range of the lowest and highest reported values in the EMF-21 study (Weyant et al., 2006). Right panel: Webster et al. (2002) and Richels et al. (2004), indicating the mean (markers) and 95% intervals of the reported ranges of these studies (for the latter, showing the 95% interval of the combined range for optimistic and pessimistic technology).*

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 having 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 3.8 and confirming the emission range of scenarios used for the TAR.

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 (Leggett *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, MARIA, IMAGE 2.1, AIM), of which MiniCAM and MARIA used more simplified land-use modules. ASF and MESSAGE also simulated land-use emissions, however ASF did not have a specific land-use module and MESSAGE incorporated land-use results from the AIM model (Nakicenovic *et al*., 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, such as UNEP's Third Global Environment Outlook (UNEP, 2002) and the Millennium Ecosystem Assessment (Carpenter *et al*., 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, such as those from agriculture, and carbon sequestration in managed terrestrial ecosystems (Kurosawa, 2006; Van Vuuren *et al*., 2006a; Rao and Riahi, 2006; Jakeman and Fisher, 2006). A few additional papers have subsequently improved upon their EMF-21 work (Riahi *et al*., 2006; Van Vuuren *et al*., 2007). 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 3.10). The clustering of the non-harmonized post-SRES scenarios in Figure 3.10 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 3.7), carbon uptake from afforestation and reforestation result in net sequestration.

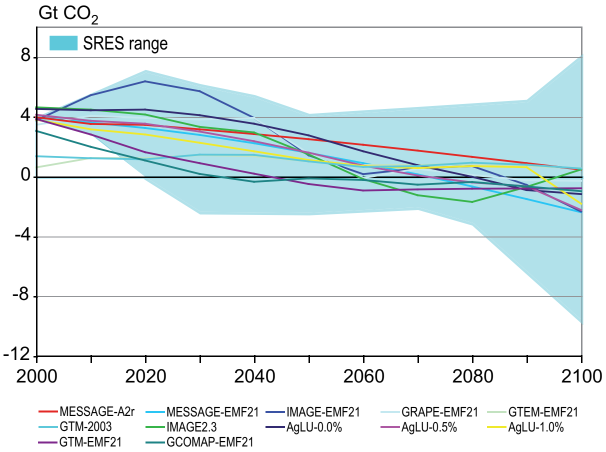

Figure 3.10: *Baseline land-use change and forestry carbon net emissions.*

Notes: MESSAGE-EMF21 = Rao and Riahi (2006) scenario from EMF-21 Study; GTEM-EMF21 = Jakeman and Fisher (2006) scenario from EMF-21 Study; MESSAGE-A2r = Riahi *et al*. (2006) scenario with revised SRES-A2 baseline; IMAGE 2.3 = Van Vuuren *et al*. (2007) scenario; see Figure 3.7 notes for additional scenario references. The IMAGE 2.3 LUCF baseline scenario also emits non-CO_2 emissions (CH_4 and N_2O) of 0.26, 0.30, 0.16 $GtCO_2$-eq in 2030, 2050, and 2100, respectively.

There also seems to be a consensus in recent non-CO_2 GHG emission baseline scenarios that agricultural CH_4 and N_2O emissions will increase until the end of this century, potentially doubling in some baselines (see Table 3.1; Kurosawa, 2006; Van Vuuren *et al*., 2006a; Rao and Riahi, 2006; Jakeman and Fisher, 2006; Riahi *et al*., 2006; Van Vuuren *et al*., 2007). The modelling of agricultural emission sources varies across scenarios, with livestock and rice paddy methane and crop soil nitrous oxide emissions consistently represented. However, the handling of emissions from biomass burning and fossil fuel combustion are inconsistent across models; and cropland soil carbon fluxes are generally not reported, probably due to the fact that soil carbon sequestration mitigation options are not currently represented in these models.

As noted in Section 3.2.1.6 climate change feedbacks could have a significant influence on long-term land use and, to date, are only partially 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, potentially important additional climate feedbacks in the carbon-climate system are currently not accounted

Table 3.1: *Baseline global agricultural non-CO_2 greenhouse gas emissions from various long-term stabilization scenarios ($GtCO_2$-eq).*

Scenario	Non-CO_2 GHG agricultural emissions sources represented*	$GtCO_2$-eq									
		CH_4					N_2O				
		2000	2020	2050	2070	2100	2000	2020	2050	2070	2100
GTEM-EMF21	Enteric, manure, paddy rice, soil (N_2O)	2.09	2.88	4.28	nm	nm	1.95	2.60	3.64	nm	nm
MESSAGE-EMF21	Enteric, manure, paddy rice, soil (N_2O)	2.58	3.42	6.05	6.00	5.06	2.57	3.48	4.65	3.79	2.32
IMAGE-EMF21	Enteric, manure, paddy rice, soil (N_2O and CO_2), biomass & agriculture waste burning, land clearing	3.07	4.15	4.34	4.37	4.55	2.02	2.75	3.11	3.23	3.27
GRAPE-EMF21	Enteric, manure, paddy rice, soil (N_2O), biomass & agricultural waste burning	2.59	2.65	2.85	2.82	2.76	2.79	3.31	3.84	3.93	4.06
MESSAGE-A2r	Enteric, manure, paddy rice, soil (N_2O)	2.58	3.43	4.78	5.52	6.57	2.57	3.48	4.37	4.77	5.22
IMAGE 2.3	Enteric, manure, paddy rice, soil (N_2O and CO_2), biomass & agricultural waste burning, land clearing	3.36	3.95	4.41	4.52	4.46	2.05	2.48	2.93	3.07	3.06

* *CO_2 emissions from fossil fuel combustion are tracked as well, but frequently reported (and mitigated) under other sector headings (e.g. energy, transportation).*

Notes: SAR GWPs used to compute carbon equivalent emissions. nm = not modelled. The GTEM-EMF21 scenario ran through 2050. See Figure 3.7 and 3.10 notes for the scenario references.

for in integrated assessment scenarios. Specifically, new insights suggest that soil drying and forest dieback may naturally reduce terrestrial carbon sequestration (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 fully couples land use change scenarios with a 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 the TAR (Morita *et al.*, 2001) recommended that future research should include GHGs other than CO_2 in 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 from energy. Nevertheless, some multi-gas scenario work existed, including the SRES baseline scenarios, but also some other modelling efforts (Manne and Richels, 2001; Babiker *et al.*, 2001; Tol, 1999). The most important non-CO_2 gases include: methane (CH_4), nitrous oxide (N_2O), and a group of fluorinated compounds (F-gases, i.e., HFCs, PFCs, and SF_6). Since the TAR, the number of modelling groups producing long-term emission scenarios for non-CO_2 gases has dramatically increased. As a result, the quantity and quality of non-CO_2 emissions scenarios has improved 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. Table 3.2 provides a list of the major GHG emitting sectors and their corresponding emissions, estimated for 2000. Note that there is significant uncertainty concerning emissions from some sources of the non-CO_2 gases, and the table summarizes the central values from Weyant *et al*. (2006) which has been used in long-term multi-gas scenario studies of the EMF-21. 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).

The most important work on non-CO_2 GHG emissions scenarios has been done in the context of EMF-21 (De la Chesnaye and Weyant, 2006). The EMF-21 study updated the capability of long-term integrated assessment models for modelling non-CO_2 GHG emissions. The results of the study are illustrated in Figure 3.11.

Evaluating the long-term projections of anthropogenic methane emissions from the EMF-21 data shows a significant range in the estimates, but this range is consistent with that found in the SRES. The methane emission differences in the SRES are due to the different storylines. The differences in the EMF-21 reference cases are mainly due to changes in the economic activity level projected in key sectors by each of the models[6]. 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 modelling groups

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[6] In the EMF-21 study, reference case scenarios were considered to be 'modeller's choice', where harmonization of input parameters and exogenous assumptions was not sought.

Table 3.2: *Global Anthropogenic GHG Emissions for 2000 at sector level, as used in EMF-21 studies ($MtCO_2$-eq/yr).*

Sector sub-total & percent of total	Sub-sectors	CO_2	CH_4	N_2O	F-gases
ENERGY	Coal	8,133	451		
	Natural gas	4,800	895		
25,098	Petroleum syst.	10,476	62		
67%	Stationary/Mobile sources		59	224	
LUCF[a] and AGRICULTURE	LUCF and agriculture (net)	3,435			
	Soils			2,607	
	Biomass		491	187	
	Enteric fermentation		1,745	-	
9,543	Manure management		224	205	
25%	Rice		649	-	
INDUSTRY	Cement	829			
	Adipic & nitric acid production			158	
	HFC-23				95
	PFCs				106
1,434	SF6				55
4%	Substitution of ODS[b]				191
WASTE	Landfills		781		
1,448	Wastewater		565	81	
4%	Other		11	11	
Total all GHG	37,524	27,671	5,933	3,472	447
	Gas as percent of total	74%	16%	9%	1%

Notes: [a] LUCF is Land-use change and forestry.
[b] HFCs are used as substitutes for ODSs in a range of applications
Sources: Weyant et al, 2006.

employed various methods of representing methane emissions in their models and also made different assumptions about how specific methane emission factors for each economic sector change over time. Finally, 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. Interestingly, the latter group of models tend to find slower emissions growth rates (see Van Vuuren *et al*., 2006b).

The range of long-term projections of anthropogenic nitrous oxide emissions is wider than for methane in the EMF-21 data. Note that for N_2O, base year emissions of the different models differ substantially. Two factors may contribute to this. First, different definitions exist as to what should be regarded as human-induced and natural emissions in the case of N_2O emissions from soils. Second, some models do not include all emission sources.

The last group of non-CO_2 gases are fluorinated compounds, which include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). The total global emissions of these gases are almost 450 $MtCO_2$-eq, or slightly over 1% 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. Total emissions of non-CO_2 GHGs are projected to increase, but somewhat less rapidly than CO_2 emissions, due to agricultural activities growing less than energy use.

3.2.2.4 *Scenarios for air pollutants and other radiative substances*

Sulphur dioxide emission scenarios

Sulphur 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. Sulphur emissions also contribute to regional and local air pollution. Global sulphur dioxide emissions have grown approximately in parallel with the increase in fossil fuel use (Smith *et al*., 2001, 2004; Stern, 2005). However, since around the late 1970s, the growth in emissions has slowed considerably (Grübler, 2002). Implementation of emissions controls, a shift to lower sulphur 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 sulphur emissions (Smith *et al*., 2001). Conversely, with accelerated economic development, the growth of sulphur emissions in many parts of Asia has been high in recent decades, although growth rates have moderated recently (Streets *et al*., 2000;

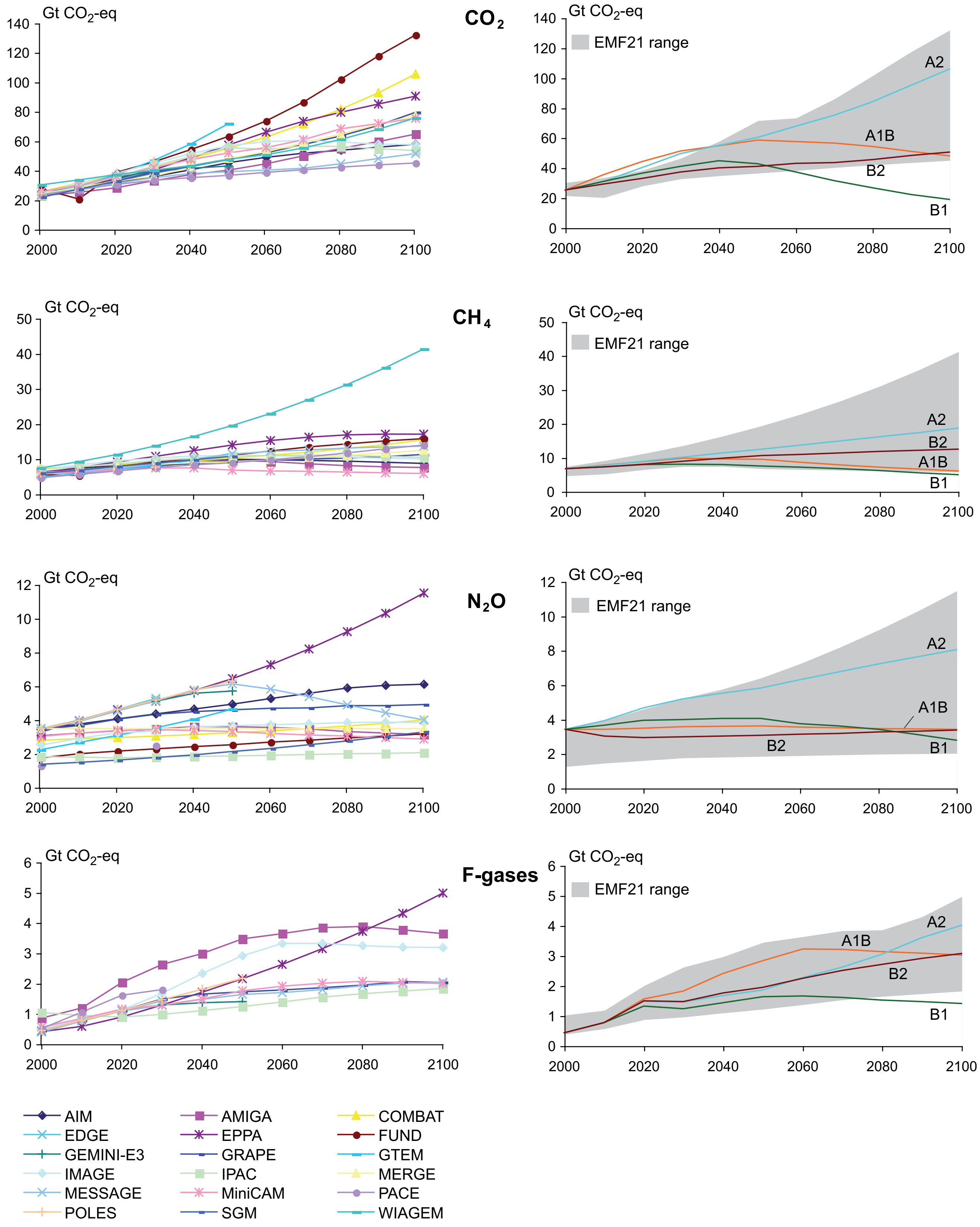

Figure 3.11: *Development of baseline emissions in the EMF-21 scenarios (left) and comparison between EMF21 and SRES scenarios (right).*

Source: De la Chesnaye and Weyant , 2006; see also Van Vuuren et al., 2006b

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 ranging between 55.2 MtS (Stern, 2005), 57.5 MtS (Cofala *et al*., 2006) and 62 MtS (Smith *et al*., 2004).[7]

Many empirical studies have explored the relationship between sulphur emissions and related drivers, such as economic development (see for example, 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 during 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 the SRES and more recent sulphur-emission scenarios is given in Van Vuuren and O'Neill (2006). Figure 3.12 illustrates that the resulting 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[8]. Scenarios at the lower boundary 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 boundaries of emissions are characterized by a rapid increase over coming decades, primarily driven by the increasing use of coal and oil at relatively low levels of sulphur 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 3.12). However, the emissions peak over the short-term of some high emissions scenarios in SRES, which lie above the upper boundary estimates of the recent scenarios. There are two main reasons for this difference. First, recent sulphur inventories for the year 2000 have shifted downward. Second, and perhaps more importantly, new information on present and planned sulphur 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 sulphur emissions to peak earlier and at lower levels compared to the SRES. Also the lower boundary projections of the recent literature have shifted downward slightly compared to the SRES scenario.

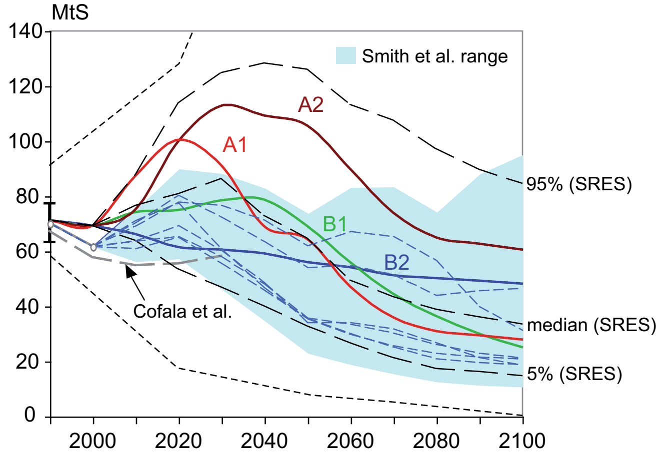

Figure 3.12: *Sulphur dioxide emission scenarios.*

Notes: Thick coloured 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 Smith *et al*. (2004). Dotted lines indicate the minimum and maximum of sulphur emissions scenarios developed pre-SRES.

NO_x emission scenarios

The most important sources of NO_x emissions are fossil fuel combustion and industrial processes, which combined with other sources such as natural and anthropogenic soil release, biomass burning, lightning, and atmospheric processes, amount to around 25 MtN per year. Considerable 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. Emissions have been increasing in most parts of Asia and other developing parts of the world, mainly due to the growing transport sector (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. However, the pace of this trend is 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 the 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*. (2000) often use IS92a as a 'loose' baseline, with new abatement policies added. Many scenarios

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[7] Note that the Cofala *et al*. (2006) inventory does not include emissions from biomass burning, international shipping and aircraft. In order to enhance comparability between the inventories, emissions from these sources (6 MtS globally) have been added to the original Cofala *et al*. (2006) values.

[8] The Amann (2002) projections were replaced by the recently updated IIASA-RAINS projection from Cofala *et al*. (2006).

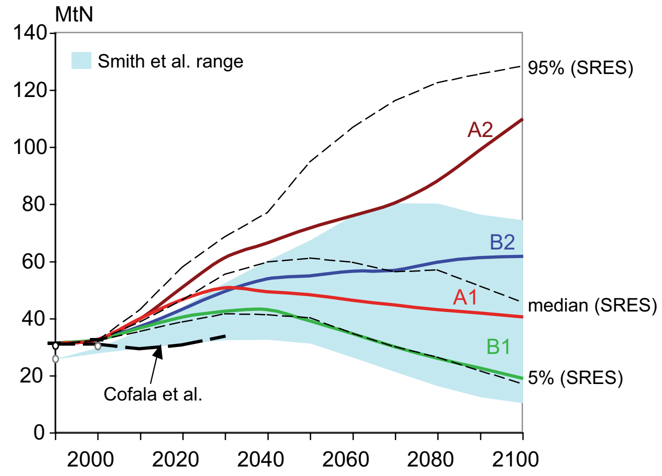

Figure 3.13: *NO$_x$ emission scenarios.*

Notes: Thick coloured 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.

report rising NO$_x$ emissions up to the 2020s (Figure 3.13), with the lower boundary 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 MtN and 47 MtN by 2020, which corresponds to an increase in emissions of around 6–50% compared to 2000. The long-term spread is considerably larger, ranging from 9 MtN to 74 MtN by 2100 (see Figure 3.13). The majority of the SRES scenarios (70%) lie within the range of the new Smith (2005) scenarios. However, the upper and lower boundaries of the range of the recent projections have shifted downward compared to the SRES.

Emission scenarios for black and organic carbon

Black and organic carbon emissions (BC and OC) are mainly formed by incomplete combustion, as well as from gaseous precursors (Penner *et al.*, 1993; Gray and 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, such as forest fires and savannah burning, are other major contributors. There has recently been some research suggesting that carbonaceous aerosols may contribute 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.*, 2004).

In the past, BC and OC emissions have been poorly represented in economic and systems engineering models due to unavailability of data. For example, in the IPCC's Third Assessment Report, BC and OC estimates were developed by using CO emissions (IPCC, 2001b). One of the main reasons for this has been the lack of adequate global inventories for different emission sources. However, some detailed global and regional emission inventories of BC and OC have recently become available (Table 3.3). In addition, some detailed regional inventories are also available including Streets *et al.* (2003) and Kupiainen and Klimont (2004). While many of these are comprehensive with regard to detail, considerable uncertainty still exists in the inventories, mainly due to the variety in combustion techniques for different fuels as well as measurement techniques. In order to represent these uncertainties, some studies, such as Bond *et al.* (2004), provide high, low and 'best-guess' values.

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 and Wigley (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 the fuel-mix and other detail in various energy scenarios and obtain corresponding BC and OC emissions.

The inclusion of technological development is an important factor in estimating future BC and OC emissions because, even though absolute fossil fuel use may increase, a combination of economic growth, increased environmental consciousness, technology development and legislation could imply decreased pollutant emissions (Figure 3.14). Liousse *et al.* (2005) neglect the effects of technological change leading to much higher

Table 3.3: *Emission inventories for black and organic carbon (Tg/yr).*

Source	Estimate year	Black carbon	Organic carbon
Penner *et al.*, 1993	1980	13	-
Cooke and Wilson, 1996	1984	14a)	-
Cooke *et al.*, 1999	1984	5-6.6a)	7-10a)
Bond *et al.*, 2004	1996	4.7 (3-10)	8.9 (5-17)
Liousse *et al.*,1996		12.3	81
Junker and Liousse, 2006	1997	5.7	9.5

Note: a) Emissions from fossil-fuel use

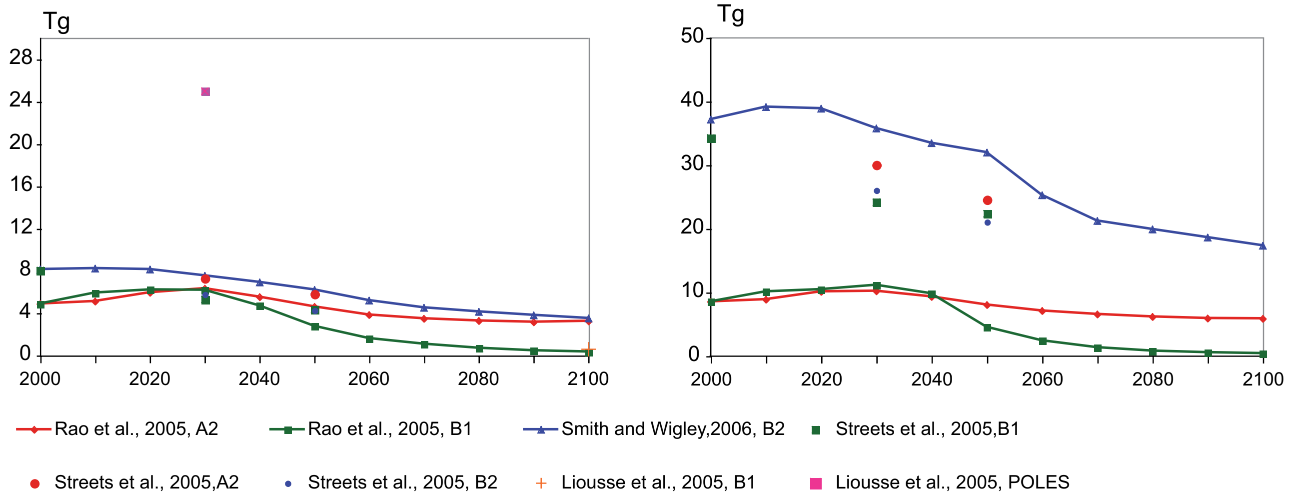

Figure 3.14: *Total black carbon (left panel) and organic carbon (right panel) emission estimates in scenarios from different studies.*

Notes: Rao *et al*., (2005) include emissions from contained combustion only. Liousse *et al*. (2005), A2 not included as 2100 value of 100 Tg lies way above range.

emission estimates for BC emissions in the long-term in some cases, as compared to other studies such as Streets *et al*. (2004), Rao *et al*. (2005) and Smith and Wigley (2006), all of which show declining emissions in the long-term. Another important factor that Rao *et al*. (2005) also account for is current and proposed environmental legislation. This suggests the necessity for technology-rich frameworks that capture structural and technological change, as well as policy dynamics in the energy system in order to estimate future BC and OC emissions.

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 in regions such as East Asia (including China). In other developing regions, such as 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.

To summarize, an important feature of the recent scenario literature is the long-term decline in BC/OC emission 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.

3.3 Mitigation scenarios

3.3.1 Introduction

This section contains a discussion of methodological issues (Sections 3.3.2–3.3.4), followed by a focus on the main characteristics of different groups of mitigation scenarios, with specific attention paid to new literature on non-CO_2 gases and land use (Sections 3.3.5.5 and 3.3.5.6). Finally, short-term scenarios with a regional or national focus are discussed in Section 3.3.6.

3.3.2 Definition of a stabilization target

Mitigation scenarios explore the feasibility and costs of achieving specified climate change or emissions targets, often in comparison to a corresponding baseline scenario. The specified target itself is an important modelling and policy issue. Because Article 2 of United Nations Framework Convention on Climate Change (UNFCCC) states as its objective the ‘stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system’, most long-term mitigation studies have focused their efforts on GHG concentration stabilization scenarios. However, several other climate change targets may be chosen, for example the rate of temperature change, radiative forcing, or climate change impacts (see e.g. Richels *et al*., 2004; Van Vuuren *et al*., 2006b; Corfee-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 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 of the emission reductions required to reach that target.

A commonly used target has been the stabilization of the atmospheric CO_2 concentration. If more than one GHG is included, most studies use the corresponding target of stabilizing 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

Table 3.4: *Advantages and disadvantages of using different stabilization targets.*

Target	*Advantages*	*Disadvantages*
Mitigation costs	Lowest uncertainty on costs.	Very large uncertainty on global mean temperature increase and impacts. Very large uncertainty on global mean temperature increase and impacts. Either needs a different metric to allow for aggregating different gases (e.g. GWPs) or forfeits opportunity of substitution.
Emissions mitigation	Lower uncertainty on costs.	Does not allow for substitution among gases, thus losing the opportunity for multi-gas cost reductions. Indirect link to the objective of climate policy (e.g. impacts).
Concentrations of different greenhouse gases	Can be translated relatively easily into emission profiles (reducing uncertainty on costs).	Allows a wide range of CO_2-only stabilization targets due to substitutability between CO_2 and non-CO_2 emissions.
Radiative forcing	Easy translation to emission targets, thus not including climate sensitivity in costs calculations. Does allow for full flexibility in substitution among gases. Connects well to earlier work on CO_2 stabilization. Can be expressed in terms of CO_2-eq concentration target, if preferred for communication with policymakers.	Indirect link to the objective of climate policy (e.g. impacts).
Global mean temperature	Metric is also used to organize impact literature; and as has shown to be a reasonable 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.

Based on: Van Vuuren *et al.*, 2006b.

the consequences for emission trajectories do not depend on climate sensitivity, which adds an important uncertainty. The disadvantage is that a wide range of temperature impacts is possible for each radiative forcing level. By contrast, temperature targets provide a more direct first-order indicator of potential climate change impacts, but are less practical to implement in the real world, because of the uncertainty about the required emissions reductions.

Another approach is to calculate risks or the probability of exceeding particular values of global annual mean temperature rise (see also Table 3.9). For example, Den Elzen and Meinshausen (2006) and Hare and Meinshausen (2006) used different probability density functions of climate sensitivity in the MAGICC simple climate model to estimate relationships between the probability of achieving climate targets and required emission reductions. Studies by Richels *et al*. (2004), Yohe *et al*. (2004), Den Elzen *et al*. (2006), Keppo *et al*. (2006), and Kypreos (2006) have used a similar probabilistic concept in an economic context. The studies analyze the relationship between potential mitigation costs and the increase in probability of meeting specific temperature targets.

The choice of different targets is not only relevant because it leads to different uncertainty ranges, but also because it leads to different strategies. Stabilization of one type of target, such as temperature, does not imply stabilization of other possible targets, such as rising sea levels, radiative forcing, concentrations or emissions. For instance, a cost-effective way to stabilize temperature is not radiative forcing stabilization, but rather to allow radiative forcing to peak 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; Kheshgi *et al*., 2005; Den Elzen *et al*., 2006). Finally, targets can also be defined to limit a rate of change, such as 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. The rate of temperature change targets, for instance, may be difficult to achieve in the short-term even, using multi-gas approaches (Manne and Richels, 2006; Van Vuuren *et al*., 2006a).

3.3.3 How to define substitution among gases

In multi-gas studies, a method is needed to compare different greenhouse gases with different atmospheric lifetimes and radiative properties. Ideally, the method would allow for substitution between gases in order to achieve mitigation cost reductions, although it may not be suitable to ensure equivalence in measuring climate impact. Fuglestvedt *et al*. (2003) provide a comprehensive overview of the different methods that have been proposed, along with their advantages and disadvantages. One of these methods, CO_2-eq emissions based on Global Warming Potentials (GWP), has been adopted by current climate policies, such as the Kyoto Protocol and the US climate policy (White House, 2002). Despite the continuing scientific and economic

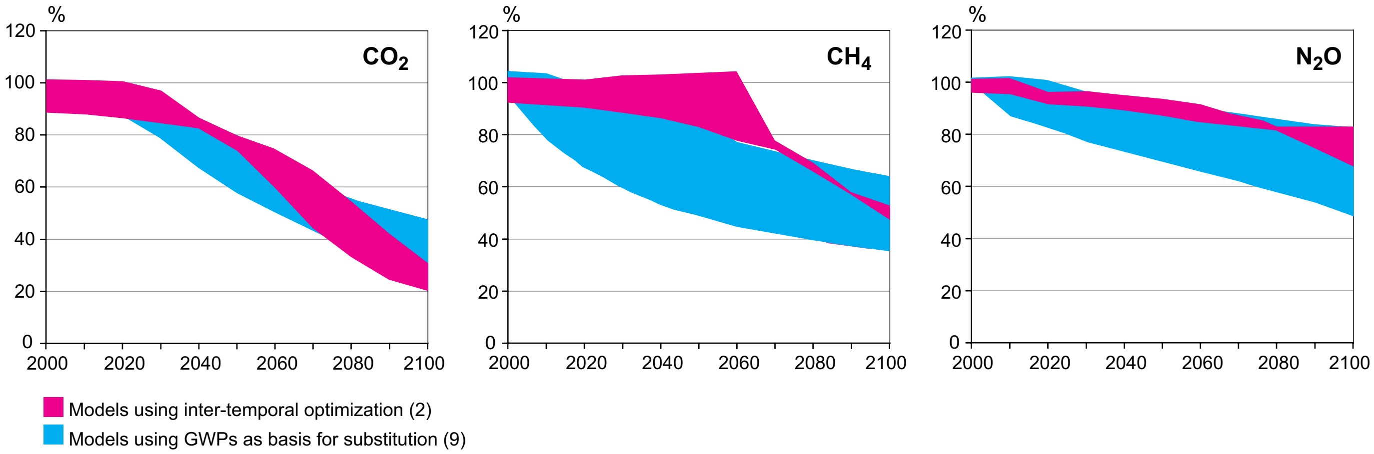

Figure 3.15: *Reduction of emissions in the stabilization strategies aiming for stabilization at 4.5 W/m^2 (multi-gas strategies) in EMF-21.*

Notes: Range for models using GWPs (blue; standard deviation) versus those not using them (purple; full range). For the first group, all nine reporting long-term models were used. For the second category, results of two of the three reporting models were used (the other model shows the same pattern with respect to the distribution among gases, but has a far higher overall reduction rate and, as such, an outlier).

Data source: De la Chesnaye and Weyant, 2006.

debate on the use of GWPs (i.e. they are not based on economic considerations and use an arbitrary time horizon) the concept is in use under the UNFCCC, the Kyoto Protocol, and the US climate policy. In addition, no alternative measure has attained comparable status to date.

Useful overviews of the mitigation and economic implication of substitution metrics are provided by Bradford (2001) and Godal (2003). Models that use inter-temporal optimization can avoid the use of substitution metrics (such as GWPs) by optimizing the reductions of all gases simultaneously under a chosen climate target. Inter-temporal optimization or perfect foresight models assume that economic agents know future prices and make decisions to minimize costs. Manne and Richels (2001) show, using their model, that using GWPs as the basis of substitution did not lead to the cost-optimal path (minimizing welfare losses) for the long-term targets analyzed. In particular, reducing methane early had no benefit for reaching the long-term target, given its short lifespan in the atmosphere. In the recent EMF-21 study some models validated this result (see De la Chesnaye and Weyant, 2006). Figure 3.15 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 inter-temporal optimization. While (for most of the gases) there are no systematic differences between the results from the two groups, for methane and some F-gases (not shown), there are clear differences related to the very different lifespans of these gases. The models that do not use GWPs, do not substantially reduce CH_4 until the end of the time horizon. However, for models using GWPs, the reduction of CH_4 emissions in the first three decades is substantial: here, CH_4 reductions become a cost-effective short-term abatement strategy, despite the short lifespan (Van Vuuren *et al.*, 2006b). It should be noted that if a short-term climate target is selected (e.g. rate of temperature change) then inter-temporal optimization models would also favour early methane reductions.

While GWPs do not necessarily lead to the most cost-effective stabilization solution (given a long-term target), they can still be a practical choice: in real-life policies an exchange metric is needed to facilitate emissions trading between gases within a specified time period. Allowing such exchanges creates the opportunity for cost savings through ‘what and where flexibility’. 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.* (2006) 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 GWP-based multi-gas strategy and a cost-optimal strategy. Aaheim *et al.* (2006) found that the cost of using GWPs compared to optimal weights, depends on the ambition of climate policies. Postponing the early CH_4 reductions of the GWP-based strategy, as is suggested by inter-temporal optimization, generally leads to larger temperature increases during the 2000–2020 period. This is because the increased reduction of CO_2 from the energy sector also leads to reduction of sulphur emissions (hence the cooling associated with sulphur-based aerosols) but allows the potential to be used later in the century.

3.3.4 Emission pathways

Emission pathway studies often focus on specific questions with respect to the consequences of timing (in terms of environmental impacts) or overall reduction rates needed for specific long-term targets, (e.g. the emission pathways developed by Wigley *et al.*, 1996). A specific issue raised in the literature on emission pathways since the TAR has concerned a temporary overshoot of the target (concentration, forcing, or temperature). Meinshausen (2006) used a simple carbon-cycle model to illustrate that for low-concentration targets (i.e. below 3 W/m^2/ 450 ppmv CO_2-eq) overshoot is inevitable, given the feasible maximum rate of reduction. Wigley (2003) argued that overshoot profiles may give important economic benefits. In response, O'Neill and Oppenheimer (2004) showed that the associated incremental warming of large overshoots may significantly increase the risks of exceeding critical climate thresholds to which ecosystems are known to be able to adapt. Other emission pathways that lead to less extreme concentration overshoots 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 analyzing overshoot strategies are made by Harvey (2004), and Kheshgi *et al*. (2005).

3.3.5 Long-term stabilization scenarios

A large number of studies on climate stabilization have been published since the TAR. Several model comparison projects contributed to the new literature, including the Energy Modelling Forum's EMF-19 (Weyant, 2004) and EMF-21 studies (De la Chesnaye and Weyant, 2006), that focused on technology change and multi-gas studies, respectively, the IMCP (International Model Comparison Project), which focused on technological change (Edenhofer *et al*., 2006), and the US Climate Change Science Programme (USCCSP, 2006). The updated emission scenario database (Hanaoka *et al*., 2006; Nakicenovic *et al*., 2006) includes a total of 151 new mitigation scenarios published since the SRES.

Comparison of mitigation scenarios is more complicated now than at the time of the TAR because:

- Parts of the modelling community have expanded their analysis to include non-CO_2 gases, while others have continued to focus solely on CO_2. As discussed in the previous section, multi-gas mitigation scenarios use different targets, thus making comparison more complicated.
- Some recent studies have 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 the TAR, many studies used the SRES scenarios as baselines for their mitigation analyses, providing a comparable set of assumptions. Now, there is a broader range of underlying assumptions.

This section introduces some metrics to group the CO_2-only and multi-gas scenarios so that they are reasonably comparable. In Figure 3.16 the reported CO_2 concentrations in 2100 are plotted against the 2100 total radiative forcing (relative to pre-industrial times). Figure 3.16 shows that a relationship exists between the two indicators. 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 existing spread across the studies is caused by several factors, including differences in the abatement rate among alternative gases, differences in specific forcing values for GHGs and other radiative gases (particularly aerosols), and differences in the atmospheric chemistry and carbon cycle models that are used. Here, the relationship is used to classify the available mitigation literature into six categories that vary in the stringency of the climate targets. The most stringent group includes those scenarios that aim to stabilize radiative forcing below 3 W/m^2. This group also includes all CO_2-only scenarios that stabilize CO_2 concentrations below 400 ppmv. In contrast, the least stringent group of mitigation scenarios have a radiative forcing in 2100 above 6 W/m^2 – associated with CO_2 concentrations above 660 ppmv. By far the most studied group of scenarios are those that aim to stabilize radiative forcing at 4–5 W/m^2 or 485–570 ppmv CO_2 (see Table 3.5).

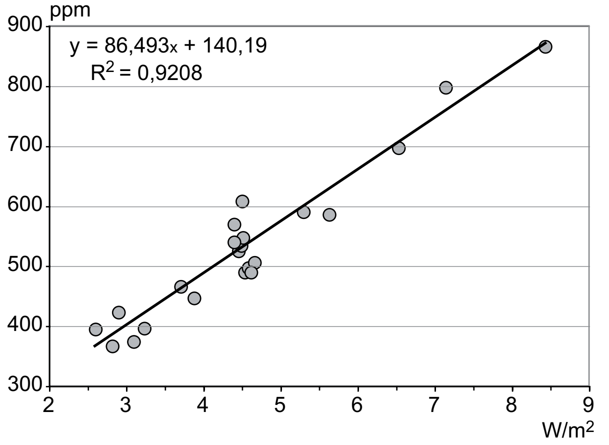

Figure 3.16: *Relationship of total radiative forcing vis-à-vis CO_2 concentration for the year 2100 (25 multi-gas stabilization scenarios for alternative stabilization targets).*

The classification of scenarios, as given in Table 3.5, permits the comparison of multi-gas and CO_2-only stabilization scenarios according to groups of scenarios with comparable level of mitigation stringency. The studies have been classified on the basis of the reported targets, using the relationship from Figure 3.16 to permit comparability of studies using different stabilization metrics. The following section uses these categories (I to VI) to analyze the underlying dynamics of stabilization scenarios as a function of the stabilization target. However, it should be noted that the classification is subject to uncertainty and should thus to be used with care.

3.3.5.1 Emission reductions and timing

Figure 3.17 shows the projected CO_2 emissions associated with the new mitigation scenarios. In addition, the figure depicts the range of the TAR stabilization scenarios (more than 80

Table 3.5: *Classification of recent (post-TAR) stabilization scenarios according to different stabilization targets and alternative stabilization metrics. Groups of stabilization targets were defined using the relationship in Figure 3.16.*

	Additional radiative forcing	CO_2 concentration	CO_2-eq concentration	Peaking year for CO_2 emissions[a]	Change in global emissions in 2050 (% of 2000 emissions)[1]	
Category	W/m²	ppm	ppm	year	%	No. of scenarios
I	2.5-3.0	350-400	445-490	2000-2015	-85 to -50	6
II	3.0-3.5	400-440	490-535	2000-2020	-60 to -30	18
III	3.5-4.0	440-485	535-590	2010-2030	-30 to +5	21
IV	4.0-5.0	485-570	590-710	2020-2060	+10 to +60	118
V	5.0-6.0	570-660	710-855	2050-2080	+25 to +85	9
VI	6.0-7.5	660-790	855-1130	2060-2090	+90 to +140	5
Total						177

Note: [a] Ranges correspond to the 15th to 85th percentile of the Post-TAR scenario distribution.
Note that the classification needs to be used with care. Each category includes a range of studies going from the upper to the lower boundary. The classification of studies was done on the basis of the reported targets (thus including modeling uncertainties). In addition, also the relationship, which was used to relate different stabilization metrics, is subject to uncertainty (see Figure 3.16).

scenarios) (Morita *et al*., 2001). Independent of the stabilization level, scenarios show that the scale of the emissions reductions, relative to the reference scenario, increases over time. Higher stabilization targets do push back the timing of most reductions, even beyond 2100.

An increasing body of literature assesses the attainability of very low targets of below 450 ppmv CO_2 (e.g. Van Vuuren *et al*., 2007; Riahi *et al*., 2006). These scenarios from class I and II extend the lower boundary beyond the range of the TAR stabilization scenarios of 450 ppmv CO_2 (see upper panels of Figure 3.17). 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, in particular the combination of bio-energy, carbon capture and geologic storage (BECCS). If biomass is grown sustainably, this combination may lead to negative emissions (Williams, 1998; Herzog *et al*., 2005), Rao and Riahi (2006), Azar *et al*. (2006) and Van Vuuren *et al*. (2007) all find that such negative emissions technologies might be essential for achieving very stringent targets.

The emission range for the scenarios with low and intermediate targets between 3.5 and 5 W/m² (scenarios in categories III and IV) are consistent with the range of the 450 and 550 ppmv CO_2 scenarios in the TAR. Emissions in this category tend to show peak emissions around 2040 – with emissions in 2100 similar to, or slightly below, emissions today. Although for these categories less rapid and forceful reductions are required than for the more stringent targets, studies focusing on these stabilization categories find that a wide portfolio of reduction measures would be needed to achieve such emission pathways in a cost-effective way.

The two highest categories of stabilization scenarios (V and VI) overlap with low-medium category baseline scenarios (see Section 3.2). This partly explains the relatively small number of new studies on these categories. The emission profiles of these scenarios are found to be consistent with the emissions ranges as published in the TAR.

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 3.18). The uncertainties associated with individual stabilization levels (shown by the different percentiles[9]) are primarily due to the ranges associated with individual stabilization categories, substitutability of CO_2 and non-CO_2-emissions, different model parameterizations of the carbon cycle, but they are also partly due to differences in emissions pathways (delayed reduction pathways can allow for somewhat higher cumulative emissions). In general, scenarios aiming for targets below 3 W/m² require cumulative CO_2 emissions of around 1100 $GtCO_2$ (range of 800–1500 $GtCO_2$). The cumulative emissions increase for subsequently less stringent targets. The middle category (4–5 W/m²) requires emissions to be in the order of 3000 $GtCO_2$ (range of 2270–3920 $GtCO_2$). The highest category (>6 W/m²) exhibits emissions, on average, around 5020 $GtCO_2$ (range of 4400–6600 $GtCO_2$).

The timing of emission reductions also depends on the stringency of the stabilization target. Timing of climate policy has always been an important topic in the scenario literature. While some studies argue for early action for smooth transitions and stimulating technology development (e.g. Azar and Dowlatabadi, 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; Tol, 2000; for a more elaborate discussion on timing see also Section 3.6). This implies that a given stabilization target can be consistent with a range of interim targets. Nevertheless, stringent targets require an earlier peak of CO_2 emissions (see Figure 3.19 and

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[9] Note that the percentiles are used to illustrate the statistical properties of the scenario distributions, and should not be interpreted as likelihoods in any probabilistic context.

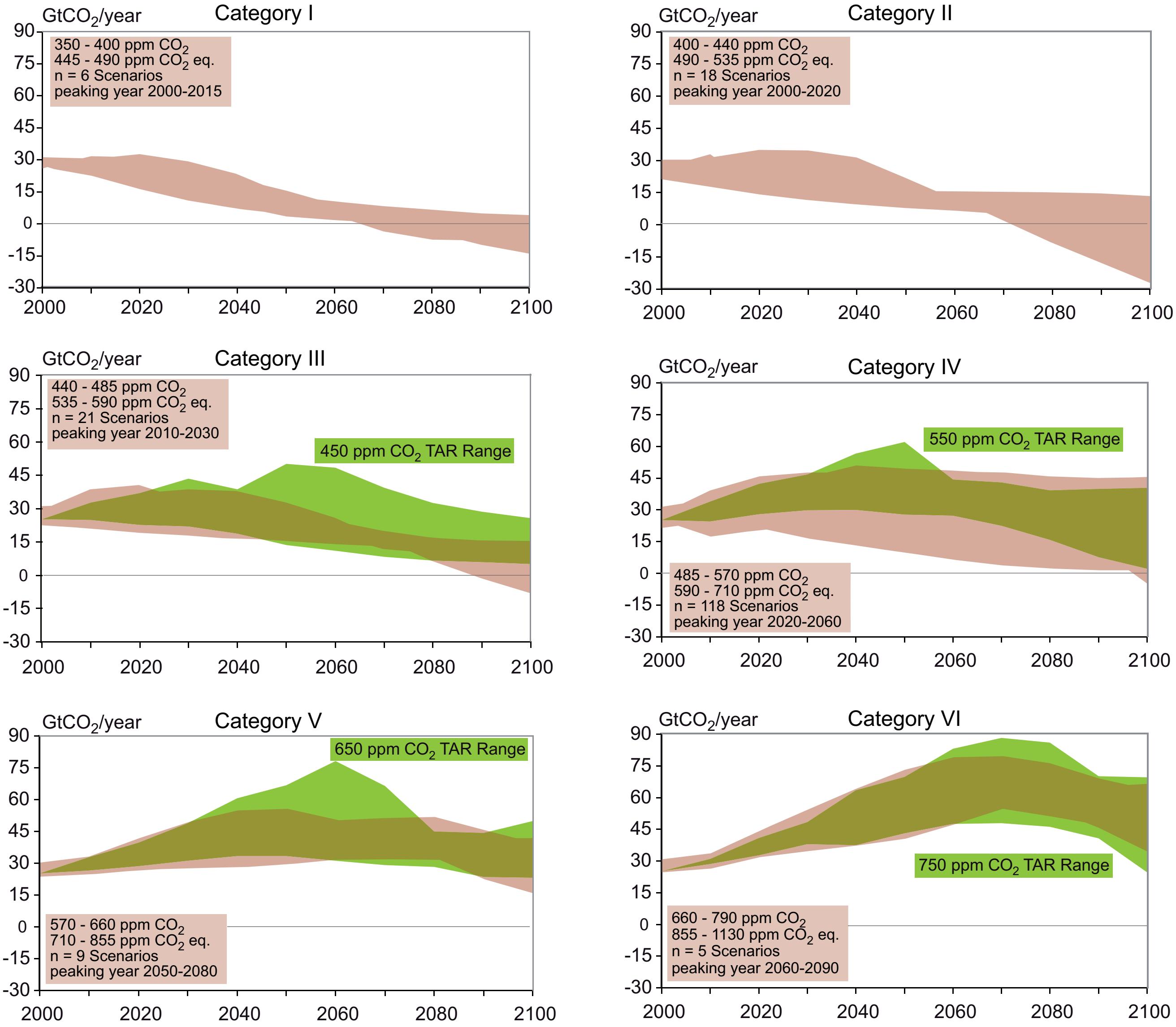

Figure 3.17: *Emissions pathways of mitigation scenarios for alternative groups of stabilization targets (Categories I to VI, see Table 3.5). The pink area gives the projected CO_2 emissions for the recent mitigation scenarios developed post-TAR. Green shaded areas depict the range of more than 80 TAR stabilization scenarios (Morita et al., 2001). Category I and II scenarios explore stabilization targets below the lowest target of the TAR.*

Source: After Nakicenovic et al., 2006, and Hanaoka et al., 2006

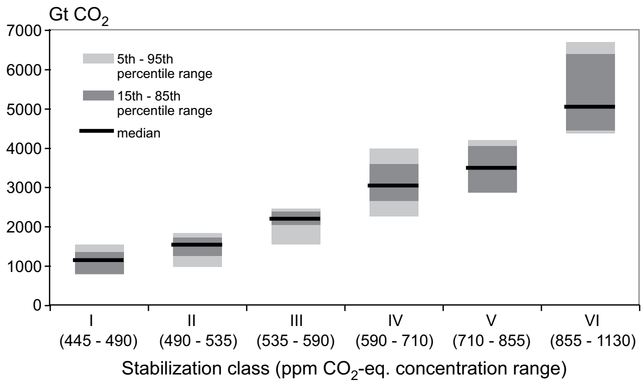

Figure 3.18: *Relationship between the scenario's cumulative carbon dioxide emissions (2000–2100) and the stabilization target (stabilization categories I to VI, of Table 3.5).*

Data source: After Nakicenovic et al., 2006, and Hanaoka et al., 2006

Table 3.5). In the majority of the scenarios concerning the most stringent group (< 3 W/m^2), emissions start to decline before 2015, and are further reduced to less than 50% of today's emissions by 2050 (Table 3.5). The emissions profiles of these scenarios indicate the need for short-term infrastructure investments for a comparatively early decarbonization of the energy system. Achieving these low-emission trajectories requires 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 stringency group (4-5 W/m^2) the peak of global emissions generally occurs around 2010 to 2030; followed by a return to 2000 levels, on average, around 2040 (with the majority of these scenarios returning to 2000 emissions levels between 2020 and 2060). For targets between 5–6 W/m^2, the median emissions peak around 2070. The figure also indicates that the uncertainty range is relatively small for the more stringent targets, illustrating the reduced flexibility of the emissions path and the requirement for early mitigation. The less stringent categories allow more flexibility in timing. Most of the stringent stabilization scenarios of category I (and some II scenarios) assume a temporal overshoot of the stabilization target (GHG concentration, radiative forcing, or temperature change) before the eventual date of stabilization between 2100 and 2150. Recent studies indicate that while such 'overshoot' strategies might be inevitable for very low targets (given the climate system and socio-economic inertia), they might also provide important economic benefits. At the same time, however, studies note that the associated rate of warming from large overshoots might significantly increase the risk of exceeding critical climate thresholds. (For further discussion, see Section 3.3.4.)

The right-hand panel of Figure 3.19 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 I, II and III) emissions return to present levels, on average, before the middle of this century, that is about one to two decades after the year in which emissions peak. In most of the scenarios for the highest stabilization category (above 6 W/m^2; category VI) emissions could stay above present levels throughout the century.

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 3.20, which illustrates the relationship between the cumulative baseline emissions and the cumulative emissions reductions for the stabilization scenarios (by 2100). In general, 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 3.20. This is indeed the case for the range of studies and the 'category averages' (large triangles). As indicated in the figure, a scenario with high baseline emissions requires much deeper emission reduction in order to reach a medium stabilization target (sometimes more than 3600 $GtCO_2$) than a scenario with low baseline emissions to reach the most stringent targets (in some cases less than 1800 $GtCO_2$). For the same target (e.g. category IV) reduction may differ from 370 to 5500 $GtCO_2$. This comes from the large spread of emissions in the baseline scenarios. While scenarios for both stringent and less-stringent targets have been developed from low and high baseline scenarios, the data suggests that, on average, mitigation scenarios aimed at the most stringent targets start from the lowest baseline scenarios.

In the short-term (2030), the relationship between emission reduction and baseline is less clear, given the flexibility in the timing of emission reductions (left-hand panel in Figure 3.20). While the averages of the various stabilization categories are aligned in a similar way to those discussed for 2100 (with exception of category I, for which the scenario sample is smaller than for the other categories); the uncertainty ranges here are very large.

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 (see also Edmonds *et al*., 2004b; 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 towards energy conservation and efficiency improvements. In addition, capturing carbon

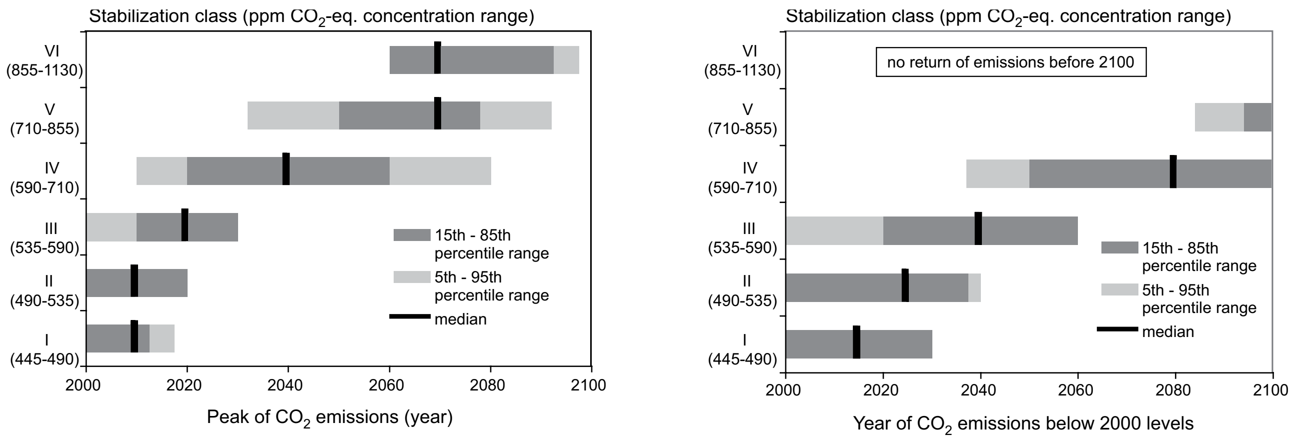

Figure 3.19: *Relationship between the stringency of the stabilization target (category I to VI) and 1) the time at which CO_2 emissions have to peak (left-hand panel), and 2) the year when emissions return to present (2000) levels.*

Data source: After Nakicenovic et al., 2006, and Hanaoka et al., 2006.

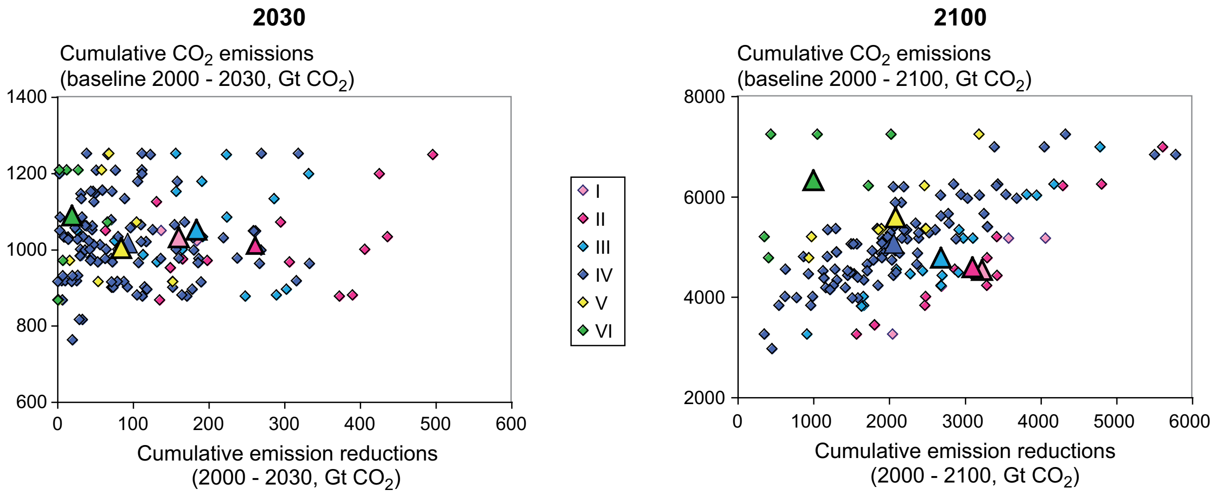

Figure 3.20: *Relationship between required cumulative emissions reduction and carbon emissions in the baseline by 2030 (left-hand panel) and 2100 (right-hand panel).*

Notes: Coloured rectangles denote individual scenarios for alternative stabilization targets (categories I to VI). The large triangles indicate the averages for each category.

Data source: After Nakicenovic et al., 2006, and Hanaoka et al., 2006

during energy conversion processes with subsequent storage in geological formations (CCS) provides an approach for reducing emissions. 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 aforementioned options can be grouped into two principal measures for achieving CO_2 reductions:

1. Improving the efficiency of energy use (or measures geared towards energy conservation).
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. A response index has been calculated (based on the full set of stabilization scenarios from the database) in order to explore the importance of these two strategies. This index is equal to the ratio of the reductions achieved through energy efficiency over those achieved by carbon-intensity improvements (Figure 3.21). Similar to Morita *et al*. (2001), it was discovered that the mitigation response to reduce CO_2 emissions would shift over time, from initially focusing on energy efficiency reductions in the beginning of the 21st century to more carbon-intensity reduction in the latter half of the century (Figure 3.21). The amount of reductions coming from carbon-intensity improvement is more important for the most stringent scenarios. The main reason is that, in the second half of the century, increasing costs of further energy efficiency improvements and decreasing costs of low-carbon or carbon-free energy sources make the latter category relatively more attractive. This trend is also visible in the scenario results of model comparison studies (Weyant, 2004; Edenhofer *et al*., 2006).

In addition to measures for reducing CO_2 emissions from energy and industry, emission reductions can also be achieved from other gases and sources. Figure 3.22 illustrates the relative contribution of measures towards achieving climate stabilization from three main sources:

1. CO_2 from energy and industry.
2. CO_2 from land-use change.
3. The full basket of non-CO_2 emissions from all relevant sources.

The figure compares the contribution of these measures towards achieving stabilization for a wide range of targets (between 2.6 and 5.3 W/m^2 by 2100) and baseline scenarios. 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% of total emissions reduction would occur in this sector. The non-CO_2 gases and land-use-related CO_2 emissions (including forests) are seen to contribute together up to 35% of total emissions reductions.[10] However, as noted further above, the majority of recent studies indicate the relative importance of the latter two sectors for the cost-effectiveness of integrated multi-gas GHG abatement strategies (see also Section 3.3.5.4 on CO_2-only versus multi-gas mitigation and 3.3.5.5 on land-use).

The strongest divergence across the scenarios concerns the contribution of land-use-related mitigation. The results range

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[10] Most of the models include an aggregated representation of the forest sector comprising the joint effects of deforestation, afforestation and avoided deforestation.

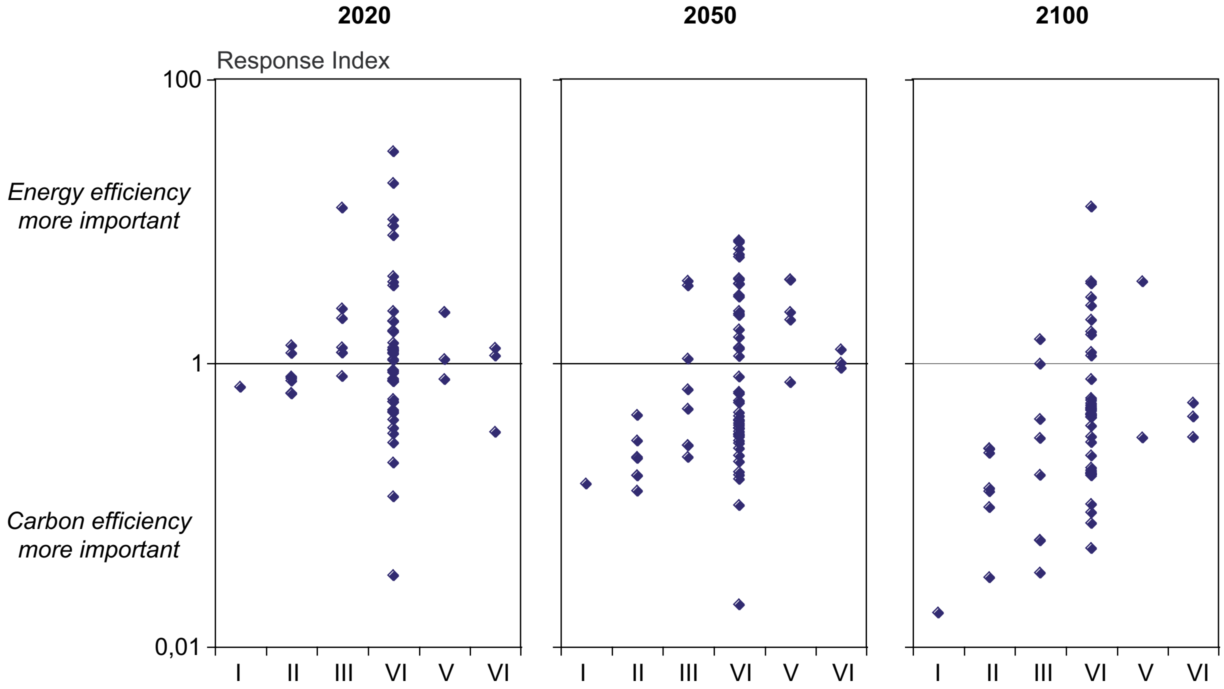

Figure 3.21: *Response index to assess priority setting in energy-intensity reduction (more than 1) or in carbon-intensity reduction (less than 1) for post-TAR stabilization scenarios.*

Note: The panels show the development of the index for the years 2020, 2050, and 2100 (66, 77, and 59 scenarios, respectively, for which data on energy, GDP and carbon emissions were available.

Data source: After Nakicenovic et al., 2006, and Hanaoka et al., 2006)

from negative contributions of land-use change to potential emissions savings of more than 1100 $GtCO_2$ over the course of the century (Figure 3.22). The primary reason for this is the considerable 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 in emissions due to net deforestation (compared to the baseline).

An illustrative example for the further breakdown of mitigation options is shown in Figure 3.23. The figure shows stabilization scenarios for a range of targets (about 3–4.5 W/m^2) based on four illustrative models (IMAGE, MESSAGE, AIM and IPAC) for which sufficient data were available. The scenarios share similar stabilization targets, but differ with respect to salient assumptions for technological change, long-term abatement potentials, as well as model methodology and structure. The scenarios are also based on different baseline scenarios. For example, cumulative baseline emissions over the course of the century range between 6000 $GtCO_2$-eq in MESSAGE and IPAC scenarios to more than 7000 $GtCO_2$-eq in the IMAGE and AIM scenarios. Figure 3.24 shows the primary energy mix of the baseline and the mitigation scenarios.

It should be noted that the figure shows reduction on top of the baseline (e.g. other renewables may already make a large baseline contribution). Above all, Figure 3.23 illustrates the importance of using a wide portfolio of reduction measures, with many categories of measures, showing contributions of more than a few hundred $GtCO_2$ over the course of the century. In terms of the contribution of different options, there is agreement for some options, while there is disagreement for others. The category types that have a large potential over the long term (2000–2100) in at least one model include energy conservation, carbon capture and storage, renewables, nuclear and non-CO_2 gases. These options could thus constitute an important part of the mitigation portfolio. However, the differences between the models also emphasize the impact of different assumptions and the associated uncertainty (e.g. for renewables, results can vary strongly depending on whether they are already used in the baseline, and how this category competes against other zero or low-emission options in the power sector, such as nuclear and CCS). The figure also illustrates that the limitations of the mitigation portfolio with respect to CCS or forest sinks (AIM and IPAC) would lead to relatively higher contributions of other options, in particular nuclear (IPAC) and renewables (AIM).

Figure 3.23 also illustrates the increase in emissions reductions necessary to strengthen the target from 4.5 to about 3–3.6 W/m^2. Most of the mitigation options increase their contribution significantly by up to a factor of more than two. This effect is particularly strong over the short term (2000–2030), indicating the need for early abatement in meeting stringent stabilization targets. Another important conclusion from the figure is that CCS and forest sink options are playing a relatively modest

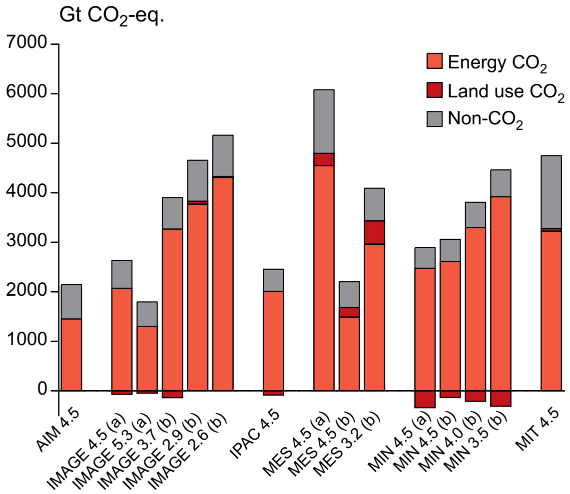

Figure 3.22: *Cumulative contribution of alternative mitigation measures by source (2000–2100)*

Note: Contributions for a wide range of stabilization targets (2.6–5.3 W/m^2), indicated after the model name) and alternative baseline scenarios. Mitigation scenarios using the same baseline are indicated for each model as (a) and (b) reprectively.

Data source: EMF-21, Smith and Wigley., 2006; Van Vuuren et al., 2007; Riahi et al., 2006

role in the short-term mitigation portfolio, particularly for the intermediate stabilization target (4.5 W/m^2). The results thus indicate that the widespread deployment of these options might require relatively more time compared to the other options and also relatively higher carbon prices (see also Figure 3.25 on increasing carbon prices over time).

As noted above, assumptions with regards to the baseline can have significant implications for the contribution of individual mitigation options in achieving stabilization. Figure 3.24 clearly shows that the baseline assumptions of the four models differ, and that these differences play a role in explaining some of the results. For instance, the MESSAGE model already includes a large amount of renewables in its baseline and further expansion is relatively costly. Nevertheless, some common trends among the models may also be observed. First of all, almost all cases show a clear reduction in primary energy use. Second, in all models coal use is significantly reduced under the climate policy scenarios, compared to the baseline. It should be noted that in those models that consider CCS, the remaining fossil fuel use is mostly in combination with carbon capture and storage. In 2030, oil use is only modestly reduced by climate policies – this also applies to natural gas use. In 2100, both oil and gas are reduced compared to the baseline in most models. Finally, renewable energy and nuclear power increase in all models – although the distribution across these two options differs.

3.3.5.3 *Stabilization costs*

Models use different metrics to report the costs of emission reductions. Top-down general equilibrium models tend to report GDP losses, while system-engineering partial equilibrium

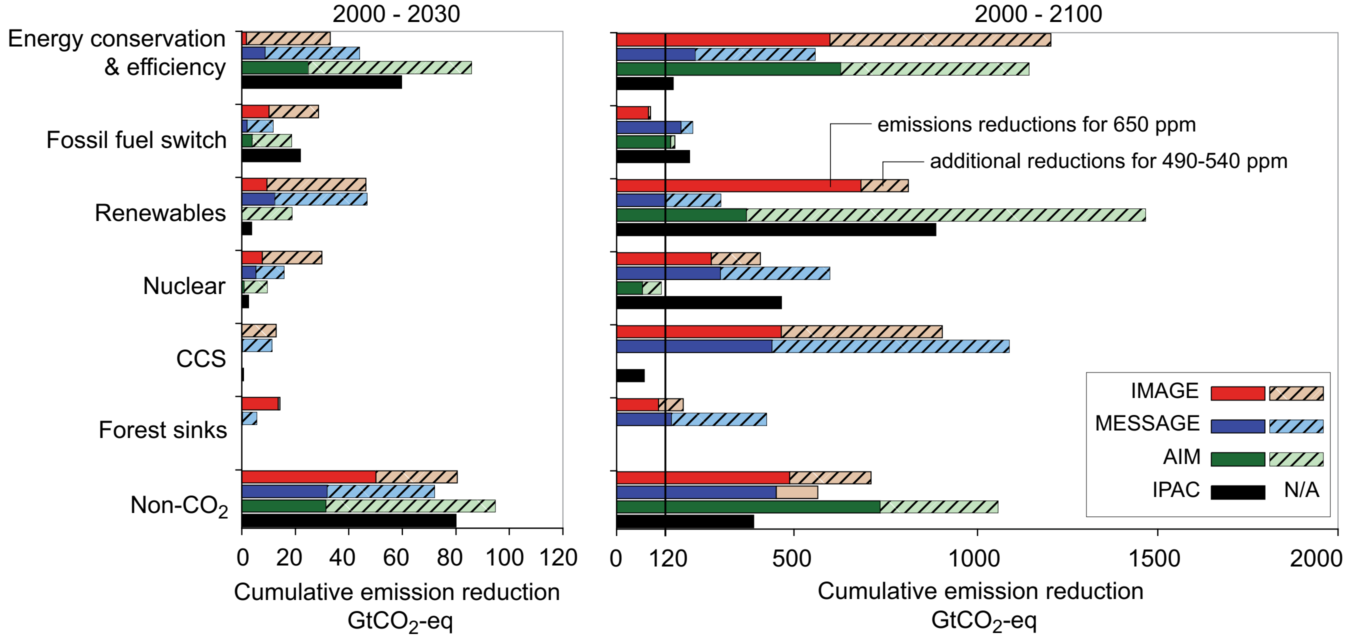

Figure 3.23: *Cumulative emissions reductions for alternative mitigation measures for 2000 to 2030 (left-hand panel) and for 2000-2100 (right-hand panel). The figure shows illustrative scenarios from four models (AIM, IMAGE, IPAC and MESSAGE) for stabilization levels of 490-540 ppmv CO_2-eq and levels of 650 ppmv CO_2-eq, respectively. Dark bars denote reductions for a target of 650 ppmv CO_2-eq and light bars the additional reductions to achieve 490-540 ppmv CO_2-eq. Note that some models do not consider mitigation through forest sink enhancement (AIM and IPAC) or CCS (AIM) and that the share of low-carbon energy options in total energy supply is also determined by inclusion of these options in the baseline. CCS includes carbon capture and storage from biomass. Forest sinks include reducing emissions from deforestation.*

Data source: Van Vuuren et al. (2007); Riahi et al. (2006); Hijioka, et al. (2006); Masui et al. (2006); Jiang et al. (2006).

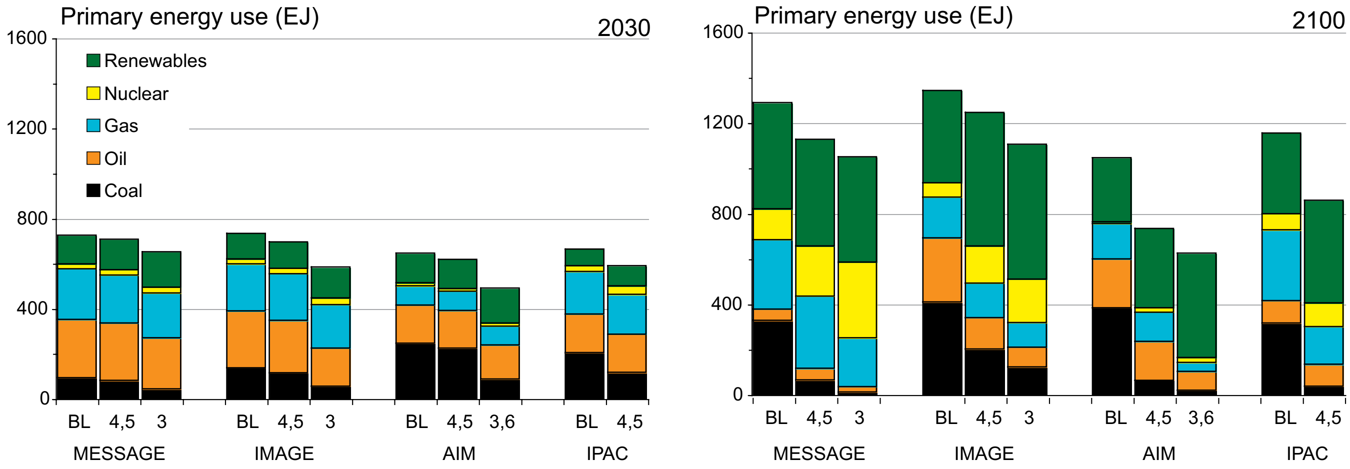

Figure 3.24: *Primary energy mix for the years 2030 and 2100. Illustrative scenarios aim at stabilizing radiative forcing at low (3–3.6 W/m^2) and intermediate levels (4.5 W/m2) respectively.*

Note: BL= Baseline. For the corresponding contribution of individual mitigation measures in (in $GtCO_2$) see also Figure 3.23.

models usually report the increase in energy system costs or the net present value (NPV) of the abatement costs. A common cost indicator is also the marginal cost/price of emissions reduction (US$/tC or US$/tCO_2).

Figure 3.25 shows the relationship between stabilization targets and alternative measures of mitigation costs, comprising GDP losses, net present value of abatement, and carbon price in terms of US$ /tCO_2-eq.

It is important to note that for the following reported cost estimates, the vast majority of the models assume transparent markets, no transaction costs, and thus perfect implementation of policy measures throughout the 21st century, leading to the universal adoption of cost-effective mitigation measures, such as carbon taxes or universal cap and trade programmes. These assumptions generally result in equal carbon prices across all regions and countries equivalent to global, least-cost estimates. Relaxation of these modelling assumptions, alone or in combination (e.g. mitigation-only in Annex I countries, no emissions trading, or CO_2-only mitigation), will lead to an appreciable increase in all cost categories.

The grey shaded area in Figure 3.25 illustrates the 10th–90th percentile of the mitigation cost ranges of recent studies, including the TAR. The area includes only those recent scenarios in the literature that report cost estimates based on a comprehensive mitigation analysis, defined as those that have a sufficiently wide portfolio of mitigation measures.[11] The selection was made on a case-by-case basis for each scenario considered in this assessment. The Figure also shows results from selected illustrative studies (coloured lines). These studies report costs for a range of stabilization targets and are representative of the overall cost dynamics of the full set of scenarios. They show cases with high-, intermediate- and low-cost estimates (sometimes exceeding the 80th (i.e. 10th–90th) percentile range on the upper and lower boundaries of the grey-shaded area). The colour coding is used to distinguish between individual mitigation studies that are based on similar baseline assumptions. Generally, mitigation costs (for comparable stabilization targets) are higher from baseline scenarios with relatively high baseline emissions (brown and red lines). By the same token, intermediate or low baseline assumptions result in relatively lower cost estimates (blue and green lines).

Figure 3.25a shows that the majority of studies find that GDP losses increase with the stringency of the target, even though there is considerable uncertainty with respect to the range of losses. Barker *et al*. (2006) found that, after allowing for baseline emissions, the differences can be explained by:

- The spread of assumptions in modelling-induced technical change.
- The use of revenues from taxes and permit auctions.
- The use of flexibility mechanisms (i.e. emissions trading, multi-gas mitigation, and banking).
- The use of backstop technologies.
- Allowing for climate policy related co-benefits.
- Other specific modelling assumptions.

Weyant (2000) lists similar factors but also includes the number and type of technologies covered, and the possible substitution between cost factors (elasticities). A limited set of studies finds negative GDP losses (economic gains) that arise from the assumption that a model's baseline is assumed to be a non-optimal pathway and incorporates market imperfections. In these models, climate policies steer economies in the direction

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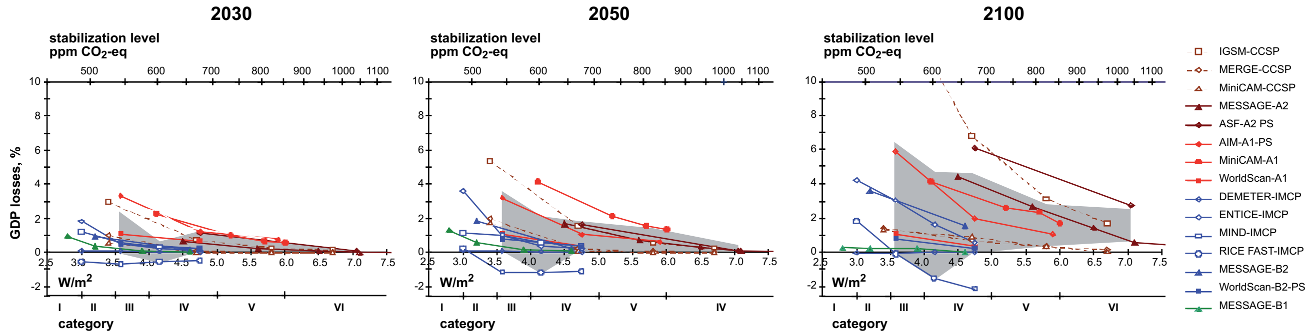
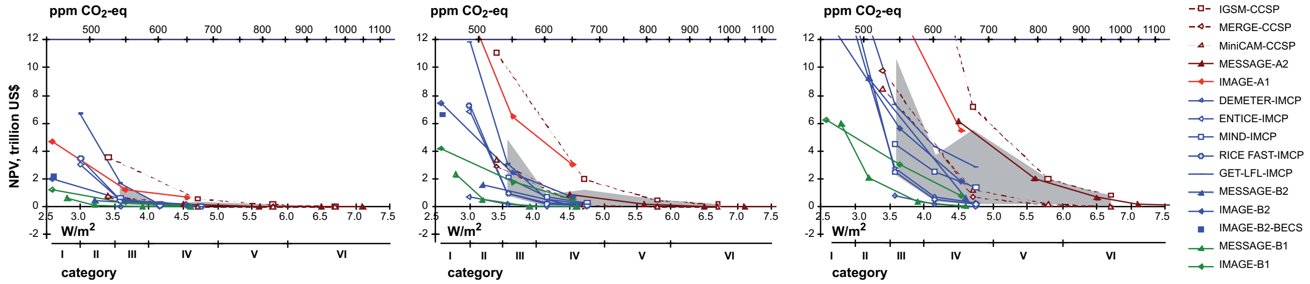
[11] The assessment of mitigation costs excludes stabilization scenarios that assume major limitation of the mitigation portfolio. For example, our assessment of costs does not include stabilization scenarios that exclude non-CO_2 mitigation options for achieving multi-gas targets (for cost implications of CO2-only mitigation see also Section 3.3.5.4). The assessment nevertheless includes CO_2 stabilization scenarios that focus on single-gas stabilization of CO_2 concentrations. The relationship between the stabilization metrics given in Figure 3.16 is used to achieve comparability of multi-gas and CO_2 stabilization scenarios.

a) Selected studies reporting GDP losses



b) Selected studies reporting abatement costs (NPV)



c) Selected studies reporting carbon prices

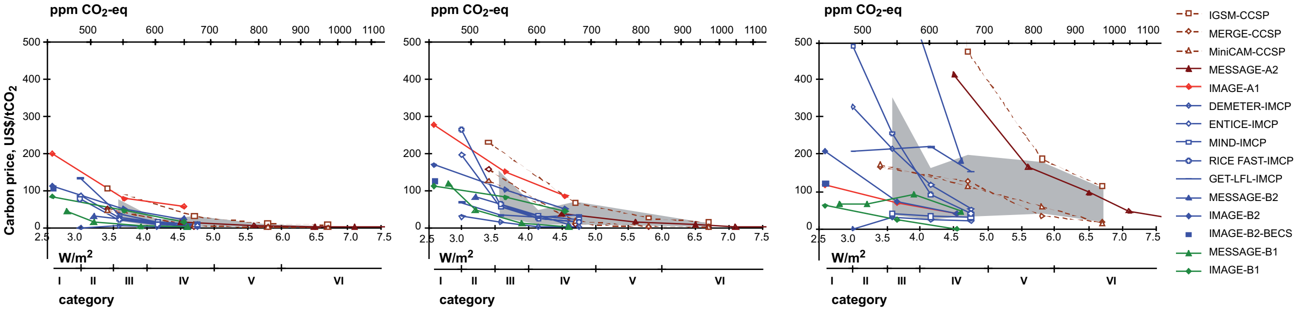


Figure 3.25: *Figure 3.25 Relationship between the cost of mitigation and long-term stabilization targets (radiative forcing compared to pre-industrial level, W/m^2 and CO$_2$-eq concentrations).*

Notes: These panels show costs measured as a % loss of GDP (top), net present value of cumulative abatement costs (middle), and carbon price (bottom). The left-hand panels give costs for 2030, the middle panel for 2050, and the right-hand panel for 2100 repectively. Individual coloured lines denote selected studies with representative cost dynamics from very high to very low cost estimates. Scenarios from models sharing similar baseline assumptions are shown in the same colour. The grey-shaded range represents the 80th percentile of the TAR and post-TAR scenarios. NPV calculations are based on a discount rate of 5%. Solid lines show representative scenarios considering all radiatively active gases. CO_2 stabilization scenarios are added based on the relationship between CO_2 concentration and the radiative forcing targets shown in Figure 3.16. Dashed lines represent multi-gas scenarios, where the target is defined by the six Kyoto gases (other multi-gas scenarios consider all radiatively active gases).

Data sources: CCSP scenarios (USCCSP, 2006); IMCP scenarios (Edenhofer et al., 2006); Post-SRES (PS) scenarios (Morita et al., 2001); Azar et al., 2006; Riahi et al., 2006; Van Vuuren et al., 2007.

of reducing these imperfections, for example by promoting more investment into research and development and thus achieving higher productivity, promoting higher employment rates, or removing distortionary taxes.

The left-hand side panel of Figure 3.25a shows that for 2030, GDP losses in the vast majority of the studies (more than 90% of the scenarios) are generally below 1% for the target categories V and VI. Also in the majority of the category III and IV scenarios (70% of the scenarios) GDP losses are below 1%. However, it is important to note that for categories III and IV costs are higher, on average, and show a wider range than those for categories V and VI. For instance, for category IV the interval lying between the 10th and 90th percentile varies from about 0.6% gain to about 1.2% loss. For category III, this range is shifted upwards (0.2–2.5%). This is also indicated by the median GDP losses by 2030, which increases from below 0.2% for categories V and VI, to about 0.2% for the category IV scenarios, and to about 0.6% for category III scenarios. GDP losses of the lowest stabilization categories (I & II) are generally below 3% by 2030, however the number of studies are relatively limited and in these scenarios stabilization is achieved predominantly from low baselines. The absolute GDP losses by 2030 correspond on average to a reduction of the *annual* GDP growth rate of less than 0.06 percentage points for the scenarios of category IV, and less than 0.1 and 0.12 percentage points for the categories III and I&II, respectively.

GDP losses by 2050 (middle panel of Figure 3.25a) are comparatively higher than the estimates for 2030. For example, for category IV scenarios the range is between -1% and 2% GDP loss compared to baseline (median 0.5%), and for category III scenarios the range is from slightly negative to 4% (median 1.3%). The Stern review (2006), looking at the costs of stabilization in 2050 for a comparable category (500–550 CO_2-eq) found a similar range of between -2% and +5%. For the studies that also explore different baselines (in addition to multiple stabilization levels), Figure 3.25a also shows that high emission baselines (e.g. high SRES-A1 or A2 baselines) tend to lead to higher costs. However, the uncertainty range across the models is at least of a similar magnitude. Generally, models that combine assumptions of very slow or incremental technological change with high baseline emissions (e.g. IGSM-CCSP) tend to show the relatively highest costs (Figure 3.25a). GDP losses of the lowest stabilization categories (I & II) are generally below 5.5% by 2050, however the number of studies are relatively limited and in these scenarios stabilization is achieved predominantly from low baselines. The absolute GDP losses numbers for 2050 reported above correspond on average to a reduction of the *annual* GDP growth rate of less than 0.05 percentage points for the scenarios of category IV, and less than 0.1 and 0.12 percentage points for the categories III and I&II, respectively.

Finally, the most right-hand side panel of Figure 3.25a shows that GDP losses show a bigger spread and tend to be somewhat higher by 2100. GDP losses are between 0.3% and 3% for category V scenarios and -1.6% to about 5% for category IV scenarios. Highest costs are given by category III (from slightly negative costs up to 6.5%). The sample size for category I is not large enough for a statistical analysis. Similarly, for category II scenarios, the range is not shown as the stabilization scenarios of category II are predominantly based on low or intermediate baselines, and thus the resulting range would not be comparable to those from the other stabilization categories. However, individual studies indicate that costs become higher for more stringent targets (see, for example, studies highlighted in green and blue for the lowest stabilization categories in Figure 3.25a).[12]

The results for the net present value of cumulative abatement costs show a similar picture (Figure 3.25b). However, given the fact that abatement costs only capture direct costs, this cost estimate is by definition more certain.[13] The interval from the 10th to the 90th percentile in 2100 ranges from nearly zero to about 11 trillion US$. The highest level corresponds to around 2–3% of the NPV of global GDP over the same period. Again, on the basis of comparison across models, it is clear that costs depend both on the stabilization level and baseline emissions. In general, the spread of costs for each stabilization category seems to be of a similar order to the differences across stabilization scenarios from different baselines. In 2030, the interval covering 80% of the NPV estimates runs from around 0–0.3 trillion for category IV scenarios. The majority of the more stringent (category III) scenarios range between 0.2 to about 1.6 trillion US$. In 2050, typical numbers for category IV are around 0.1–1.2 trillion US$ and, for category III, this is 1–5 trillion US$ (or below about 1% of the NPV of GDP). By 2100 the NPV estimates increase further, with the range up to 5 trillion for category IV scenarios and up to 11 trillion for category III scenarios, respectively. The results of these studies, published since the TAR, are consistent with the numbers presented in the TAR, although the new studies extend results to substantially lower stabilization levels.

Finally, a similar trend is found for carbon price estimates. In 2030, typical carbon prices across the range of models and baselines for a 4.5 W/m^2 stabilization target (category IV) range from around 1–24 US$/$tCO_2$ (80% of estimates), with the median of about 11 US$/$tCO_2$. For category III, the corresponding prices are somewhat higher and range from 18–79 US$/$tCO_2$ (with the median of the scenarios around 45 US$/$tCO_2$). Most individual studies for the most stringent category cluster around prices of about 100 US$/$tCO_2$.[14] Carbon prices by 2050 are comparatively higher than those in 2030. For example, costs of category IV scenarios by 2050 range between 5 and 65 US$/$tCO_2$, and those for category III range between 30 and 155 US$/$tCO_2$. Carbon prices in 2100 vary over a much wider range – mostly reflecting uncertainty in baseline emissions and technology development. For the medium target of 4.5 W/m^2, typical carbon prices in 2100 range from 25–200 US$/$tCO_2$ (80% of estimates). This is primarily a consequence of the nature of this metric, which often represents costs at the margin. Costs tend to slowly increase for more stringent targets – with a range between the 10th and 90th percentile of more than 35 to about 350 US$/$tCO_2$ for category III.

3.3.5.4 *The role of non-CO_2 GHGs*

As also illustrated by the scenario assessment in the previous sections, more and more attention has been paid since the TAR to incorporating non-CO_2 gases into climate mitigation and stabilization analyses. As a result, there is now a body of literature (e.g. Van Vuuren *et al*., 2006b; De la Chesnaye and Weyant, 2006; De la Chesnaye *et al*., 2007) showing that mitigation costs for these sectors can be lower than for energy-

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[12] If not otherwise mentioned, the discussion of the cost ranges (Figure 3.25) refers to the 80th percentile of the TAR and post-TAR scenario distribution (see the grey area in Figure 3.25).

[13] NPV calculations are based on carbon tax projections of the scenarios, using a discount rate of 5%, and assuming that the average cost of abatement would be half the marginal price of carbon. Some studies report abatement costs themselves, but for consistency this data was not used. The assumption of using half the marginal price of carbon results in a slight overestimation.

[14] Note that the scenarios of the lowest stabilization categories (I and II) are mainly based on intermediate and low baseline scenarios.

related CO_2 sectors. As a result, when all these options are employed in a multi-gas 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. While the previous sections have focused on the joint assessment of CO_2 and multi-gas mitigation scenarios, this section explores the specific role of non-CO_2 emitting sectors.[15]

A number of parallel numerical experiments have been carried out by the Energy Modelling Forum (EMF-21; De la Chesnaye and Weyant, 2006). The overall conclusion is that economic benefits of multi-gas strategies are robust across all models. This is even true, despite the fact that different methods were used in the study to compare the relative contribution of these gases in climate forcing (see Section 3.3.3). The EMF-21 study specifically focused on comparing stabilization scenarios aiming for 4.5 W/m^2 compared to pre-industrial levels. There were two cases 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).
2. Mitigate all available GHG in costs-effective approaches using full 'what' flexibility.

In the CO_2-only mitigation scenario, all models significantly reduced CO_2 emissions, on average by about 75% in 2100 compared to baseline scenarios. Models still indicated some emission reductions for CH_4 and N_2O as a result of systemic changes in the energy system. Emissions of CH_4 were reduced by about 20% and N_2O by about 10% (Figure 3.26).

In the multi-gas mitigation scenario, all models found that 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 therefore drops (on average) from 75% to 67%. This percentage is still rather high, caused by the large share of CO_2 in total emissions (on average, 60% in 2100) and partly due to the exhaustion of reduction options for non-CO_2 gases. The reductions of CH_4 across the different models averages around 50%, 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%). 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%) 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. 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 increased flexibility of a multi-gas 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 multi-gas mitigation is significantly cheaper than CO_2-only. The potential reductions of the GHG price ranges in the majority of the studies between 30% and 85% (See Figure 3.27).

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). For long-term scenarios (and more stringent targets) in particular, 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*. (2007).

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 4, 8, and 9 of this report for discussions of detailed land-related mitigation alternatives). Available information before the TAR suggested that land has the technical potential to sequester up to an additional 319 billion tonnes of CO_2 ($GtCO_2$) by 2050 in global forests alone (IPCC, 1996a; IPCC, 2000; IPCC, 2001a). In addition, current technologies are capable of substantially reducing CH_4 and N_2O emissions from agriculture (see Chapter 8). A number of global biomass energy potential assessments have also been conducted (see Berndes *et al*. 2003 for an overview).[16]

The explicit modelling 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 the Special Report on Land use, Land-use Change, and Forestry (IPCC, 2000) or the TAR. This section assesses the modelling 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.

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[15] Note that the multi-gas stabilization scenarios, which consider only CO_2 abatement options (discussed in this section), are not considered in the overall mitigation cost assessment of Section 3.3.5.3.

[16] Most of the assessments are conducted with large regional spatial resolutions; exceptions are Fischer and Schrattenholzer (2001), Sørensen (1999), and Hoogwijk *et al*. (2005).

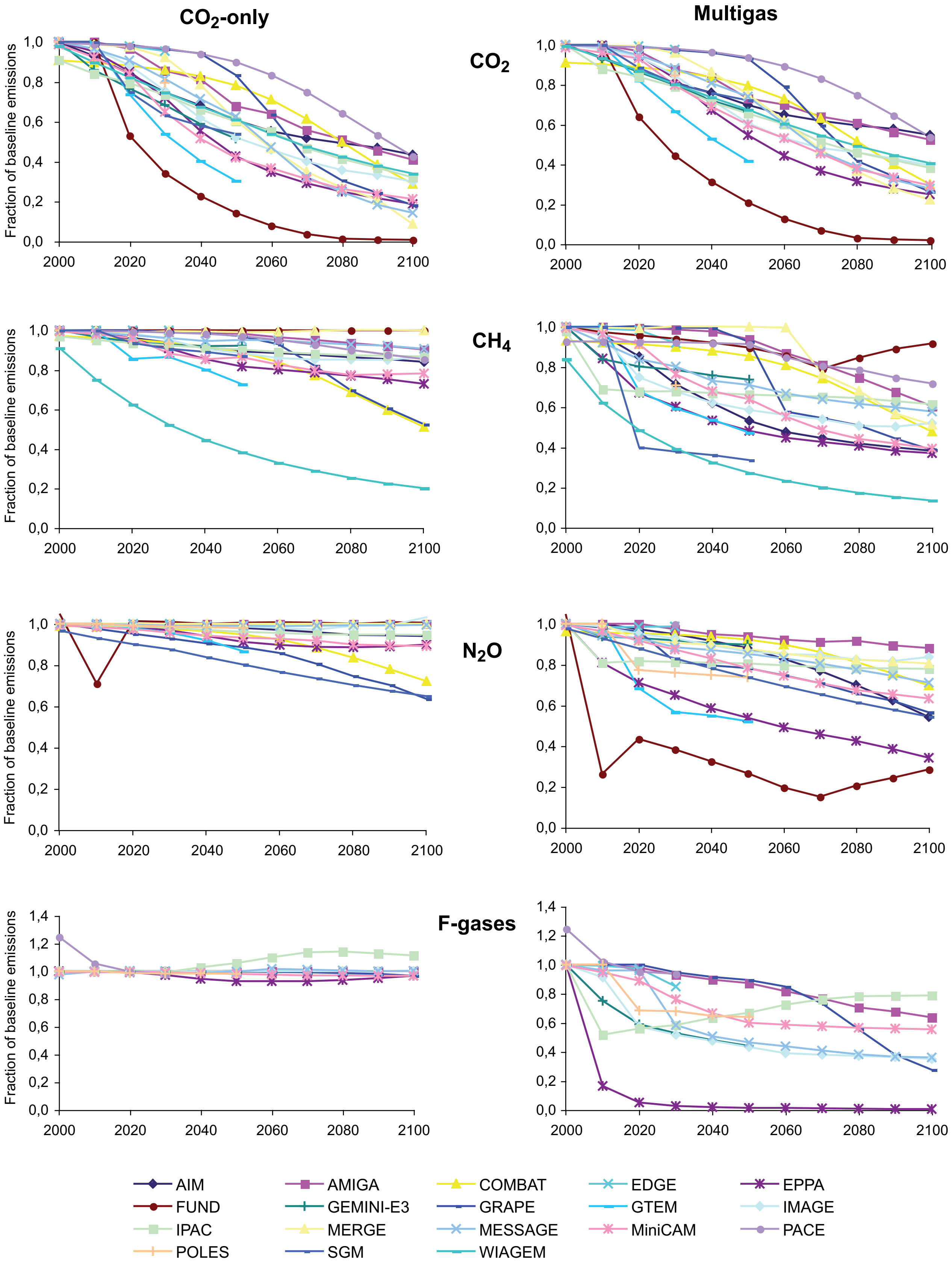

Figure 3.26: *Reduction of emissions in the CO$_2$-only versus multi-gas strategies.*

Source: De la Chesnaye and Weyant, 2006 (see also Van Vuuren et al., 2006b)

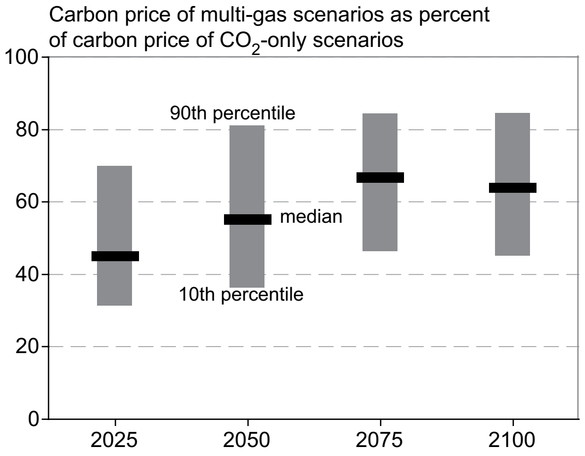

Figure 3.27: *Reduction in GHG abatement price (%) in multi-gas stabilization scenarios compared to CO_2-only cases. Ranges correspond to alternative scenarios for a stabilization target of 4.5 W/m^2.*

Data source: De la Chesnaye and Weyant, 2006

Development of, among other things, global sectoral land mitigation models (e.g. Sohngen and Sedjo, 2006), bottom-up agricultural mitigation costs for specific technologies (e.g. USEPA, 2006b), and biomass technical potential studies (e.g. Hoogwijk *et al*., 2005) has facilitated the formal incorporation of land mitigation in long-term integrated assessment of climate change stabilization strategies. 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 20% of 2001 total energy demand). Sands and Leimbach (2003) conducted one of the first studies 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; De la Chesnaye and Weyant, 2006) was the first coordinated stabilization modelling effort to include an explicit evaluation of the relative role of land in stabilization; however, only a few models participated. Building on their EMF-21 efforts, some modelling teams have also generated even more recent stabilization scenarios with revised land modelling. These studies are conspicuously different in the specifics of their modelling of land and land-based mitigation (Rose *et al*., 2007). Differences in the types of land considered, emissions sources, and mitigation alternatives and implementation imply different opportunities and opportunity costs for land-related mitigation; and, therefore, different outcomes.

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 (Kurosawa, 2006; Van Vuuren *et al*., 2006a; Rao and Riahi, 2006; Jakeman and Fisher, 2006). Jakeman and Fisher (2006), 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 stabilization was reduced to 2.3% at 2050 (3.4 trillion US$), versus losses of around 7.1% (10.6 trillion US$) and 3.3% (4.9 trillion US$) for the CO_2-only and multi-gas scenarios, respectively.[17] 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 (discussed below), 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 on the economic cost of stabilization. Notably, strategies for increasing cropland soil carbon have not been incorporated to date into this class of models (see Chapter 8 for an estimate of the short-term potential for enhancing agricultural soil carbon).

Figure 3.28 presents the projected mitigation from forestry, agriculture, and biomass for the EMF-21 4.5 W/m^2 stabilization scenarios, as well as additional scenarios produced by the MESSAGE and IMAGE models – an approximate 3 W/m^2 scenario from Rao and Riahi (2006), a 4.5 W/m^2 scenario from Riahi *et al*. (2006), and approximately 4.5, 3.7, and 2.9 W/m^2 scenarios from Van Vuuren *et al*. (2007) (see Rose *et al*., 2007, for a synthesis). While there are clearly different land-based mitigation pathways being taken across models for the same stabilization target, and across targets with the same model and assumptions, some general observations can be made. First, forestry, agriculture, and biomass are called upon to provide significant cost-effective mitigation contributions (Rose *et al*., 2007). In the short-term (2000–2030), forest, agriculture, and biomass together could account for cumulative abatement of 10–65 $GtCO_2$-eq, with 15–60% of the total abatement considered by the available studies, and forest/agricultural non-CO_2 abatement providing at least three quarters of total land abatement.[18] Over the entire century (2000–2100), cumulative land-based abatement of approximately 345–1260 $GtCO_2$-eq is estimated to be cost-effective, accounting for 15–40% of total cumulative abatement. Forestry, agriculture, and biomass abatement levels are each projected to grow annually with relatively stable annual increases in agricultural mitigation and gradual deployment of biomass mitigation, which accelerates dramatically in the last half of the century to become the dominant land-mitigation strategy.

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[17] All values here are given in constant US dollars at 2000 prices.

[18] The high percentage arises because some scenarios project that the required overall abatement from 2000–2030 is modest, and forestry and agricultural abatement options cost-effectively provide the majority of abatement.

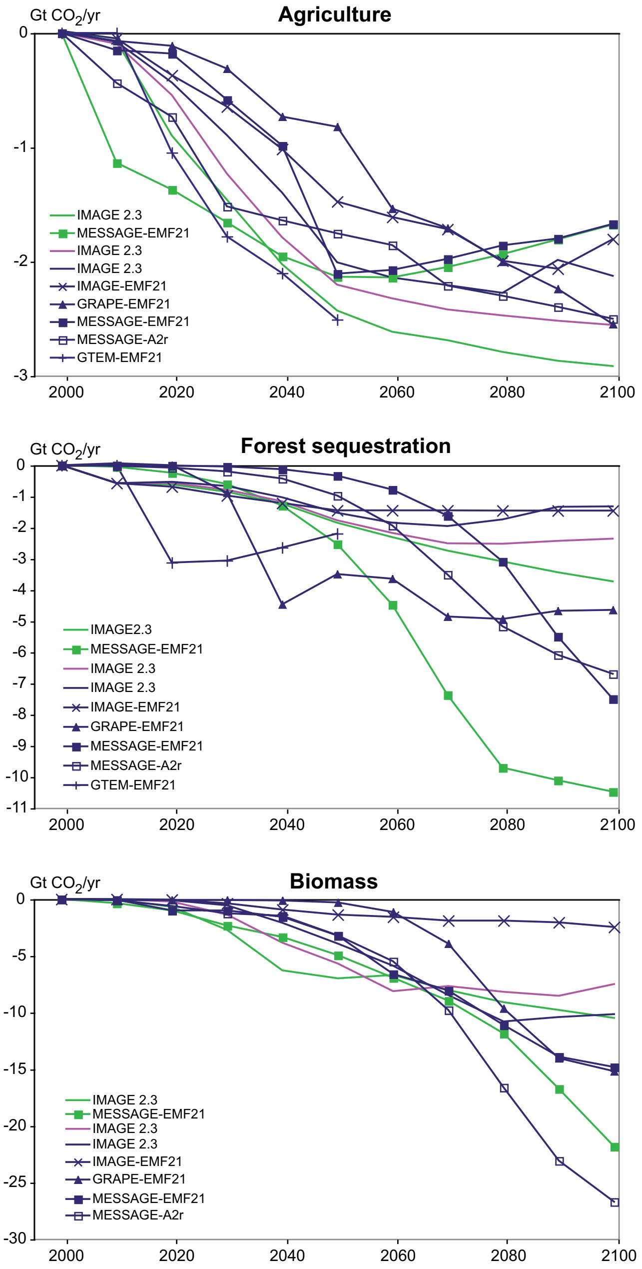

Figure 3.28: *Cost-effective agriculture, forest, and commercial biomass annual greenhouse gas emissions abatement from baselines from various 2100 stabilization scenarios (note y-axes have different ranges).*

Notes: The colour of the line indicates the 2100 stabilization target modelled: green < 3.25 W/m^2 (< 420 CO$_2$ concentration, < 510 CO$_2$-eq concentration), pink 3.25–4 (42–490, 510–590), and dark blue 4–5 (490–570, 59–710). The IMAGE-EMF21 and IMAGE 2.3 forest results are net of deforestation carbon losses induced by bio-energy crop extensification. These carbon losses are accounted for under forestry by the other scenarios. The MESSAGE-EMF21 results are taken from the sensitivity analysis of Rao and Riahi (2006). The GTEM-EMF21 scenarios ran through 2050 and the GTEM agriculture mitigation results include fossil fuel emissions reductions in agriculture (5-7% of the annual agricultural abatement). Scenario references: IMAGE-EMF21 (Van Vuuren *et al*., 2006a); MESSAGE-EMF21 (Rao and Riahi, 2006); MESSAGE-A2r (Riahi *et al*., 2006); GRAPE-EMF21 (Kurosawa, 2006); GTEM-EMF21 (Jakeman and Fisher, 2006); and IMAGE 2.3 (Van Vuuren *et al*., 2007).

Source: Rose et al. (2007)

Figures 3.28 and 3.29 show that additional land-based abatement is expected to be cost-effective with tighter stabilization targets and/or higher baseline emissions (e.g. see the IMAGE 2.3 results for various stabilization targets and the MESSAGE 4.5 W/m^2 stabilization results with B2 (EMF-21) and A2r baselines). Biomass is largely responsible for the additional abatement; however, agricultural and forestry abatement are also expected to increase. How they might increase is model and time dependent. In general, the overall mitigation role of agricultural abatement of rice methane, livestock methane, nitrous oxide (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.

However, there are substantial uncertainties. There is little agreement about the magnitudes of abatement (Figures 3.28 and 3.29). The scenarios disagree about the role of agricultural strategies targeting CH$_4$ versus N$_2$O, as well as the timing and annual growth of forestry abatement, with some scenarios suggesting substantial early deployment of forest abatement, while others suggest gradual annual growth or increasing annual growth.

A number of the recent scenarios suggest that biomass energy alternatives could be essential for stabilization, especially as a mitigation strategy that combines the terrestrial sequestration mitigation benefits associated with bio-energy CO$_2$ capture and storage (BECCS), where CO$_2$ emissions are captured during biomass energy combustion for storage in geologic formations (e.g. Rao and Riahi, 2006; Riahi *et al*., 2006; Kurosawa, 2006; Van Vuuren *et al*., 2007; USCCSP, 2006). BECCS has also been suggested as a potential rapid-response prevention strategy for abrupt climate change. Across stabilization scenarios, absolute emissions reductions from biomass are projected to grow slowly in the first half of the century, and then rapidly in the second half, as new biomass processing and mitigation technologies become available. Figure 3.28 suggests biomass mitigation of up to 7 GtCO$_2$/yr in 2050 and 27 GtCO$_2$/yr in 2100, for cumulative abatement over the century of 115–749 GtCO$_2$ (Figure 3.29). Figure 3.30 shows the amount of commercial biomass primary energy utilized in various stabilization scenarios. For example, in 2050, the additional biomass energy provides approximately 5–55 EJ for a 2100 stabilization target of 4–5 W/m^2 and approximately 40–115 EJ for 3.25–4 W/m^2, accounting for about 0–10 and 5–20% of 2050 total primary energy respectively (USCCSP, 2006; Rose *et al*., 2007). Over the century, the additional bio-energy accounts for 500–6,700 EJ for targets of 4–5 W/m^2 and 6100–8000 EJ for targets of 3.25–4 W/m^2 (1–9% and 9–13% of total primary energy, respectively).

More biomass energy is supplied with tighter stabilization targets, but how much is required for any particular target depends on the confluence of the many different modelling assumptions. Modelled demands for biomass include electric power and end-use sectors (transportation, buildings, industry, and non-energy uses). Current scenarios suggest that electric power is

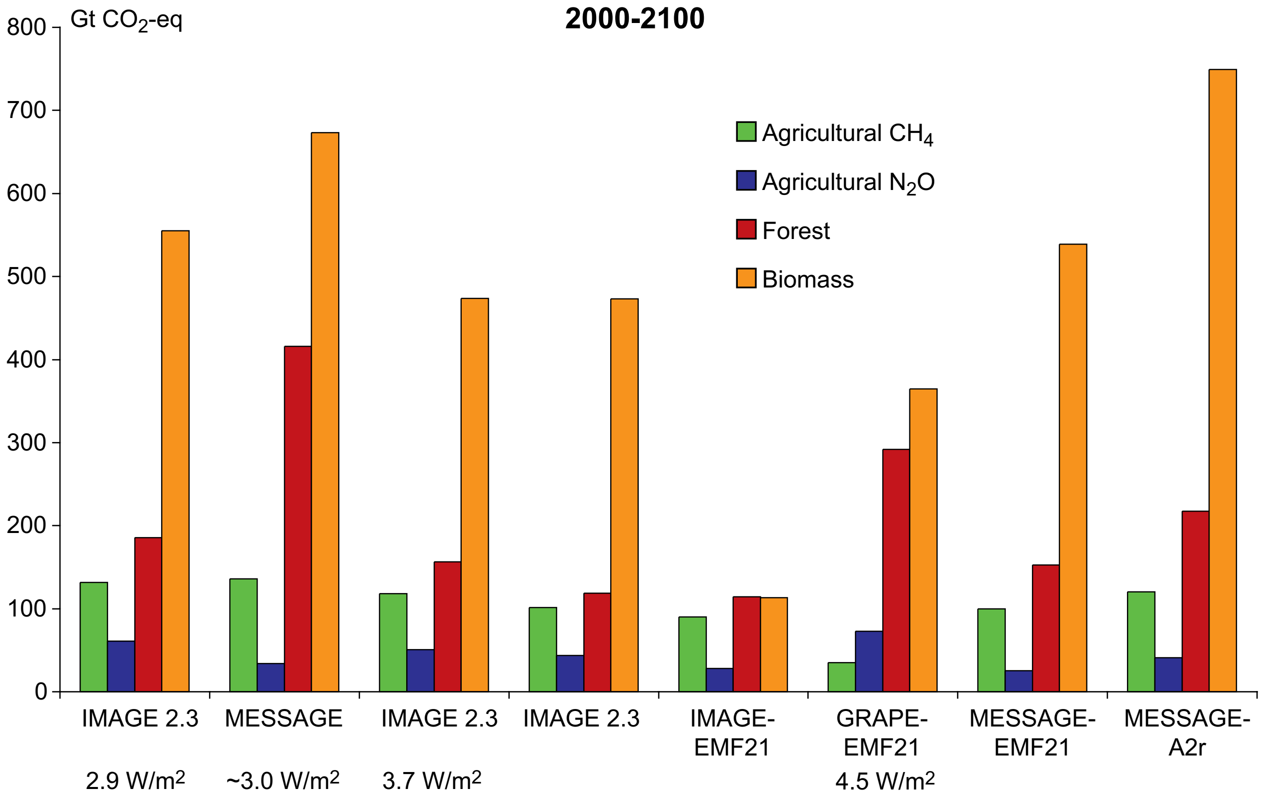

Figure 3.29: *Cumulative cost-effective agricultural, forestry, and biomass abatement 2000–2100 from various 2100 stabilization scenarios.*

Source: Rose et al. (2007)

projected to dominate biomass demand in the initial decades and, in general, with less stringent stabilization targets. Later in the century (and for more stringent targets) transportation is projected to dominate biomass use. When biomass is combined with BECCS, biomass mitigation shifts to the power sector late in the century, to take advantage of the net negative emissions from the combined abatement option, such that BECCS could represent a signifant share of cumulative biomass abatement over the century (e.g. 30–50% of total biomass abatement from MESSAGE in Figure 3.29).

To date, detailed analyses of large-scale biomass conversion with CO_2 capture and storage is scarce. As a result, current integrated assessment BECCS scenarios are based on a limited and uncertain understanding of the technology. In general, further research is necessary to characterize biomass' long-term mitigation potential, especially in terms of land area and water requirements, constraints, and opportunity costs, infrastructure possibilities, cost estimates (collection, transportation, and processing), conversion and end-use technologies, 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).

Terrestrial mitigation projections are expected to be regionally unique, while still linked across time and space by changes in global physical and economic forces. For example, Rao and Riahi (2006) offer intuitive results on the potential role of agricultural methane and nitrous oxide mitigation across industrialized and developing country groups, finding that agriculture is expected to form a larger share of the developing countries' total mitigation portfolio; and, developing countries

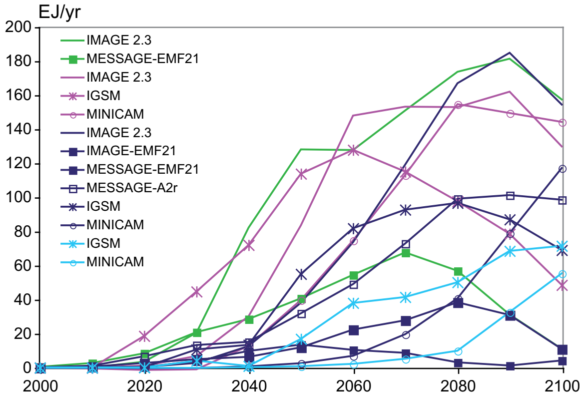

Figure 3.30: *Commercial biomass primary energy scenarios above baseline from various 2100 stabilization scenarios.*

Notes: The colour of the line indicates the 2100 stabilization target modelled: green < 3.25 W/m^2 (< 420 CO_2 concentration, < 510 CO_2-eq concentration), pink 3.25–4 (420–490, 510–590), dark blue 4–5 (490–570, 590–710), and light blue 5–6 (570–660, 710–860). Scenario references: IMAGE-EMF21 (Van Vuuren *et al*., 2006a); MESSAGE-EMF21 (Rao and Riahi, 2006); MESSAGE-A2r (Riahi *et al*., 2006); IMAGE 2.3 (Van Vuuren *et al*., 2007); IGSM and MiniCAM (USCCSP, 2006).

Source: Rose et al. (2007) ; USCCSP (2006) are likely to provide the vast majority of global agricultural mitigation. Some aggregate regional forest mitigation results also are discussed below. However, given the paucity of published regional results from integrated assessment models, it is currently not possible to assess the regional land-use abatement potential in stabilization. Future research should direct attention to this issue in order to more fully characterize mitigation potential.

In addition to the stabilization scenarios discussed thus far from integrated assessment and climate economic models, the literature includes long-term mitigation scenarios from global land sector economic models (e.g. Sohngen and Sedjo, 2006; Sathaye *et al*., 2006; Sands and Leimbach, 2003). Therefore, a comparison is prudent. The sectoral models use exogenous carbon price paths to simulate different climate policies and assumptions. It is possible to compare the stabilization and sectoral scenarios using these carbon price paths. Stabilization (e.g. EMF-21, discussed above) and 'optimal' (e.g. Sohngen and Mendelsohn, 2003) climate abatement policies suggest that carbon prices will rise over time.[19] Table 3.6 compares the forest mitigation outcomes from stabilization and sectoral scenarios that have similar carbon price trajectories (Rose *et al*., 2007).[20] Rising carbon prices will provide incentives for additional forest area, longer rotations, and more intensive management to increase carbon storage. Higher effective energy prices might also encourage shorter rotations for joint production of forest bioenergy feedstocks.

Table 3.6 shows that the vast majority of forest mitigation is projected to occur in the second half of the century, with tropical regions in all but one scenario in Table 3.6 assuming a larger share of global forest sequestration/mitigation than temperate regions. The IMAGE results from EMF-21 are discussed separately below. Lower initial carbon prices 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 current stabilization scenarios model more limited and aggregated forestry GHG abatement technologies that do not distinguish the detailed responses seen in the sectoral models.

The sectoral models, in particular, Sohngen and Sedjo (2006), suggest substantially more mitigation in the second half of the century compared to the stabilization scenarios. 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 modelling 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:

(i) Their explicit consideration of competing mitigation alternatives across all sectors and regions, and, in some cases, land-use alternatives.
(ii) Their more limited set of forest-related abatement options, with all integrated assessment models modelling afforestation strategies, but only some considering avoided deforestation, and none modelling forest management options at this point.
(iii) Some integrated assessment models (including those in Table 3.6) sequentially allocate land, satisfying population food and feed-demand growth requirements first.
(iv) Climate feedbacks in integrated assessment models can lead to terrestrial carbon losses relative to the baseline.

The IMAGE results in Table 3.6 provide a dramatic illustration of the potential implications and importance of some of these counterbalancing effects. Despite the planting of additional forest plantations in the IMAGE scenario, net tropical forest carbon stocks decline (relative to the baseline) due to deforestation induced by bioenergy crop extensification, as well as reduced CO_2 fertilization that affects forest carbon uptake, especially in tropical forests, and decreases crop productivity, where the latter effect induces greater expansion of food crops onto fallow lands, thereby displacing stored carbon.

In addition to reducing uncertainty about the maginitude and timing of land-based mitigation, biomass potential, and regional potential, 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 (Betts, 2000; Schaeffer *et al*., 2006), 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 should also be considered. As shown in the Millennium Ecosystem Assessment (Carpenter *et al*., 2005), land use has implications for social welfare (e.g. food security, clean water access), environmental services (water quality, soil retention), and economic welfare (output prices and production).

A number of relevant key baseline land modelling challenges have already been discussed in Sections 3.2.1.6 and 3.2.2.2. Central to future long-term land mitigation modelling are

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[19] Optimal is defined in economic terms as the equating of the marginal benefits and costs of abatement.

[20] Rose *et al*. (2007) report the carbon price paths from numerous stabilization and sectoral mitigation scenarios.

Table 3.6: *Cumulative forest carbon stock gains above baseline by 2020, 2050 and 2100, from long-term global forestry and stabilization scenarios (GtCO$_2$).*

US$2.73/tCO$_2$ (in 2010) + 5% per year				
		2020	*2050*	*2100*
Sathaye *et al*., (2006)	World	na	91.3	353.8
	Temperate	na	25.3	118.8
	Tropics	na	55.1	242.0
Sohngen and Sedjo (2006) original baseline	World	0.0	22.7	537.5
	Temperate	3.3	8.1	207.9
	Tropics	-3.3	14.7	329.6
Sohngen and Sedjo (2006) accelerated deforestation baseline	World	1.5	15.0	487.3
	Temperate	1.1	12.1	212.7
	Tropics	0.7	2.9	275.0
Stabilization at 4.5 W/m^2 (~650 CO$_2$-eq ppmv) by 2100				
		2020	*2050*	*2100*
GRAPE-EMF21	World	-0.6	70.3	291.9
	Temperate	-0.2	10.0	45.2
	Tropics	-0.5	60.3	246.7
IMAGE-EMF21	World	-22.5	-13.4	10.4
	Temperate	14.1	31.9	78.3
	Tropics	-36.6	-45.3	-67.9
MESSAGE-EMF21*	World	0.0	3.5	152.5
	Temperate	0.0	0.1	23.4
	Tropics	0.0	3.4	129.1

Notes: * Results based on the 4.5 W/m^2 MESSAGE scenario from the sensitivity analysis of Rao and Riahi (2006).
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.
Source: Stabilization data assembled from Rose et al. (2007)

improvements in the dynamic modelling of regional land use and land-use competition and mitigation cost estimates, as well as modelling of the implications of climate change for land-use and land mitigation opportunities. 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 biophysical and economic circumstances. In addition, the results presented in this section do not consider climate shifts that could dramatically alter land-use conditions, such as a permanent El-Nino-like state in tropical regions (Cox *et al*., 1999).

To summarize, recent stabilization studies have found that land-use mitigation options (both non-CO$_2$ and CO$_2$) provide cost-effective abatement flexibility in achieving 2100 stabilization targets, in the order of 345–1260 GtCO$_2$-eq (15–40%) of cumulative abatement over the century. In some scenarios, increased commercial biomass energy (solid and liquid fuel) is significant in stabilization, providing 115–749 GtCO$_2$-eq (5–30%) of cumulative abatement and 500–9500 EJ of additional bio-energy above the baseline over the century (potentially 1–15% of total primary energy), especially as a net negative emissions strategy that combines biomass energy with CO$_2$ capture and storage. Agriculture and forestry mitigation options are projected to be cost effective short-term and long-term abatement strategies. 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. Overall, the explicit modelling of land-based climate change mitigation in long-term global scenarios is relatively immature, with 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 on the implications of climate mitigation for air pollutants such as SO$_2$, NO$_x$, CO, VOC (volatile organic compounds), BC (black carbon) and OC (organic carbon), are relatively scarce. 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, 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 of future policies and technological change in the baseline against which they are measured, as discussed in Morgenstern (2000). For example, Smith *et al*. (2005) and Rao *et al*. (2005) assume an overall growth in environmental awareness and formulation of new environmental policies with increased affluence in the baseline scenario, and thus reduced air pollution, even in the absence of any climate policies. 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 emission-control technologies reduce both air pollutants and greenhouse gases, such as selective catalytic reduction (SCR) on gas boilers, which 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, substituting more fuel-efficient diesel engines for petrol 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 (2002) and Mayerhofer *et al*. (2002) assess in detail the linkages between regional air pollution and climate change in Europe. They emphasize important co-benefits between climate policy and air pollution control but also indicate that, depending on assumptions, air pollution policies in Europe will play a greater role in air pollutant reductions than climate policy. Smith and Wigley (2006) suggest that there will be a slight reduction in global sulphur aerosols as a result of long-term multi-gas climate stabilization. Rao *et al*. (2005) and Smith and Wigley (2006) 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% for SO_2 and around 50% for NO_x when combined with GHG policies. Similarly, in the shorter-term, Van Vuuren *et al*. (2006c) find that for the Kyoto Protocol, about half the costs of climate policy might be recovered from reduced air pollution control costs. The exact benefits, however, critically depend on how the Kyoto Protocol is implemented.

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 *et al*. (2005) suggest the possibility of including some local pollutants, such as CO and VOCs, in global climate agreement with others (e.g. NO_x) and aerosols being regulated by regional agreements. It should be noted that some air pollutants, such as sulphate and carbonaceous aerosols, exert radiative forcing and thus global warming, but their contribution is uncertain. Smith and Wigley (2006) 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 VOCs act as indirect greenhouse gases having an influence for example via their impact on OH (hydroxil) radicals and therefore the lifetime of direct greenhouse gases (e.g. methane and HFCs). Further, the climatic effects of some pollutants, such as 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.

3.3.6 Characteristics of regional and national mitigation scenarios

Table 3.7 summarizes selected national mitigation scenarios. There are broadly two types of national scenarios that focus on climate mitigation. First, there are the scenarios that study mitigation options and related costs under a given national emissions cap and trade regime. The second are the national scenarios that focus on 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 European Union and Japan. The latter type has been explored in the USA, Canada and Japan. There is also an increasing body of literature, mainly in developing countries, which analyses national GHG emissions in the context of domestic concerns, such as energy security and environmental co-benefits. Many of these developing country 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, such as the contraction and convergence (C&C) approach (GCI, 2005) for calculating the allocation of worldwide emissions to estimate national emissions ceilings. The UK's Energy White Paper (DTI, 2003) examined measures to achieve a 60% reduction in CO_2 emissions by 2050 as compared to the current level. Several studies have explored renewable energy options, for example, the possibility of expanding the share of renewable energy and the resulting prospects for 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 *et al*., 2002; Treffers *et al*., 2005), has explored the possibilities of reducing emissions in the Netherlands by 80% in 2050 compared to 1990 levels. In France, the Inter Ministerial Task Force on Climate Change (MIES, 2004) has examined mitigation options that

Table 3.7: *National scenarios with quantification up to 2050 and beyond.*

Country	Author/Agency	Model	Time horizon	Target variables	Base year	Target of reduction to the value of the base year
USA	Hanson *et al*. (2004)	AMIGA[1]	2000-2050	-	2000	(about 44% in 2050)
Canada	Natural Resource Canada (NRCan) (2000)	N.A.	2000-2050	GHG emissions	2000	(53% in 2050)
India	Nair *et al*. (2003)	Integrated modelling framework[1,3]	1995-2100	Cumulative CO_2 emissions		550 ppmv, 650 pmv
	Shukla *et al*. (2006)	ERB[2]	1990-2095	CO_2 emissions		550 ppmv
China Netherlands	Chen (2005)	MARKAL-MACRO[2,3]	2000-2050	CO_2 emissions	Reference	5-45% in 2050
	Van Vuuren *et al*. (2003)	IMAGE/TIMER[2,4]	1995-2050	GHG emissions	1995	-
	Jiang and Xiulian (2003)	IPAC-emission[2,3]	1990-2100	GHG emissions	1990	-
	Tuinstra et al. (2002) (COOL)		1990-2050	GHG emissions	1990	80% in 2050
Germany	Deutscher Bundestag (2002)	WI[4], IER	2000-2050	CO_2 emissions	1990	80% in 2050
UK	Department of Trade and Industry (DTI) (2003)	MARKAL[3]	2000-2050	CO_2 emissions	2000	45%, 60%, 70% in 2050
France	Interministerial Task Force on Climate Change (MIES) (2004)	N.A.	2000-2050	CO_2 emissions	2000	0.5 tC/cap (70% in 2050)
Australia	Ahammad et al. (2006)	GTEM[1]	2000-2050	GHG emissions	1990	50% in 2050
Japan	Japan LCS Project (2005)	AIM/Material[1] MENOCO[4]	2000-2050	CO_2 emissions	1990	60-80% in 2050
	Ministry of Economy, Trade and Industry (2005)	GRAPE[3]	2000-2100	CO_2/GDP	2000	1/3 in 2050, 1/10 in 2100
	Masui *et al*. (2006)	AIM/Material[1]	2000-2050	CO_2 emissions	1990	74% in 2050
	Akimoto *et al*. (2004)	Optimization model[3]	2000-2050	CO_2 emissions	2000	0.5% /yr (21% in 2050)
	Japan Atomic Industrial Forum (JAIF) (2004)	MARKAL[3]	2000-2050	CO_2 emissions	2010 (1990)	40% in 2050

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

could lead to significant reductions in per capita 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 that include wind power, electricity-saving possibilities in households and office appliances, and emission abatement of fluorinated GHGs.

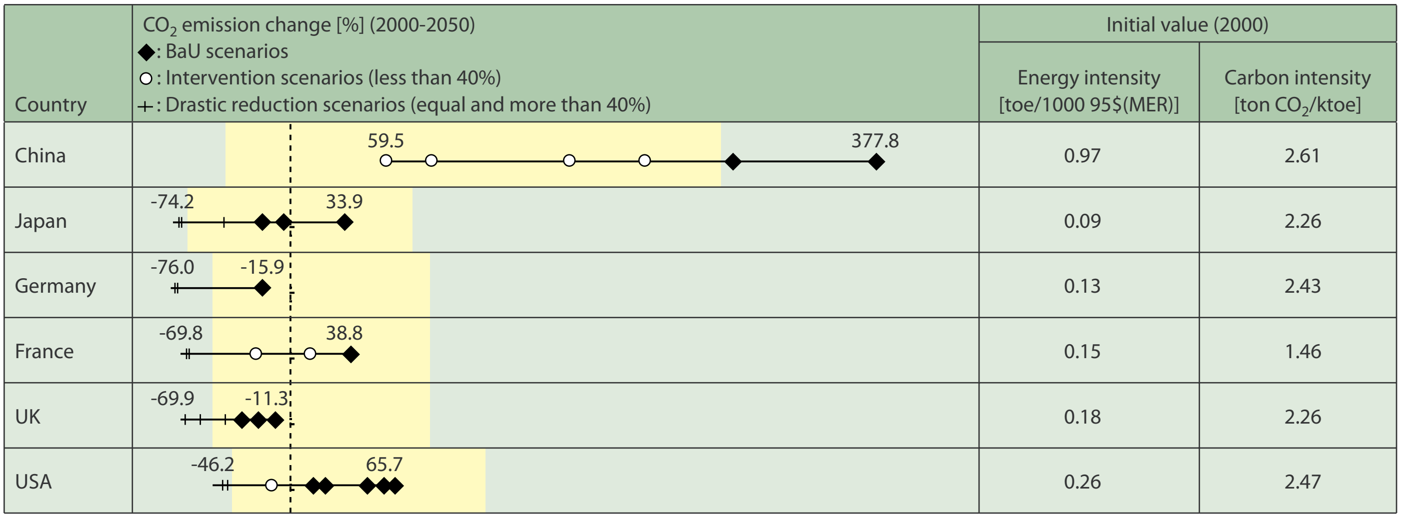
Scenario studies in the USA have explored the implications of climate mitigation for energy security (Hanson *et al*., 2004). For example, Mintzer *et al*. (2003) developed a set of scenarios describing three divergent paths for US energy supply and use from 2000 through 2035. These scenarios were used to identify 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 potential emissions reductions and associated costs for Japan. For example, Masui *et al*. (2006) developed a set of scenarios that explore the implications of severe emissions cutbacks of between 60 and 80% CO_2 by 2050 (compared to 1990). Another important study by Akimoto *et al*. (2004) evaluates the possibilities of introducing the 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 such as 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

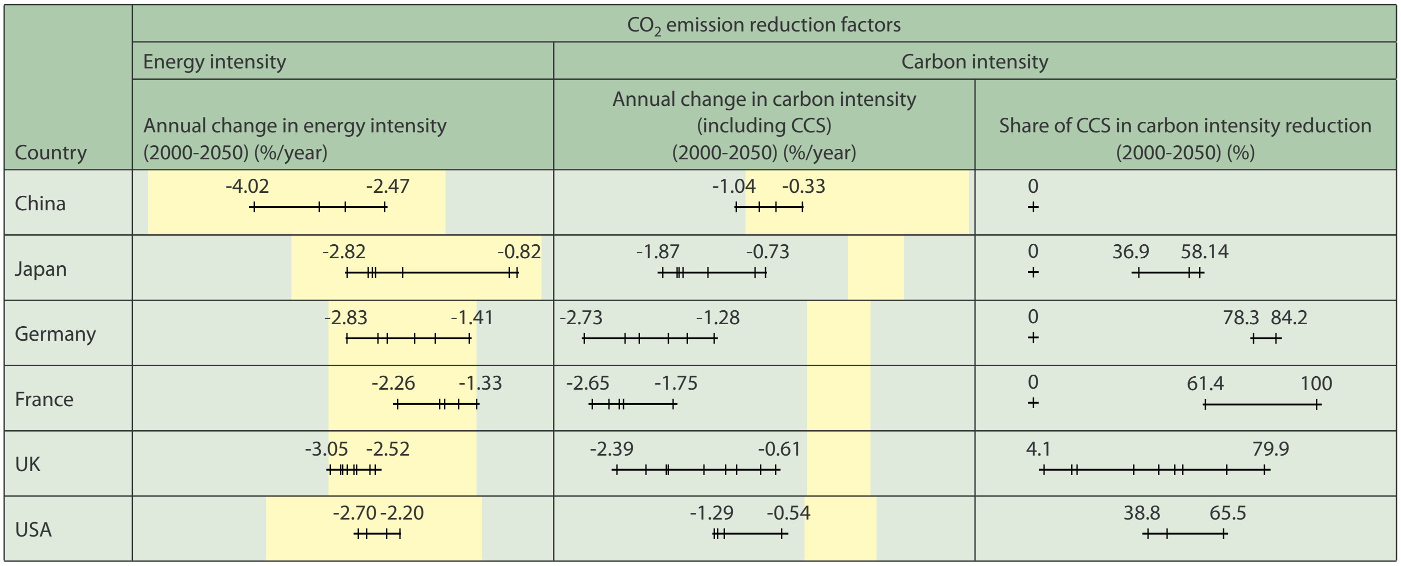
Table 3.8: *Developed countries scenarios with more than 40% reduction (compared to 2000 emissions), and some Chinese scenarios: CO_2 emission changes from 2000 to 2050; Energy intensity and carbon intensity in 2000, and their changes from 2000 up to 2050.*

(A) CO_2 emission changes, energy intensity, and carbon intensity in 2000.



Country	CO_2 emission change [%] (2000-2050) ◆: BaU scenarios ○: Intervention scenarios (less than 40%) +: Drastic reduction scenarios (equal and more than 40%)	Initial value (2000): Energy intensity [toe/1000 95$(MER)]	Initial value (2000): Carbon intensity [ton CO_2/ktoe]
China	59.5 377.8	0.97	2.61
Japan	-74.2 33.9	0.09	2.26
Germany	-76.0 -15.9	0.13	2.43
France	-69.8 38.8	0.15	1.46
UK	-69.9 -11.3	0.18	2.26
USA	-46.2 65.7	0.26	2.47

(B) Changes in energy intensity and carbon intensity.



Country	CO_2 emission reduction factors: Energy intensity: Annual change in energy intensity (2000-2050) (%/year)	Carbon intensity: Annual change in carbon intensity (including CCS) (2000-2050) (%/year)	Carbon intensity: Share of CCS in carbon intensity reduction (2000-2050) (%)
China	-4.02 -2.47	-1.04 -0.33	0
Japan	-2.82 -0.82	-1.87 -0.73	0 36.9 58.14
Germany	-2.83 -1.41	-2.73 -1.28	0 78.3 84.2
France	-2.26 -1.33	-2.65 -1.75	0 61.4 100
UK	-3.05 -2.52	-2.39 -0.61	4.1 79.9
USA	-2.70 -2.20	-1.29 -0.54	38.8 65.5

Notes: Data sources: China: Jiang and Xulian (2003), Van Vuuren et al. (2003), Japan: Masui et al. (2006), Akimoto et al. (2004), JAIF (2004), Germany: Deutscher Bundestag (2002), France: MIES (2004), UK: DTI (2003), USA: Hanson et al. (2004). The coloured areas show the range of the global model results of EMF-21 with the target of 4.5 W/m^2. The range of EU-15 is shown for European countries

specify limits on emissions (Van Vuuren *et al*., 2003; Jiang and Xiulian, 2003). Chen (2005) shows that structural change can be a more important contributor to CO_2 reduction than technology efficiency improvement. The scenario construction for India pays specific attention to developing-country dynamics, underlying the multiple socio-economic transitions during the century, including demographic transitions (Shukla *et al*., 2006). Nair *et al*. (2003) studied potential shifts away from coal-intensive baselines to the use of natural gas and renewables.

There are several country scenarios that consider drastic reduction of CO_2 emissions. In these studies, which consider 60–80% reductions of CO_2 in 2050, rates of improvement in energy intensity and carbon intensity increase by about two to three times their historical levels (Kawase *et al*., 2006).

Table 3.8 summarizes scenarios with more than 40% CO_2 reductions (2000–2050) in several developed countries. The table also includes some Chinese scenarios with deep cuts of CO_2 emissions compared to the reference cases. Physical indicators of the Chinese economy show that current efficiency is below the OECD average in most sectors, thus indicating a greater scope for improvement (Jiang and Xiulian, 2003). It should be noted that comparing the energy intensity of the Chinese economy on the basis of market exchanges rates to OECD averages suggests even larger differences, but this is

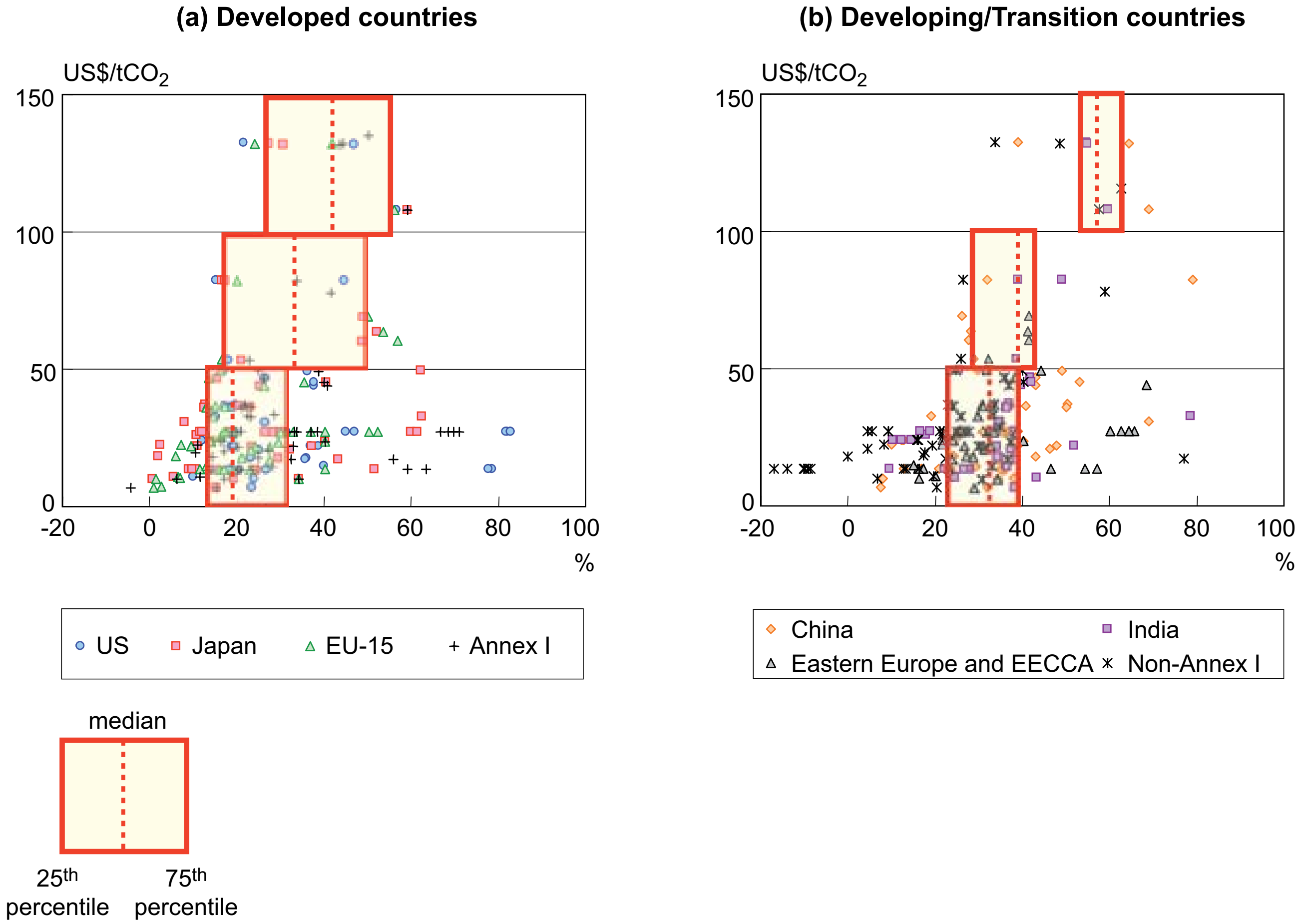


Figure 3.31: *Relationship between carbon prices and CO_2 reduction from baseline in 2050 in selected countries taken from the literature published since the TAR.*

Note: The red box shows the range between the 25th and 75th percentile of the scenarios for each price range. EECCA= Countries of Eastern Europe, the Caucasus and Central Asia.

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 the data and different economic structures).

In the countries with low energy intensity levels in 2000 (such as Japan, Germany and France), the scenarios specify solutions for meeting long-term drastic reduction goals by carbon intensity improvement measures, such as shifting to natural gas in the UK, renewable energy in the Netherlands, and CCS in certain scenarios in France, Germany, the UK and the USA. France has a scenario where CCS accounts for 100% of carbon intensity improvement. Most of the scenarios with drastic CO_2 reductions for the USA and the UK assume the introduction of CCS.

The light yellow coloured area in Table 3.8 shows the range of the global model results of EMF-21 with the stabilization target of 4.5 W/m^2. Most country results show the need for greater improvement in carbon intensity during 2000 to 2050 compared to the global results. The results of scenario analysis since the TAR show that energy intensity improvement is superior to carbon intensity reduction in the first half of the 21st century, but that carbon intensity reduction becomes more dominant in the latter half of the century (Hanaoka *et al.*, 2006).

3.3.6.1 Costs of mitigation in regional and country scenarios

Figure 3.31 shows the relationship between carbon prices and the CO_2 mitigation rates from the baseline in 2050 in some major countries and regions such as the USA, Japan, EU-15, India, China, Former Soviet Union (FSU) and Eastern Europe, taken from the literature since the TAR (Hanaoka *et al.*, 2006). In the developing countries there are many scenarios where relatively high CO_2 reductions are projected even with low carbon prices. With high prices in the range of 100-150 US\$/tCO_2 (in 2000 US dollars) more CO_2 reductions are expected in China and India than in developed countries when the same level of carbon price is applied.

3.4 The 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 of GHGs (see Chapter 2, Section 2.7.1.2, which assesses the role of technology in climate change mitigation, including long-term emissions and stabilization scenarios).

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 cycle 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 for 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 in the nuclear share of global energy, depending 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 agreements.
- New technology configurations and systems, e.g. hydrogen as a carbon-free carrier to complement electricity, fuel cells and new storage technologies.
- Reducing GHG and CO_2 emissions from agriculture and land use in general critically depends on the diffusion of new technologies and practices that could include 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 reductions in emissions compared to the hypothetical case of attempting to 'keep' emissions intensities of GDP and structure the same as today (see Chapter 2, Section 2.7.1.1, which discusses the role of technology in baseline scenarios). Figure 3.32 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*., 2006). 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 25th and the 75th percentile of the scenarios in the scenario database.[21] The hypothetical cumulative emissions (without technology and structural change) range from about 9000 (25th percentile) to 12000 (75th percentile), with a median of about 10400 $GtCO_2$ by 2100.

The next bar in Figure 3.32 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% (75th and 25th 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. Any mitigation measures and policies need to go beyond these baseline assumptions.

The next bar in Figure 3.32 also allows carbon intensities of energy to change as originally assumed in the underlying scenarios. Again, the baseline assumptions lead to further and substantial reductions of cumulative emissions, by some 13% to more than 20% (25th and 75th percentile, respectively), *or less than half the emissions*, as compared to the case of no improvement in energy or carbon intensities. This results in the original cumulative emissions as specified by reference scenarios in the literature, from 4050 (25th percentile) to 5400 (75th percentile), with a median of 4730 $GtCO_2$ 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 2075 to 7240 $GtCO_2$.[22]

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

[22] The cumulative emissions range represents a huge increase compared to the historical experience. Cumulative global emissions were about 1100 $GtCO_2$ from the 1860s to today, a very small fraction indeed of future expected emissions across the scenarios.

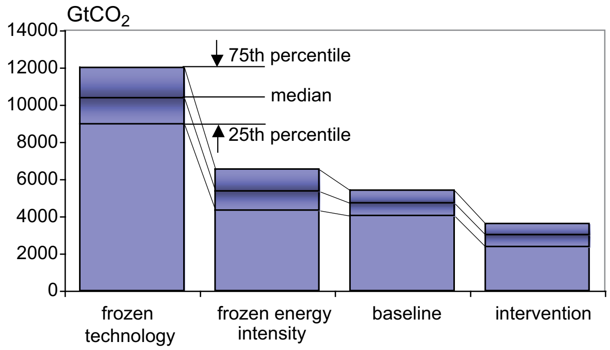

Figure 3.32: *Median, 25th and 75th percentile of global cumulative carbon emissions by 2100 in the scenarios developed since 2001.*

Note: The range labelled 'frozen technology' refers to hypothetical futures without improvement in energy and carbon intensities in the scenarios; the range labelled 'frozen energy intensity' refers to hypothetical futures where only carbon intensity of energy is kept constant, while energy intensity of GDP is left the same as originally assumed in scenarios; the range labelled CO_2 baseline refer to the 83 baseline scenarios in the database, while the region labelled CO_2 intervention includes 211 mitigation and/or stabilization scenarios.

Source: After Nakicenovic et al. (2006)

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 3.32 shows (in the last bar) yet another significant reduction of future cumulative emissions from 2370 to 3610 (corresponding to the 25th to the 75th percentile of the full scenario range), with a median of 3010 $GtCO_2$ by 2100. This corresponds to about 70% 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%, reduction compared to the respective baseline scenarios.[23]

This illustrates the importance of technology and structural changes, both in reference and mitigation scenarios. However, this is an aggregated illustration across all scenarios and different mitigation levels for cumulative emissions. Thus, it is useful to also give a more specific illustrative example. Figure 3.33 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. 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 with 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 3.33) illustrates the impact of technological change, which leads to improved efficiency and 'decarbonization' in energy systems already incorporated into the baseline emission scenario.

The impacts of technological options leading to emission reductions are illustrated by the colour-shaded areas in Figure 3.33, regrouped into three categories: demand reductions (e.g. through deployment of more efficient end-use technologies, such as lighting or vehicles), fuel switching (substituting high-GHG-emitting technologies for 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 3.33), as well as with the degree of stringency of the stabilization target adopted (not shown in Figure 3.33). 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 3.33) 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 with less diversified technology scenarios. This illustrative example also confirms the conclusion reached in Section 3.3 that was based on a broader range of 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 *et al*., 2002; and Köhler *et al*., 2006, see also Chapter 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. Although decarbonization of the world's energy system is comparatively slow (0.3% per year), the trend has persisted throughout the past two centuries (Nakicenovic, 1996). The overall tendency towards 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 the World Energy Outlook 2004 (IEA, 2004), the reference scenario to 2030 shows the replacement of gas for other fossil fuels as well as cleaner fuels due to limited growth of nuclear and bioenergy.

Another effect contributing towards reduced carbon intensity of the economy is the declining energy requirements per unit

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[23] In comparison, the full range of cumulative emissions from mitigation and stabilization scenarios in the database runs from 785 to 6794 $GtCO_2$.

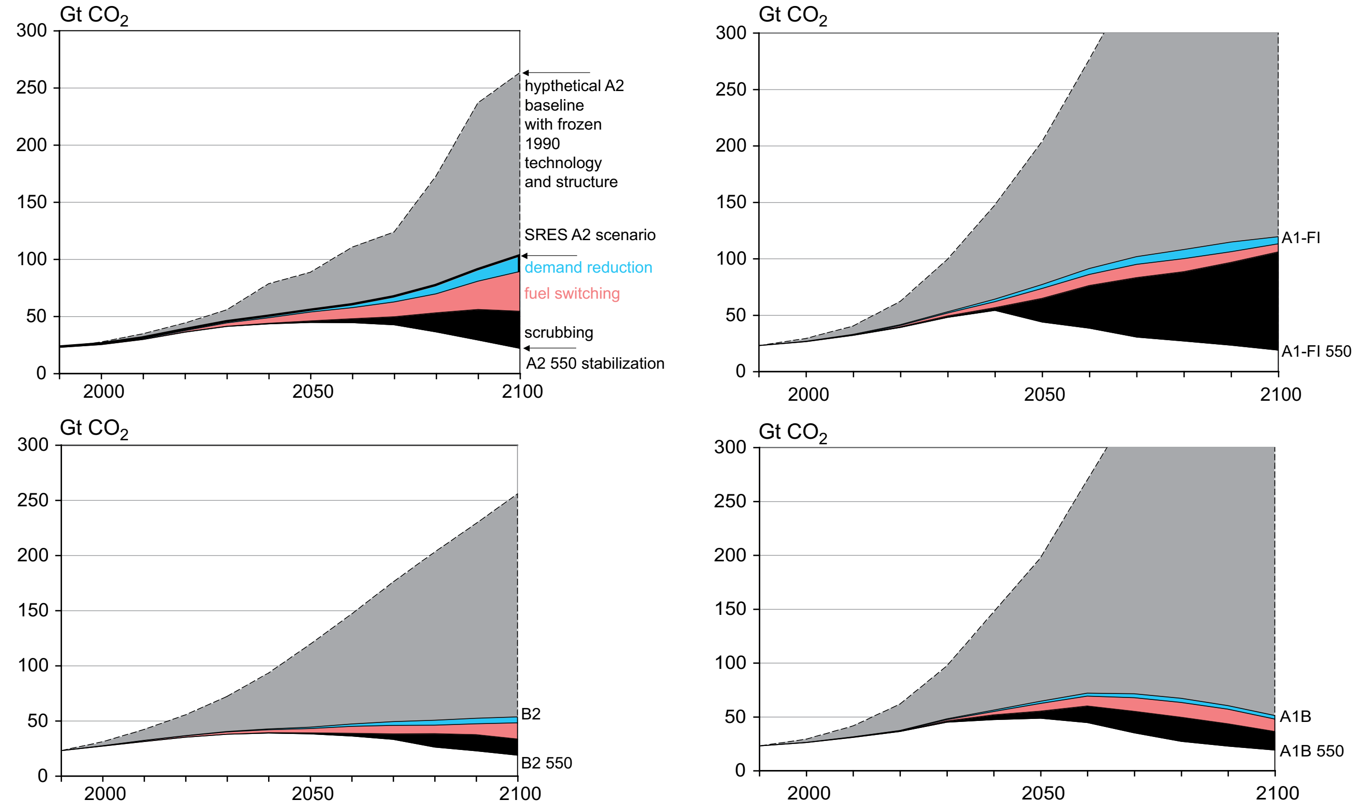

Figure 3.33: *Impact of technology on global carbon emissions in reference and climate mitigation scenarios.*

Note: 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). The grey-shaded area indicates 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. Colour-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, thus making differences in technology assumptions more directly comparable.

Source: Adapted from Nakicenovic et al. (2000), IPCC (2001a), Riahi and Roehrl (2001), and Edmonds (2004).

of GDP, or energy intensity of GDP. Globally, energy intensity has been declining more rapidly than carbon intensity of energy (0.9% per year) during the past two centuries (Nakicenovic, 1996). Consequently, carbon intensity of GDP declined globally at about 1.2% per year.

The carbon intensity of energy and energy intensities of GDP were shown in Section 3.2 of this chapter, Figure 3.6, 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).

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 year, which is a significantly more rapid decrease compared to the historical rates of about 0.3% per year. Decarbonization of GDP is also more rapid (about 2.5% per year for both pre- and post-2001 literature medians) compared with the historical rates of about 1.2% 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, even extending into the negative range. This means that towards 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 amounts of biomass energy. Such developments represent a radical paradigm shift compared to the current and more short-term energy systems, implying significant and radical technological changes.

In contrast, the scenarios that are most intensive in the 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 boundary of the recent scenarios developed after 2001 depict slightly increasing (about 0.3% per year) carbon intensities of energy (A2 reference scenario, Mori (2003), see Figure 3.8, 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, recarbonization. In the long term, these scenarios lie 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.*, 2006). 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 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 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). 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 of 1.1% per year over the course of the century, compared to just 0.3% for the non-intervention scenarios. Note, nevertheless, that the modest increase in carbon intensity of energy improvements in the intervention scenarios above the 75th percentile of the distribution of the recent scenarios. 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.*, 2006); or have comparatively modest CO_2 reductions measures, such as the implementation of a relatively minor carbon tax of 10 US$/tC (about 2.7 US$/tCO_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 towards 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 in order 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.

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 source in the world some 80 years ago, to the dominance of crude oil during the 1970s. Achieving such a transition in the future towards lower GHG intensities is one of the major technological challenges addressed in mitigation and stabilization scenarios.

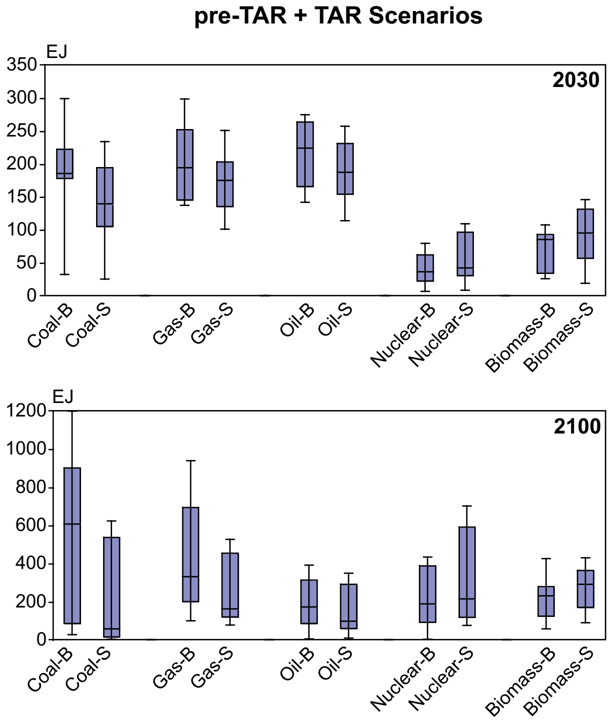

Figure 3.34: *Deployment of primary energy technologies across pre-2001 scenarios by 2030 and 2100: Left-side 'error' bars show baseline (non-intervention) scenarios and right-side ones show intervention and stabilization scenarios. The full ranges of the distributions (full vertical line with two extreme tic marks), the 25th and 75th percentiles (blue area) and the median (middle tic mark) are also shown.*

Figures 3.34 and 3.35 show the ranges of energy technology deployment across scenarios by 2030 and 2100 for baseline (non-intervention) and intervention (including stabilization) scenarios, respectively. 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, thereby exceeding by 50% the current deployment of all primary energy technologies in the world. Deployment of nuclear and biomass is comparatively lower, in the range of about 50–100 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.

The deployment ranges are large for each of the technologies but do not differ much when 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

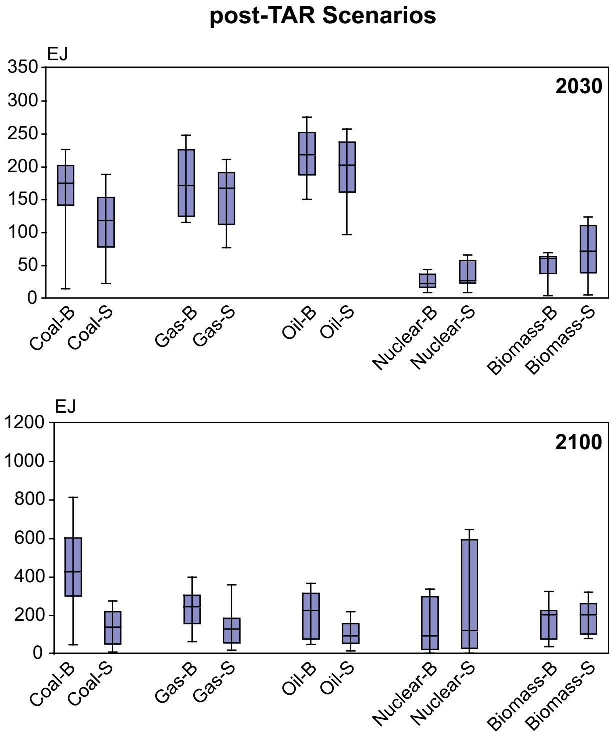

Figure 3.35: *Deployment of primary energy technologies across post-2001 scenarios by 2030 and 2100: Left-side 'error' bars show baseline (non-intervention) scenarios and right-side ones show intervention and stabilization scenarios. The full ranges of the distributions (full vertical line with two extreme tic marks), the 25th and 75th percentiles (blue area) and the median (middle tic mark) are also shown.*

with the older) scenarios. What is significant in both sets of literature 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. 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 is 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 Chapter 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 are 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 that 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 3.36.

Generally, economic benefits from improved technology increase non-linearly with:

1. The distance to *current* economic characteristics (or the ones assumed to be characteristic of the scenario baseline).
2. The stringency of environmental targets.
3. The comprehensiveness and diversity of a particular technology portfolio considered in the analysis.

Thus, the larger the improvement of future technology characteristics compared to current ones, the lower the stabilization target, and the more comprehensive the suite of available technologies, the greater 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[24]) 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 considerable 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 the TAR

The IPCC-TAR concluded that reduction of greenhouse gas emissions is highly dependent on both technological innovation and implementation of technologies (a conclusion broadly confirmed in Chapter 2, Section 2.7.1). However, the rate of introduction of new technologies, and the drivers for adoption are different across different parts of the world, particularly

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[24] See Newell et al., 1999.

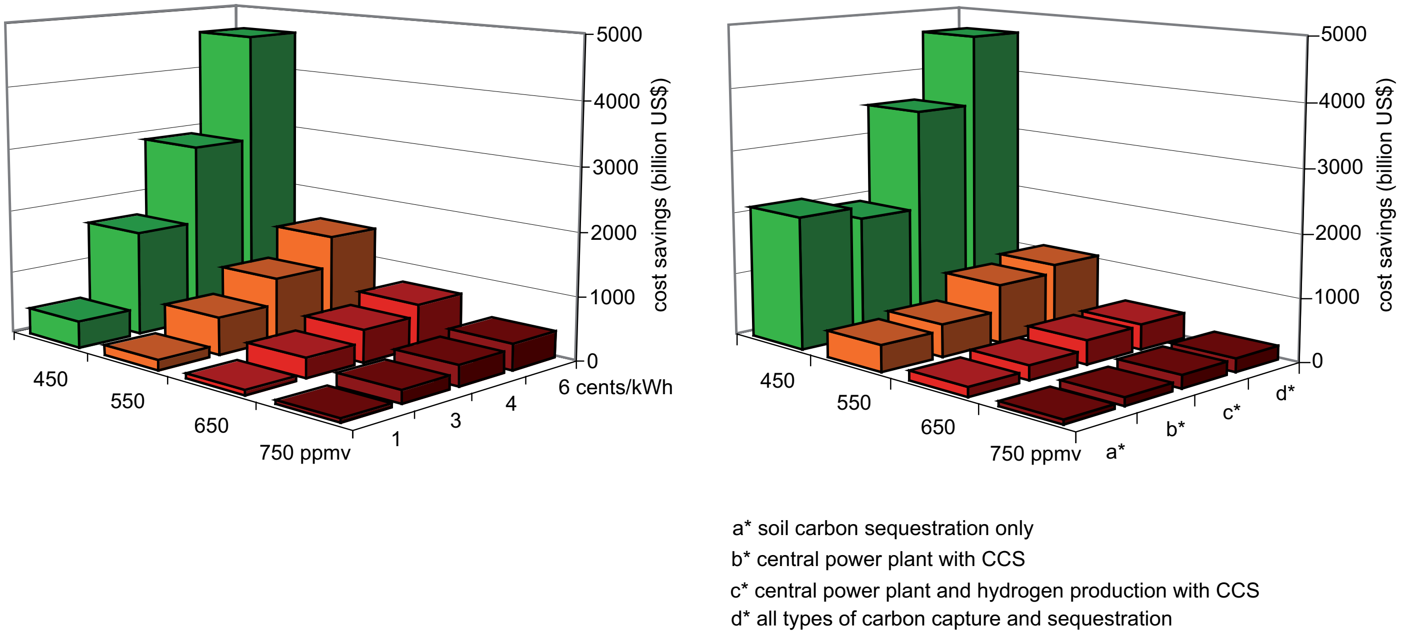

Figure 3.36: *The value of improved technology.*

Note: Modelling studies enable experts 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 on 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. Left panel: cost savings (billions of 1996 US$) compared to the reference scenario when lowering the costs of solar photovoltaics (PV) from a reference value of 9 US cents per kWh (top) by 1, 3, 4, and 6 cents/kWh, respectively. For instance, the value of reducing PV costs from 9 to 3 cents per kWh could amount to up to 1.5 trillion US$ in an illustrative 550 ppmv stabilization scenario compared to the reference scenario in which costs remain at 9 cents/kWh). Right 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 US$ in an illustrative 450 ppmv stabilization scenario. Removing all carbon capture sequestration technologies would triple the costs of stabilization for all concentration levels analyzed.

Source: GTSP, 2001.

in industrial market economies, economies in transition and developing countries. To some extent this is reflected in global emissions scenarios as they often involve technological change at a level that includes 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 in assumptions about policy instruments such as taxes, emissions permits, technology standards, costs, and lower and upper boundaries of technology diffusion.

3.4.3.2 Dynamics of technology

R&D, technological learning, and spillovers are the three broad categories of drivers behind technological change. These are discussed in Chapter 2, Section 2.7, and Chapter 11, Section 11.5. The main conclusion is that, on the whole, all three of the sources of induced technological change (ITC) play important roles in technological advance. Here, we focus on the dynamics of technology and ITC in emissions and stabilization scenarios.

Emissions scenarios generally treat technological change as an exogenous assumption about costs, market penetration and other technology characteristics, with some notable exceptions such as in Gritsevskyi and Nakicenovic (2000). Hourcade and Shukla (2001), in their review of scenarios from top-down models, indicate that technology assumptions are a critical factor that affects 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 and 1.75% 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 specialization 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, 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 learning benefits 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 costs 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*. (2004a) 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 *et al*. consider advanced technology development to be far more important as a driver of emission reductions than carbon taxes. Weyant (2004) concluded that stabilization will require the large-scale development 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 of the IIASA in particular, 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 the authors have also illustrated that the baseline choice is crucial in determining the nature (and by implication also the 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 for energy system development. Some modelling reported in the TAR suggests that a reduction (up to 5 GtC a year) by 2020 (some 50% 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 US$/tC-equivalent (27 US$/tCO_2-eq).

3.4.3.3 Barriers to technology transfer, diffusion and deployment for long-term mitigation

Chapter 2, Section 2.7.2 includes a discussion of the barriers to development and commercialization of technologies. 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 the 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.

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 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. The success of policies that address short-term development concerns will determine the pace at which the quality of life in the developing and the developed world converges over the long term.

In the long term, the key drivers of technological change in developing countries will depend on three 'changes' that are simultaneous and inseparable within the context of development: exogenous behavioural changes or changes in social infrastructure; endogenous policies driven by 'development goals'; and any 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-term uncertainty

3.5.1 The interaction between mitigation and adaptation, an iterative climate policy process

Responses to climate change include a portfolio of measures:

a. Mitigation – actions that reduce net carbon emissions and limit long-term climate change.
b. Adaptation – actions that help human and natural systems to adjust to climate change.
c. Research on new technologies, on institutional designs and on climate and impacts science, which should reduce uncertainties and facilitate future decisions (Richels *et al*., 2004; Caldeira *et al*., 2003; Yohe *et al*., 2004).

A key question for policy is what combination of short-term and long-term actions will minimize the total costs of climate change, in whatever form these costs are expressed, across mitigation, adaptation and the residual climate impacts that society is either prepared or forced to tolerate. Although there are different views on the form and dynamics of such trade-offs in climate policies, there is a consensus that they should be aligned with (sustainable) development policies, since the latter determine the capacity to mitigate and to adapt in the future (TAR, Hourcade and Shukla, 2001). In all cases, policy decisions will have to be made with incomplete understanding of the magnitude and timing of climate change, of its likely consequences, and of the cost and effectiveness of response measures.

3.5.1.1 An iterative risk-management framework to articulate options

Previous IPCC reports conclude that climate change decision-making is not a once-and-for-all event, but an iterative risk-management process that is likely to take place over decades, where there will be opportunities for learning and mid-course corrections in the light of new information (Lempert *et al*., 1994; Keller *et al*., 2006).

This iterative process can be described using a decision tree (Figure 3.37), where the square nodes represent decisions, the circles represent the reduction of uncertainty and the arrows indicate the range of decisions and outcomes. Some nodes summarize today's options – how much should be invested in mitigation, in adaptation, in expanding mitigative and adaptive capacity, or in research to reduce uncertainty? Other nodes represent opportunities to learn and make mid-course corrections. This picture is a caricature of real decision processes, which are continuous, overlapping and iterative.

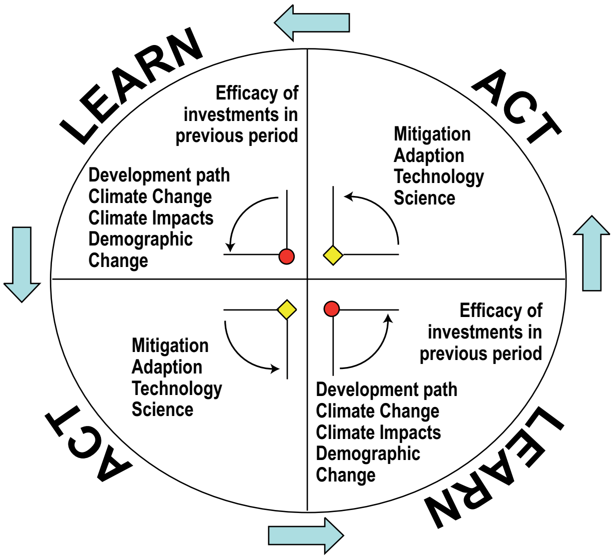

Figure 3.37: *The Iterative Nature of the Climate Policy Process.*

However, it is useful to conceptually put the many determinants of any short-term strategy in a context of progressive resolution of uncertainty.

3.5.1.2 Qualitative insights into interactions between mitigaton, adaptation and development

Until recently, a main focus in the policy and integrated assessment literature has been on comparing mitigation costs and avoided damages. Since the TAR, attention has shifted towards the interaction between mitigation and adaptation in reducing damages in a risk-management framework. This has accompanied a growing realization that some climate change in the coming decades is inevitable.

Limited treatment of adaptation in climate policy assessments is still a problem and a number of reasons explain 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. Second, adaptation is largely undertaken at the local scale, by individual households, farmers, companies or local governments; it is thus difficult to target through coordinated international incentives, and is more complicated to handle quantitatively by models in global scenarios. Third, it is difficult to generalize the ways that individuals or communities are likely to adapt to specific impacts. However, the literature is evolving quickly and recent work is available in a number of regions; for example, in Finland (Carter *et al*., 2005), the UK (West and Gawith, 2005), Canada (Cohen *et al*., 2004) and the USA (e.g. California, Hayhoe *et al*., 2004).

Despite the scarcity of global systematic assessments (Tol, 2005a), some interesting insights into the interaction between adaptation and mitigation emerge from recent regional-scale studies. Some adaptation measures are 'no-regret' measures and should be undertaken anyway (Agrawala, 2005), such as preservation of mangroves in coastal zones, which provide a buffer for increased coastal flood risk due to climate change and help to maintain healthy marine ecosystems (Nicholls *et al*., 2006). A few may be synergistic with mitigation (Bosello, 2005) such as investing in more efficient buildings that will limit human vulnerability to increasingly frequent heatwaves and also reduce energy use, hence emissions. But many adaptation options involve net costs with a risk of committing to irreversible and misplaced investment given the considerable uncertainty about climate change at a local scale. Given this uncertainty, and the fact that learning about adaptation to climate change imposes some costs and takes time (Kelly *et al*., 2005), mis-allocation of investments may occur, or the rate of long-term investment in adaptation strategies may slow (Kokic *et al*., 2005; Kelly *et al*., 2005).

Finally, the interactions between adaptation and mitigation are intertwined with development pathways. A key issue is to understand at what point (over)investment in mitigation or adaptation might limit funds available for development, and thus reduce future adaptive capacity (Sachs, 2004; Tol, 2005a; Tol and Yohe, 2006). Another issue concerns the point at which climate change damages, and the associated investment in adaptation, could crowd out more productive investments later and harm development (Kemfert, 2002; Bosello and Zhang, 2005; Kemfert and Schumacher, 2005). The answer to these questions depends upon modelling assumptions that drive repercussions in other sectors of the economy and other regions and the potential impacts on economic growth. These are 'higher-order' social costs of climate change from a series of climate-change-induced shocks; they include the relative influence of: a) the cross-sectoral interactions across all major sectors and regions; b) a crowding out effect that slows down capital accumulation and technical progress, especially if technical change is endogenous. These indirect impacts reduce development and adaptive capacity and may be in the same order of magnitude, or greater than, the direct impact of climate change (Fankhauser and Tol, 2005; Roson and Tol, 2006; Kemfert, 2006).

Both the magnitude and the sign of the indirect macro-economic impacts of climate change are conditional upon the growth dynamics of the countries concerned. When confronted by the same mitigation policies and the same climate change impacts, economies experiencing strong disequilibrium (including 'poverty traps') and large market and institutional imperfections will not react in the same way as countries that are on a steady and high economic growth pathway. The latter are near what economists call their 'production frontier' (the maximum of production attainable at a given point in time); the former are more vulnerable to any climatic shock or badly calibrated mitigation policies, but symmetrically offer more opportunities for synergies between mitigation, adaptation and development policies (Shukla *et al*., 2006). On the adaptation side for example, Tol and Dowlatabadi (2001) demonstrate that there is significant potential to reduce vulnerability to the spread of malaria in Africa. In some circumstances, mitigation measures can be aligned with development policies and alleviate important sources of vulnerability in these countries, such as dependency on oil imports or local pollution. But this involves transition costs over the coming 10–20 years (higher domestic energy prices, higher investments in the energy sector), which in turn suggests opportunities for international cooperative mechanisms to minimize these costs.

Bosello (2005) shows complementarity between adaptation, mitigation and investment in R&D, whilst others consider these as substitutes (Tol, 2005a). Schneider and Lane (2006) consider that mitigation and adaptation only trade off for small temperature increments where adaptation might be cheaper, whereas for larger temperature increases mitigation is always the cheaper option. Goklany (2003) promotes the view that the contribution by climate change to hunger, malaria, coastal flooding, and water stress (as measured by populations at risk) is small compared to that of non-climate-change-related factors, and that through the 2080s, efforts to reduce vulnerability would be more cost-effective in reducing these problems than mitigation. This analysis neglects critical thresholds at the regional level (such as the temperature ceiling on feasibility of regional crop growth) and at the global level (such as the onset of ice sheet melting or release of methane from permafrost), and, like many others studies, it neglects the impacts of extreme weather events. It also promotes a very optimistic view of adaptive capacity, which is increasingly challenged in the literature (Tompkins and Adger, 2005). An adaptation-only policy scenario in the coming decades leads to an even greater challenge for adaptation in decades to follow, owing to the inertia of the climate system. In the absence of mitigation, temperature rises will be much greater than would otherwise occur with pusuant impacts on economic development (IPCC, 2007b, Chapter 19.3.7; Stern 2006). Hence adaptation alone is insufficient to avoid the serious risks due to climate change (see Table 3.11; also IPCC, 2007b, Chapter 19, Table 19.1).

To summarize, adaptation and mitigation are thus increasingly viewed as complementary (on the global scale), whilst locally there are examples of both synergies and conflicts between the two (IPCC, 2007b, Chapter 18). Less action on mitigation raises the risk of greater climate-change-induced damages to economic development and natural systems and implies a greater need for adaptation. Some authors maintain that adaptation and mitigation are substitutes, because of competition for funds, whilst others claim that such tradeoffs occur only at the margin when considering incremental temperature change and incremental policy action, because for large temperature changes mitigation is always cheaper than adaptation.

Table 3.9: *Global mean temperature increase at equilibrium, greenhouse gas concentration and radiative forcing. Equilibrium temperatures here are calculated using estimates of climate sensitivity and do not take into account the full range of bio-geophysical feedbacks that may occur.*

Equilibrium temperature increase in °C above pre-industrial temperature	CO_2-eq concentration and radiative forcing corresponding to best estimate of climate sensitivity for warming level in column 1[1,2]		CO_2-eq concentration that would be expected to limit warming below level in column 1 with an estimated likelihood of about 80% [3]
	CO_2-equivalent (ppm)	*Radiative forcing (W/m^2)*	
0.6	319	0.7	305
1.6	402	2.0	356
2.0	441	2.5	378
2.6	507	3.2	415
3.0	556	3.7	441
3.6	639	4.5	484
4.0	701	4.9	515
4.6	805	5.7	565
5.0	883	6.2	601
5.6	1014	6.9	659
6.0	1112	7.4	701
6.6	1277	8.2	768

Note: see Figure 3.38 on page 228 for footnotes.

3.5.2 Linking emission scenarios to changes in global mean temperature, impacts and key vulnerabilities

In a risk-management framework, a first step to understanding the environmental consequences of mitigation strategies is to look at links between various stabilization levels for concentrations of greenhouse gases in the atmosphere, and the global mean temperature change relative to a particular baseline. A second step is to link levels of temperature change and key vulnerabilities. Climate models indicate significant uncertainty at both levels. Figure 3.38 shows CO_2-eq concentrations that would limit warming at equilibrium below the temperatures indicated above pre-industrial levels, for 'best estimate' climate sensitivity, and for the likely range of climate sensitivity (see Meehl *et al*., 2007, Section 10.7, and Table 10.8; and the notes to Figure 3.38). It also shows the corresponding radiative forcing levels and their relationship to equilibrium temperature and CO_2-eq concentrations. The table and the figure illustrate how lower temperature constraints require lower stabilization levels, and also that, if the potential for climate sensitivities is higher than the 'best estimate' and is taken into account, the constraint becomes more stringent. These more stringent constraints lower the risks of exceeding the threshold.

Figure 3.38 and Table 3.10 provide an overview of how emission scenarios (Section 3.3) relate to different stabilization targets and to the likelihood of staying below certain equilibrium warming levels. For example, respecting constraints of 2°C above pre-industrial levels, at equilibrium, is already outside the range of scenarios considered in this chapter, if the higher values of likely climate sensitivity are taken into account (red curve in Figure 3.38), whilst a constraint of respecting 3°C above pre-industrial levels implies the most stringent of the category I scenarios, with emissions peaking in no more than the next 10 years, again if the higher likely values of climate sensitivity are taken into account. Using the 'best estimate' of climate sensitivity (i.e. the estimated mode) as a guide for establishing targets, implies the need for less stringent emission constraints. This 'best estimate' assumption shows that the most stringent (category I) scenarios could limit global mean temperature increases to 2°C–2.4°C above pre-industrial levels, at equilibrium, requiring emissions to peak within 10 years. Similarly, limiting temperature increases to 2°C above pre-industrial levels can only be reached at the lowest end of the concentration interval found in the scenarios of category I (i.e. about 450 ppmv CO_2-eq using 'best estimate' assumptions). By comparison, using the same 'best estimate' assumptions, category II scenarios could limit the increase to 2.8°C–3.2°C above pre-industrial levels at equilibrium, requiring emissions to peak within the next 25 years, whilst category IV scenarios could limit the increase to 3.2°C–4°C above pre-industrial at equilibrium requiring emissions to peak within the next 55 years. Note that Table 3.10 category IV scenarios could result in temperature increases as high as 6.1°C above pre-industrial levels, when the likely range for the value of climate sensitivity is taken into account. Hence, setting policy on the basis of a 'best estimate' climate sensitivity accepts a significant risk of exceeding the temperature thresholds, since the climate sensitivity could be higher than the best estimate.

Table 3.11 highlights a number of climate change impacts and key vulnerabilities organized as a function of global mean temperature rise (IPCC, 2007b, Chapter 19). The table highlights a selection of key vulnerabilities representative of categories covered in Chapter 19 (Table 19.1) in IPCC (2007b).

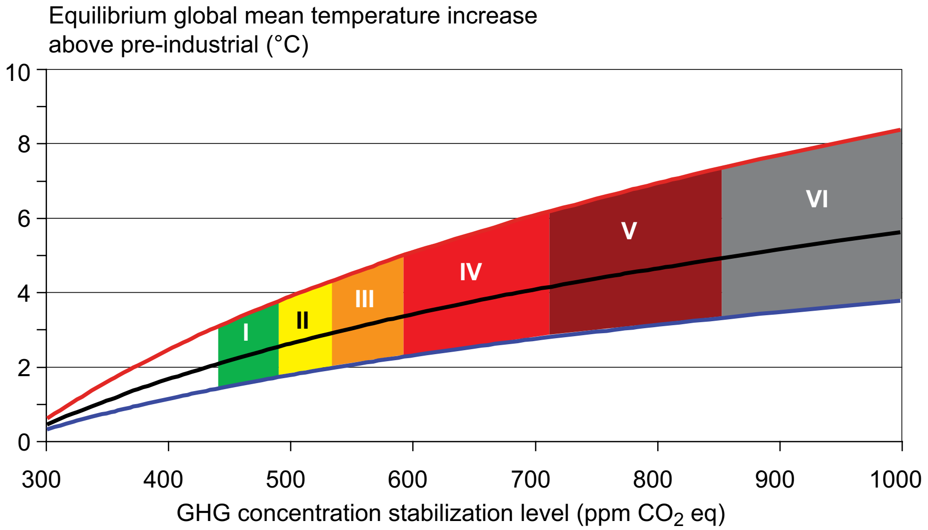

Figure 3.38: *Relationship between global mean equilibrium temperature change and stabilization concentration of greenhouse gases using: (i) 'best estimate' climate sensitivity of 3°C (black), (ii) upper boundary of likely range of climate sensitivity of 4.5°C (red), (iii) lower boundary of likely range of climate sensitivity of 2°C (blue) (see also Table 3.9).*

Notes:

1. IPCC (2007a) finds that the climate sensitivity is likely to be in the range 2°C –4.5°C, with a 'best estimate' of about 3°C, very unlikely to be less than 1.5°C and values substantially higher than 4.5°C 'cannot be excluded' (IPCC (2007a, SPM).
2. The simple relationship $T_{eq} = T_{2xCO_2} \times \ln([CO_2]/280)/\ln(2)$ is used (see Meehl *et al*. (2007), Section 10.7, and Table 10.8), with upper and lower values of T_{2xCO_2} of 2 and 4.5°C.
3. Non-linearities in the feedbacks (including e.g. ice cover and carbon cycle) may cause time dependence of the effective climate sensitivity, as well as leading to larger uncertainties for greater warming levels. This likelihood level is consistent with the IPCC Working Group I assessment of climate sensitivity, see Note 1, and drawn from additional consideration of Box 10.2, Figure 2, in IPCC (2007a).

The *italic text* in Table 3.11 highlights *examples* of avoided impacts derived from ensuring that temperatures are constrained to any particular temperature range compared to a higher one. For example, significant benefits result from constraining temperature change to not more than 1.6°C–2.6°C above pre-industrial levels. These benefits would include lowering (with different levels of confidence) the risk of: widespread deglaciation of the Greenland Ice Sheet; avoiding large-scale transformation of ecosystems and degradation of coral reefs; preventing terrestrial vegetation becoming a carbon source; constraining species extinction to between 10–40%; preserving many unique habitats (see IPCC, 2007b, Chapter 4, Table 4.1 and Figure 4.5) including much of the Arctic; reducing increases in flooding, drought, and fire; reducing water quality declines, and preventing global net declines in food production. Other benefits of this constraint, not shown in the Table 3.11, include reducing the risks of extreme weather events, and of at least partial deglaciation of the West Antarctic Ice Sheet (WAIS), see also IPCC, 2007b, Section 19.3.7. By comparison, for 'best guess' climate sensitivity, attaining these benefits becomes unlikely if emission reductions are postponed beyond the next 15 years to a time period between the next 15–55 years. Such postponement also results in increasing risks of a breakdown of the Meridional Overturning Circulation (IPCC, 2007b, Table 19.1).

Even for a 2.6°C –3.6°C temperature rise above pre-industrial levels there is also medium confidence in net negative impacts in many developed countries (IPCC, 2007b, Section 19.3.7). For emission-reduction scenarios resulting in likely temperature increases in excess of 3.6°C above pre-industrial levels, successively more severe impacts result. Low temperature constraints are necessary to avoid significant increases in the impacts in less developed regions of the world and in polar regions, since many market sectors in developing countries are already affected below 2.6°C above pre-industrial levels (IPCC, 2007b, Section 19.3.7), and indigenous populations in high latitude areas already face significant adverse impacts.

It is possible to use stablization metrics (i.e. global mean temperature increase, concentrations in ppmv CO_2-eq or radiative forcing in W/m2) in combination with the mitigation scenarios literature to assess the cost of alternative mitigation pathways that respect a given equilibrium temperature, key vulnerability (KV) or impact threshold. Whatever the target, both early and delayed-action mitigation pathways are possible, including 'overshoot' pathways that temporarily exceed this level. A delayed mitigation response leads to lower discounted costs of mitigation, but accelerates the rate of change and the risk of transiently overshooting pre-determined targets (IPCC, 2007b, Section 19.4.2).

A strict comparison between mitigation scenarios and KVs is not feasible as the KVs in Table 3.11 refer to realized transient temperatures in the 21st century rather than equilibrium temperatures, but a less rigorous comparison is still useful. Avoidance of many KVs requires temperature change in 2100 to be below 2°C above 1990 levels (or 2.6°C above pre-industrial levels). Using equilibrium temperature as a guide, impacts or KV could be less than expected, for example if impacts

Table 3.10: *Properties of emissions pathways for alternative ranges of CO_2 and CO_2-eq stabilization targets. Post-TAR stabilization scenarios in the scenario database (see also Sections 3.2 and 3.3); data source: after Nakicenovic et al., 2006 and Hanaoka et al., 2006)*

Class	Anthropogenic addition to radiative forcing at stabilization (W/m^2)	Multi-gas concentration level (ppmv CO_2-eq)	Stabilization level for CO_2 only, consistent with multi-gas level (ppmv CO_2)	Number of scenario studies	Global mean temperature C increase above pre-industrial at equilibrium, using best estimate of climate sensitivity[c]	Likely range of global mean temperature C increase above pre-industrial at equilibrium[a]	Peaking year for CO_2 emissions[b]	Change in global emissions in 2050 (% of 2000 emissions)[b]
I	2.5-3.0	445-490	350-400	6	2.0-2.4	1.4-3.6	2000-2015	-85 to -50
II	3.0-3.5	490-535	400-440	18	2.4-2.8	1.6-4.2	2000-2020	-60 to -30
III	3.5-4.0	535-590	440-485	21	2.8-3.2	1.9-4.9	2010-2030	-30 to +5
IV	4.0-5.0	590-710	485-570	118	3.2-4.0	2.2-6.1	2020-2060	+10 to +60
V	5.0-6.0	710-855	570-660	9	4.0-4.9	2.7-7.3	2050-2080	+25 to +85
VI	6.0-7.5	855-1130	660-790	5	4.9-6.1	3.2-8.5	2060-2090	+90 to +140

Notes:

a. Warming for each stabilization class is calculated based on the variation of climate sensitivity between 2°C –4.5°C, which corresponds to the likely range of climate sensitivity as defined by Meehl *et al.* (2007,Chapter 10).

b. Ranges correspond to the 70% percentile of the post-TAR scenario distribution.

c. 'Best estimate' refers to the most likely value of climate sensitivity, i.e. the mode (see Meehl *et al.* (2007,Chapter 10) and Table 3.9

do not occur until the 22nd century, because there is more time for adaptation. Or they might be greater than expected, as temperatures in the 21st century may transiently overshoot the equilibrium, or stocks at risk (such as human populations) might be larger. Some studies explore the link between transient and equilibrium temperature change for alternative emission pathways (O'Neill and Oppenheimer, 2004; Schneider and Mastrandrea, 2005; Meinshausen, 2006).

It is transient climate change, rather than equilibrium change, that will drive impacts. More research is required to address the question of emission pathways and transient climate changes and their links to impacts.[25] In the meantime, equilibrium temperature change may be interpreted as a gross indicator of change, and given the caveats above, as a rough guide for policymakers' consideration of KV and mitigation options to avoid KV.

3.5.3 Information for integrated assessment of response strategies

Based upon a better understanding of the links between concentration levels, magnitude and rate of warming and key vulnerabilities, the next step in integrated assessment is to make informed decisions by combining information on climate science, impact analysis and economic analysis within a consistent analytical framework. These exercises can be grouped into three main categories depending on the way uncertainty is dealt with, the degree of complexity and multi-disciplinary nature of models and on the degree of ambition in terms of normative insights:

1. Assessment and sensitivity analysis of climate targets.
2. Inverse analyses to determine emission-reduction corridors (trajectories) to avoid certain levels of climate change or of climate impacts.
3. Monetary assessment of climate change damages.

Section 3.6 discusses how this information is used in economic analyses to determine optimal emission pathways.

3.5.3.1 Scenario and sensitivity analysis of climate targets

Probabilistic scenario analysis can be used to assess the risk of overshooting some climate target or to produce probabilistic projections that quantify the likelihood of a particular outcome. Targets for such analysis can be expressed in several different ways: absolute global mean temperature rise by 2100, rate of climate change, other thresholds beyond which dangerous anthropogenic interference (DAI) may occur, or additional numbers of people at risk to various stresses. For example, Arnell *et al.* (2002) show that such stresses (conversion of forests to grasslands, coastal flood risk, water stress) are far less at 550 ppmv than at 750 ppmv.

Recent Integrated Assessment Models (IAM) literature reflects a renewed attention to climate sensitivity as a key driver of climate dynamics (Den Elzen and Meinshausen, 2006; Hare and Meinshausen, 2006; Harvey, 2006; Keller *et al.*, 2006; Mastrandrea and Schneider, 2004; Meehl *et al.*, 2005; Meinshausen *et al.*, 2006, Meinshausen, 2006; O'Neill and Oppeinheimer, 2002, 2004; Schneider and Lane, 2004; Wigley, 2005). The consideration of a full range of possible climate sensitivity increases the probability of exceeding thresholds for specific DAI. It also magnifies the consequence of delaying mitigation efforts. Hare and Meinshausen (2006) estimate that each 10-year delay in mitigation implies an additional 0.2°C–0.3°C warming over a 100–400 year time horizon. For a climate sensitivity of 3°C, Harvey (2006) shows that immediate mitigation is required to constrain temperature rise to roughly

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[25] See IPCC (2007b, Section 19.4, Figure 19.2) and Meehl *et al*. (2007, Section 10.7) for further discussion of equilibrium and transient temperature increases in relation to stabilization pathways

Table 3.11: _Examples of key vulnerabilities (taken from IPCC, 2007b, Table 19.1)._

GMT range relative to 1990 (pre-industrial)	Geophysical systems Example: Greenland ice sheet[a] (IPCC, 2007b: 6.3; 19.3.5.2; IPCC, 2007a: 4.7.4; 6.4.3.3; 10.7.4.3; 10.7.4.4)	Global biological systems Example: terrestrial ecosystems[b] (IPCC, 2007b: 4.4.11; 1.3.4; 1.3.5)	Global social systems Example: water[c] (IPCC, 2007b: 3 ES; 3.4.3; 13.4.3)	Global social systems Example: food supply[c] (IPCC, 2007b: 5.6.1; 5.6.4)	Regional systems Example: Polar Regions[d] (IPCC, 2007b: 15.4.1; 15.4.2; 15.4.6; 15.4.7)	Extreme events Example: fire risk[e] (IPCC, 2007a: 7.3; IPCC, 2007b; 1.3.6)
>4 (>4-6)	Near-total deglaciation**	Large-scale transformation of ecosystems and ecosystem services** At least 35% of species committed to extinction (3°C)**	Severity of floods, droughts, erosion, water quality deterioration will increase with increasing climate change***	Further declines in global food production o/*	Continued warming likely to lead to further loss of ice cover and permafrost**. Arctic ecosystems further threatened**, although net ecosystem productivity estimated to increase (o)	Frequency and intensity likely to be greater, especially in boreal forests and dry peat lands after melting of permafrost**
3-4 (3.6-4.6)	Commitment to widespread** to near-total deglaciation* 2-7 m sea level rise over centuries to millennia	Global vegetation becomes net source of C above 2-3°C */**	Sea level rise will extend areas of salinization of ground water, decreasing freshwater availability in coastal areas***		While some economic opportunities will open up (e.g. shipping), traditional ways of life will be disrupted**	
2-3 (2.6-3.6)	_Lowers risk of near-total deglaciation_	Widespread disturbance, sensitive to rate of climate change and land use*** 20 to 50% species committed to extinction* _Avoids widespread disturbance to ecosystems and their services***, and constrains species losses_	Hundreds of millions people would face reduced water supplies (**)	Global food production peaks and begins to decrease o/* (1-3°C) _Lowers risk of further declines in global food production associated with higher temperatures*_		
1-2 (1.6-2.6)	Localized deglaciation (already observed due to local warming), extent would increase with temperature**	10-40% of species committed to extinction* _Reduces extinctions to below 20-50%*, prevents vegetation becoming carbon source*/**_ Many ecosystems already affected***	Increased flooding and drought severity** _Lowers risk of floods, droughts, deteriorating water quality*** and reduced water supplied for hundreds of millions of people**_	Reduced low latitude production*. Increased high latitude production* (1-3°C)	Climate change is already having substantial impacts on societal and ecological systems***	Increased fire frequency and intensity in many areas, particularly where drought increases**
0-1 (0.6-1.6)	_Lowers risk of widespread** to near-total deglaciation*_	_Reduces extinctions to below 10-30%*; reduces disturbance levels***_		Increased global production o/* _Lowers risk of decrease in global food production and reduces regional losses (or gains) o/*_	_Reduced loss of ice cover and permafrost; limits risk to Arctic ecosystems and limits disruption of traditional ways of life**_	_Lowers risk of more frequent and more intense fires in many areas**_

Notes:

Plain text shows predicted vulnerabilities in various temperature ranges for global annual mean temperature rise relative to 1990. Italic text shows benefits (or damage avoided) upon constraining temperature increase to lower compared to higher temperature ranges.

Confidence symbol legend: o low confidence; * medium confidence; ** high confidence; *** very high confidence

Excerpts from IPCC, 2007b, Table 19.1;

a. Refer to IPCC (2007b, Table 19.1) for further information, also concerning bio-geochemical cycles, West Antarctic Ice Sheet and Meridional Overturning Circulation

b. Refer to IPCC (2007b, Table 19.1) for further information, also concerning marine and freshwater ecosystems

c. Refer to IPCC (2007b, Table 19.1) for further information, also concerning infrastructure, health, migration and conflict, and aggregate market impacts

d. Refer to IPCC (2007b, Table 19.1) for further information and also for other regions

e. Refer to IPCC (2007b, Table 19.1) for further information, also concerning tropical cyclones, flooding, extreme heat, and drought

2°C above pre-industrial levels. Only in the unlikely situation where climate sensitivity is 1°C or lower would immediate mitigation not be necessary.[26] Harvey also points out that, even in the case of a 2°C threshold (above pre-industrial levels), acidification of the ocean would still occur and that this might not be considered safe.

Another focus of sensitivity analysis is on mitigation scenarios that overshoot and eventually return to a given stabilization or temperature target (Kheshgi, 2004; Wigley, 2005; Harvey, 2004; Izrael and Semenov, 2005; Kheshgi *et al*., 2005; Meinshausen *et al*., 2006). Schneider and Mastrandrea (2005) find that this risk of exceeding a threshold of 2ºC above pre-industrial levels is increased by 70% for an overshoot scenario stabilizing at 500 ppmv CO_2-eq (as compared to a scenario stabilizing at 500 ppmv CO_2-eq). Such overshoot scenarios are likely to be necessary if there is a decision to achieve stablization of GHG concentrations close to (or at) today's levels. They are indeed likely to lower the costs of mitigation but, in turn, raise the risk of exceeding such thresholds (Keller *et al*., 2006; Schneider and Lane, 2004) and may limit the ability to adapt by increasing the rate of climate change, at least temporarily (Hare and Meinshausen, 2006). O'Neill and Oppenheimer (2004) find that the transient temperature up to 2100 is equally, or more, controlled by the pathway to stabilization than by the stabilization target, and that overshooting can lead to a peak temperature increase that is higher than in the long-term (equilibrium) warming.

The last and important contribution of this approach is to test the sensitivity of results to carbon cycle and climate change feedbacks (Cox *et al*., 2000; Friedlingstein *et al*., 2001; Matthews, 2005) and other factors that may affect carbon cycle dynamics, such as deforestation (Gitz and Ciais, 2003). For example, carbon cycle feedbacks amplify warming (Meehl *et al*., 2007) and are omitted from most other studies that thus underestimate the risks of exceeding (or overshooting) temperature targets for a given effort of mitigation in the energy sector only. This could increase warming by up to 1°C in 2100, according to a simple model (Meehl *et al*., 2007). The amplification, together with further potential amplification due to feedbacks of uncertain magnitude, such as the potential release of methane from permafrost, peat bogs and seafloor clathrates (Meehl *et al*., 2007) are also not included in the analysis presented in Figure 3.38 and Table 3.10. This analysis reflects only known feedbacks for which the magnitude can be estimated and are included in General Circulation Models (GCMs). Hence, scenario and sensitivity analysis shows that the risks of exceeding a given temperature threshold for a given temperature target may be higher than that shown in Table 3.10 and Figure 3.38.

3.5.3.2 Inverse modelling and guardrail analysis

Inverse modelling approaches such as Safe Landing Analysis (Swart *et al*., 1998) and Tolerable Windows Approach (Toth, 2003), aim to define a guardrail of allowable emissions for sets of unacceptable impacts or intolerable mitigation costs. They explore how the set of viable emissions pathways is constrained by parameters such as the starting date, the rate of emission reductions, or the environmental constraints. They provide insights into the influence of short-term decisions on long-term targets by delineating allowable emissions corridor, but they do not prescribe unique emissions pathways, as per cost-effectiveness or costs-benefit analysis.

For example, Toth *et al*. (2002) draw on climate impact response functions (CIRFs) by Füssel and van Minnen (2001) that use detailed biophysical models to estimate regionally specific, non-monetized impacts for different sectors (i.e. agricultural production, forestry, water runoff and biome changes). They show that the business-as-usual scenario of GHG emissions (which resembles the SRES A2 scenario) to 2040 precludes the possibility of limiting the worldwide transformation of ecosystems to 30% or less, even with very high willingness to pay for the mitigation of GHG emissions afterwards. Some applications of guardrail analyses assess the relationship between emission pathways and abrupt change such as thermohaline circulation (THC) collapse (Rahmstorf and Zickfeld, 2005). The latter study concludes that stringent mitigation policy reduces the probability of THC collapse but cannot entirely avoid the risk of shutdown.

Corfee-Morlot and Höhne (2003) conclude that only low stabilization targets (e.g. 450 ppmv CO_2 or 550 ppmv CO_2-eq) significantly reduce the likelihood of climate change impacts. They use an inverse analysis to conclude that more than half of the SRES (baseline) emission scenarios leave this objective virtually out of reach as of 2020.

More generally, referring to Table 3.10, if the peaking of global emissions is postponed beyond the next 15 years to a time period somewhere between the next 15–55 years, then constraining global temperature rise to below 2°C above 1990 (2.6°C above pre-industrial levels) becomes unlikely (using 'best estimate' assumptions of climate sensitivity), resulting in increased risks of the impacts listed in Table 3.11 and discussed in Section 3.5.2.

3.5.3.3 Cost-benefit analysis, damage cost estimates and social costs of carbon

The above analysis provides a means of eliminating those emissions scenarios that are outside sets of pre-determined guardrails for climate protection and provides the raw material for cost-effectiveness analysis of optimal pathways for GHG emissions. If one wants to determine these pathways through a cost-benefit analysis it is necessary to assess the trade-off between mitigation, adaptation and damages, and consequently, to measure damages in the same monetary metric as mitigation

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[26] This is below the range accepted by IPCC Working Group I.

and adaptation expenditures. Such assessment can be carried out directly in the form of 'willingness to pay for' avoiding certain physical consequences.

Some argue that it is necessary to specify more precisely why certain impacts are undesirable and to comprehensively itemize the economic consequences of climate change in monetary terms. The credibility of such efforts has often been questioned, given the uncertainty surrounding climate impacts and the efficacy of societal responses to them, plus the controversial meaning of a monetary metric across different regions and generations (Jacoby, 2004). This explains why few economists have taken the step of monetizing global climate impacts. At the time of the TAR, only three such comprehensive studies had been published (Mendelsohn *et al*., 2000; Nordhaus and Boyer, 2000; and Tol, 2002a, 2002b). Their estimates ranged from negligible to 1.5% of the GDP for a global mean temperature rise of +2.5°C and Nordhaus and Boyer carefully warned: 'Along the economically efficient emission path, the long-run global average temperature after 500 years is projected to increase 6.2°C over the 1900 global climate. While we have only the foggiest idea of what this would imply in terms of ecological, economic, and social outcomes, it would make the most thoughtful people, even economists, nervous to induce such a large environmental change. Given the potential for unintended and potentially disastrous consequences….'

Progress has been made since the TAR in assessing the impacts of climate change. Nonetheless, as noted in Watkiss *et al*. (2005), estimates of the social costs of carbon (SCC) in the recent literature still reflect an incomplete subset of relevant impacts; many significant impacts have not yet been monetized (see also IPCC, 2007b; for SCC see IPCC (2007b, Section 20.6) and others are calibrated in numeraires that may defy monetization for some time to come. Existing reviews of available SCC estimates show that they span several orders of magnitude – ranges that reflect uncertainties in climate sensitivity, response lags, discount rates, the treatment of equity, the valuation of economic and non-economic impacts, and the treatment of possible catastrophic losses (IPCC, 2007b, Chapter 20). The majority of available estimates in the literature also capture only impacts driven by lower levels of climate change (e.g. 3°C above 1990 levels). IPCC (2007b) highlights available estimates of SCC that run from -3 to 95 US$ /tCO_2 from one survey, but also note that another survey includes a few estimates as high as 400 US$/t$CO_2$ (IPCC, 2007b, Chapter 20, ES and Section 20.6.1). However the lower boundary of this range includes studies where climate change is presumed to be low and aggregate benefits accrue. Moreover, none of the aggregate estimates reflect the significant differences in impacts that will be felt across different regions; nor do they capture any of the social costs of other greenhouse gases. A more recent estimate by Stern (2006) is at the high end of these estimates (at 85 US$/t$CO_2$) because an extremely low discount rate (of 0.1%) is used in calculating damages that include additional costs attributed to abrupt change and increases in global mean temperature for some scenarios in excess of 7°C (Nordhaus, 2006a; Yohe, 2006; Tol and Yohe, 2006). The long-term high-temperature scenarios are due to inclusion of feedback processes. IPCC (2007b) also highlights the fact that the social costs of carbon and other greenhouse gases could increase over time by 2–4% per year (IPCC, 2007b; Chapter 20, ES and Section 20.6.1).

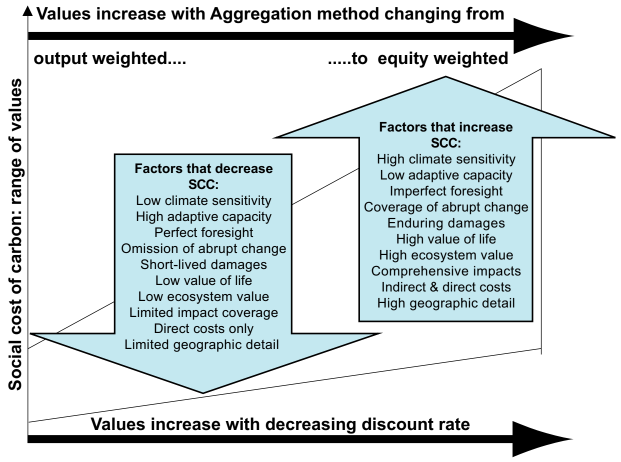

Figure 3.39: *Factors influencing the social costs of carbon.*

Source: Downing et al., 2005

For a given level of climate change, the discrepancies in estimates of the social costs of carbon can be explained by a number of parameters highlighted in Figure 3.39. These stem from two different types of questions: normative and empirical. Key normative parameters include the inter-temporal aggregation of damages through discount rates and aggregation methods for impacts across diverse populations within the same time period (Azar and Lindgren, 2003; Howarth, 2003; Mastrandrea and Schneider, 2004) and are responsible for much of the variation.

The other parameters relate to the empirical validity of their assessment, given the poor quality of data and the difficulty of predicting how society will react to climate impacts in a given sector, at a given scale in future decades. Pearce (2003) suggests that climate damages and SCC may be over-estimated due to the omission of possible amenity benefits in warmer climates or high-latitude regions (Maddison 2001) and possible agricultural benefits. However, overall, it is likely that current SCC estimates are understated due to the omission of significant impacts that have not yet been monetized (IPCC, 2007b, Chapters 19 and 20; Watkiss *et al*., 2005).

Key empirical parameters that increase the social value of damages include:

- *Climate sensitivity and response lag*. Equilibrium temperature rise for a doubling of CO_2, and the modelled response time of climate to such a change in forcing. Hope (2006) in his PAGE 2002 model found that, as climate sensitivity was varied from 1.5°–5°C, the model identified a strong correlation with SCC.

- *Coverage of abrupt or catastrophic changes*, such as the crossing of the THC threshold (Keller *et al*., 2000 and 2004; Mastrandrea and Schneider, 2001; Hall and Behl, 2006) or the release of methane from permafrost and the weakening of carbon sinks. The Stern Review (2006) finds that such abrupt changes may more than double the market damages (e.g. from 2.1% to 5% of global GDP) if temperatures were to rise by 7.4°C in 2200.
- *Inclusion and social value of non-market impacts*: what value will future generations place on impacts, such as the quality of landscape or biodiversity?
- *Valuation methods for market impacts such as the value of life.*
- *Adaptative capacity*: social costs will be magnified if climate change impacts fall on fragile economies.
- *Predictive capacity*: studies finding efficient adaptation assume that actors decide using perfect foresight (after a learning process; see Mendelsohn and Williams, 2004). Higher costs are found if one considers the volatility of climate signals and transaction costs. For agriculture, Parry *et al*. (2004) shows the costs of a mismatch between expectations and real climate change (sunk costs, value of real estates, and of capital stock).
- *Geographic downscaling*: using a geographic-economic cross-sectional (1990) database, Nordhaus (2006a) concludes that this downscaling leads to increased damage costs, from previous 0.7% estimates to 3% of world output for a 3°C increase in global mean temperature.
- *The propagation* of local economic and social shocks: this blurs the distinction between winners and losers. The magnitude of this type of indirect impact depends on the existence of compensation mechanisms, including direct assistance and insurance as well as on how the cross-sectoral interdependences and transition costs are captured by models (see Section 3.5.1).

The influence of this set of parameters, which is set differently in various studies, explains the wide range of estimates for the SCC.

In an economically-efficient mitigation response, the marginal costs of mitigation should be equated to the marginal benefits of emission reduction. The marginal benefits are the avoided damages for an additional tonne of carbon abated within a given emission pathway, also known as the SCC. As discussed in Section 3.6, both sides of this equation are uncertain, which is why a sequential or iterative decision-making framework, with progressive resolution of information, is needed. Despite a paucity of analytical results in this area, it is possible to draw on today's literature to make a first comparison between the range of SCC estimates and the range of marginal costs of mitigation across different scenarios. IPCC (2007b, Chapter 20) reviews ranges of SCC from available literature. Allowing for a range of SCC between 4–95 US\$/tCO_2 (14–350 US\$/tC from Tol (2005b) median and 95th percentile estimates) and assuming a 2.4% per year increase (IPCC, 2007b, Chapter 20), produces a range of estimates for 2030 of 8–189 US\$/tCO_2. The mitigation studies in this chapter suggest carbon prices in 2030 of 1–24 US\$/tCO_2-eq for category IV scenarios, 18–79 US\$/tCO_2-eq for category III scenarios, and 31–121 US\$/tCO_2-eq for category I and II scenarios (see Sections 3.3 and 3.6).

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

In selecting the most appropriate portfolio of policies to deal with climate change, it is important to distinguish between the case of 'certainty', where the ultimate target is known from the outset, and a 'probabilistic' case, where there is uncertainty about the level of a 'dangerous interference' and about the costs of greenhouse gas abatement.

In the case of certainty, the choice of emissions pathway can be seen as a pure GHG budget problem, depending on a host of parameters (discounting, technical change, socio-economic inertia, carbon cycle and climate dynamics, to name the most critical) that shape its allocation across time. The IPCC Second and Third Assessment Reports demonstrated why this approach is an oversimplification and therefore misleading. Policymakers 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 in the light of new information. The choice of short-term abatement rate (and adaptation strategies) involves balancing the economic risks of rapid abatement now and the reshaping of the capital stock that could later be proven unnecessary, against the corresponding risks of delay. Delay may entail more drastic adaptation measures and more rapid emissions reductions later to avoid serious damages, thus necessitating premature retirement of future capital stock or taking the risk of losing the option of reaching a certain target altogether (IPCC, 1996b, SPM).

The calculation of such short-term 'optimal' decisions in a cost-benefit framework assumes the existence of a metaphorical 'benevolent planner' mandated by cooperative stakeholders. The planner maximizes total welfare under given economic, technical and climate conditions, given subjective visions of climate risks and attitudes towards 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 averse to risk – that is, interested in avoiding worst-case outcomes – it would prefer hedging behaviour, implying more intense and earlier mitigation efforts.

A significant amount of material has been produced since the SAR and the TAR to upgrade our understanding of the parameters influencing the decisions about the appropriate timing of climate action in a hedging perspective. We review these recent developments, starting with insights from a body of literature drawing on analytical models or compact IAMs. We then assess the findings from the literature for short-term sectoral emission and mitigation estimates from top-down economy-wide models.

3.6.1 Insights into the choice of a short-term hedging strategy in the context of long-term uncertainty

There are two main ways of framing the decision-making approaches for addressing the climate change mitigation and adaptation strategies. They depend on different metrics used to assess the benefits of climate policies:

a. A cost-effectiveness analysis that minimizes the discounted costs of meeting various climate constraints (concentration ceiling, temperature targets, rate of global warming).
b. A cost-benefit analysis that employs monetary estimates of the damages caused by climate change and finds the optimal emissions pathway by minimizing the discounted present value of adaptation and mitigation costs, co-benefits and residual damages.

The choice between indicators of the mitigation benefits reflects a judgment on the quality of the available information and its ability to serve as a common basis in the decision-making process. Actually the necessary time to obtain comprehensive, non-controversial estimates of climate policy benefits imposes a trade-off between the measurement **accuracy** of indicators describing the benefits of climate policies (which diminishes as one moves down the causal chain from global warming to impacts and as one downscales simulation results) and their **relevance**, that is their capacity to translate information that policymakers may desire, ideally prior to a fully-informed decision. 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 monetary-metric, or valuation approach, the same expectation can be translated through using damage curves with *dangerous* thresholds. The only serious source of divergence between the two approaches is the discount rate. Within a cost-effectiveness framework, environmental constraints are not influenced by discounting. Conversely, in a cost-benefit framework, some benefits occur later than costs and thus have a lower weighting when discounted.

3.6.1.1 Influence of passing from concentration targets to temperature targets in a cost-effectiveness framework

New studies such as Den Elzen *et al*. (2006) confirm previous results. They establish that reaching a concentration target as low as 450 ppmv CO_2-eq, under even optimistic assumptions of full participation, poses significant challenges in the 2030–2040 timeframe, with rapidly increasing emission reduction rates and rising costs. In a stochastic cost-effectiveness framework, reaching such targets requires a significant and early emissions reduction with respect to respective baselines.

But concentration ceilings are a poor surrogate for climate change risks: they bypass many links from atmospheric chemistry to ultimate damages and they only refer to long-term implications of global warming. A better proxy of climate change impacts can be found in global mean temperature: every regional assessment of climate change impacts refers to this parameter, making it easier for stakeholders to grasp the stakes of global warming for their region; one can also take into account the rate of climate change, a major determinant of impacts and damages.

Therefore, with a noticeable acceleration in the last few years, the scientific community has concentrated on assessing climate policies in the context of climate stabilization around various temperature targets. These contributions have mainly examined the influence of the uncertainty about climate sensitivity on the allowable (short-term) GHGs emissions budget and on the corresponding stringency of the climatic constraints, either through sensitivity analyses (Böhringer *et al*., 2006; Caldeira *et al*., 2003; Den Elzen and Meinshausen, 2006; Richels *et al*., 2004) or within an optimal control frame-work (Ambrosi *et al*., 2003; Yohe *et al*., 2004).

On the whole, these studies reach similar conclusions, outlining the significance of uncertainty about climate sensitivity. Ambrosi *et al*. (2003) demonstrates the information value of climate sensitivity before 2030, given the significant economic regrets from a precautionary climate policy in the presence of uncertainty about this parameter. Such information might not be available soon (i.e. at least 50 years could be necessary – Kelly *et al*., 2000). Yohe *et al*. (2004) thus conclude: ‘uncertainty (about climate sensitivity) is the reason for acting in the near term and uncertainty cannot be used as a justification for doing nothing’.

A few authors analyze the trade-off between a costly acceleration of mitigation costs and a (temporary) overshoot of targets, and the climate impacts of this overshoot. Ambrosi *et al*. (2003) did so through a willingness to pay for not interfering with the climate system. They show that allowing for overshoot of an *ex-ante* target significantly decreases the required acceleration of decarbonization and the peak of abatement costs, but does not drastically change the level of abatement in the first period. However, the overshoot may significantly increase climate change damages as discussed above (see Section 3.5). Another result is that higher climate sensitivity magnifies the rate of warming, which in turn exacerbates adaptation difficulties, and leads to stringent abatement policy recommendations for the coming decades (Ambrosi, 2007). This result is robust for the choice of discount rate; uncertainty about the rate constraint is proven to be more important for short-term decisions than uncertainty about the magnitude of warming. Therefore, research should be aimed at better characterizing early climate change risks with a view to helping decision-makers in agreeing on a safe guardrail to limit the rate of global warming.

3.6.1.2 *Implications of assumptions concerning damage functions in cost-benefit analysis*

What is remarkable in cost-benefit studies of the optimal timing of mitigation is that the shape (or curvature) of the damage function matters even more than the ultimate level of damages – a fact long established by Peck and Teisberg (1995). With damage functions exhibiting smooth and regular damages (such as power functions with integer exponents or polynomial functions), GHG abatement is postponed. This is because, for several decades, the temporal rate of increase in marginal climate change damage remains low enough to conclude that investments to accelerate the rate of economic growth are more socially profitable that investing in abatement.

This result changes if singularities in the damage curve represent non-linear events. Including even small probabilities of catastrophic 'nasty surprises' may substantially alter optimal short-term carbon taxes (Mastrandea and Schneider, 2004; Azar and Lindgren, 2003). Many other authors report similar findings (Azar and Schneider, 2001; Howarth, 2003; Dumas and Ha-Duong, 2005; Baranzini *et al*., 2003), whilst Hall and Behl (2006) suggest a damage function reflecting climate instability needs to include discontinuities in capital stock and the rate of return on capital, and hysteresis with respect to heating and cooling – resulting in a non-convex optimization function such that economic optimization models can provide no solution. But these surprises may be caused by forces other than large catastrophic events. They may also be triggered by smooth climate changes that exceed a vulnerability threshold (e.g. shocks to agricultural systems in developing countries leading to starvation) or by policies that lead to maladaptations to climate change.

In the case of an irreversible THC collapse, Keller *et al*. (2004) point out another seemingly paradoxical result: if a climate catastrophe seems very likely within a short-term time horizon, it might be economically sound to accept its consequences instead of investing in expensive mitigation to avoid the inevitable. This shows that temporary overshoot of a pre-determined target may be preferable to bearing the social costs of an exaggerated reduction in emission, as well as the need to be attentive to 'windows of opportunity' for abatement action. The converse argument is that timely abatement measures, especially in the case of ITC, can reduce long-term mitigation costs and avoid some of the catastrophic events. In this respect, limited differences in GMT curves for different emissions pathways within coming decades are often misinterpreted. It does not imply that early mitigation activities would make no material difference to long-term warming. On the contrary, if the social value of the damages is high enough to justify deep emission cuts decades from now, then early action is necessary due to inertia in socio-economic systems. For example, one challenge is to avoid further build-up of carbon-intensive capital stock.

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

3.6.2.1 *Studies reporting short-term sectoral reduction levels*

While there are many potential emissions pathways to a particular stabilization target from a specific year, it is possible to define emissions trajectories based on short-term mitigation opportunities that are consistent with a given stabilization target. This section assesses scenario results (by sector) from top-down models for the year 2030, to evaluate the range of short-term mitigation opportunities in long-term stabilization scenarios. To put these identified mitigation opportunities in context, Chapter 11, Section 11.3 compares the short-term mitigation estimates across all of the economic sectors.

Many of the modelling scenarios represented in this section were an outcome from the Energy Modelling Forum Study 21 (EMF-21), which focused specifically on multi-gas strategies to address climate change stabilization (see De la Chesnaye and Weyant, 2006). Models that were evaluated in this assessment are listed in Table 3.12.

For each model, the resulting emissions in the mitigation case for each economic sector in 2030 were compared to projected emissions in a reference case. Results were compared across a range of stabilization targets. For more detail on the relationship between stabilization targets defined in concentrations, radiative forcing and temperature, see Section 3.3.2.

Key assumptions and attributes vary across the models evaluated, thus having an impact on the results. Most of the top-down models evaluated have a time horizon beyond 2050 such as AIM, IPAC, IMAGE, GRAPE, MiniCAM, MERGE, MESSAGE, and WIAGEM. Top-down models with a time horizon up to 2050, such as POLES and SGM, were also evaluated. The models also vary in their solution concept. Some models provide a solution based on inter-temporal optimization, allowing mitigation options to be adopted with perfect foresight as to what the future carbon price will be. Other models are based on a recursive dynamic, allowing mitigation options to be adopted based only on today's carbon price. Recursive dynamic models tend to show higher carbon prices to achieve the same emission reductions as in inter-temporal optimization models, because emitters do not have the foresight to take early mitigation actions that may have been cheaper (for more discussion on modelling approaches, refer to Section 3.3.3).

Three important considerations need to be remembered with regard to the reported carbon prices. First, these mitigation scenarios assume complete 'what' and 'where' flexibility (i.e.

Table 3.12: *Top-down models assessed for mitigation opportunities in 2030*

Model	Model type	Solution concept	Time horizon	Modelling team and reference
AIM (Asian-Pacific Integrated Model)	Multi-Sector General Equilibrium	Recursive Dynamic	Beyond 2050	NIES/Kyoto Univ., Japan Fujino *et al*., 2006.
GRAPE (Global Relationship Assessment to Protect the Environment)	Aggregate General Equilibrium	Inter-temporal Optimization	Inter-temporal Optimization	Institute for Applied Energy, Japan Kurosawa, 2006.
IMAGE (Integrated Model to Assess The Global Environment)	Market Equilibrium	Recursive Dynamic	Beyond 2050	Netherlands Env. Assessment Agency Van Vuuren *et al*., Energy Journal, 2006a. (IMAGE 2.2) Van Vuuren *et al*., Climatic Change, 2007. (IMAGE 2.3)
IPAC (Integrated Projection Assessments for China)	Multi-Sector General Equilibrium	Recursive Dynamic	Beyond 2050	Energy Research Institute, China Jiang *et al*., 2006.
MERGE (Model for Evaluating Regional and Global Effects of GHG Reduction Policies)	Aggregate General Equilibrium	Inter-temporal Optimization	Beyond 2050	EPRI & PNNL/Univ. Maryland, U.S. USCCSP, 2006.
MESSAGE-MACRO (Model for Energy Supply Strategy Alternatives and Their General Environmental Impact)	Hybrid: Systems Engineering & Market Equilibrium	Inter-temporal Optimization	Beyond 2050	International Institute for Applied Systems Analysis, Austria Rao and Riahi, 2006.
MiniCam (Mini-Climate Assessment Model)	Market Equilibrium	Recursive Dynamic	Beyond 2050	PNNL/Univ. Maryland, U.S. Smith and Wigley, 2006.
SGM (Second Generation Model)	Multi-Sector General Equilibrium	Recursive Dynamic	Up to 2050	PNNL/Univ. Maryland and EPA, U.S. Fawcett and Sands, 2006.
POLES (Prospective Outlook on Long-Term Energy Systems)	Market Equilibrium	Recursive Dynamic	Up to 2050	LEPII-EPE & ENERDATA, France Criqui et al., 2006.
WIAGEM (World Integrated Applied General Equilibrium Model)	Multi-Sector General Equilibrium	Inter-temporal Optimization	Beyond 2050	Humboldt University and DIW Berlin, Germany Kemfert *et al*., 2006.

Source: Weyant et al., 2006.

there is full substitution among GHGs and reductions take place anywhere in the world, according to the principle of least cost). Limiting the degree of flexibility in these mitigation scenarios, such as limiting mitigation only to CO_2, removing major countries or regions from undertaking mitigation, or both, will increase carbon prices, all else being equal. Second, the carbon prices of realizing these levels of mitigation increase in the time horizon beyond 2030. See Figure 3.25 for an illustration of carbon prices across longer time horizons from top-down scenarios. Third, at the economic sector level, estimated emission reduction for all greenhouse gases varies significantly across the different model scenarios, in part because each model uses sector definitions specific to that type of model.

Across all the models, the long-term target in the stabilization scenarios could be met through the mitigation of multiple greenhouse gases (CO_2, CH_4, N_2O and high-GWP gases). However the specific mitigation options and the treatment of technological progress vary across the models. For example, only some of the models include carbon capture and storage as a mitigation option (GRAPE, IMAGE, IPAC, MiniCAM, and MESSAGE). Some models also include forest sinks as a mitigation option. The model results shown in Table 3.13 do not include forest sinks as a mitigation option, while the results shown in Table 3.14 do include forest sinks, as described in further detail below.

Table 3.13 illustrates the amount of global GHG mitigation reported by sector for the year 2030 across a range of multi-gas stabilization targets. Across the higher *Category IV* stabilization target scenarios, emission reductions of 3–31% from the reference case emissions across all greenhouse gases can be achieved for a carbon price of 2–57 US\$/tCO_2-eq. The results from the POLES models fall into the higher end of the price range, in part due to the recursive dynamic nature of the model, and also due to its shorter time horizon over which to plan. The results from the GRAPE model fall into the lower end of the price range, which is the only inter-temporally optimizing model shown in the higher stabilization scenarios. In the GRAPE results, only 3% of the emissions are reduced by 2030, implying that the majority of the mitigation necessary to meet the target is undertaken beyond 2030. In scenarios

Table 3.13: *Global emission reductions from top-down models in 2030 by sector for multi-gas scenarios.*

Model		POLES	IPAC	AIM	GRAPE	MiniCAM	SGM	MERGE	WIAGEM
Stabilization category		Category VI						Category II	Category I
Stabilization target		550 ppmv	550 ppmv	4.5 W/m² from pre-Industrial	4.5 W/m² from pre-Industrial	4.5 W/m² from pre-Industrial	From MiniCAM trajectory	3.4 W/m² from pre-Industrial	2% from pre-Industrial
Carbon price in 2030 (2000 US$/tCO$_2$-eq)		57	14	29	2	12	21	192	9
Reference emissions 2030 Total all gases (GtCO$_2$-eq)		53.0	55.3	49.4	57.0	54.2	53.5	47.2	43.1
Sector Mitigation estimates in 2030 (total all gases GtCO$_2$-eq)	Energy supply: electric	9.5	6.4	5.2	0.5	7.3	3.1	9.5	7.0
	Energy supply: non-electric	3.0	0.6	1.1	0.0	1.5	1.6[a]	3.2	1.7
	Transportation demand	0.5	0.8	0.5	0.1	0.2	0.4[a]	Included in Energy supply	Included in Energy supply
	Buildings demand	1.0	0.6	0.5	0.4	0.3	Included in Energy supply	Included in Energy supply	Included in Energy supply
	Industry demand	1.9	1.2	0.5	Included in Buildings demand	1.7	Included in Energy supply	Included in Energy supply	Included in Energy supply
	Industry production	0.8	0.0	0.8	0.3[h]	0.2[d]	1.7[a]	3.6[b]	3.6
	Agriculture	(0.2)	(1.0)[e]	2.0	0.6	0.3	1.7	Included in industry production	1.1
	Forestry	No mitigation options modelled						No mitigation options modelled	
	Waste management	Included in another sector	0.0[g]	Included in Buildings demand	0.0[f]	0.3	0.5	Included in Industry production	No mitigation options modelled
Global total		16.4	8.7	10.6	1.9	11.9	11.2[a]	16.3	15.5[c]
Mitigation as % of reference emissions		31%	16%	21%	3%	22%	21%	35%	35%

Notes:

[a] SGM sector mitigation estimates for Transportation Demand and Industry Production are not complete global representation due to varying levels of regional aggregation.

[b] MERGE sector mitigation estimates for Industry Production, Agriculture, and Waste Management are aggregated. No Forestry mitigation options were modelled.

[c] WIAGEM sector mitigation estimates do not sum to global total due to the breakout of the household and chemical sectors.

[d] MiniCAM CO$_2$ mitigation from Industrial Production is accounted for in the Industry Demand.

[e] Higher IPAC Agriculture emissions in the stabilization scenario than in the reference case reflects the loss of permanent forest due to growing bioenergy crops.

[f] GRAPE Waste sector mitigation reflects only GDP activity factor changes in 2030, and reflects emission factor reductions in later years.

[g] IPAC Waste sector cost-effective mitigation options are included in the baseline.

[h] GRAPE CO$_2$ from cement production is included in Buildings Demand.

with lower *Category I and II* stabilization targets, higher levels of short-term mitigation are required to achieve the target in the long run, resulting in a higher range of prices. Emission reductions of approximately 35% can be achieved at a price of 9–92 US$/tCO$_2$-eq.

Several of the models included in the EMF-21 study also ran multi-gas scenarios that included forest sinks as a mitigation option. Table 3.14 shows the 2030 mitigation estimates for these scenarios that model net land-use change (including forest carbon sinks) as a mitigation option. When terrestrial sinks are modelled as a mitigation option, it can lessen the pressure to mitigate in other sectors. Further discussion of forest sequestration as a mitigation option is presented in Section 3.3.5.5. Across the higher *Category IV* stabilization target scenarios, emission reductions of 4–24% from the reference case emissions across all greenhouse gases can be achieved at a price of 2–21 US$/tCO$_2$-eq. In scenarios with lower *Category I and II* stabilization targets, emission reductions of 26–40% can be achieved at a price of 31–121 US$/tCO$_2$-eq.

3.6.2.2 Assessment of reduction levels at different marginal prices

To put these identified mitigation opportunities into context they will be compared with mitigation estimates from bottom-up

Table 3.14: *Global emission reductions from top-down models in 2030 (by sector) for multi-gas plus sinks scenarios.*

Model		**GRAPE**	**IMAGE 2.2**	**IMAGE 2.3**	**MESSAGE**	**MESSAGE**	**IMAGE 2.3**	**IMAGE 2.3**	**MESSAGE**
Stabilization categories		*Category VI*					**Category III**	**Category I/II**	
Stabilization target		4.5 Wm2 from pre-Industrial	4.5 Wm2 from pre-Industrial	4.5 Wm2 from pre-Industrial	B2 scenario, 4.5 Wm2 from pre-Industrial	A2 scenario, 4.5 Wm2 from pre-Industrial	3.7 Wm2 from pre-Industrial	3.0 Wm2 from pre-Industrial	B2 scenario, 3.0 Wm2 from pre-Industrial
Carbon price in 2030 (2000 US$/tCO$_2$-eq)		2	18	21	6	15	50	121	31
Reference emissions 2030 Total all gases (GtCO$_2$-eq)		57.0	65.5	59.7	57.8	70.9	59.7	59.7	57.8
Sector mitigaiton estimates in 2030 (total all gases GtCO$_2$-eq)	Energy supply: electric	0.5	2.4	1.7	1.1	7.3	3.9	8.7	4.3
	Energy supply: non-electric	0.0	2.2	1.6	0.5	3.5	2.3	3.7	2.2
	Transportation demand	0.0	1.3	0.7	0.3	1.0	1.5	2.8	2.2
	Buildings demand	0.3	0.8	0.3	0.5	1.2	0.5	1.0	1.4
	Industry demand	Included in Buildings demand	0.8	0.5	0.1	0.4	1.6	3.2	0.8
	Industry production	0.1[b]	1.1	0.8	0.3	0.6	1.1	2.0	0.8
	Agriculture	0.3	0.7	0.6	0.6	1.5	1.0	1.2	1.7
	Forestry	0.9	1.4	0.3	0.0	0.2	0.2	0.2	0.6
	Waste management	0.0[a]	0.7	1.0	0.9	1.1	1.0	1.1	0.9
Global total		2.1	11.5	7.6	4.4	16.8	13.0	24.0	15.0
Mitigation as % reference emissions		4%	18%	13%	8%	24%	40%	40%	26%

Notes:

[a] GRAPE Waste sector mitigation reflects only GDP activity factor changes in 2030, and reflects emission factor reductions in later years.

[b] GRAPE CO$_2$ from cement production is included in Buildings Demand.

models. Chapters 4 through 10 describe mitigation technologies available in specific economic sectors. Chapter 11, Section 11.3 compares the short-term mitigation estimates across all of the economic sectors for selected marginal costs levels (20, 50 and 100 US$/tCO$_2$-eq). For that purpose, we have plotted the permit price and (sectoral) reduction levels of the different studies. These plots have been used to explore whether the combination of the studies suggests certain likely reduction levels at the three target levels of 20, 50 and 100 US$/tCO$_2$-eq. As far more studies were available that reported economy-wide reduction levels than the ones that provided sectoral information, we were able to use a formal statistical method for the former. For the latter, a statistical method was also applied, but outcomes have been used with more care.

Economy-wide reduction levels

Figure 3.40 shows the available data from studies that report economy-wide reduction levels (multi-gas) and permit prices. The data has been taken from the emission scenario database (Hanaoka *et al.*, 2006; Nakicenovic *et al.*, 2006) – and information directly reported in the context of EMF-21 (De la Chesnaye and Weyant, 2006) and IMCP (Edenhofer *et al.*, 2006). The total sets suggest some form of a relationship with studies reporting higher permit prices: also, in general, reporting higher reduction levels.

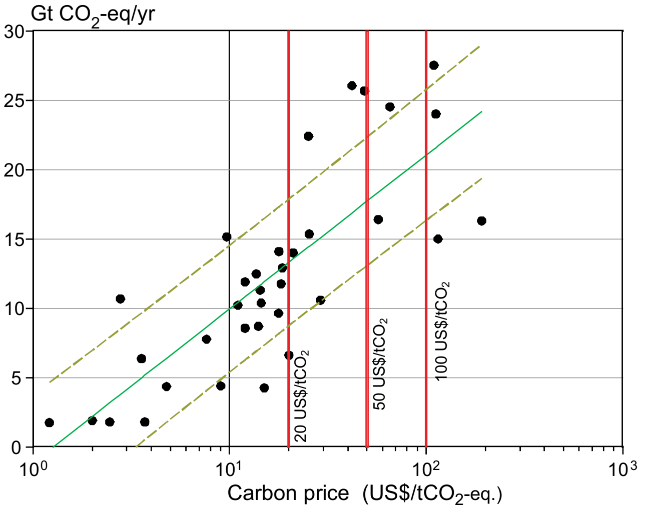

Figure 3.40: *Permit price versus level of emission reduction – total economy in 2030 (the natural logarithm of the permit price is used for the x-axis). The uncertainty range indicated is the 68% interval.*

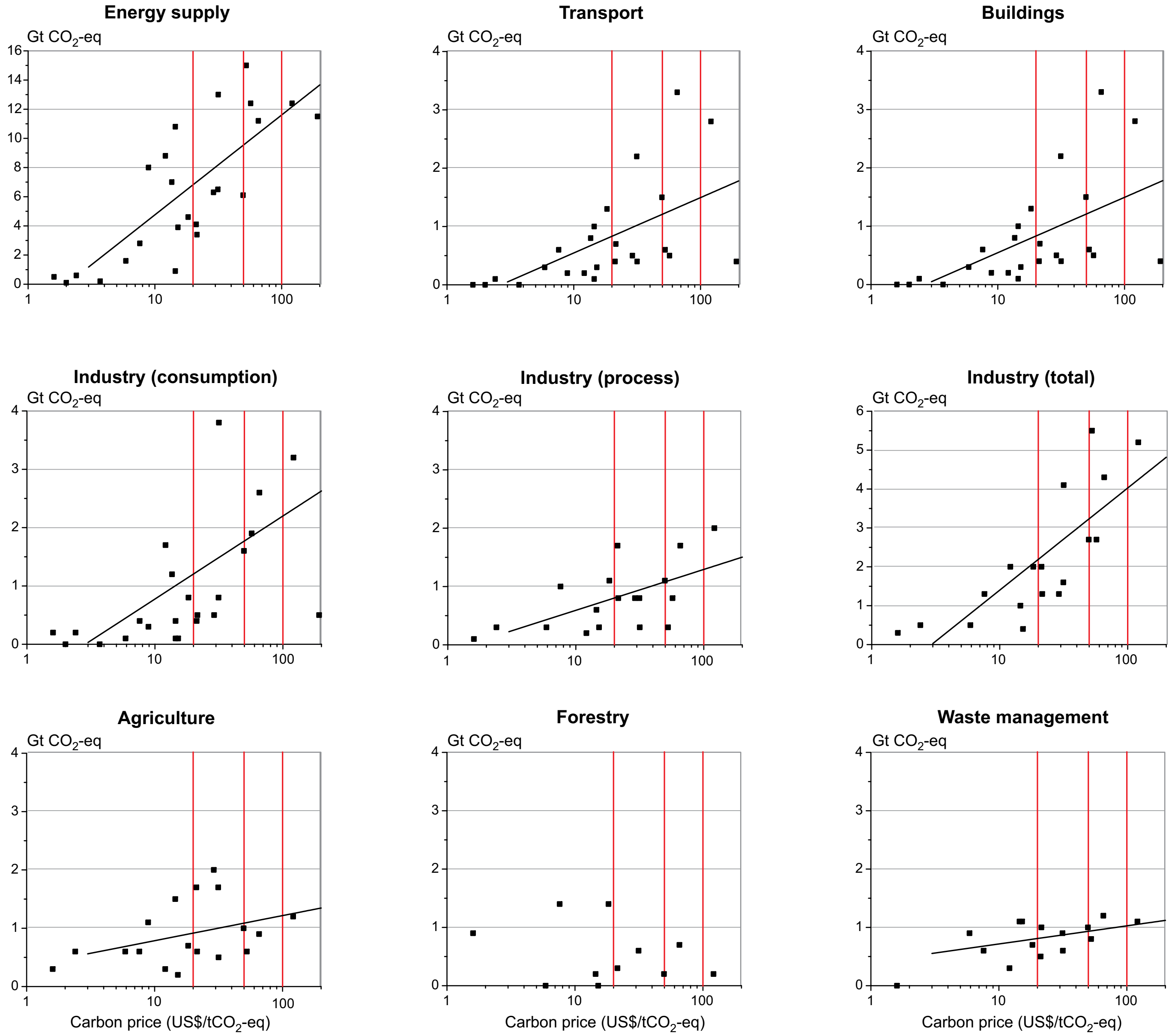

Figure 3.41: *Permit price versus emission reduction level – several sectors in 2030 (vertical lines indicate levels at 20, 50 and 100 US$/t$CO_2$).*

Obviously, a considerable range of results is also found – this is a function of factors such as:

- Model uncertainties, including technology assumptions and inertia.
- Assumed baseline developments.
- The trajectory of the permit price prior to 2030.

The suggested relationship across the total is linear if permit prices are plotted on a logarithmic scale as shown in Figure 3.40. In other words, the relationship between the two variables is logarithmic, which is a form that is consistent with the general form of marginal abatement curves reported in literature: increasing reduction levels for higher prices, but diminishing returns at higher prices as the reduction tends to reach a theoretical maximum. The figure not only shows the best-guess regression line, but also 68% confidence interval. The latter can be used to derive the 68 percentile interval of the reduction potential for the 20 and 100 US$/t$CO_2$-eq price levels, which are 13.3 ± 4.6 GtCO_2-eq/yr and 21.5 ± 4.7 GtCO_2-eq/yr, respectively.

Sectoral estimates

A more limited set of studies reported sectoral reduction levels. The same plot as Figure 3.40 has been made for the sectoral data (see Figure 3.41), again plotting the logarithm of the permit price against emission reduction levels. The data here are directly taken from Table 3.13 and Table 3.14. As less data are available, the statistical analysis becomes less robust. Nevertheless, for most sectors, a similarly formed relationship was found across the set of studies as for the economy-wide potential (logarithmic relationship showing increasing reduction

Table 3.15: *Reduction potential at various marginal prices, averages across different models (low and high indicate one standard deviation variation).*

	20 US$/tCO$_2$-eq		50 US$/tCO$_2$-eq		100 US$/tCO$_2$-eq	
	Low	High	Low	High	Low	High
Energy supply	3.9	9.7	6.7	12.4	8.7	14.5
Transport	0.1	1.6	0.5	1.9	0.8	2.5
Buildings	0.2	1.1	0.4	1.3	0.6	1.5
Industry	1.2	3.2	2.2	4.3	3.0	5.0
Agriculture	0.6	1.2	0.8	1.4	0.9	1.5
Forestry	0.2	0.8	0.2	0.8	0.2	0.8
Waste	0.7	0.9	0.8	1.0	0.9	1.1
Overall[1]	8.7	17.9	13.7	22.6	16.8	26.2

Note: 1) The overall potential has been estimated separately from the sectoral totals.

levels at relatively low prices, and a much slower increase at higher prices). As expected, in several sectors, the spread across models in the 2030 set is larger than in the economy-wide estimates.

In general, a relatively strong relationship is found in the sectors for energy supply, transport, and industrial energy consumption. The relationship between the price and emission reduction level is less clear in other sectors – and more-or-less absent for the limited reported data on the forestry sector. It should be noted here that definitions across studies may be less well-defined – and also, forest sector emissions may actually increase in mitigation scenarios as a result of net deforestation due to bio-energy production.

It should be noted that emission data (and thus also reduction levels) are reported on a 'point of emission basis' (emissions are reported for the sectors in which the emissions occur). For example, the efficiency improvements in end-use sectors for electricity lead to reductions in the energy supply sector. Likewise, using bio-energy leads to emission reductions in the end-use sectors, but at the same time (in some models) may lead to increases in emissions for forestry, due to associated land-use changes. The latter may explain differences in the way that data from top-down models are represented elsewhere in this report, as here (in most cases) only the emission changes from mitigation measures in the forestry sector itself are reported. It also explains why the potential in some of the end-use sectors is relatively small, as emission reductions from electricity savings are reported elsewhere.

Reported estimates

On the basis of the available data, the following ranges have been estimated for the reduction potential at a 20, 50 and 100 US$/tCO$_2$-eq price (Table 3.15). As estimates have been made independently, the total of the different sectors does not add up to the overall range (as expected, the sum of the sectors gives a slightly wider range).

The largest potential is found in energy supply – covering both the electricity sector and energy supply – with a relatively high capability of responding to permit prices. Relatively high reduction levels are also found for the industry sector. Relatively small reduction levels are reported for the forestry sector and the waste management sector.

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